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Post-Contingency Management of Power System in Presence of Interline Power Flow Controller using Line-Based Indices

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ABSTRACT: Day-to-day increased demand on the power system causing transmission network to transmit power at their maximum transmission limits. So secured operation of power system is an important issue in order to supply reliable power to the customer when contingencies are occurs in the system. In this paper we propose a composite severity index (CSI) which gives precise degree of stress in the line regarding to the MVA overloading and voltage instability. Based on this composite severity index (CSI) the interline power flow controller (IPFC) is placed in the system to relieve the overload on the transmission lines under the post contingency condition. The proposed methodology has been implemented on IEEE30 bus system and the results have been presented in MATLAB by using N-R power flow method.

KEYWORDS: Contingency, Line Utilization Factor, Line Stability Index, Composite Severity Index, Interline Power Flow Controller, Optimal Placement, Newton's Raphson method.

I. INTRODUCTION

In recent years, power demand has increased substantially while the expansion of power generation and transmission has been severely limited due to limited resources and environmental restrictions. As a consequence, some transmission lines are heavily loaded. Unpredictable operating conditions, a lot of vulnerable networks demands to monitor the transmission system security level [1]. Contingency analysis is that the study of the outage of components such as transmission lines, transformers and generators, and investigation of the resulting effects on the power flows and bus voltages of the remaining system. It represents a very important tool to check the impact of component outages in power grid security throughout operation and planning. Contingencies concerning disturbances like transmission element outages or generator outages might cause fulminant and huge changes in both the configuration and the state of the system. Contingencies might lead to severe violations of the operational constraints. Consequently, planning for contingencies forms a very important aspect of secure operation [2]

Contingency analysis permits the system to be operated defensively. Several of the issues that occur within the power system will cause serious troubles within a short time if the operator couldn't take quick corrective action. Therefore, modern computers are equipped with contingency analysis programs which model the power system and are used to study outage events and alert the operators of potential overloads and voltage violations [2]. During system disturbances, system becomes extremely unstable and there's a high risk of moving towards global instability or blackout if preventive measures are not taken on time.

FACTS devices are preferred in modern power system based on requirement. Placement of FACTS devices at an appropriate location provides a good solution to blackout prevention [3]. The interline power flow controller (IPFC) is a new member of FACTS controllers. Just like the static synchronous compensator (STATCOM), static synchronous

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

series compensator (SSSC) and unified power flow controller (UPFC), the IPFC also employs the voltage sourced converter as a basic building block. The UPFC and IPFC consists a minimum of two converters. It is found that, in the past, much effort has been made in the modeling of the UPFC for power flow analysis [4-8]. However, UPFC aims to compensate a single transmission line, where as the IPFC is conceived for the compensation and power flow management of multi-line transmission system.

The basic theory and operating characteristics of the IPFC with phasor diagrams, P-Q plots and simulated wave forms has been explained in [9]. A simple model of IPFC with optimum power flow control method to solve overload problem and the power flow balance for the minimum cost has been proposed in [10]. A multi control functional model of static synchronous series compensator (SSSC) used for steady state management of power system parameters with current and voltage operating constraints has been given in [11]. The injection model for congestion management and total active power loss reduction in electric power system has been developed in [12]. Mathematical models of generalized unified power flow controller (GUPFC) and IPFC and their implementation in Newton power flow methodology are reported in [13] to demonstrate the performance of GUPFC and IPFC. Based on the review above, this paper presents an offline long term investment strategy for placement of IPFC for protection of power system against contingency and here a composite severity index (CSI) is used to evaluate line overloads and bus voltage violations and it is formed by using Line utilization factor (LUF) and Line stability index (L_{mn}). Line utilization factor (LUF) is used for the measurement of line overloads in terms of both real and reactive power flows. Line stability index (L_{mn}) has been used for voltage stability assessment. This proposed methodology has been enforced and tested on IEEE30 bus system. Power injection model of IPFC and its placement in IEEE30 bus system has been enforced in NR methodology to study the effect of IPFC in the overload relieve on the occurrence of contingency.

II. MATHEMATICAL MODEL OF IPFC

In this section, a mathematical model for IPFC which is known as power injection model is derived. This model is useful in understanding the impact of the IPFC on power system in the steady state. Further, the IPFC model can easily be incorporated in the power flow algorithm. Usually IPFC employs a number of dc-to-ac converters, each provides series compensation for multi line transmission system. The simplest IPFC consists of two back-to-back dc-to-ac converters, which are connected in series with two transmission lines through series coupling transformers and the dc terminals of the converters are connected together via a common dc link as shown in Fig. 1.

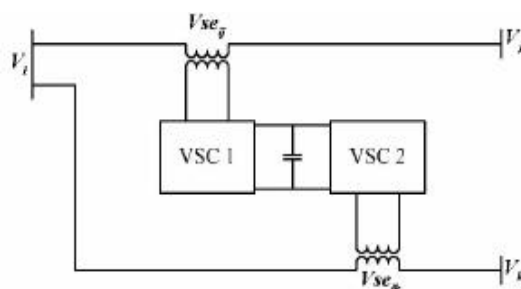


Fig. 1 Schematic diagram of two converter IPFC

With this IPFC in addition to providing series reactive compensation, any converter can be controlled to supply real power to the common dc link from its own transmission lines [14]. Usually, in the steady state analysis of power system, the voltage source converter (VSC) may be represented as a synchronous voltage source injecting an almost sinusoidal voltage with controllable magnitude and angle. Based on this, the equivalent circuit of IPFC is shown in Fig. 2.

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

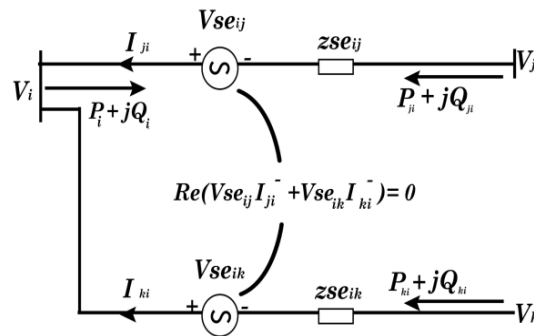


Fig. 2 Equivalent circuit of two converter IPFC

In Fig-2, V_i, V_j and V_k are the complex bus voltages at the buses i, j and k respectively, defined as

$V_x = V_x \angle \theta_x$ ($x = i, j$ and k). Vse_{in} is the complex controllable series injected voltage source, defined as $Vse_{in} = Vse_{in} \angle \theta se_{in}$ ($n = j, k$) and Zse_{in} ($n = j, k$) is the series coupling transformer impedance. The active and reactive power injections at each bus can be easily calculated by representing IPFC as current source. For the sake of simplicity, the resistance of the transmission lines and the series coupling transformers are neglected. The power injections at buses are summarized as

$$P_{inj,i} = \sum_{n=j,k} V_i Vse_{in} b_{in} \sin (\theta_i - \theta se_{in}) \quad (1)$$

$$Q_{inj,i} = -\sum_{n=j,k} V_i Vse_{in} b_{in} \cos (\theta_i - \theta se_{in}) \quad (2)$$

$$P_{inj,n} = -V_n Vse_{in} b_{in} \sin (\theta_n - \theta se_{in}) \quad (3)$$

$$Q_{inj,n} = V_n Vse_{in} b_{in} \cos (\theta_n - \theta se_{in}) \quad (4)$$

Where $n = j, k$. The equivalent power injection model of an IPFC is shown in Fig. 3.

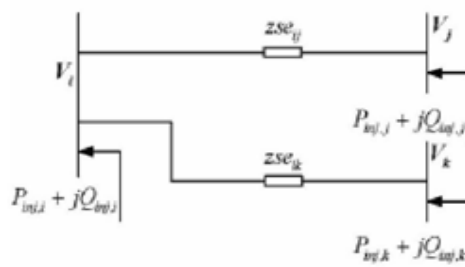


Fig. 3 power injection model of two converter IPFC

As IPFC neither absorbs nor injects active power with respect to the ac system. The active power exchange between the converters via the dc link is zero, i.e

$$Re (Vse_{ij} I_{ji}^* + Vse_{ik} I_{ki}^*) = 0 \quad (5)$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

Where the superscript * denotes the conjugate of a complex number. If the resistance of series transformers are neglected, equation (5) can be written as

$$\sum_{m=i,j,k} P_{inj,m} = 0 \quad (6)$$

Normally in the steady state operation, the IPFC is used to control the active and reactive power flows in the transmission lines in which it is placed. The active and reactive power flow control constraints are

$$P_{ni} - P_{ni}^{spec} = 0 \quad (7)$$

$$Q_{ni} - Q_{ni}^{spec} = 0 \quad (8)$$

Where $n = j, k$; P_{ni}^{spec} , Q_{ni}^{spec} are the specified active and reactive power flow control references respectively, and

$$P_{ni} = \text{Re} (V_n I_{ni}^*) \quad (9)$$

$$Q_{ni} = \text{Im} (V_n I_{ni}^*) \quad (10)$$

Thus, the power balance equations are as follows

$$P_{gm} + P_{inj,m} - P_{lm} - P_{line,m} = 0 \quad (11)$$

$$Q_{gm} + Q_{inj,m} - Q_{lm} - Q_{line,m} = 0 \quad (12)$$

Where P_{gm} and Q_{gm} are generation active and reactive powers, P_{lm} and Q_{lm} are load active and reactive powers. $P_{line,m}$ and $Q_{line,m}$ are conventional transmitted active and reactive powers at the bus $m = i, j$ and k .

III. COMPOSITE INDEX

Composite severity index is formulated such as it provides an exact measure of stress in the line in terms of mega watt (MW) overloading and voltage instability has been proposed in [15]. Based on this review, this paper presents a composite severity index as it provides an exact measure of stress in the line in terms of Mega Volt Ampere (MVA) overloading and voltage instability.

A. LINE UTILIZATION FACTOR

Line utilization factor is an index used for determining the extent of MVA loading under normal and contingency condition. It is given by equation (13)

$$LUF_{ij} = \frac{MVA_{ij}}{MVA_{ijmax}} \quad (13)$$

Where LUF_{ij} is the line utilization factor (LUF) of the line connected to bus i and j . MVA_{ijmax} is maximum MVA rating of the line connected between bus i and j and MVA_{ij} is actual MVA rating of the line connected between bus i and bus j . LUF Will be small when the line under consideration carries an apparent power within its specified limits and reaches a high value during overloads. Thus it provides a precise measure of severity of the line overloads for a given state of the power system. When $LUF \geq 1$ the line is considered to be overload. The overall LUF of the system is sum of LUF 's of all lines and is given by equation (14)

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

$$\text{Overall LUF} = \sum_{\forall L} \text{LUF} \quad (14)$$

Where L is the total no. of lines in the system.

B. LINE STABILITY INDEX

Line stability index (L_{mn}) is a voltage collapse proximity indicator. Considering each line in a network as a single line the line stability index can be calculated from the formula given in equation (15)

$$L_{mn} = \frac{4 \times Q_n}{[V_m \sin(\theta - \delta)]^2} \quad (15)$$

Where $\delta = \delta_m - \delta_n$

$$\theta = \tan^{-1}(X/R)$$

Where X is the reactance of line between bus m and n

R is the resistance of line between bus m and n

θ is the line angle between voltage and current

δ_m is the voltage phase angle of bus m

δ_n is the voltage phase angle of bus n

Q_n is the reactive power at bus n

V_m is the voltage magnitude at bus m .

Based on the value of the stability indices of the lines the proximity of voltage collapse can be accurately predicted. A line with L_{mn} value nearer to zero is considered to be a healthy line pertaining to stability. Higher the value of L_{mn} of a line weaker is the line with respect to stability. A system is considered to be unstable if $L_{mn} \geq 1$. Using this technique the lines in the system which are in the stressed condition can be identified. The overall L_{mn} of the system is given by

$$\text{Overall } L_{mn} = \sum_{\forall L} L_{mn} \quad (16)$$

C. COMPOSITE SEVERITY INDEX (CSI)

LUF gives an estimate of line overloads in terms of apparent power. L_{mn} indicates the voltage stability of the system. Both indices have been combined to form a composite severity index which is used to get an accurate estimation of overall stress on the line. After obtaining the LUF and L_{mn} values of all the lines for a particular line outage, the composite severity index is calculated as given in equation (17).

$$CSI = W_1 \times LUF + W_2 \times L_{mn} \quad (17)$$

Where $W_1 + W_2 = 1$

W_1 and W_2 are the weighting factors of the two indices for each line. The weighting factors may be used to reflect the relative important of the indices. In this study, we take as $W_1 = 0.8$, $W_2 = 0.2$.

The overall CSI of the system is given by equation (18)

$$\text{Overall } CSI = \sum_{\forall L} CSI \quad (18)$$

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

IV. RESULTS AND DISCUSSIONS

IEEE 30 bus system is shown in Fig. 4

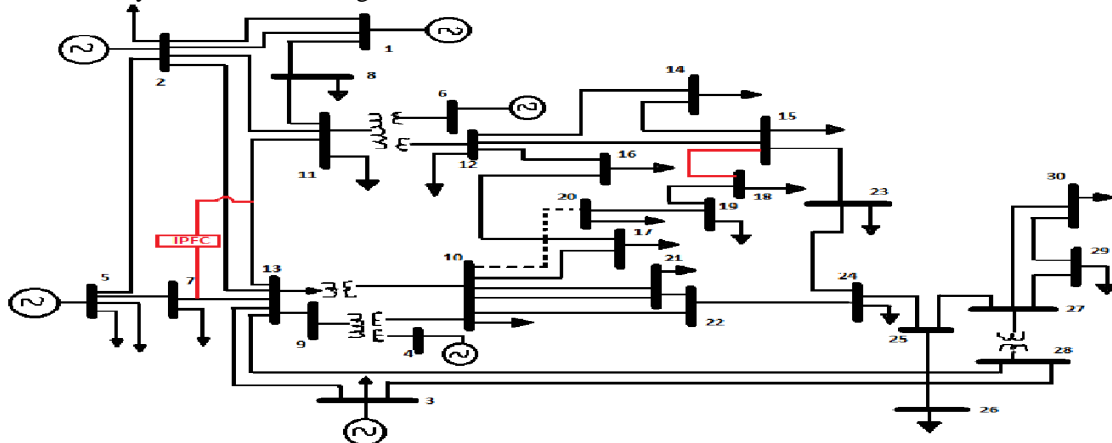


Fig. 4 IEEE 30 bus test system with outage in line 10-20 and IPFC placement on line connected between buses 7-13 and 11-13.

Contingency studies are carried for normal and severe line loading conditions .Table 1 shows the line loading under normal operating condition. Figure 1 shows the line loading of IEEE30 bus system with N-R load flow.

Table. 1 At pre-contingency condition loading (%MVA) on transmission lines

Line no	F.B	T.B	Loading (%MVA)	Line no	F.B	T.B	Loading (%MVA)
01	13	09	21.417257	22	16	17	39.904993
02	13	10	32.582610	23	15	18	45.953081
03	11	12	40.831896	24	18	19	25.153646
04	28	27	25.362499	25	20	19	19.739350
05	01	02	43.894767	26	10	20	27.236414
06	01	08	33.513069	27	10	17	15.051433
07	02	11	49.849164	28	10	21	57.883340
08	08	11	30.887268	29	10	22	27.476050
09	02	05	35.451681	30	22	21	8.144874
10	02	13	61.167503	31	15	23	47.283665
11	11	13	39.168463	32	22	24	39.479579
12	05	07	10.920554	33	23	24	25.034393
13	13	07	17.726537	34	25	24	10.552228
14	13	03	43.452813	35	25	26	26.662382
15	04	09	36.727938	36	27	25	34.742439
16	09	10	54.007533	37	27	29	40.112460
17	06	12	33.934920	38	27	30	45.580424
18	12	14	27.627278	39	29	30	23.467941
19	12	15	66.748679	40	03	28	9.986584
20	12	16	32.434115	41	13	28	48.393712
21	14	15	14.903037				

F.B = From Bus T.B = To Bus MVA = Mega Volt Ampere

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

Table 2 Index values of transmission lines after removal of each transmission line
F.B = From Bus T.B = To Bus MVA = Mega Volt Ampere

line outage FB TB		severe line FB TB	LUF value	severe line FB TB	L_{mn}	Severe line FB TB	C.S.I
01	02	01 08	0.787189	02 11	0.139942	01 08	0.649774
01	08	02 13	0.841929	11 12	0.140923	02 13	0.678800
02	11	02 13	0.807887	09 04	0.113007	02 13	0.652845
08	11	02 13	0.828284	11 12	0.139549	02 13	0.668254
02	05	02 13	0.928248	05 07	0.124221	02 13	0.743403
02	13	02 11	0.747378	11 12	0.129082	02 11	0.605712
11	13	02 13	0.879440	11 12	0.116275	02 13	0.705408
05	07	12 15	0.669062	11 12	0.118917	12 15	0.546750
13	07	12 15	0.657212	11 12	0.111206	12 15	0.537163
13	03	13 28	0.833521	11 12	0.118820	13 28	0.667116
09	10	16 17	0.924503	13 09	0.133441	16 17	0.753789
12	14	12 15	0.892063	11 12	0.117855	12 15	0.727623
12	15	14 15	0.799682	11 12	0.131912	14 15	0.653476
12	16	12 15	0.782721	11 12	0.133618	12 15	0.638702
14	15	12 15	0.728162	11 12	0.117135	12 15	0.595092
16	17	12 15	0.737383	11 12	0.128694	12 15	0.602243
15	18	02 13	0.616020	11 12	0.123301	02 13	0.504014
18	19	02 13	0.613639	11 12	0.121158	02 13	0.502071
19	20	15 18	0.865551	11 12	0.111880	15 18	0.702146
10	20	15 18	1.022090	11 12	0.109493	15 18	0.829194
10	17	16 17	0.680032	11 12	0.111569	16 17	0.553519
10	21	10 22	0.757081	11 12	0.113832	10 22	0.622726
10	22	10 21	0.820170	11 12	0.115528	10 21	0.665368
21	22	12 15	0.662881	11 12	0.116564	12 15	0.541521
15	23	22 24	0.755408	11 12	0.126380	22 24	0.615578
22	24	12 15	0.73309	11 12	0.113334	12 15	0.599051
23	24	10 21	0.637532	11 12	0.122764	10 21	0.517684
24	25	12 15	0.676149	11 12	0.113429	12 15	0.552919
25	27	12 15	0.715450	09 04	0.111926	12 15	0.585366
27	29	27 30	0.890810	11 12	0.116178	27 30	0.731627
27	30	27 29	0.902385	11 12	0.116155	27 29	0.737250
29	30	27 30	0.707823	11 12	0.116219	27 30	0.578726
3	28	12 15	0.670440	11 12	0.117400	12 15	0.547891
13	28	13 03	0.804255	11 12	0.114081	13 03	0.646120

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

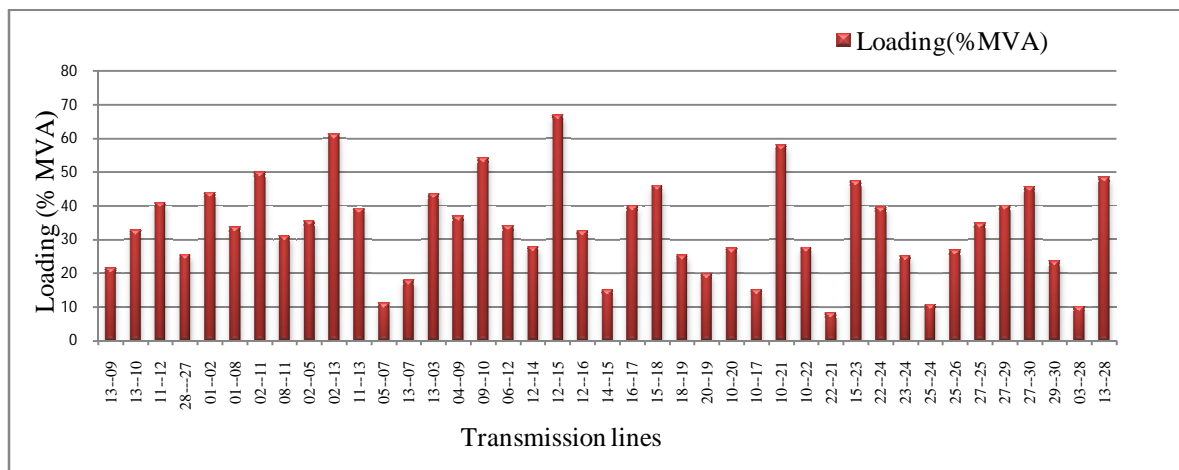


Fig. 5 At Pre- contingency condition loading (%MVA) on transmission lines

Table 2 indicates composite severity index with each line outage. It is observed from the CSI values the line 15-18 has highest severity and increased line loading with the outage of line 10-20. Table 3 and Figure 6 shows corresponding line loadings.

It is also observed from the results lines connected to the bus 13th are having high line utilization factor and less voltage stability. Hence bus 13th is chosen as common bus for the placement of IPFC converters. In order to relieve the line overloading IPFC first converter is connected to line between 13 -7. Second converter of IPFC is connected to line between 13-11. The parameter taken in consideration is line loading and overall LUF . With the proposed location of IPFC transmission lines overload and LUF of severe line and overall system LUF's are reduced.

Table 3: At post-contingency condition without placement of IPFC in IEEE30 bus system loading (%MVA) on transmission lines

Line no	F.B	T.B	Loading(%MVA)	Line no	F.B	T.B	Loading(%MVA)
01	13	09	20.010935	22	16	17	29.893982
02	13	10	29.570912	23	15	18	102.20909
03	11	12	44.516995	24	18	19	78.578703
04	28	27	25.503359	25	20	19	7.224169
05	01	02	43.979476	26	10	20	0
06	01	08	33.807215	27	10	17	24.308571
07	02	11	50.497038	28	10	21	62.568323
08	08	11	31.161970	29	10	22	30.568546
09	02	05	35.385890	30	22	21	5.778046
10	02	13	60.867864	31	15	23	33.969562
11	11	13	36.606134	32	22	24	55.764109
12	05	07	10.860077	33	23	24	17.040679
13	13	07	17.796575	34	25	24	11.183975
14	13	03	42.964071	35	25	26	26.663054

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

15	04	09	36.075290	36	27	25	35.570040
16	09	10	50.649291	37	27	29	40.113356
17	06	12	35.292936	38	27	30	45.581511
18	12	14	31.906763	39	29	30	23.468186
19	12	15	83.431118	40	3	28	9.948155
20	12	16	25.498236	41	13	28	48.735807
21	14	15	22.874998				

F.B = From Bus T.B = To Bus MVA = Mega Volt Ampere

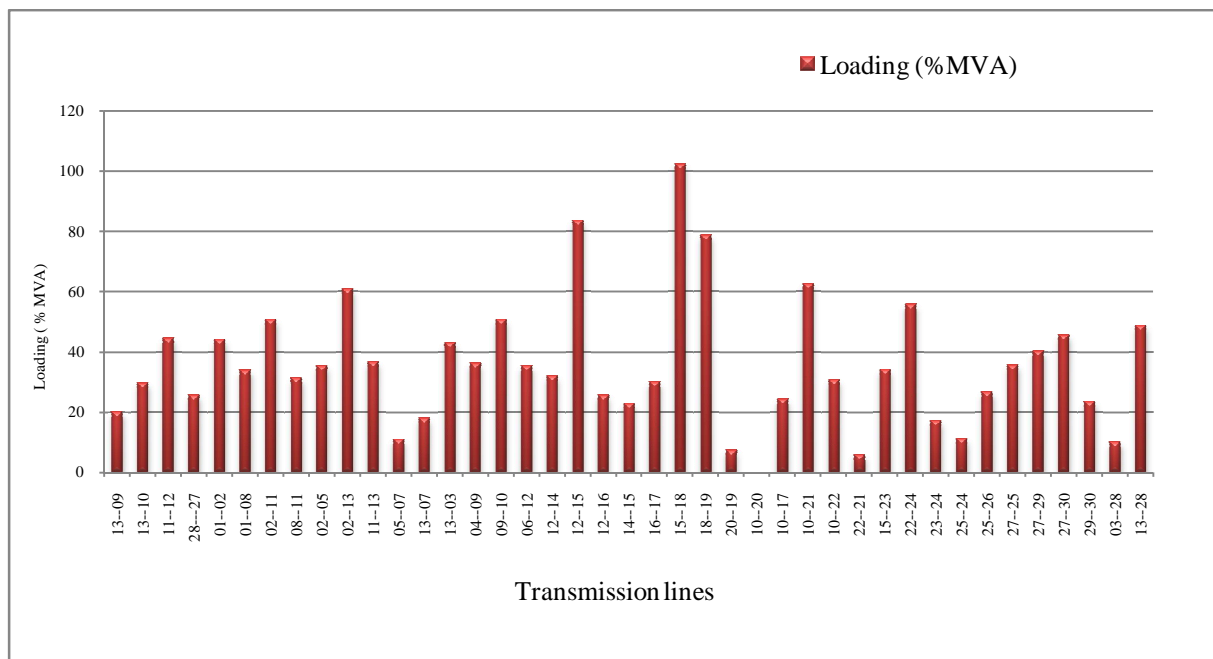


Figure 6 At Post- contingency condition loading (%MVA) on transmission lines with out placement of IPFC in the IEEE30 bus system

Table 4: At post- contingency condition with the placement of IPFC in the IEEE30 bus system loading (%MVA) on transmission lines

Line no	F.B	T.B	Loading (%MVA)	Line no	F.B	T.B	Loading (%MVA)
1	13	09	26.1292	22	16	17	37.5048
2	13	10	33.4701	23	15	18	95.5599
3	11	12	33.7951	24	18	19	73.7674
4	28	27	27.7349	25	20	19	13.9525
5	01	02	56.7662	26	10	20	0
6	01	08	33.2183	27	10	17	14.5512
7	02	11	38.4836	28	10	21	49.5075
8	08	11	30.8420	29	10	22	23.8182

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

9	02 05	31.6365	30	22 21	12.2407
10	02 13	49.5934	31	15 23	31.2982
11	11 13	37.4317	32	22 24	45.2952
12	05 07	27.2648	33	23 24	21.6451
13	13 07	22.7139	34	25 24	15.5078
14	13 03	43.9982	35	25 26	26.6571
15	04 09	17.3656	36	27 25	41.8920
16	09 10	36.3563	37	27 29	44.2799
17	06 12	49.6510	38	27 30	44.1386
18	12 14	29.8648	39	29 30	28.3911
19	12 15	80.0355	40	3 28	19.4162
20	12 16	31.5661	41	13 28	44.0433
21	14 15	21.3714			

F.B = From Bus T.B = To Bus MVA = Mega Volt Ampere

The comparison of loading on line 15-18 at different conditions is shown in table 5. The LUF of severe line and the overall LUF of the system at different conditions is shown in table 6. Loading on transmission lines at different conditions is shown in figure 8.

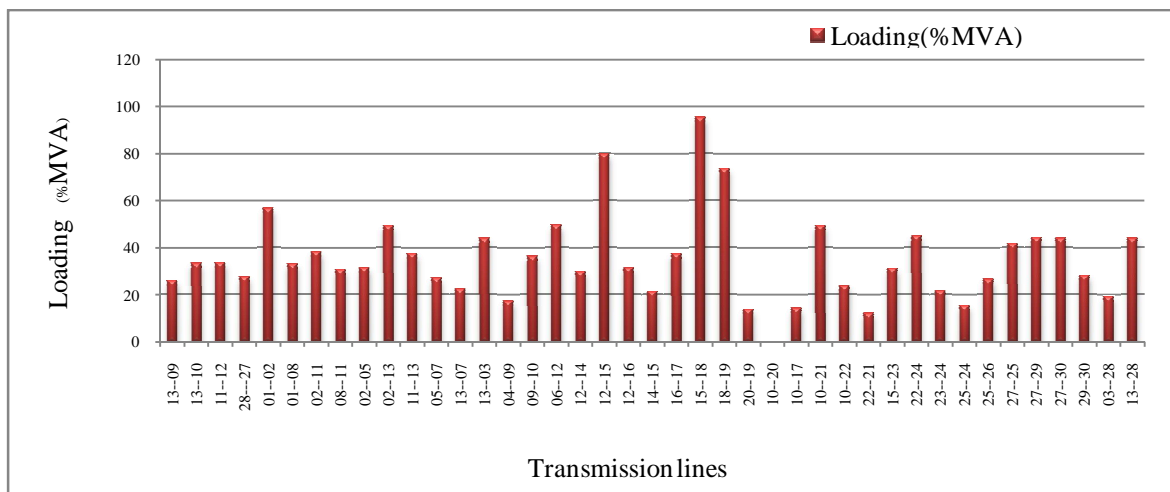


Figure 7 At post- contingency condition with the placement of IPFC in IEEE30 bus system loading (%MVA) on transmission lines

Table 5: Comparison of results on overload occurring transmission line 15-18 with IPFC and with out IPFC at post- contingency condition

Loading	Without IPFC	With IPFC
%MVA	102.209090	95.5599
MVA	16.353454	15.289584

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 5, Issue 11, November 2016

Table 6: Comparison of results on LUF of severe line and LUF of overall system at different conditions

	Before contingency	After contingency without IPFC	After contingency with IPFC
LUF of severe line (15-18)	0.459530	1.022090	0.955599
Overall LUF of the system	13.704464	14.584228	14.54508

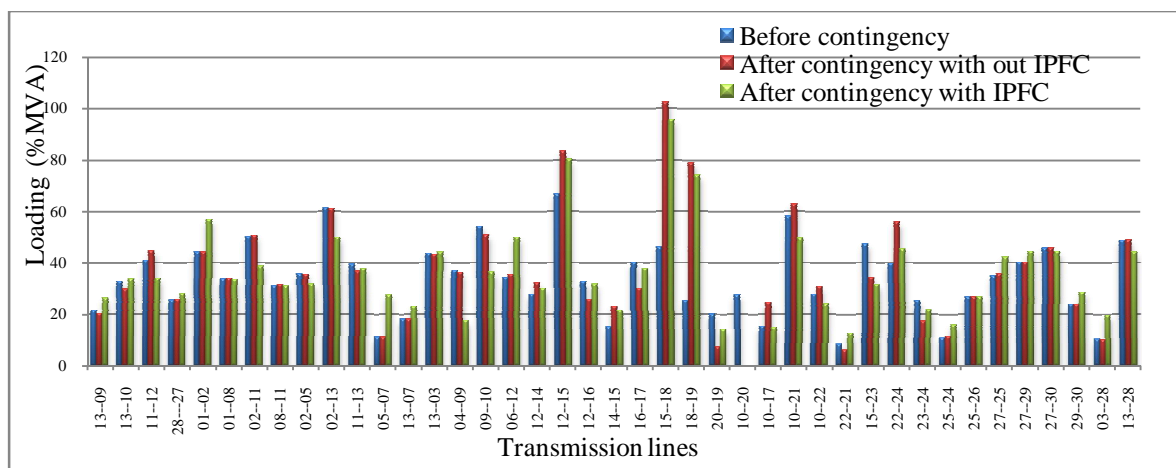


Figure 8 Loading (% MVA) on transmission lines at different conditions.

V. CONCLUSION

In this paper, a detailed power injection model of inter line power flow controller (IPFC) has been presented. This model is incorporated in Newton - Raphson power flow algorithm to demonstrate the performance of IPFC under post contingency condition. Numerical results on test system shows that, with the placement of IPFC the overload on the transmission line at post contingency is reduced.

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Vol. 5, Issue 11, November 2016

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