Journal of Engineering Science and Technology
Vol. 12, No. 7 (2017) 1833 - 1844

SEVERITY BASED CONTINGENCY MANAGEMENT APPROACH: AN INDIAN SCENARIO

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Abstract

In today's electronic world, secured operation of the electric power system is one of the foremost requirements. Contingency analysis and management thus becomes the basic requirement of system analysis. In this paper, the contingency study has been done on a heavily loaded practical power system in an Indian scenario. A Composite Severity Index (CSI) has been proposed for the determination of critical line. The contingency analysis has been done using Rapid Contingency Ranking Technique (RCRT). By this method the number of lines on which the contingency analysis is to be performed is greatly reduced. Thereafter, an Interline Power Flow Controller (IPFC) has been placed in the system on the basis of CSI for improvement of the system situation post-contingency. An IPFC has been found to be very effective in the improvement of system condition of the heavily loaded Indian system.

Keywords: Contingency, Interline power flow Controller, Line utilization factor, Fast voltage stability index, Composite index, Optimal placement.

1. Introduction

The transmission lines, as a result of deregulation in recent times, are forced to carry more electrical power than their design limits. Therefore, chances of system disruption due to outages have increased to a great extent. Hence, Contingency analysis has become one of the most vital requirements of the power system. The security assessment may be of dynamic type [1] or may be done in static conditions. Many methods are available in literature for static type contingency analysis, which is basically a planning issue. The static methods used in literature

Nomenclatures

b_{in}	Series transformer susceptance of line i-n in p.u.
g_{in}	Series transformer conductance of line i-n in p.u.
I_{ji}, I_{ki}	Current in line j-i and k-i respectively in p.u.
LUF_{ij}	Line utilization factor (LUF) of the line connected to bus i and bus j
MVA_{ij}	Actual MVA rating of the line between bus i and bus j
$MVA_{ij(max)}$	Maximum MVA rating of line between bus i and bus j
n	Bus j, k
P_i ,Q_i	Sum of Active and reactive power leaving bus I in MW and MVAR respectively.
P_{ni} , Q_{ni}	IPFC branch active and reactive powers leaving bus n in MW and MVAR respectively.
Q_j	reactive power at bus j
$\boldsymbol{V_i}$	Complex voltage at bus I in p.u.
V_i , θ_i	Magnitude and angle of V_i respectively in p.u.
V_n	Complex voltage at bus (j, k) in p.u.
V_n , θ_n	Magnitude and angle of V_n respectively in p.u.
Vse_{in}	Complex controllable series injected voltage source in p.u.
Vse_{in} , θse_{in}	Magnitude and angle of Vse_{in} respectively in p.u.
X	line reactance
Z	line impedance
Zse_{in}	Series transformer impedance of line i-n in p.u.
Q_j	reactive power at bus j
$\boldsymbol{V_i}$	Complex voltage at bus I in p.u.
V_i , θ_i	Magnitude and angle of V_i respectively in p.u.
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Abbreviations

CSI	Composite Severity Index
FVSI	Fast Voltage Stability Index
IPFC	Interline Power Flow Controller
LUF	Line Utilization Factor
TCSC	Thyristor Controlled Series Compensator
UPFC	Unified Power Flow Controller

are analytical hierarchy process [2], artificial neural network programming [3],and eigen-value method [4]. The traditional method of analysis of contingency is accurate but extremely burdensome. The power systems become greatly vulnerable during system disturbances and if proper actions are not taken promptly then the chances of blackout become very high. One of the most popular and successful preventive measure in this regard is the proper allocation of FACTS devices in the power systems. Many computational intelligence methods have been adopted in literature for obtaining correct location for the devices and their proper tuning. Improved teaching learning based technique [5], cat swarm optimization [6], differential evolution [7], gravitational search algorithm and artificial bee colony [8], have been applied for optimal placement and tuning of UPFC. A multi-objective rescheduling with FACTS devices technique has also been used to enhance voltage stability of the power system [9].

A strategy for prevention of blackout by using FACTS devices has been proposed by Mozzami et al. [10]. Some researchers have also used index based methods for obtaining the optimal location for the FACTS devices. Jayasankar et al. [11] have estimated voltage stability index using artificial neural network for the placement of TCSC. Visakha et al. [12] have used composite index by a fuzzy-based method for optimal location of UPFC. Index based methods for optimal placement of FACTS devices have been found to be very accurate and computationally fast. It is well adapted for both static and dynamic analysis of the system. With increase in load on the problem of line overload and voltage collapse both become a major issue with the power systems. Therefore, it is essential to contemplate a combination of a voltage stability index and a line overload index for measuring the actual system stress under contingency situation. Out of all FACTS devices IPFC is considered to be most flexible, powerful and versatile as it employs multiple VSC's with a common DC link. IPFC has the ability to compensate multiple transmission lines. It can control both real power flow and reactive power flow besides performing transfer of real power amid the lines [13]. Optimum allocation of IPFC for contingency management is expected to be a very good option to resolve the post-contingency issues.

In this paper, a Composite Severity Index (CSI) has been formulated to evaluate line overloads and bus voltage violations. Line Utilization Factor (LUF) is measures the line overloads using apparent power. Fast Voltage Stability Index (FVSI) measures the voltage stability. The Composite Severity Index thus formed gives an accurate estimation of overall stress on the line. A very simple but accurate method for contingency screening has been used in this study based on the outage of lines connected to only few important buses. Thus, the contingency screening procedure is carried out by the analysis of only few selective transmission lines. IPFC is placed on the most critical line in the power system as specified by the value of CSI. The proposed method is implemented and tested on Indian utility 62 bus system under varied loading. The results have been presented and analyzed for illustration purposes.

2. Modelling of IPFC

An IPFC is a combination of multiple series connected converters working together. The elementary IPFC, shown in Fig. 1, consists of two static synchronous series compensators (SSSC) connected through a common DC capacitor [14]. The converters of IPFC can be represented as synchronous voltage source with controllable magnitude and angle. The mathematical equations in regards to IPFC modelling are as mentioned in the Eq. (1) to Eq. (4).

$$P_i = V_i^2{}_{ii} - \sum_n V_i V_n \left[g_{in} \cos(\theta_i - \theta_n) + b_{in} \sin(\theta_i - \theta_n) \right]$$

$$- \sum_n V_i Vse_{in} \left[g_{in} \cos(\theta_i - \theta se_{in}) - b_{in} \sin(\theta_i - \theta se_{in}) \right] \quad (1)$$

$$Q_i = -V_i^2 b_{ii} - \sum_{n=j,k} V_i V_n \big[g_{in}\sin(\theta_i-\theta_n) - b_{in}\cos(\theta_i-\theta_{n)})\big]$$

$$-\sum_{n=j,k} V_i Vse_{in}\big[g_{in}\sin(\theta_i-\theta_{se\,in}) - b_{in}\cos(\theta_i-\theta_{se\,in})\big] \tag{2}$$

$$\begin{aligned} P_{ni} = V_n^2 g_{nn} - V_i V_n \big[g_{in}\cos(\theta_n-\theta_i) + b_{in}\sin(\theta_n-\theta_i)\big] \\ + V_n V_{se\,in}\big[g_{in}\sin(\theta_n-\theta_{se\,in}) - b_{in}\cos(\theta_n-\theta_{se\,in})\big] \end{aligned} \tag{3}$$

$$\begin{aligned} Q_{ni} = -V_n^2 b_{nn} - V_i V_n \big[g_{in}\sin(\theta_n-\theta_i) - b_{in}\cos(\theta_n-\theta_i)\big] \\ + V_n V_{se\,in}\big[g_{in}\sin(\theta_n-\theta_{se\,in}) - b_{in}\cos(\theta_n-\theta_{se\,in})\big] \end{aligned} \tag{4}$$

where $n = j, k$

$g_{in} + jb_{in} = 1/zse_{in} = yse_{in}, g_{nn} + jb_{nn} = 1/zse_{in} = yse_{in}$

$g_{ii} = \sum_{n=j,k} g_{in}, b_{ii} = \sum_{n=j,k} b_{in}$

Assuming no loss, the active power supplied by one converter equals the active power demanded by the other, if there are no underlying storage systems.

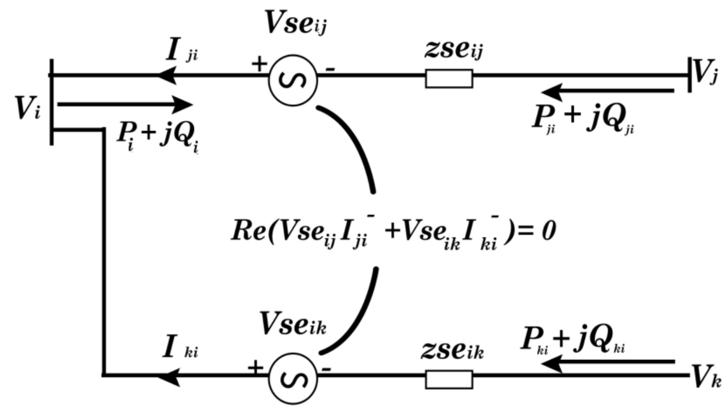

Fig. 1. IPFC equivalent circuit.

Proposed Composite Severity Index (CSI)

The Composite Severity Index of a line is calculated as given in Eq. (5).

$$CSI_{ij} = w_1 \times LUF_{ij} + w_2 \times FVSI_{ij} \tag{5}$$

where,

$$w_1 + w_2 = 1$$

w_1 and w_2 are the weighting factors of the two indices for line i-j.

$$LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij\max}} \tag{6}$$

$$FVSI_{ij} = \frac{4Z^2Q_j}{V_i^2X} \tag{7}$$

The line loading is measured using the index LUF [15] as mentioned in Eq. (6). When LUF ≥ 1, the line is considered to be overloaded. FVSI [16] is used to measure the voltage stability of a line as given in Eq. (7). A system is considered to be unstable if FVSI ≥ 1.

The weighting factors show the relative importance of the indices. Maximum value of overall CSI of the system has been obtained for $w_1 = w_2 = 0.5$. It has been observed for both the bus systems that the value of overall LUF of the system is higher than the value of overall FVSI. Hence, any further reduction in the value of w_2 is not advisable. Therefore, in this study, the equal weightage has been given to both the indices. Since, CSI is a weighted average of LUF and FVSI, CSI also represents stable region if CSI ≤ 1. The overall CSI of the system is given by Eq. (12)

$$OverallCSI = \sum_{\forall L} CSI \tag{8}$$

$$OverallFVSI = \sum_{\forall L} FVSI \tag{9}$$

$$OverallLUF = \sum_{\forall L} LUF \tag{10}$$

$$\Rightarrow \sum_{\forall L} CSI = w_1 \times \sum_{\forall L} LUF + w_2 \times \sum_{\forall L} FVSI \tag{11}$$

$$\Rightarrow OverallCSI = OverallLUF + OverallFVSI \tag{12}$$

3. Implemented Contingency Analysis Method

Contingency analysis of large power systems is a very tedious job by the conventional technique of considering each outage and analyzing the system for individual contingencies. Computational intelligence method suggested in some studies also seem to be quite complex. Hence, in this study a method of contingency analysis is used founded on choice of some significant buses, the line connected to which are expected to severely affect the system in case of an outage. The method is therefore termed as Rapid Contingency Ranking Technique (RCRT), due to its feature of fast contingency analysis of power systems. The flow chart for placement of IPFC is given in Fig. A-1 (*Appendix A*).

The method for selection of the important buses is as given below-

- Select the slack bus.
- Select all the generator buses.
- Select the load buses connecting maximum number of transmission lines.
- Select a load bus at the far end with maximum number of transmission lines.

The proposed technique has been implemented on an Indian Utility 62 bus system presented in Fig. 2 with Bus data given in Fig. A-2 (*Appendix A*). The system has one slack bus, eighteen generator buses, forty-three load buses and eighty-nine transmission lines. Following the rules given in section 4 the lines connected to bus 61 and 41 along with the lines connected to all generator and slack buses have been selected for the analysis. Thus in the process 49 lines have been selected for contingency analysis out of 89 lines of the 62 bus system.

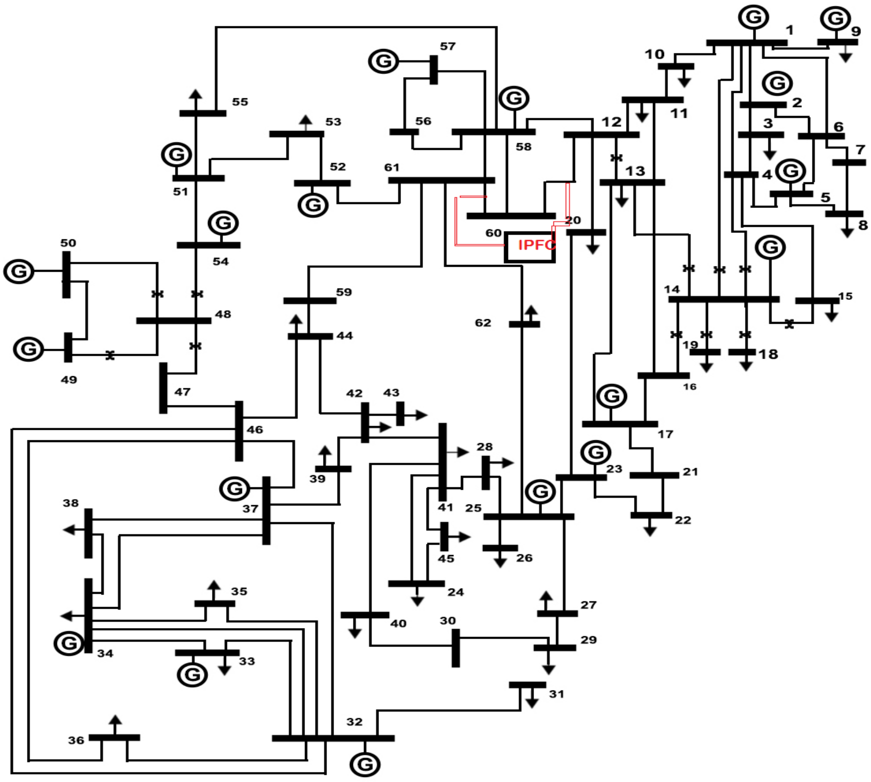

Fig. 2. A typical Indian utility 62 bus system with IPFC installed at line connected between buses 60-61 and 60-12.

The reduction in the lines for contingency analysis have been mentioned in Table 1. It is observed that the number of lines for analysis for both the bus systems have been reduced to almost half the previous value.

Table 1. Lines selected by RCRT for different bus systems.

Bus System	Total lines	Line selected for contingency analysis	Percentage reduction
Indian Utility 62 bus system	89	49	55%

4. General Procedure for Management of Contingency

The general procedure for contingency management using IPFC has been mentioned below.

Step 1: Perform Severity analysis of the bus system on the basis of RCRT technique

Step 2: Select the most critical line of the system on the basis of CSI and the corresponding most critical contingency

Step 3: Place the 2nd converter of the IPFC on the line connected to the critical line with the least value of CSI [17].

Step 4: Study the performance of the system for normal and overloaded condition.

Step 5: If any more IPFC is to be placed repeat the process from step 3.

5. Results of IPFC Placement on Indian Utility 62 Bus System

The most critical lines of the system with respect to CSI after performing the contingency analysis by the traditional method have been presented in Table 2. It is observed that the most critical line on the basis of CSI is line 60-61 with CSI value about 1.53 p.u. for contingency of line 58-61. Next Rapid Contingency Ranking has been performed. The results obtained have been presented in Table 3. It is observed that for line 58-61 outage line 60-61 has the highest value of LUF of 3.029 p.u. whereas with respect to FVSI the critical line is 24-41 with FVSI equal to 0.1515p.u.

Table 2. Conventional method of contingency analysis.

Contingency		Critical line		CSI (p.u.)
SB	RB	SB	RB	
58	61	60	61	1.525544
4	14	4	15	1.390444
1	14	4	15	1.285265
23	24	41	42	1.254915
1	10	11	16	1.168837
47	46	59	61	1.055024
11	10	4	15	1.038379
|	|	|	|	|
|	|	|	|	|
|	|	|	|	|
2	3	4	15	0.851067
4	15	21	22	0.76121
34	33	24	41	0.376588

*SB- Sending-end Bus * RB- Receiving-end Bus

The most critical line on the basis of CSI is line 60-61 with CSI value about 1.53 p.u. Line 60-61 for line 58-61 outage is found to have the highest severity in comparison to all other outages. Thus, it is found that although analysis of much less lines has been done similar results have been obtained using RCRT and traditional method. Line 60-61 is connected to lines 61-62, 59-61, and line 52-61. The CSI values of these lines after contingency in line 58-61 have been presented in Table 4. It is observed that line 60-12 is the healthiest line (least CSI value) connected to line 60-61. Hence, the IPFC is placed in line 60-61(critical line) and line 60-12.

In Table 5 various parameters of the system have been compared for different system conditions, namely, without contingency, with contingency, and with optimal placement of IPFC. The parameters taken into consideration are active power loss, reactive power loss, Overall FVSI, Overall CSI, Overall LUF, FVSI, LUF, and CSI of line 60-61. It is observed that contingency in line 58-61 increases the values of the system parameters. Severity of the line 60-61 also increases as given by LUF, FVSI and CSI values. Placement of IPFC at the proposed location reduces the system parameters to a good extent. The voltage profile of the 62 bus system has been given in Fig. 3. It shows a very good improvement in the voltage of the buses with placement of IPFC at the proposed location.

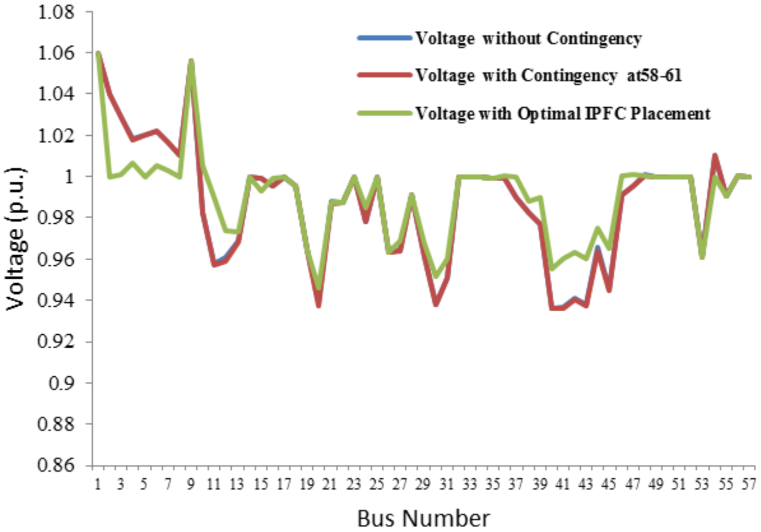

Fig. 3. Comparison of voltage profile for various system settings.

Table 3. Severe-most lines from RCRT based contingency analysis.

Contingency		**Critical line**		**LUF (p.u.)**	**Critical line**		**FVSI (p.u.)**	**Critical line**		**CSI (p.u.)**
SB	**RB**	**SB**	**RB**		**SB**	**RB**		**SB**	**RB**	
58	61	60	61	3.029	24	41	0.1515	60	61	1.5255
4	14	4	15	2.7204	24	41	0.1516	4	15	1.3904
1	14	4	15	2.5272	24	41	0.1518	4	15	1.2852
23	24	41	42	2.4724	39	42	0.2752	41	42	1.2549
1	10	11	16	2.18	12	11	0.198	11	16	1.1688
32	31	4	15	1.8191	29	30	0.1946	39	37	1.0261
17	21	61	62	1.8361	24	41	0.1670	12	13	0.9557
13	17	4	15	1.851	24	41	0.1504	4	15	0.9524
16	17	4	15	1.8467	24	41	0.1522	4	15	0.9503
1	2	4	15	1.8466	24	41	0.1515	4	15	0.9430
4	5	4	15	1.6924	24	41	0.1516	3	4	0.9375
2	6	4	15	1.8231	24	41	0.1515	4	15	0.9350
51	53	4	15	1.8227	24	41	0.1550	4	15	0.9331
25	27	4	15	1.8196	39	42	0.1967	4	15	0.9315
52	53	4	15	1.8178	24	41	0.1488	4	15	0.9306
5	8	4	15	1.8163	24	41	0.1515	4	15	0.9299
39	37	4	15	1.8161	24	41	0.2585	4	15	0.9298
55	58	4	15	1.8159	24	41	0.1476	4	15	0.9297
37	46	4	15	1.8153	24	41	0.1593	4	15	0.9294
5	6	4	15	1.8142	24	41	0.1515	4	15	0.9289

*SB- Sending-end Bus * RB- Receiving-end Bus

Table 4. CSI of lines inter-connected with line 60-61 for line 58-61 contingency.

Sending-end Bus	Receiving-end Bus	CSI (p.u.)
61	62	0.6203
59	61	0.6905
60	12	0.2383

Table 5. Comparison of results without contingency, with contingency and with optimal placement of IPFC at 60-61 and 60-12.

Parameter	Without contingency	With contingency	With optimal placement of IPFC
Active Power Loss (MW)	75.904	92.074	58.589
React. Power Loss (MVAR)	380.742	469.338	467.286
Voltage Deviation (p.u.)	0.7766	1.3261	0.9403
Overall LUF (p.u.)	81.799	94.2165	89.2918
Overall FVSI (p.u.)	4.24608	4.6772	4.0645
Overall CSI (p.u.)	43.0226	49.4469	46.6782

6. Conclusion

In this paper, a Composite Severity Index based method has been used for the identification of severity of the system. CSI has been found to be very effective in determination of the most critical line due to contingency. A method called Rapid Contingency Ranking Technique has been used for the contingency analysis of an Indian Utility 62 bus system. The technique reduces the computation time to a great extent, by reducing the number of lines for contingency analysis. An IPFC has been placed on the line with the highest value of CSI. It has been deduced that the IPFC placement successfully reduces line congestion, improves voltage stability and reduces the system losses. There is an improvement in voltage profile due to reduction in voltage deviation. The overall CSI, overall LUF and overall FVSI of the system are also found to be reduced to the healthy state.

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Appendix A

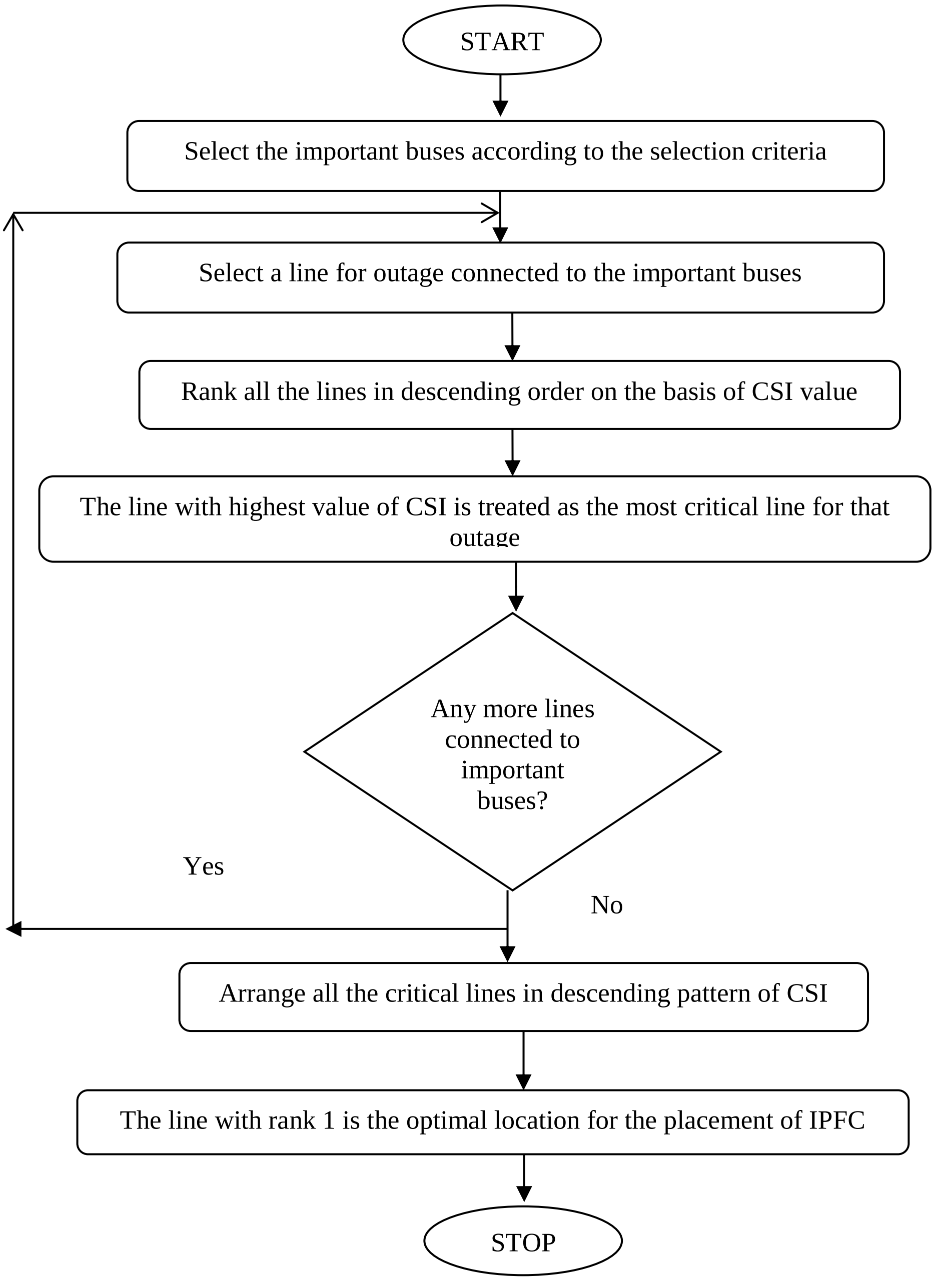

Fig. A-1. Flow Chart for placement of IPFC.

Bus No.	**Type**	**V_{sp}**	**theta**	**P_{gi}**	**Q_{gi}**	**P_{Li}**	**Q_{Li}**	**Q_{min}**	**Q_{max}**
1	1	1.06	0	0	0	0.0	0.0	0	0
2	2	1.0	0	350	0	0.0	0.0	0	500
3	3	1.0	0	0	0	40.0	10.0	0	0
4	3	1.0	0	0	0	0.0	0.0	0	0
5	2	1.0	0	200	0	0.0	0.0	-	500
6	3	1.0	0	0	0	0.0	0.0	50	0
7	3	1.0	0	0	0	0.0	0.0	0	0
8	2	1.0	0	50	0	109.0	78.0	0	150
9	3	1.0	0	0	0	66.0	23.0	0	0
10	3	1.0	0	0	0	40.0	10.0	0	0
11	3	1.0	0	0	0	161.0	93.0	0	0
12	3	1.0	0	0	0	155.0	79.0	0	0
13	3	1.0	0	0	0	132.0	46.0	0	0
14	2	1.0	0	50	0	0.0	0.0	0	300
15	3	1.0	0	0	0	155.0	63.0	-50	0
16	3	1.0	0	0	0	0.0	0.0	0	0
17	2	1.0	0	200	0	0.0	0.0	0	500
18	3	1.0	0	0	0	121.0	46.0	-50	0
19	3	1.0	0	0	0	130.0	70.0	0	0
20	3	1.0	0	0	0	80.0	70.0	0	0
21	3	1.0	0	0	0	0.0	0.0	0	0
22	3	1.0	0	0	0	64.0	50.0	0	0
23	2	1.0	0	50	0	0.0	0.0	0	250
24	3	1.0	0	0	0	58.0	34.0	-50	0
25	2	1.0	0	250	0	0.0	0.0	0	600
26	3	1.0	0	0	0	116.0	52.0	-100	0
27	3	1.0	0	0	0	85.0	35.0	0	0
28	3	1.0	0	0	0	63.0	8.0	0	0
29	3	1.0	0	0	0	0.0	0.0	0	0
30	3	1.0	0	0	0	77.0	41.0	0	0
31	3	1.0	0	0	0	51.0	25.0	0	0
32	2	1.0	0	350	0	0.0	0.0	0	550
33	2	1.0	0	50	0	46.0	25.0	-100	150
34	2	1.0	0	100	0	100.0	70.0	0	200
35	3	1.0	0	0	0	107.0	33.0	-50	0
36	3	1.0	0	0	0	20.0	5.0	0	0
37	2	1.0	0	50	0	0.0	0.0	0	75
38	3	1.0	0	0	0	166.0	22.0	0	0
39	3	1.0	0	0	0	30.0	5.0	0	0
40	3	1.0	0	0	0	25.0	5.0	0	0
41	3	1.0	0	0	0	92.0	191.0	0	0
42	3	1.0	0	0	0	30.0	25.0	0	0
43	3	1.0	0	0	0	25.0	5.0	0	0
44	3	1.0	0	0	0	109.0	17.0	0	0
45	3	1.0	0	0	0	20.0	4.0	0	0
46	3	1.0	0	0	0	0.0	0.0	0	0
47	3	1.0	0	0	0	0.0	0.0	0	0
48	3	1.0	0	0	0	0.0	0.0	0	0
49	2	1.0	0	50	0	0.0	0.0	0	300
50	2	1.0	0	50	0	0.0	0.0	-50	200
51	2	1.0	0	100	0	0.0	0.0	-50	550
52	2	1.0	0	50	0	0.0	0.0	-50	200
53	3	1.0	0	0	0	248.0	78.0	-50	0
54	2	1.0	0	50	0	0.0	0.0	0	150
55	3	1.0	0	0	0	94.0	29.0	0	0
56	3	1.0	0	0	0	0.0	0.0	0	0
57	2	1.0	0	50	0	0.0	0.0	0	400
58	2	1.0	0	400	0	0.0	0.0	-50	600
59	3	1.0	0	0	0	0.0	0.0	-100	0
60	3	1.0	0	0	0	0	0	0	0
61	3	1.0	0	0	0	0.0	0.0	0	0
62	3	1.0	0	0	0	98.0	23.0	0	0

Fig. A-2. Bus data for IEEE 62 bus system.