“Design of 118-bus system for Observability”

Coursework Final Report

Power System State Estimation (EECE 7224)

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by

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Executive Summary

Problem Statement

To accomplish the most economical measurement design for a test power system making sure that the design complies with the technical/cost specifications given below.
Design a measurement system for the IEEE 118-bus test system with the following design specifications:

• System is observable for the base case, AND
• System contains no critical measurements, AND
• System remains observable under the following single contingencies.

Loss of any one of the lines: 25-27; 69-70; 56-57; 54-59; 109-110; 77-80; 82-96; 92-93
Assume that the following buses are zero injection buses: 5;9;30;71;37;47;38;63;64;68;81
Assume the following costs in your design:
Substation communications, labor and instrumentation costs: $ 40,000.00
V-measurement: $ 3,000.00
A "P-Q pair" measurement (flow or injection): $ 5,000.00

Solution Strategy
Implemented the meter placement on the PET software and then once the system became observable, started with contingency removal, followed by critical measurement analysis using Sensitivity matrix and then making the cost calculation based on the unique set of bus where the meter is placed as it will be considered as substation.
Additionally, ILP with zero injection topology was implemented to test another method for removing randomness in meter placement.

Implementation
Execution was done using PET software and MATLAB software. The PET presented the observability analysis and branch connection data, which was utilized in MATLAB program to make the further constraint analysis.

		Manual Placement	**ILP Method**
Total number of placed measurements	Flow measurement	95	87
	Bus measurement	28	34
Number of Substation		74	60

	Manual Placement	**ILP Method**
Total Cost	**$3,661,000**	**$3,011,000**
Voltage placement	6000	6000
PQ placement	615000	605000
Substation Cost	2960000	2400000

1. Problem Statement

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Assume the following costs in your design:
Substation communications, labor and instrumentation costs: $ 40,000.00
V-measurement: $ 3,000.00
A "P-Q pair" measurement (flow or injection): $ 5,000.00
Assume that none of the substations have any existing communications or devices and thus an initial fixed investment of $ 40,000 will be required before any type of measurement can be placed at a given substation. Assume also that the fixed cost is the same for all substations irrespective of their location and the number of measurements placed at that substation.

2. Technical approach in design

As the project focuses on achieving an economical measurement design along with system reliability for a test power system, ensuring alignment with specified technical and cost requirements. We have used two different approaches to reach a reliable system.
It involves the manual placement of measurements and an Integer Linear Programming (ILP) method with topological approach that considers zero-injection locations. These techniques collectively identify optimal measurement locations.

Part1. Meter placement

- → Manually placed P-Q measurement through Power Education Toolbox(PET) software to create the connected graphical network.
- → Collect the list of measurements once whole system becomes observable from measure.dat file.
- → Also, in second topology, are using the ILP method for meter placement with topology of zero injection placement and hence during optimal results, that condition would be incorporated in program. (For ILP Zero injection topology – refer Appendix)

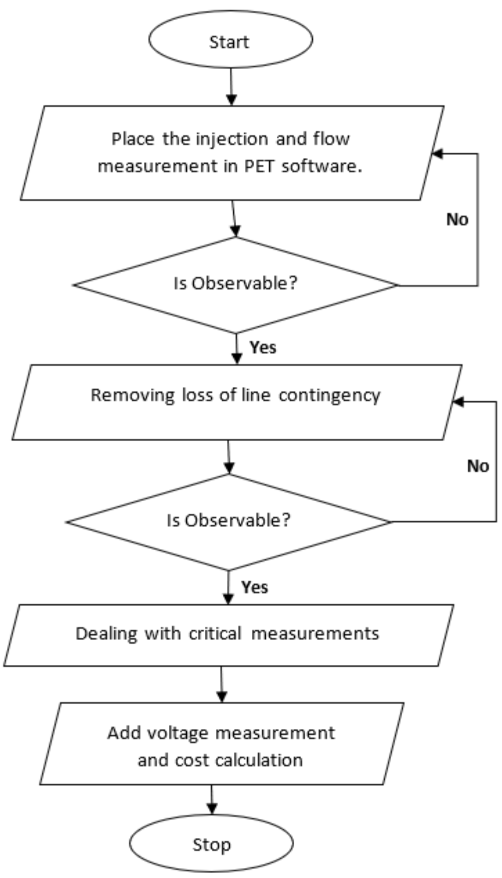


Fig1. Manual Placement and analysis

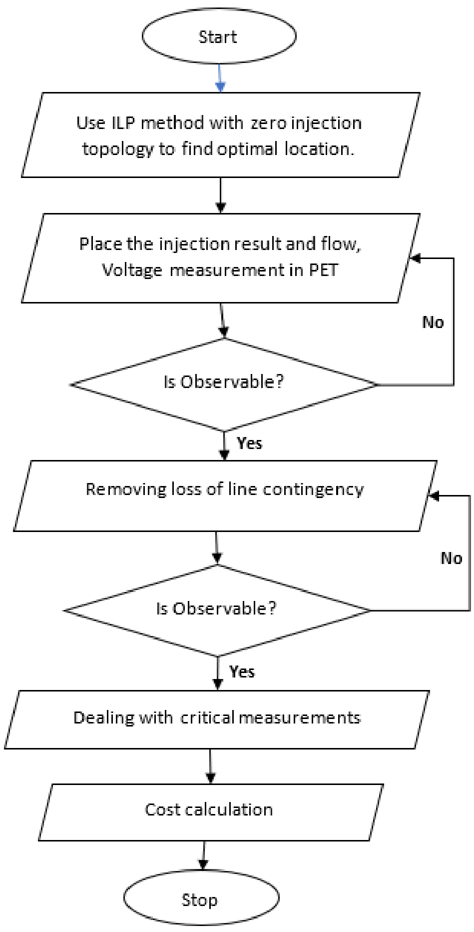


Fig2. ILP Placement with zero injection topology and analysis

Part 2. Reduction of contingent branches

- → Using that data, in MATLAB form A matrix (Bus connection matrix), and H matrix from list of injections.
- → Using the formation of G matrix and then LDL decomposition to check system observability using Numerical Observability method.
- → Reduction of contingent branches – From the list of Flow measurement, start removal of any meter placement found within the H and try to insert injection so, when we lose that line, the system remains observable.

Part 3. Reduction of Critical measurements

- → We form the sensitivity matrix to analyse the measurements which are critical.
- → The columns which are majorly '0' in Sensitivity analysis is marked as critical
- → Accordingly measurement is manipulated to remove that criticality.

Part 4. Cost analysis

- → Placed the Voltage measurement.
- → From the list of measurements, all the bus where measurement was placed, we find the unique set.
- → It gives all the bus where we need substation cost.
- → Accordingly, we calculated the cost.

Conclusion

A MATLAB code has been developed to facilitate planning and calculation processes. It incorporates observability analysis, sensitivity matrix computation for critical analysis, and cost estimation for installation. The cost calculations are based on data derived from the power system's branch information, bus injections, flow injections, and voltage measurements.

3. Results:

Scenario 1 - Manual Placement and analysis

Total Number of P- Q measurements		(28 Bus Inj. +95 Flow meas.) = 123
V measurement	**Bus Injection measurement**	**Flow measurement**
12,100	27, 12, 11, 15, 33, 49, 40, 35, 56, 103, 94, 100, 96, 85, 77, 70, 31, 61, 65, 69, 17, 57, 3, 89, 110, 44, 9, 1	27-32, 27-115, 25-23, 23-32, 32-114, 115-114, 2-1, 3-5, 5-6, 12-16, 14-12, 4-5, 8-30, 11-4, 3-1, 11-13, 17-18, 19-15, 18-19, 37-34, 15-33, 39-37, 40-42, 41-42, 49-48, 46-47, 45-46, 42-49, 34-43, 34-36, 58-56, 49-50, 56-54, 54-55, 57-50, 106-107, 105-106, 105-108, 110-112, 104-105, 103-100, 93-94, 92-94, 98-100, 100-101, 92-89, 102-92, 110-103, 109-108, 111-110, 91-90, 89-90, 88-89, 86-87, 84-85, 83-85, 85-89, 80-97, 79-80, 96-94, 94-95, 80-99, 77-75, 76-77, 75-118, 71-73, 70-74, 23-24, 72-71, 75-74, 69-75, 70-24, 17-31, 28-29, 60-62, 59-63, 63-64, 65-66, 61-62, 68-116, 81-80, 78-79, 66-67, 51-52, 53-54, 52-53, 69-47, 30-17, 12-117, 25-26, 19-20, 21-22, 21-20, 44-45, 8-9

Places of Substation instrumentation setup
2, 3, 4, 5, 8, 11, 12, 14, 15, 17, 18, 19, 21, 23, 25, 27, 28, 30, 32, 34, 37, 39, 40, 41, 42, 44, 45, 46, 49, 51, 52, 53, 54, 56, 57, 58, 59, 60, 61, 63, 65, 66, 68, 69, 70, 71, 72, 75, 76, 77, 78, 79, 80, 81, 83, 84, 85, 86, 88, 89, 91, 92, 93, 94, 96, 98, 100, 102, 103, 104, 105, 106, 109, 110, 111, 115

40,000 * (Unique Bus where measurement is installed = 76) + 3000*(No. of Voltages = 2) + 5000*(No. of P-Q pair(flow + bus injection) = 123) = **$3,661,000**

Scenario 2 - ILP Placement with zero injection topology and analysis

Total Number of P- Q measurements		(34 Bus inj. + 87 Flow meas.) = 123
V measurement	**Bus Injection measurement**	**Flow measurement**
5, 64	2, 6, 10, 12, 15, 17, 21, 25, 29, 35, 41, 43, 49, 52, 56, 62, 72, 75, 77, 80, 85, 65, 90, 94, 101, 105, 110, 114, 116, 5, 92, 84, 63, 23	2-12, 3-12, 5-4, 6-7, 12-16, 15-17, 30-17, 17-113, 31-32, 32-114, 27-28, 27-32, 21-22, 26-25, 25-23, 72-24, 75-69, 70-74, 71-73, 70-24, 46-48, 47-49, 46-45, 47-69, 45-49, 41-40, 35-37, 39-37, 43-34, 15-33, 12-11, 11-13, 34-37, 15-19, 19-20, 56-58, 52-51, 59-55, 54-56, 54-55, 62-67, 49-66, 59-60, 62-61, 94-100, 91-92, 85-88, 100-92, 101-102, 110-103, 105-108, 104-105, 108-109, 85-89, 92-89, 110-112, 83-85, 77-82, 80-79, 80-96, 96-97, 80-99, 100-98, 94-95, 95-96, 83-82, 79-78, 106-100, 106-105, 62-66, 64-61, 65-68, 30-38, 17-18, 30-26, 75-118, 76-118, 68-81, 57-50, 39-40, 49-51, 37-38, 3-5, 8-9, 30-8, 9-10, 86-87

Places of Substation instrumentation setup
2, 3, 5, 6, 8, 9, 11, 12, 15, 17, 19, 21, 25, 26, 27, 30, 31, 32, 34, 35, 37, 39, 41, 43, 45, 46, 47, 49, 52, 54, 56, 57, 59, 62, 64, 65, 68, 70, 71, 72, 75, 76, 77, 79, 80, 83, 85, 86, 91, 92, 94, 95, 96, 100, 101, 104, 105, 106, 108, 110

40,000 * (Unique Bus where measurement is installed = 60) + 3000*(No. of Voltages = 2) + 5000*(No. of P-Q pair(flow + bus injection) = 121) = **$3011000**

Comparative results demonstrate that the ILP method yields a lower overall cost in comparison to manually placed meters. This study contributes to the measurement design methodologies, providing insights into the cost-effective planning of power system measurements.

4. References

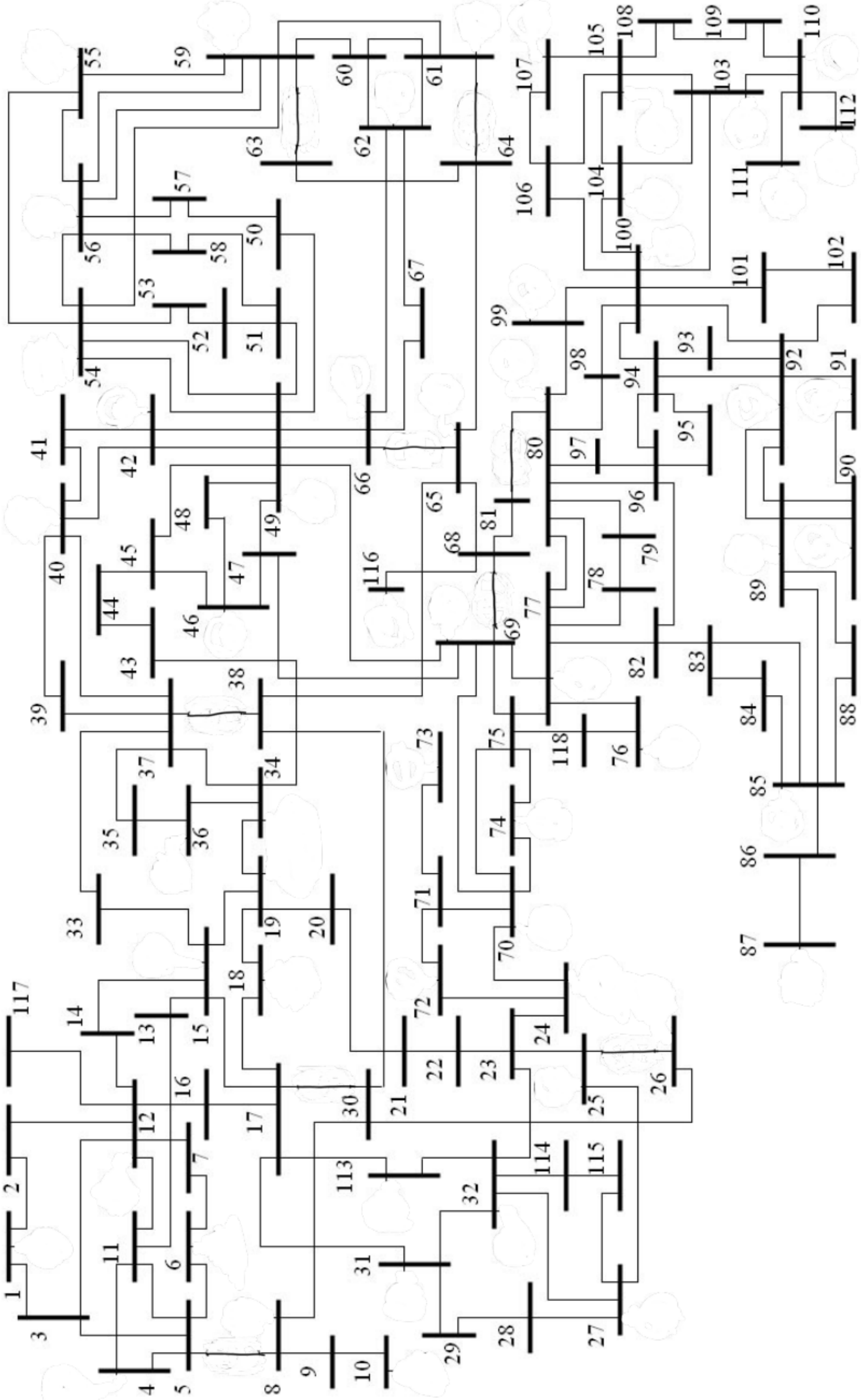
[1] Abur, A., & Exposito, A. G. (2004). Power system state estimation. CRC Press.

[2] Xu, B., & Abur, A. (Year of Publication). Optimal Placement of Phasor Measurement Units for State Estimation: Final Project Report. Texas A&M University.

[3] Lecture and Notes (EECE-7224 Power System State Estimation)

5. Appendix

5.1. System diagram



5.2. Zero Injection topology with ILP Method

Linear Programming is a mathematical modeling technique in which a linear function is maximized or minimized when subjected to various constraints.
For n bus system, the Bus injection placement problem can be formulated as

$$min \sum_{1}^{n} w.x$$

Subject to $f(X) \geq 1$
X is a binary decision variable vector, whose entries are defined as:

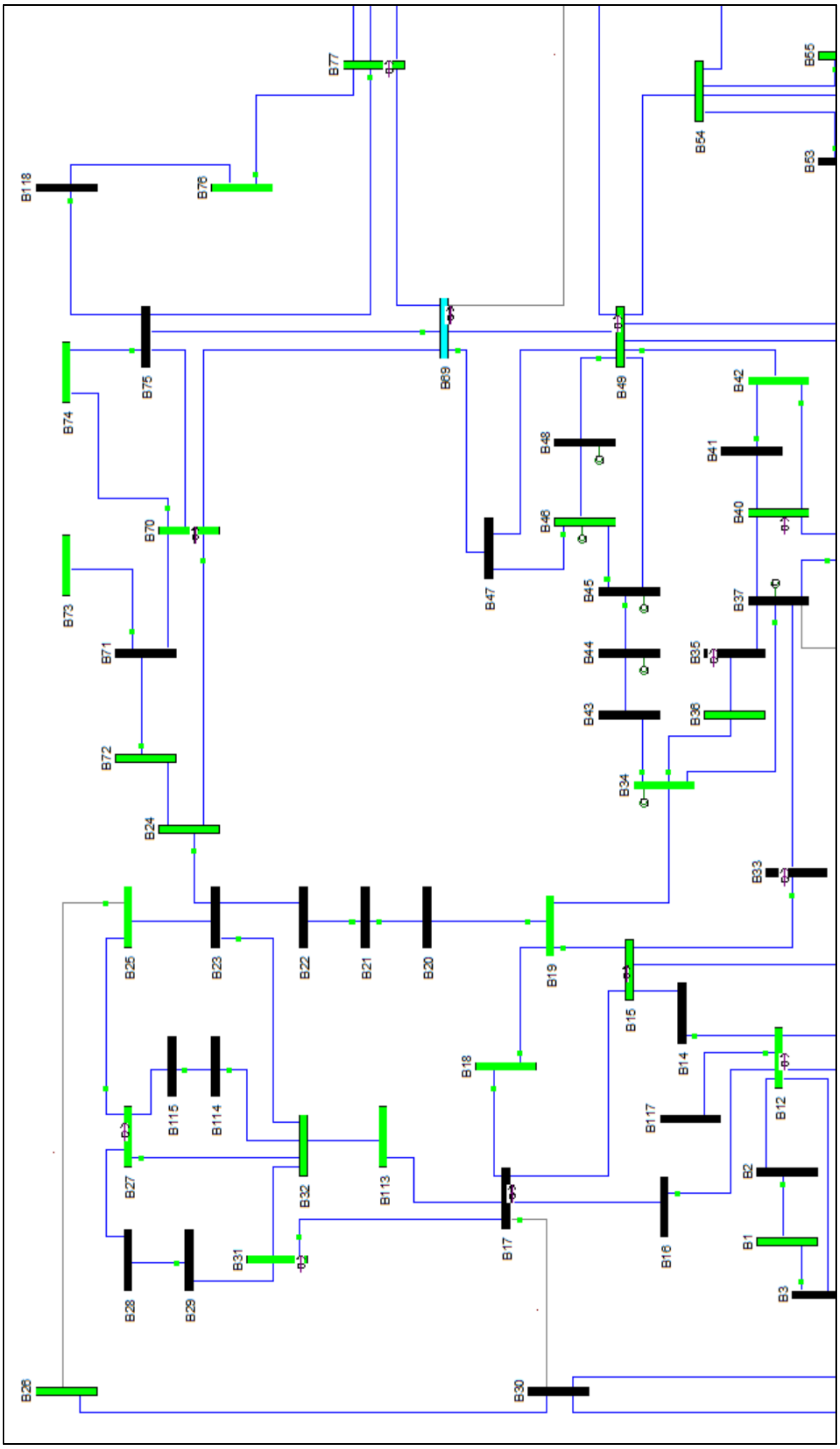
$$X = \begin{Bmatrix} 1 \; if \; a \; Bus \; injection \; measurement \; is \; present \\ 0 \qquad\qquad\qquad\qquad\qquad\qquad otherwise \end{Bmatrix}$$

For zero injection [2]–

Topology transformation is developed for handling injection measurements. The main idea is to merge the bus having zero injection measurement, with any one of its neighbors.
For this project, I have merged –
% Values to find and replace
valuesToFind = [5, 9, 30, 71, 37, 47, 38, 63, 64, 68, 81];
correspondingValues = [4, 10, 26, 72, 35, 46, 65, 59, 61, 69, 80];

5.3. Simulation Results –

Placing of Measurement and checking observability of system



Output of PET measure.dat file

new 120 | new 121 | 118measure_iter3.dat

```
   0
  21
 27     0.00000 0.001 0
 12     0.00000 0.001 0
 11     0.00000 0.001 0
 15     0.00000 0.001 0
 33     0.00000 0.001 0
 49     0.00000 0.001 0
 40     0.00000 0.001 0
 35     0.00000 0.001 0
 56     0.00000 0.001 0
103     0.00000 0.001 0
 94     0.00000 0.001 0
100     0.00000 0.001 0
 96     0.00000 0.001 0
 85     0.00000 0.001 0
 77     0.00000 0.001 0
 70     0.00000 0.001 0
 31     0.00000 0.001 0
 61     0.00000 0.001 0
 65     0.00000 0.001 0
 69     0.00000 0.001 0
 17     0.00000 0.001 0
  21
 27     0.00000 0.001 0
 12     0.00000 0.001 0
 11     0.00000 0.001 0
 15     0.00000 0.001 0
 33     0.00000 0.001 0
 49     0.00000 0.001 0
 40     0.00000 0.001 0
 35     0.00000 0.001 0
 56     0.00000 0.001 0
103     0.00000 0.001 0
 94     0.00000 0.001 0
100     0.00000 0.001 0
 96     0.00000 0.001 0
 85     0.00000 0.001 0
 77     0.00000 0.001 0
 70     0.00000 0.001 0
 31     0.00000 0.001 0
 61     0.00000 0.001 0
 65     0.00000 0.001 0
 69     0.00000 0.001 0
 17     0.00000 0.001 0
  96
  27  32     0.00000 0.001 0
  25  27     0.00000 0.001 0
  23  32     0.00000 0.001 0
  32 114     0.00000 0.001 0
 115 114     0.00000 0.001 0
   2   1     0.00000 0.001 0
   3   5     0.00000 0.001 0
   6   7     0.00000 0.001 0
  12  16     0.00000 0.001 0
  14  12     0.00000 0.001 0
```

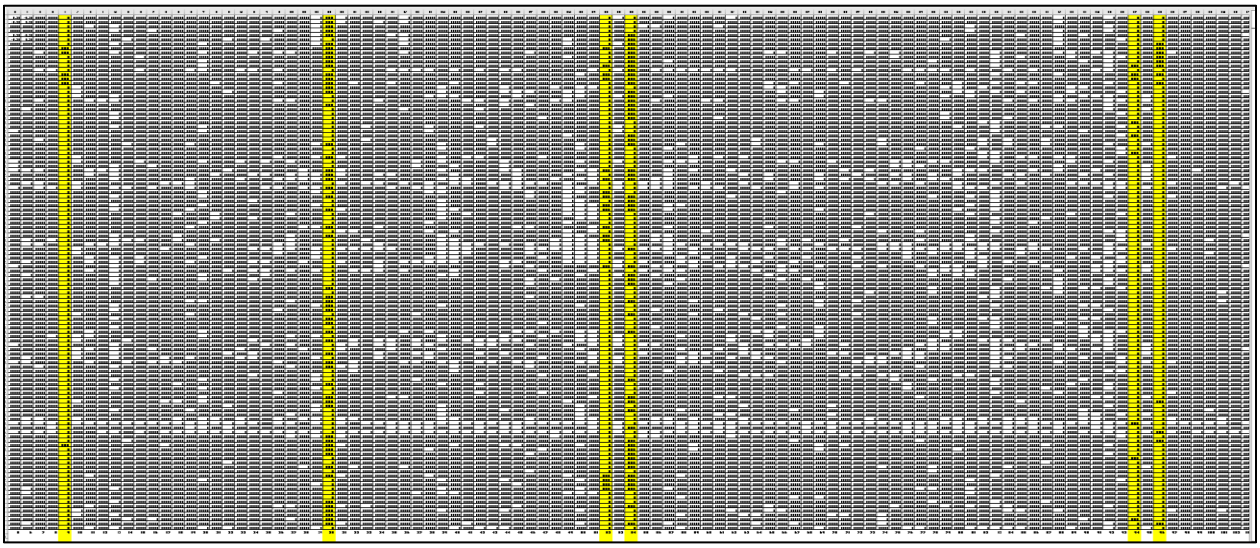
Bus injection measurement

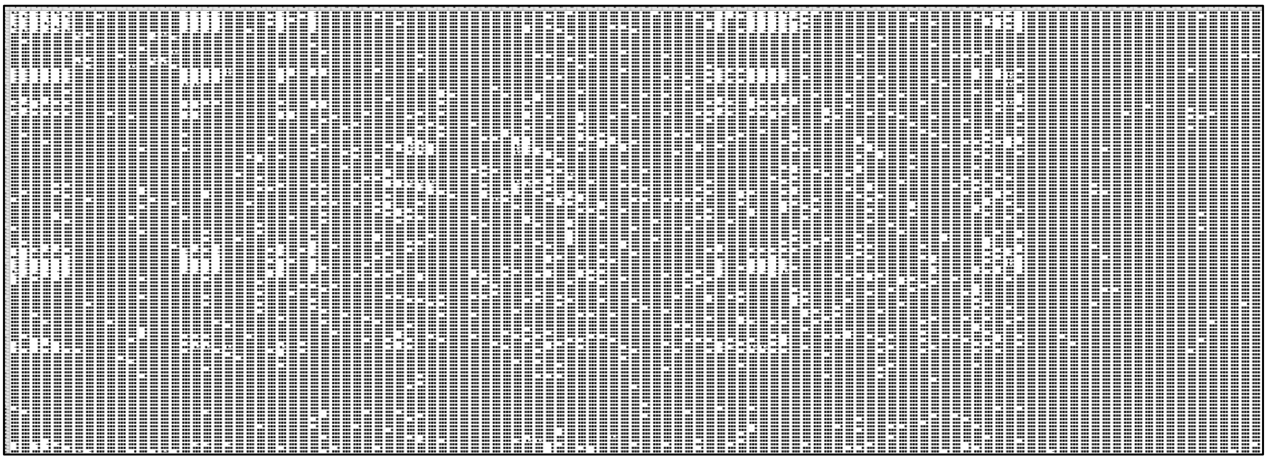
Branch flow measurement

Normal text file

Sensitivity matrix

Before Removal of Criticality vs after removal of criticality





Refer beforeILP and AfterILP sheet in data.xlsx attached.

For removal of Senstivity, generally we add more relevant measurements

For eg.

Critical measurements		
Type	**Location**	**Action taken to improve**
Flow	5-4	Added bus inj. at 5
Flow	91-92	At 92 bus, put injection meas.
Flow	83-84	remove 83-84 and put injection at 84
Flow	64-63	Remove and add 63 injection meas.
Flow	65-68	New injection meas. at 65
Injection	10	New Flow meas. at 9-10
Injection	87	Removed 87 Added flow on 86-87

5.4. Program developed

ILP with Zero Injection

```
clc; clear;
branchdata = [ ];
branchdata_unmod = branchdata;
%% making zero injection using topology method
% Values to find and replace
valuesToFind = [5, 9, 30, 71, 37, 47, 38, 63, 64, 68, 81];
correspondingValues = [4, 10, 26, 72, 35, 46, 65, 59, 61, 69, 80];

% Loop through each value to find and replace
for i = 1:numel(valuesToFind)
    valueToFind = valuesToFind(i);
    newValue = correspondingValues(i);

    % Find indices of the value to replace
    [row, col] = find(branchdata == valueToFind);

    % Replace the values
    for j = 1:length(row)
        branchdata(row(j), col(j)) = newValue;
    end
end

%% ILP method
frombus = branchdata(:,1);
tobus = branchdata(:,2);

busdata = transpose(1:118);
n = size(busdata,1);

A=eye(n,n);
m = size(frombus);

for i = 1:m
    A(frombus(i),tobus(i))=1;
    A(tobus(i),frombus(i))=1;
end

%% Modifying A matrix
rowsToRemove = [5, 9, 30, 71, 37, 47, 38, 63, 64, 68, 81];

% Remove specified rows
A(rowsToRemove, :) = [];
A(:, rowsToRemove) = [];

Aeq = [];
beq = [];
b = -ones(n-11,1);
A = -A;
LB = zeros(n-11,1);
UB = ones(n-11,1);
intcon = [1:n-11];
f = ones(n-11,1);
X = intlinprog(f,intcon,A,b,Aeq,beq,LB,UB);
```

```
%PMUs_at_buses = find(X==1)

%% Removing the exculded zero injection bus
Bus = transpose(1:118);
rowsToRemove = [5, 9, 30, 71, 37, 47, 38, 63, 64, 68, 81];

% Remove specified rows
Bus(rowsToRemove, :) = [];
NewX = [Bus X];

j = 0;
for i=1:n-11
    if NewX(i,2) == 0
    else
        j = j+1;
        pmu(j) = NewX(i,1);
    end
end
pmu
```

Analysis of Observability Data

```
clc; clear;
branchdata = [];

%% Forming A matrix
frombus = branchdata(:,1);
tobus = branchdata(:,2);

busdata = transpose(1:118);
n = size(busdata,1);

A=eye(n,n);
m = size(frombus);

for i = 1:m
    A(frombus(i),tobus(i))=1;
    A(tobus(i),frombus(i))=1;
end

%% Bus injections
%%iter3%%ninj =[27  12      11      15      33      49      40      35      56      103     94
       100     96      85      77      70      31      61      65      69      17 57 3 89 110
44 9 1];
%%optimalILP
ninj = [2      6       10      12      15      17      21      25      29      35      41      43
       49      52      56      62      72      75      77      80      85      65      90      94
       101     105     110     114     116 5 92 84 63 23];
V = [5 64];
[vrr,vcc] = size(V);
[rr,inj] = size(ninj);
%% Bus flow

M = [ ]; %%Bus Flows data
```

```
[rrb,ccc] = size(M);
H=zeros(rrb+inj+vcc,118);
for i=1:rrb
    H(i,M(i,1))=1;
    H(i,M(i,2))=-1;
end
outputString = ['Flow meas. = ', num2str(rrb) ' and Bus Injection = ',
num2str(inj)];
disp(outputString);

for i1 = 1:length(ninj)
    i=i+1;
    bustoprocess = ninj(i1);
    t = find(A(bustoprocess,:)==1);
    indexToRemove = find(t == bustoprocess);
    t(indexToRemove) = [];
    [ro,col]=size(t);
    H(i,bustoprocess) = col;
    for i2 = 1:length(t)
        H(i,t(i2)) = -1;
    end
end

%voltage placement
for i11 = 1:vcc
    i=i+1;
    H(i,V(i11))=1;
end

%% Calculation Obs
G=H'*H;
[n,n]=size(G);
br = branchdata;
[nbr,d]=size(br);

%Forms admittance matrix
A = zeros(nbr,n);
for i=1:nbr
   A(i,br(i,1)) = 1;
   A(i,br(i,2)) = -1;
end

%Finds rhs as new theta (rhs)
k=0;
rhs = zeros(n,1);
[L,D,p]=ldl(G,'vector');
for i=1:n
    if abs(D(i,i)) < 1.0e-6
        D(i,i)=1;
        rhs(i,1)=k;
        k=k+1;
    else
    end
end

%List all unobservabl branches
G = L*D*L';
xunobs = G\rhs;
fb = A*xunobs;
```

```
brno = [1:nbr];
flag= zeros(nbr,1);

for j=1:nbr
   if abs(fb(j)) > 1.0e-8
      disp([br(j,1) br(j,2)])
      flag(j)=1;
   else
   end
end

      disp('Remove the following injections and rerun')
ff=0;
for i=1:inj
   for j=1:nbr
    if flag(j) ==1
        if br(j,1) == ninj(i) | br(j,2) == ninj(i)
           ff=1;
        else
        end
     else
    end
   end
   if ff ==1
       disp(ninj(i))
       ff=0;
   else
   end
end

G = transpose(H)*H;
inv(G);

%% Sensitivity/ Critical measurement check
[m,n]=size(H);
H1=H(:,2:n);
[m,n]=size(H1);
H=H1;  % H_AA measurement jacobian
W=eye(m,m)*1.0e6;
G=H'*W*H;
K=H*inv(G)*H'*W;
S=eye(m,m)-K;  %  Sensitivity matrix


%% Calculation of cost
%%inj = count of the bus injection measurement
%%rrb = count of flow measurement

Alla = [inj; M(:,1); V'];
%Allb = [inj; M(:,2)];

AlluqA = unique(Alla);
%AlluqB = unique(Allb)

Cost = 40000*length(AlluqA) + 3000*vcc + 5000*(inj+rrb)
outputString = ['The system cost is = $', num2str(Cost)];
disp(outputString);
```