DEPARTMENT OF INFORMATION TECHNOLOGY DELHI TECHNOLOGICAL UNIVERSITY (Formerly Delhi College of Engineering) Bawana Road, Delhi-110042

Reliability Assessment of Smart Grid

PROJECT REPORT

SUBMITTED BY

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SUBMITTED TO

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CANDIDATE'S DECLARATION

I hereby declare that the work presented in this report entitled "**Reliability Assessment of Smart Grid"** in fulfilment of the requirement for the assessment of 3rd semester in Information Technology, in Object Oriented Programming submitted in Information Technology Department at DELHI TECHNOLOGICAL UNIVERSITY, New Delhi, is an authentic record of my own work carried out during my degree under the guidance of Prof Swati Sharda.

The work reported in this has been submitted by me for an award of 3rd Semester assessment.

Date: 15th October , 2020
Place: New Delhi

Ashwani Kumar (2K19/IT/033)

Avishek Bhagat (2K19/IT/035)

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CERTIFICATE

On the basis of the Major Project submitted by Ashwani Kumar (2K19/IT/033), and Avishek Bhagat (2K19/IT/035) students of B.Tech. (IT). I hereby certify that the project titled "**Reliability Assessment of Smart Grid**" which has been submitted to Department of Information Technology, Delhi Technological University in partial fulfilment of the requirement for the assessment of 3rd semester in Information Technology is an original contribution with existing knowledge and faithful record of work carried out by them under my guidance and supervision.

Place: -Delhi

Date: - 5th Nov 2020

Mrs. Swati Sharda

Delhi Technological University

ACKNOWLEDGMENT

The success and final outcome of this project required a lot of guidance and assistance from many people and we all are extremely privileged to have got all this along the completion of our project.

All that we have done is due to such assistance and we would not forget to thank them.

As the completion of this project gave us much pleasure, we would like to express our special thanks of gratitude to Mrs. Swati Sharda at Delhi Technological University who gave us the opportunity to do this Wonderful project. I would also like to extend my gratitude to all those who have directly and indirectly guided me in completing this project .

Secondly, we would like to thank our parents and friends who have helped us with their suggestions and guidance that has been very helpful in finalizing this project.

Many people, especially our classmates have helped us a lot by giving their suggestions on our project which gave us an inspiration to improve the quality of the project.

ABSTRACT

Modern societies are more and more dependent on the secure and reliable functioning of Critical Infrastructures (CI), such as power systems. However, with widely deployed Industrial Communication Technology (ICT) networks into these CIs, for the purpose of a more observable and controllable physical environment, cyber components' failures introduced another layer of uncertainty in the assessment of the reliability of the CI systems. We have introduced an analytical method, based on the Complex Network Theory (CNT), to assess the risk of the Smart Grid failure due to communication network malfunction, associated with latency and ICT network reliability. Firstly, the communication architecture is modelled using a two-step CNT framework – an Operation Graph (OG) in step one and a Reliability Graph (RG) in step two. Secondly, the latency of data packets and the reliability of each communication device are incorporated into the model to identify the reliability of all operational communication paths. Then, the risk of Smart Grid failure due to the communication network malfunction is quantified using a System Reliability Index (SRI). Next, sensitivity analysis is performed to assess the importance of each communication network component using two innovative Importance Measures (IM), namely System Reliability Deterioration Worth (SRDW).
Then the effect of adding PV(Photo-voltaic) sources to the grid is quantified on the overall system reliability. We simulate the effect of gradually injecting limited amount of real power at the load buses of the IEEE 14 bus system.

TABLE OF CONTENT

INTRODUCTION

SMART GRIDS

A smart grid is an electricity network enabling a two-way flow of electricity and data with digital communications technology enabling to detect, react and pro-act to changes in usage and multiple issues. Smart grids have self-healing capabilities and enable electricity customers to become active participants.

A smart grid serves several purposes and the movement from traditional electric grids to smart grids is driven by multiple factors, including the deregulation of the energy market, evolutions in metering, changes on the level of electricity production, decentralization (distributed energy*)*, the advent of the involved ‘prosumer’, changing regulations, the rise of microgeneration and (isolated) microgrids, renewable energy mandates with more energy sources and new points where and purposes for which electricity is needed (e.g. electrical vehicle charging points).

FEATURES OF SMART GRID

- Smart grid has several positive features that give direct benefit to consumers:
- Real time monitoring.
- Automated outage management and faster restoration.
- Dynamic pricing mechanisms.
- Incentivize consumers to alter usage during different times of day based on pricing signals.
- Better energy management.
- In-house displays.
- Web portals and mobile apps.
- Track and manage energy usage.
- Opportunities to reduce and conserve electricity etc.
- Smart Grid will also facilitate distributed generation, especially the roof top solar generation, by allowing movement and measurement of energy in both directions using control systems and net metering that will help “prosumers” i.e. the consumers who both produce and consume electricity, to safely connect to the grid.

BENEFITS OF SMART GRID DEPLOYMENTS

- Several groups of the society are provided with multiple benefits through the Smart Grid implementations. Such include utility, customers and the regulators while some of the benefits include:
- Reduction of T&D losses.
- Peak load management, improved QoS and reliability.
- Reduction in power purchase cost.
- Better asset management.
- Increased grid visibility and self-healing grids.
- Renewable integration and accessibility to electricity.
- Increased options such as ToU tariff, DR programs, net metering.
- Satisfied customers and financially sound utilities etc.

THE SMART GRID COMPARED TO TRADITIONAL ELECTRICITY GRIDS – THE ESSENCE AND DIFFERENCES

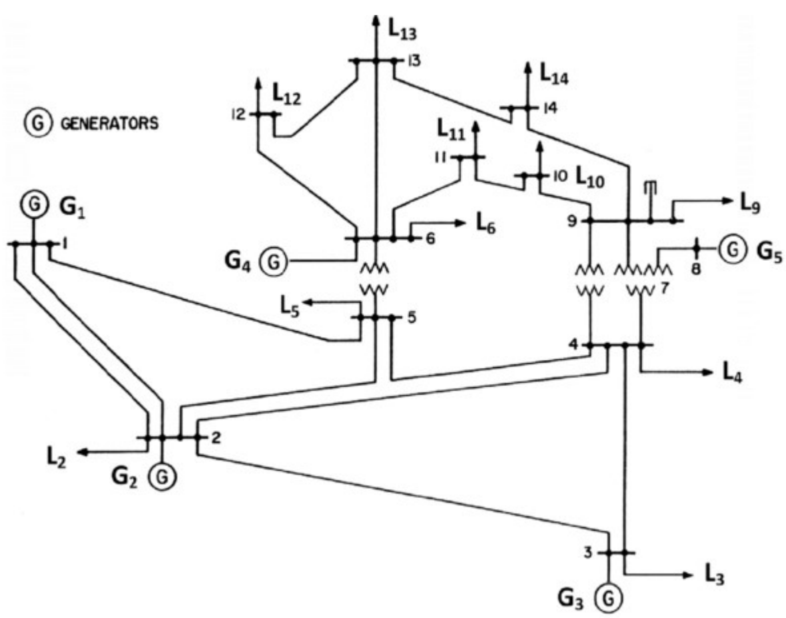
Traditional electricity grids had almost no storage capabilities, are demand-driven and have a hierarchical structure. In an electricity network voltage is gradually lowered so the electricity can be used by these different consumers: from transmission voltage levels to distribution voltage levels to service voltage levels (in reality it's both gearing up and down and thus a bit more complex).

In smart grids, self-healing capabilities enable to automatically detect and respond to grid problems and to ensure quick recovery after disturbances.

IEEE 14-BUS SYSTEM

IEEE bus systems are used by researchers to implement new ideas and concepts. The system consists of loads, capacitor banks, transmission lines, and generators.

The IEEE 14-bus test case represents a simple approximation of the American Electric Power system as of February 1962. It has 14 buses, 5 generators, and 11 loads.



PROJECT DESCRIPTION

COMPLEX NETWORK MODEL

A. Operation Graph and Reliability Graph

The first step to evaluate the risk of misoperation of ICT network structure is to identify the event to be analyzed and its consequences. To comprehensively analyze the risk of the ICT network, all faulty or hazardous events should be considered. For demonstration purposes, this paper considers only one event at a time, and all consequences equal to one. It can equally be applied though, to include the possibilities of occurrence of other events and associated consequence values.

The structure of the ICT network is mapped onto an Operation Graph (OG) G_O, which is a pair of sets (V_O, E_O), and a Reliability Graph (RG) G_R, which is a pair of sets (V_R, E_R). Based on the time constraints of a power system control action, critical paths can be identified in the OG. The number affiliated with each edge is edge weight W_e, and the number associated with each vertex is vertex weight W_v, which represent the latency (or "delay") that occurs at each communication channel and node, respectively.

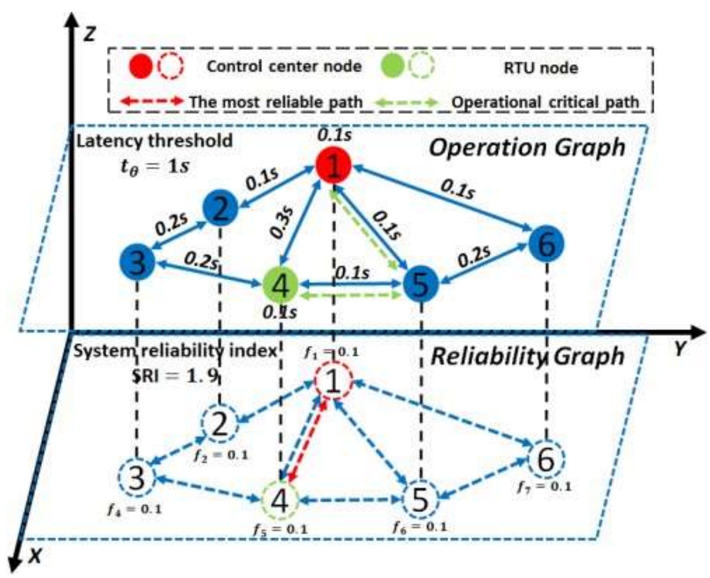
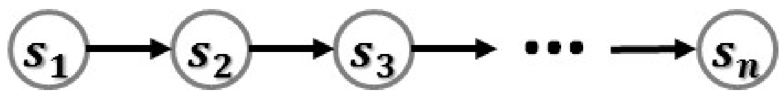


Illustration of the operation graph and reliability graph (the numerical values shown are for the illustration purposes only)

The reliability of an N-node route from a source node to a target node is the product of the reliability of each node along the route, assuming each node fails independently with a failure rate f_{sn}, as given in (2).

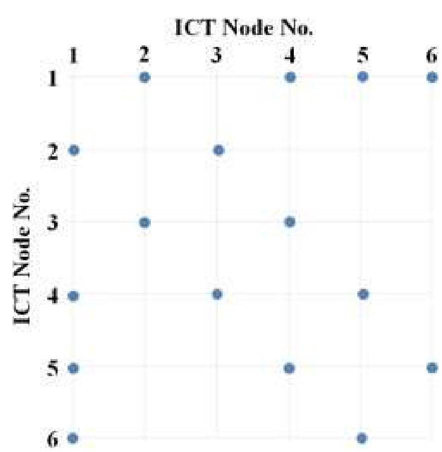
$$R = \prod_{n=1}^{N} r_{s_n} = \prod_{n=1}^{N} (1 - f_{s_n}) \qquad (2)$$

in which r_{s_n} and f_{s_n} are the reliability and failure rate of node s_n, respectively.

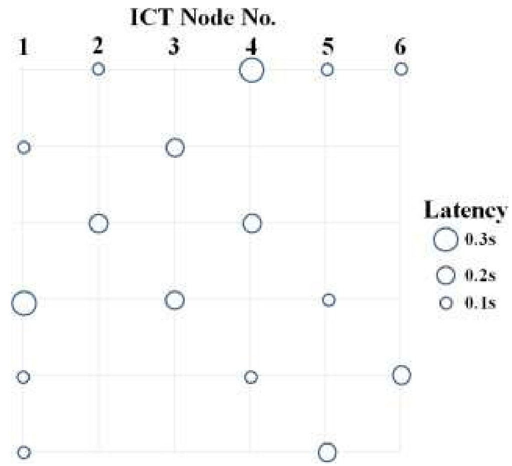


B. Operation Matrix and Reliability Matrix

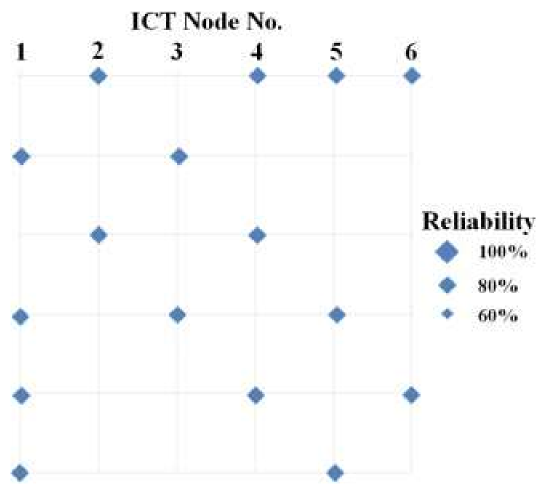
Let matrix C be the mathematical representation of the topology of a graph. Its entry c_{hj} = 1 if there is a link between node h and j; otherwise if c_{hj} = 0, node h and j have no direct connections. Figure 3 a) shows the connectivity of the example graph of Fig. 1 represented by blue dots (i.e. "1s"). Fig. 3 b) shows the corresponding operation matrix O, where the entry o_{hj} is represented by blue circles whose sizes correspond to the latency of the connection – the larger the size, the larger the latency. Fig. 3 c) presents the reliability matrix R of the example graph. Similarly, the size of the diamond in Fig. 3 c) corresponds to the reliability value of the link represented by entry r_{hj}. Symmetric patterns can be observed between the upper part and the lower diagonal matrix in each of these matrices, as it is assumed in this paper that all communication technologies used in the ICT network are full-duplex, and the forward and backward latencies between two nodes are identical.



a)



b)



c)

Matrix representation of the example graph a) Connection matrix; b) Operation matrix; c) Reliability matrix

SYSTEM RELIABILITY INDEX

A novel CNT- based index, System Reliability Index (SRI) is introduced in this paper, and its calculation procedure is presented in Fig. 4. First, the depth first search (DFS) is applied to find all available routes between source(s) and target(s) for a complete power system monitoring and control action. Then, paths that meet the latency criteria required for a specific type of power system application are screened out, denoted as n_c. Next, the sum of the natural logarithm of the reliability value of each cut r_{hj} within the path n_x is calculated for all $n_x \in n_c$. Finally, the SRI of the system is calculated by

$$SRI = \frac{1}{N(N-1)} \sum_{x=1}^{M} \frac{1}{\sum_{h,j \in V_R, h \neq j} - \ln r_{hj}}$$

SRDW(SYSTEM RELIABILITY DETERIORATION WORTH)

Commonly used criticality measures in industrial practices for Nuclear Power Plants are Risk Reduction Worth (RRW) and Risk Achievement Worth (RAW) , to evaluate the significance of a system component's failure, and the influence of the improvement of the component's reliability to one to the overall system reliability, respectively.

$$SRDW = SRI(1f)/SRI$$

ANALYSING EFFECT OF PV SOURCES TO SYSTEM

We will be using the Newton Raphson Power flow analysis for measuring the effect of PV sources.

<u>The following assumptions were made for the DG sources that we added to the system.</u>

• The DG source injects only real power to the grid. No reactive power is injected at this point.
• The amount of power injected by the DG source is relatively small compared to the power generated by the conventional sources. In this experiment, the power injected by each DG source ranged between 2-14MW, which represents less than 10% of the capability of the main generator connected at bus 1.
• The power injected by the DG source was assumed constant. For intermittent sources like solar and wind power, the intermittencies in the source usually cause the output of such source not to be constant at all times. This assumption can be justified for now, as our goal is to get an idea of the effect of adding DG sources with a certain amount of averaged power input. More detailed models for the DG sources will be used when greater detail is needed.

TABLE I
DEFINING LINE CAPACITIES FOR THE IEEE 14 BUS SYSTEM

Line Number	From Bus	To Bus	Normal Operation	Set Capacity
L1	1	2	159.3054	238.9581
L2	1	5	75.6087	113.41305
L3	2	3	73.3241	109.98615
L4	2	4	56.2127	84.31905
L5	2	5	41.5327	62.29905
L6	3	4	24.0783	36.11745
L7	4	5	63.6703	95.50545
L8	4	7	30.2946	45.4419
L9	4	9	16.1728	24.2592
L10	5	6	45.8171	68.72565
L11	6	11	8.1699	12.25485
L12	6	12	8.1786	12.2679
L13	6	13	19.1591	28.73865
L14	7	8	17.6235	26.43525
L15	7	9	28.6627	42.99405
L16	9	10	6.7178	10.0767
L17	9	14	10.094	15.141
L18	10	11	4.1387	6.20805
L19	12	13	1.7817	2.67255
L20	13	14	5.9081	8.86215

CODE SNIPPETS

Plotting Graph and Calculating SRI & SRDW

digraph.mlx

```
g=graph({'1','1','2','2','2','3','4','4','4','5','6','6','6','7','7','9','9','10','12','13'} ...
      ,{'2','5','3','4','5','4','5','9','7','6','12','13','11','8','9','10','14','11','13','14'})

% 3 label = 5 node
% 4 label = 3 node
% 5 label = 4 node
% 6 label = 9 node
% 8 label = 6 node
% 9 label = 12 node
% 10 label = 13 node
% 12 label = 8 node
% 13 label = 10 node

p=plot(g)

n2 = neighbors(g,2)
highlight(p,[2 3],'EdgeColor','green')
highlight(p,[2 5 3],'LineWidth',3)
highlight(p,[2 5 3],'EdgeColor','red')
highlight(p,[2 1 3],'LineWidth',3)
highlight(p,[2 1 3],'EdgeColor','red')
highlight(p,[2 3],'LineWidth',3)
highlight(p,n2,'MarkerSize',8)
highlight(p,3,'MarkerSize',12)
highlight(p,2,'MarkerSize',16)
```

COMMAND WINDOW

digraph.mlx

```
full(adjacency(g))
degree(g)

A=full(adjacency(g));
p = AllPath(A,6,11);  % function defined in mfile below

fprintf('--- All paths between source and target ---\n \n');
for k=1:size(p,1)
   fprintf('path #%d: %s\n', k, mat2str(p{k}));
end

I = 1;
%BB = [];

for k=1:size(p,1)
%%fprintf('path #%d: %s\n',k,mat2str(p{k}));
NOE = numel(p{k});
fprintf('No. of Nodes in path %d: %d\n',k,NOE);

%% The reliability of an N-node route from a source node to a
%% target node is given by:
```

$$\prod_{N=1}^{N}(1-\mathrm{fsn})$$

```
syms x
Rsn = 1-0.1;
```

COMMAND WINDOW

digraph.mlx


```
%% The reliability of an N-node route from a source node to a
%% target node is given by:
```

$$\prod_{N=1}^{N}(1-\mathrm{fsn})$$


```
syms x
Rsn = 1-0.1;
reliability = vpa(symprod(Rsn, x, 1, NOE))
BB(I) = reliability;
BB2(I) = -log(reliability);
LATENCY = ((0.1.*(NOE+1)+(2*(0.3.*(NOE-1)))));
I=I+1;
end




NOP = numel(p);
%%display(BB)
%%display(BB2)
S = sum(BB2,'all');
SS = 1/S;

SRI = 1/13.*symsum(SS,x,1,NOP)

%%%%% SRDW CALCULATION %%%%%%%%%%%
```

COMMAND WINDOW

digraph.mlx

```
%%%%%% SRDW CALCULATION %%%%%%%%%%%%

AA = [];
Z = 1;
for W=1:size(p,1)
G = rmnode(g,W)
p = AllPath(full(adjacency(G)),6,11);  % function defined in mfile below
fprintf('--- Removing Node %d ---',W);
plot(G)
fprintf('--- All paths between source and target ---\n \n');
for k=1:size(p,1)
   fprintf('path #%d: %s\n', k, mat2str(p{k}));
end
I = 1;
%BB = [];

for k=1:size(p,1)
NOE = numel(p{k});
%%fprintf('No. of Nodes encountered in path %d: %d\n',k,NOE);

%% The reliability of an N-node route from a source node to a
%% target node is given by:
syms x
Rsn = 1-0.1;
reliability = vpa(symprod(Rsn, x, 1, NOE));
BB2(I) = -log(reliability);
LATENCY = ((0.1.*(NOE+1)+(2*(0.3.*(NOE-1)))));
I=I+1;
end
```

COMMAND WINDOW

```
NOP = numel(p);
S = sum(BB2,'all');
SS = 1/S;

SRI1f = vpa(1/13.*symsum(SS,x,1,NOP));
CSRDW = (SRI-SRI1f)/SRI;
AA(Z) = CSRDW;
fprintf('SRI OF SYS AFTER REMOVING NODE %d: = %s',W,SRI1f)
Z = Z+1;
end

display(BB2)
display(AA)
bar(100*AA)
%%%%%% ---------- %%%%%%%%%%
```

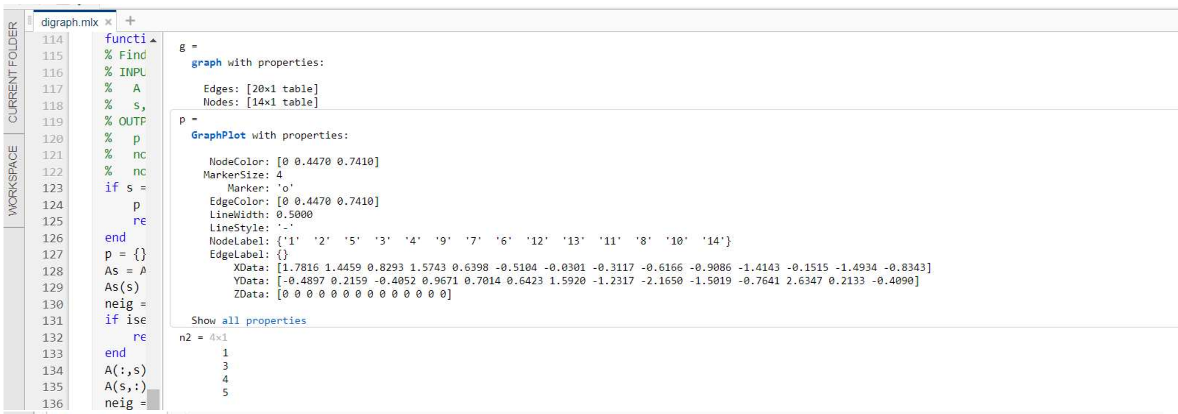
COMMAND WINDOW

digraph.mlx

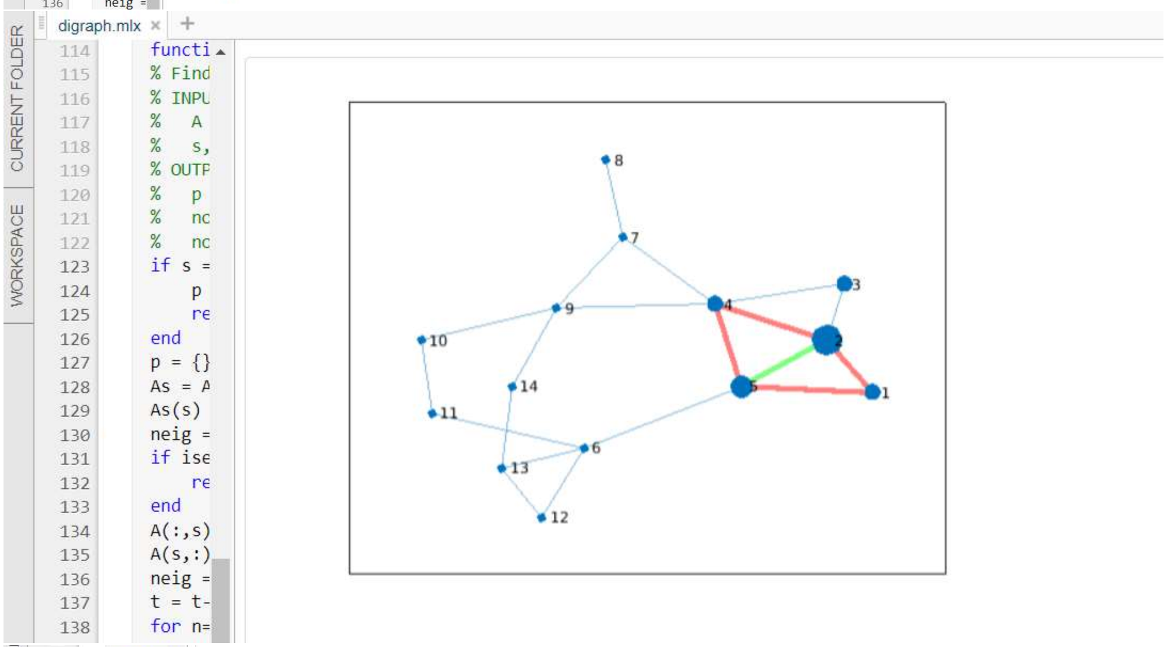
```
function p = AllPath(A, s, t)
% Find all paths from node #s to node #t
% INPUTS:
%   A is (n x n) symmetric ajadcent matrix
%   s, t are node number, in (1:n)
% OUTPUT
%   p is M x 1 cell array, each contains array of
%   nodes of the path, (it starts with s ends with t)
%   nodes are visited at most once.
if s == t
    p =  {s};
    return
end
p = {};
As = A(:,s)';
As(s) = 0;
neig = find(As);
if isempty(neig)
    return
end
A(:,s) = [];
A(s,:) = [];
neig = neig-(neig>=s);
t = t-(t>=s);
for n=neig
    p = [p; AllPath(A,n,t)]; %#ok
end
p = cellfun(@(a) [s, a+(a>=s)], p, 'unif', 0);
end %AllPath
```

COMMAND WINDOW

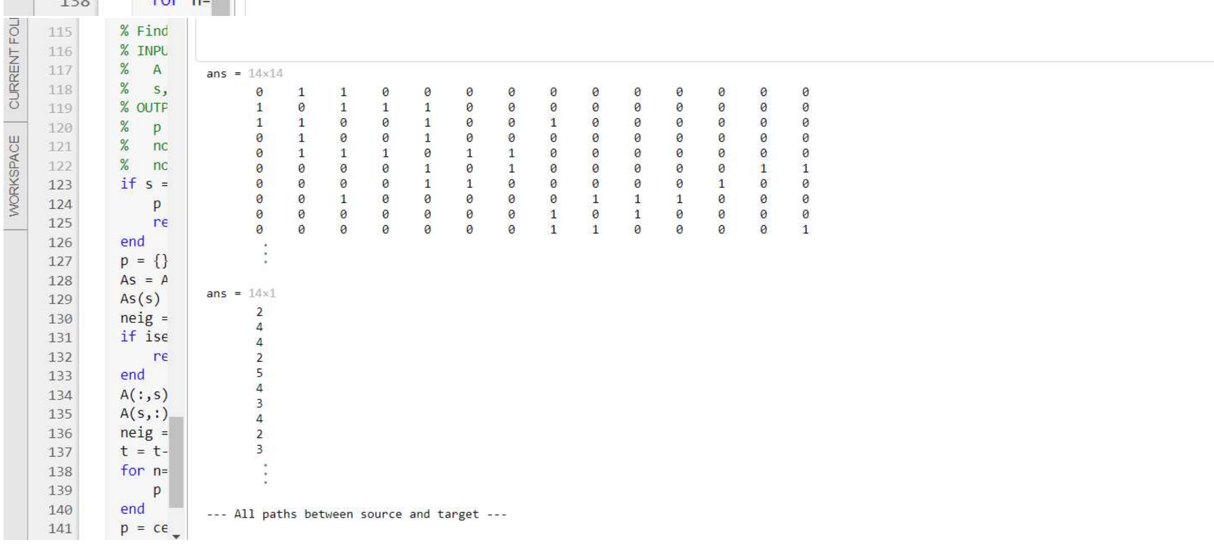
Result:



digraph.mlx
g =
graph with properties:
Edges: [20×1 table]
Nodes: [14×1 table]
p =
GraphPlot with properties:
NodeColor: [0 0.4470 0.7410]
MarkerSize: 4
Marker: 'o'
EdgeColor: [0 0.4470 0.7410]
LineWidth: 0.5000
LineStyle: '-'
NodeLabel: {'1' '2' '5' '3' '4' '9' '7' '6' '12' '13' '11' '8' '10' '14'}
EdgeLabel: {}
XData: [1.7816 1.4459 0.8293 1.5743 0.6398 -0.5104 -0.0301 -0.3117 -0.6166 -0.9086 -1.4143 -0.1515 -1.4934 -0.8343]
YData: [-0.4897 0.2159 -0.4052 0.9671 0.7014 0.6423 1.5920 -1.2317 -2.1650 -1.5019 -0.7641 2.6347 0.2133 -0.4090]
ZData: [0 0 0 0 0 0 0 0 0 0 0 0 0 0]
Show all properties
n2 = 4×1
1
3
4
5



digraph.mlx
8
7
3
9
4
10
2
14
5
1
11
6
13
12



ans = 14×14
0 1 1 0 0 0 0 0 0 0 0 0 0 0
1 0 1 1 1 0 0 0 0 0 0 0 0 0
1 1 0 0 1 0 0 1 0 0 0 0 0 0
0 1 0 0 1 0 0 0 0 0 0 0 0 0
0 1 1 1 0 1 1 0 0 0 0 0 0 0
0 0 0 0 1 0 1 0 0 0 0 0 1 1
0 0 0 0 1 1 0 0 0 0 0 1 0 0
0 0 1 0 0 0 0 0 1 1 1 0 0 0
0 0 0 0 0 0 0 1 0 1 0 0 0 0
0 0 0 0 0 0 0 1 1 0 0 0 0 1
ans = 14×1
2
4
4
2
5
4
3
4
2
3
--- All paths between source and target ---

```
--- All paths between source and target ---

path #1: [6 5 2 1 3 8 11]
path #2: [6 5 2 3 8 11]
path #3: [6 5 3 8 11]
path #4: [6 5 4 2 1 3 8 11]
path #5: [6 5 4 2 3 8 11]
path #6: [6 7 5 2 1 3 8 11]
path #7: [6 7 5 2 3 8 11]
path #8: [6 7 5 3 8 11]
path #9: [6 7 5 4 2 1 3 8 11]
path #10: [6 7 5 4 2 3 8 11]
path #11: [6 13 11]
path #12: [6 14 10 8 11]
path #13: [6 14 10 9 8 11]
No. of Nodes in path 1: 7
reliability = 0.4782969
No. of Nodes in path 2: 6
reliability = 0.531441
No. of Nodes in path 3: 5
reliability = 0.59049
No. of Nodes in path 4: 8
```

COMMAND WINDOW

digraph.mlx

```
reliability = 0.43046721
No. of Nodes in path 5: 7
reliability = 0.4782969
No. of Nodes in path 6: 8
reliability = 0.43046721
No. of Nodes in path 7: 7
reliability = 0.4782969
No. of Nodes in path 8: 6
reliability = 0.531441
No. of Nodes in path 9: 9
reliability = 0.387420489
No. of Nodes in path 10: 8
reliability = 0.43046721
No. of Nodes in path 11: 3
reliability = 0.729
No. of Nodes in path 12: 5
reliability = 0.59049
No. of Nodes in path 13: 6
reliability = 0.531441
SRI = 0.11166143036505768265894038454691
```

COMMAND WINDOW

digraph.mlx

```
SRI = 0.11166143036505768265894038454691
G =
  graph with properties:

    Edges: [18×1 table]
    Nodes: [13×1 table]
--- Removing Node 1 ---
--- All paths between source and target ---

path #1: [6 11]
SRI OF SYS AFTER REMOVING NODE 1: = 0.0091261745971441375250095506600838
G =
  graph with properties:

    Edges: [16×1 table]
    Nodes: [13×1 table]
--- Removing Node 2 ---
--- All paths between source and target ---

path #1: [6 11]
SRI OF SYS AFTER REMOVING NODE 2: = 0.0091261745971441375250095506600838
G =
  graph with properties:

    Edges: [16×1 table]
    Nodes: [13×1 table]
--- Removing Node 3 ---
--- All paths between source and target ---

path #1: [6 11]
SRI OF SYS AFTER REMOVING NODE 3: = 0.0091261745971441375250095506600838
```

COMMAND WINDOW

```
SRI OF SYS AFTER REMOVING NODE 7: = 0
G =
  graph with properties:

    Edges: [16×1 table]
    Nodes: [13×1 table]
--- Removing Node 8 ---
--- All paths between source and target ---

path #1: [6 5 7 11]
path #2: [6 7 11]
SRI OF SYS AFTER REMOVING NODE 8: = 0.018483391589152683594956051969779
G =
  graph with properties:

    Edges: [18×1 table]
    Nodes: [13×1 table]
--- Removing Node 9 ---
--- All paths between source and target ---

path #1: [6 5 7 11]
path #2: [6 7 11]
path #3: [6 12 10 8 3 1 2 4 5 7 11]
path #4: [6 12 10 8 3 1 2 5 7 11]
path #5: [6 12 10 8 3 2 4 5 7 11]
path #6: [6 12 10 8 3 2 5 7 11]
path #7: [6 12 10 8 3 5 7 11]
path #8: [6 13 9 8 3 1 2 4 5 7 11]
path #9: [6 13 9 8 3 1 2 5 7 11]
path #10: [6 13 9 8 3 2 4 5 7 11]
path #11: [6 13 9 8 3 2 5 7 11]
path #12: [6 13 9 8 3 5 7 11]
SRI OF SYS AFTER REMOVING NODE 9: = 0.080377317552829101137698794804408
```

```
SRI OF SYS AFTER REMOVING NODE 9: = 0.080377317552829101137698794804408
G =
  graph with properties:

    Edges: [17×1 table]
    Nodes: [13×1 table]
--- Removing Node 10 ---
--- All paths between source and target ---

path #1: [6 5 7 11]
path #2: [6 7 11]
path #3: [6 12 10 8 3 1 2 4 5 7 11]
path #4: [6 12 10 8 3 1 2 5 7 11]
path #5: [6 12 10 8 3 2 4 5 7 11]
path #6: [6 12 10 8 3 2 5 7 11]
path #7: [6 12 10 8 3 5 7 11]
SRI OF SYS AFTER REMOVING NODE 10: = 0.046886768572483642330324296969238
G =
  graph with properties:

    Edges: [18×1 table]
    Nodes: [13×1 table]
--- Removing Node 11 ---
--- All paths between source and target ---

path #1: [6 5 7 11]
path #2: [6 7 11]
path #3: [6 13 10 8 3 1 2 4 5 7 11]
path #4: [6 13 10 8 3 1 2 5 7 11]
path #5: [6 13 10 8 3 2 4 5 7 11]
path #6: [6 13 10 8 3 2 5 7 11]
path #7: [6 13 10 8 3 5 7 11]
path #8: [6 13 10 9 8 3 1 2 4 5 7 11]
path #9: [6 13 10 9 8 3 1 2 5 7 11]
```

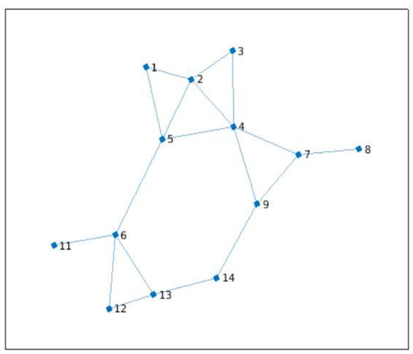
digraph.mlx

```
path #8: [6 13 10 9 8 3 1 2 4 5 7 11]
path #9: [6 13 10 9 8 3 1 2 5 7 11]
path #10: [6 13 10 9 8 3 2 4 5 7 11]
path #11: [6 13 10 9 8 3 2 5 7 11]
path #12: [6 13 10 9 8 3 5 7 11]
SRI OF SYS AFTER REMOVING NODE 11: = 0.076851996607529579157975163453338
G =
  graph with properties:

    Edges: [19×1 table]
    Nodes: [13×1 table]
--- Removing Node 12 ---
--- All paths between source and target ---

path #1: [6 5 2 1 3 8 11]
path #2: [6 5 2 3 8 11]
path #3: [6 5 3 8 11]
path #4: [6 5 4 2 1 3 8 11]
path #5: [6 5 4 2 3 8 11]
path #6: [6 7 5 2 1 3 8 11]
path #7: [6 7 5 2 3 8 11]
path #8: [6 7 5 3 8 11]
path #9: [6 7 5 4 2 1 3 8 11]
path #10: [6 7 5 4 2 3 8 11]
path #11: [6 12 11]
path #12: [6 13 10 8 11]
path #13: [6 13 10 9 8 11]
SRI OF SYS AFTER REMOVING NODE 12: = 0.11166143036505768265894038454691
G =
  graph with properties:

    Edges: [18×1 table]
    Nodes: [13×1 table]
--- Removing Node 13 ---
```

COMMAND WINDOW

digraph.mlx

```
--- Removing Node 13 ---
```

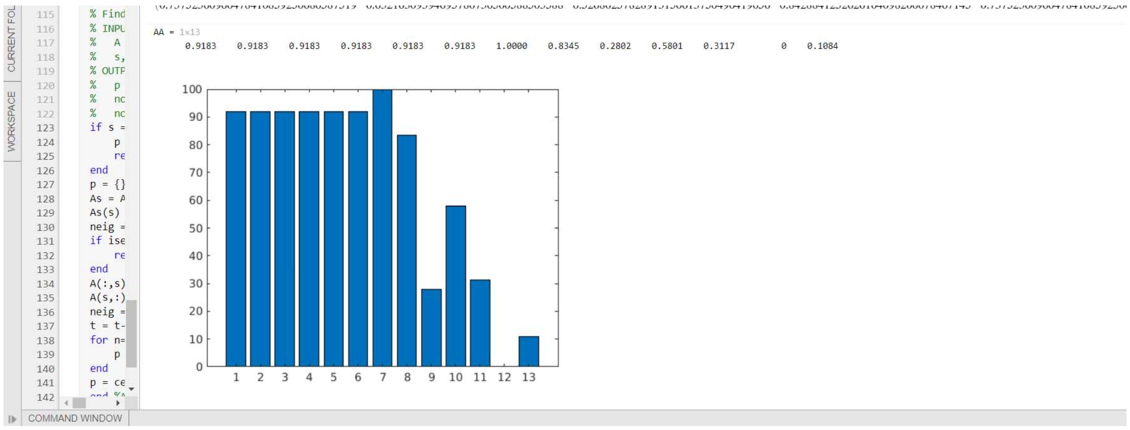



```
--- All paths between source and target ---

path #1: [6 5 2 1 3 8 11]
path #2: [6 5 2 3 8 11]
```

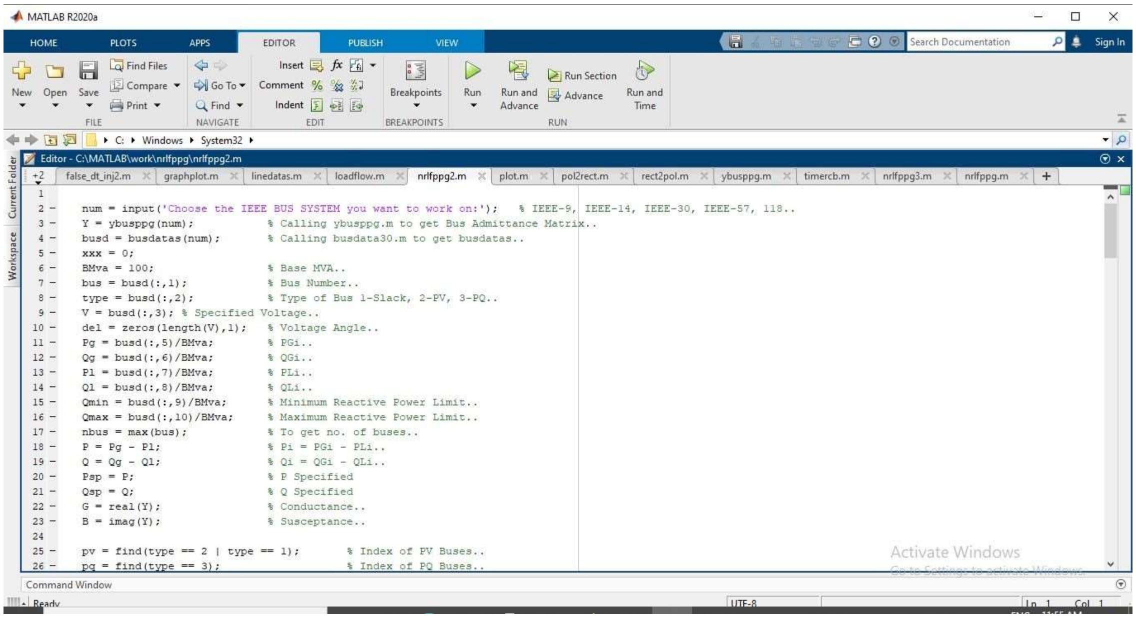
COMMAND WINDOW

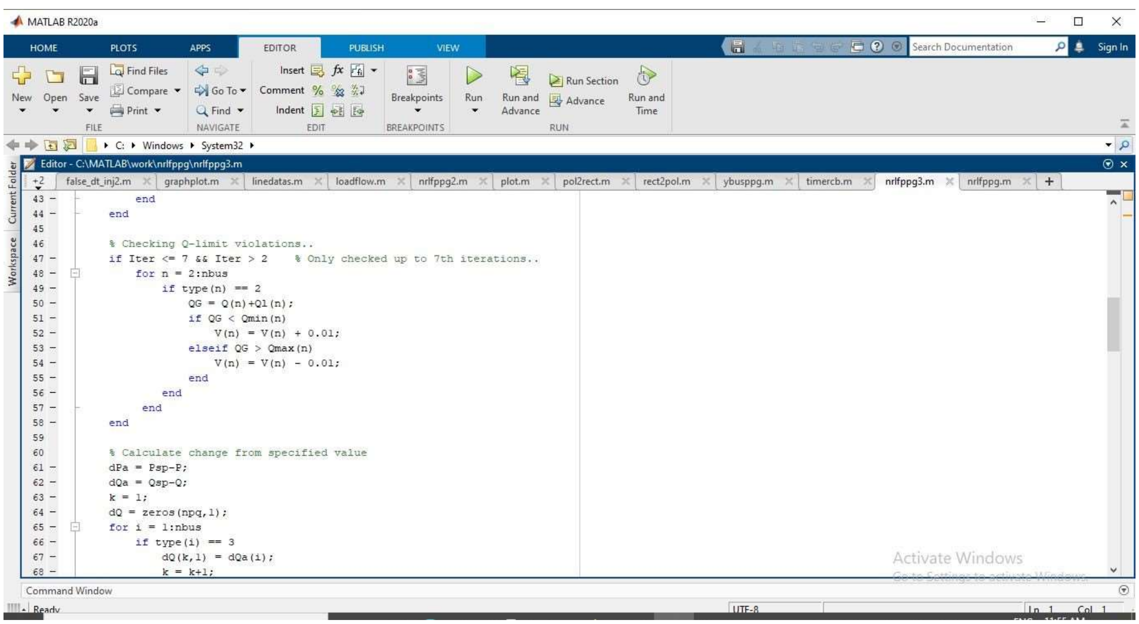
```
--- All paths between source and target ---

path #1: [6 5 2 1 3 8 11]
path #2: [6 5 2 3 8 11]
path #3: [6 5 3 8 11]
path #4: [6 5 4 2 1 3 8 11]
path #5: [6 5 4 2 3 8 11]
path #6: [6 7 5 2 1 3 8 11]
path #7: [6 7 5 2 3 8 11]
path #8: [6 7 5 3 8 11]
path #9: [6 7 5 4 2 1 3 8 11]
path #10: [6 7 5 4 2 3 8 11]
path #11: [6 13 10 8 11]
path #12: [6 13 10 9 8 11]
SRI OF SYS AFTER REMOVING NODE 13: = 0.099558268332481500272831461746369
BB2 =
(0.73752360960478410859250686587519  0.63216309394695780736500588503588  0.52680257828913150613750490419656  0.84288412526261040982000078467145  0.737523609604784108592506865875

AA = 1×13
    0.9183    0.9183    0.9183    0.9183    0.9183    0.9183    1.0000    0.8345    0.2802    0.5801    0.3117         0    0.1084
```

COMMAND WINDOW

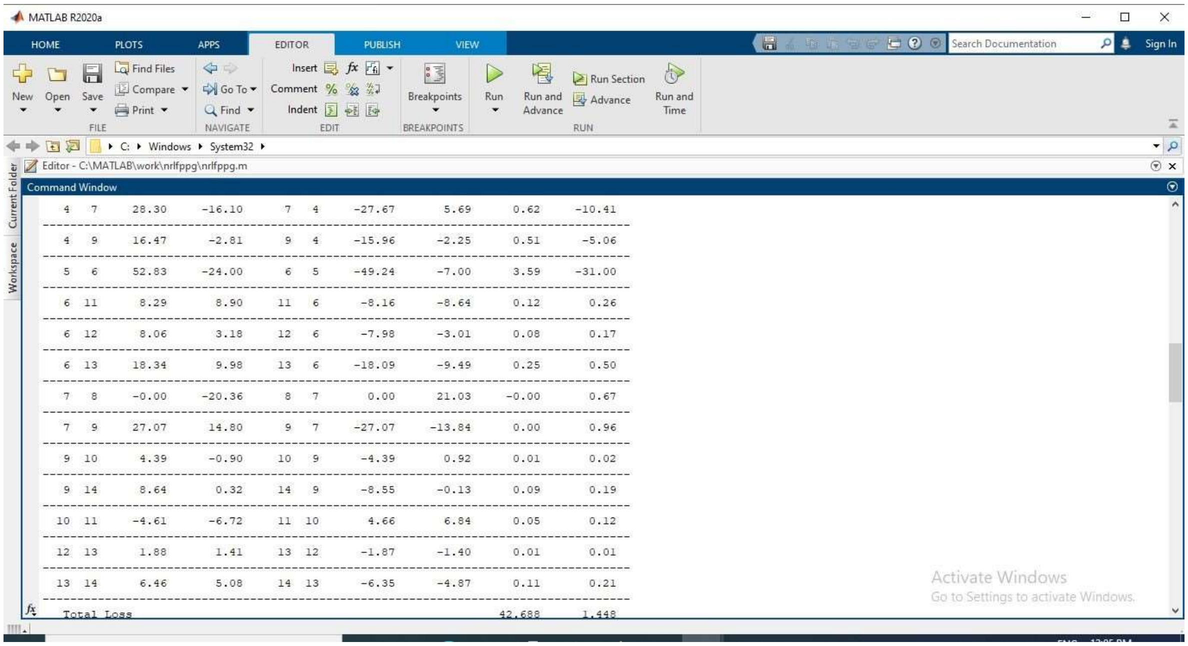

CURRENT FOL
WORKSPACE
% Find
% INPU
%   A
%   s,
% OUTP
%   p
%   nc
%   nc
if s =
p
re
end
p = {}
As = A
As(s)
neig =
if ise
re
end
A(:,s)
A(s,:)
neig =
t = t-
for n=
p
end
p = ce
AA = 1×13
0.9183 0.9183 0.9183 0.9183 0.9183 0.9183 1.0000 0.8345 0.2802 0.5801 0.3117 0 0.1084
100
90
80
70
60
50
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10 11 12 13
COMMAND WINDOW

CODE SNIPPETS(Newton Raphson):

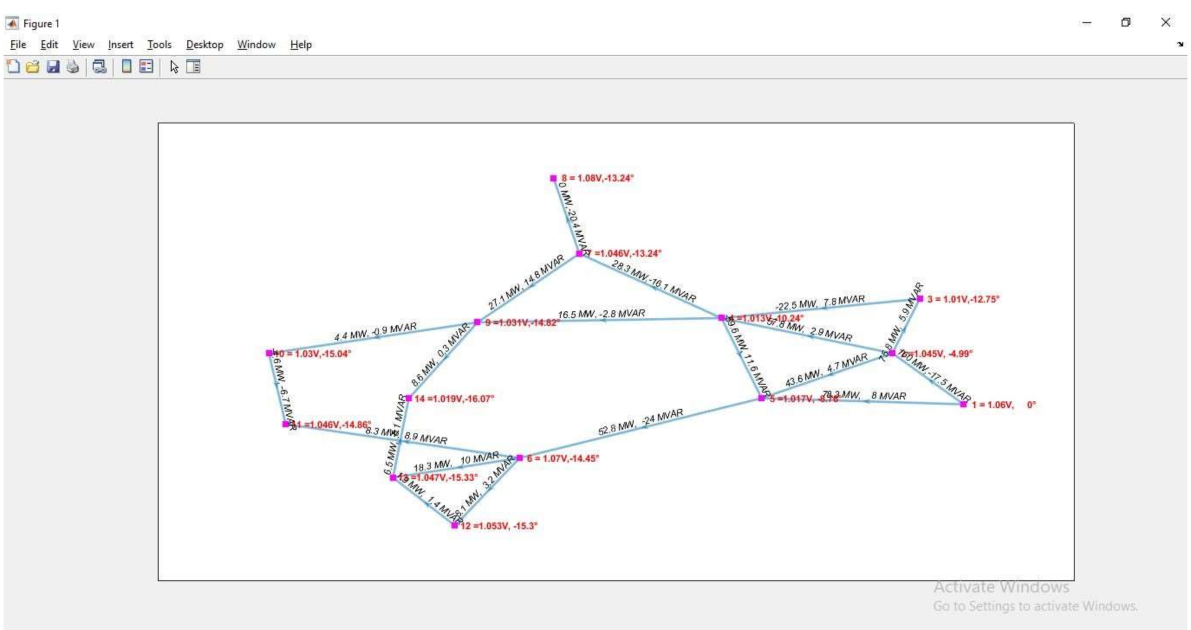




RESULTS (NORMAL POWER FLOW ANALYSIS)



4	7	28.30	-16.10	7	4	-27.67	5.69	0.62	-10.41
4	9	16.47	-2.81	9	4	-15.96	-2.25	0.51	-5.06
5	6	52.83	-24.00	6	5	-49.24	-7.00	3.59	-31.00
6	11	8.29	8.90	11	6	-8.16	-8.64	0.12	0.26
6	12	8.06	3.18	12	6	-7.98	-3.01	0.08	0.17
6	13	18.34	9.98	13	6	-18.09	-9.49	0.25	0.50
7	8	-0.00	-20.36	8	7	0.00	21.03	-0.00	0.67
7	9	27.07	14.80	9	7	-27.07	-13.84	0.00	0.96
9	10	4.39	-0.90	10	9	-4.39	0.92	0.01	0.02
9	14	8.64	0.32	14	9	-8.55	-0.13	0.09	0.19
10	11	-4.61	-6.72	11	10	4.66	6.84	0.05	0.12
12	13	1.88	1.41	13	12	-1.87	-1.40	0.01	0.01
13	14	6.46	5.08	14	13	-6.35	-4.87	0.11	0.21
Total Loss								42.688	1.448



RESULTS (PHOTO-VOLTAIC SOURCE EMBEDDED)

busdatas.m | linedatas.m | nrlfppg.m | Figure 1

COMMAND WINDOW

Line Flow and Losses

From Bus	To Bus	P MW	Q MVar	From Bus	To Bus	P MW	Q MVar	Line Loss MW	Line Loss MVar
1	2	85.10	1.75	2	1	-78.09	1.81	7.01	3.55
1	5	40.78	6.51	5	1	-34.69	-3.56	6.09	2.95
2	3	58.95	7.86	3	2	-52.92	-1.95	6.03	5.91
2	4	32.48	1.34	4	2	-28.33	0.18	4.15	1.52
2	5	21.98	2.87	5	2	-18.04	-2.21	3.94	0.66
3	4	-30.39	3.00	4	3	32.36	-1.37	1.97	1.63
4	5	-44.45	7.68	5	4	44.71	-6.87	0.26	0.81
4	7	-0.05	-16.00	7	4	0.05	3.81	-0.00	-12.19

busdatas.m | linedatas.m | nrlfppg.m | Figure 1

COMMAND WINDOW

6	12	1.07	2.55	12	6	-1.06	-2.53	0.01	0.02
6	13	7.18	8.86	13	6	-7.11	-8.71	0.08	0.15
7	8	-8.00	-19.50	8	7	8.00	20.19	0.00	0.70
7	9	15.95	15.77	9	7	-15.95	-15.27	-0.00	0.49
9	10	-4.82	0.83	10	9	4.83	-0.81	0.01	0.02
9	14	2.42	1.31	14	9	-2.41	-1.29	0.01	0.02
10	11	-5.83	-4.99	11	10	5.87	5.09	0.04	0.10
12	13	2.96	0.93	13	12	-2.94	-0.91	0.02	0.02
13	14	4.55	3.82	14	13	-4.49	-3.71	0.05	0.11
Total Loss								30.811	-35.681

##

>>

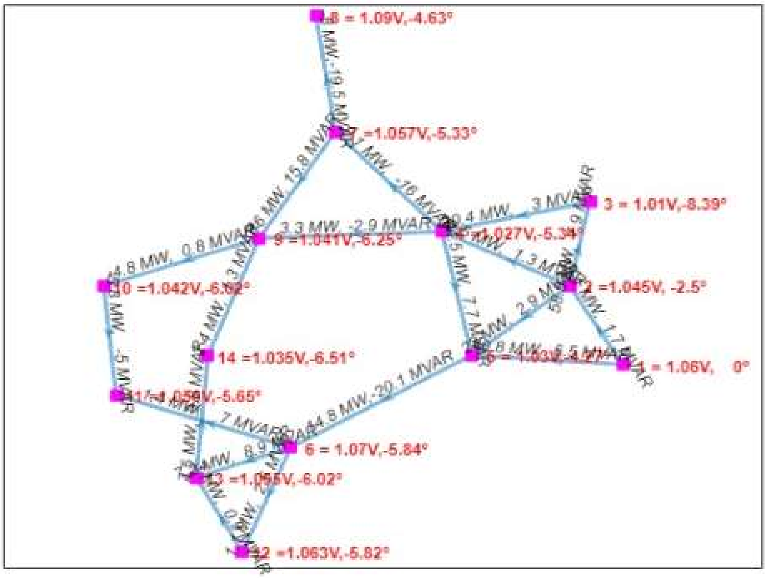


TABLE II
NUMBER OF OVERLOADED LINES, DUE TO SINGLE LINE CONTINGENCY

Line Number	No DG Added	2MW	4MW	6MW	8MW	10MW
L1	3	4	3	5	5	5
L2	2	1	0	0	1	1
L3	4	4	2	1	3	3
L4	2	0	0	0	1	1
L5	0	0	0	0	1	1
L6	0	0	0	0	0	1
L7	5	3	5	4	3	3
L8	4	5	2	2	2	1
L9	1	1	1	1	1	1
L10	10	8	5	3	2	0
L11	1	1	0	0	1	3
L12	1	1	0	0	0	1
L13	4	4	2	2	1	1
L14	1	1	1	1	2	3
L15	5	5	3	2	2	4
L16	2	1	1	1	1	1
L17	3	2	2	2	1	1
L18	1	0	0	1	1	1
L19	0	0	0	0	0	0
L20	2	1	1	1	1	1
Total	**51**	**42**	**28**	**26**	**29**	**33**

TABLE III

AMOUNT OF EXCESS FLOW, DUE TO SINGLE LINE CONTINGENCY

Line Number	**No DG Added**	**2MW**	**4MW**	**6MW**	**8MW**	**10MW**
L1	240.5	200.2	144.1	125.2	90.79	57.97
L2	25.02	7.83	0	0	0.001	0.269
L3	104.6	87.06	76.66	72.53	72.08	71.83
L4	10.04	0	0	0	0.194	0.437
L5	0	0	0	0	0.019	0.287
L6	0	0	0	0	0	0.205
L7	21.57	9.78	10.45	10.64	11.57	13.27
L8	18.35	6.82	3.38	2.15	0.927	0.34
L9	1.019	0.705	0.399	0.101	0.194	0.397
L10	119.2	67.98	0	13.47	2.14	0
L11	4.72	1.43	0	0	0.127	1.53
L12	3.73	1.78	8.56	0	0	1.55
L13	23.37	15.55	0.203	6.90	5.42	4.21
L14	0.62	0.373	6.32	0.103	0.319	0.594
L15	21.45	12.42	1.56	5.1	4.46	4.52
L16	7.62	3.03	1.56	0.404	0.207	0.639
L17	9.54	6.74	4.70	2.75	1.02	0.968
L18	0.707	0	0	0.105	0.380	0.66
L19	0	0	0	0	0	0
L20	14.15	0.516	0.457	0.425	0.414	0.421
Total	**626.2**	**422.2**	**258.3**	**239.8**	**190.3**	**160.1**

TABLE V
AMOUNT OF EXCESS FLOW, DUE TO SINGLE LINE CONTINGENCY, AFTER MODIFYING THE DG FLOW IN SOME OF THE BUSES

Line Number	**10MW**	**10MW modified**	**12MW modified**	**14MW modified**
L1	57.97	83.48	40.34	36.39
L2	0.269	0	0	0
L3	71.83	71.55	70.98	70.45
L4	0.437	0	0	0
L5	0.287	0	0	0
L6	0.205	0	0	0
L7	13.27	4.08	3.30	7.46
L8	0.34	0	0	1.68
L9	0.40	0	0	1.80
L10	0	15.29	8.42	11.92
L11	1.53	1.25	6.40	13.84
L12	1.55	1.78	1.78	3.53
L13	4.21	7.52	5.98	6.41
L14	0.59	0	0	1.81
L15	4.52	1.74	0.94	2.85
L16	0.64	0	2.12	8.30
L17	0.968	0	0	1.88
L18	0.663	0	0	0
L19	0	0	0	0
L20	0.421	0	0	0
Total	**160.1**	**186.68**	**140.26**	**168.33**

CONCLUSION

The SRI provides a reliable quantification of cyber network's risks related to specific latency requirements. The results obtained from the case study on the substation Ethernet network show that SRDW criticalities provide insights into the importance of communication network components –highlights components' structural importance. The results also highlight the importance of equipment redundancy as well as the significance of efficient management of data and optimal design of routing strategies in the reliable operation of communication networks. Nevertheless, different types of communication device might have different reliability, and real engineering networks contain uncertainties such as uncertain latencies that are difficult to anticipate.

The results alsoshowed a generally positive effect of adding PV sources, there were cases where this addition caused more overloads in the system. PV sources with a limited capability for power injection can be helpful in reducing the stress level of the transmission network, too much DG power injection can introduce unnecessary overloads to the transmission system

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