Ain Shams Engineering Journal (2016) 7, 209–222

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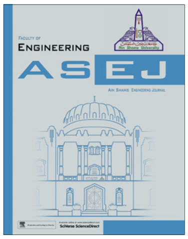

ELECTRICAL ENGINEERING

Contingency management of power system with Interline Power Flow Controller using Real Power Performance Index and Line Stability Index

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Received 19 August 2015; revised 29 October 2015; accepted 5 November 2015
Available online 19 December 2015

KEYWORDS

Contingency;
Interline Power Flow Controller;
Real Power Performance Index;
Line Stability Index;
Composite Severity Index;
Optimal Placement

Abstract As a result of privatization of the electrical industry the power transmission lines have to transfer power at their maximum transmission limits because of the competitive scenario of the electrical market. Hence, secured operation of power system has become one of the most important issues of modern era. In this paper, a probability of severity based placement strategy for Interline Power Flow Controller (IPFC) has been proposed based on Composite Severity Index (CSI). The composite severity index provides an exact measure of stress in the line in terms of mega watt overloading and voltage instability. IPFC is placed on the line which has the highest probability of severity during the occurrence of different outages. The IPFC has been tuned for a multi-objective function using Differential Evolution (DE) and the results have been compared with genetic Algorithm (GA). To verify the proposed method, it has been tested and implemented on IEEE 14 and 57 bus systems.

1. Introduction

Electric power is the backbone of every industrialized country and its economy. The increased reliance on electricity of the modern world in terms of electronics, industrial production and other daily life activities makes continuous uninterrupted supply extremely important. A complete interruption of electricity (blackout) of even a few hours can totally disrupt the basic infrastructures of the region such as communication, transport, hospital, water supply and even emergency services such as fire, ambulance, and police. On the other hand due to increased stress on the transmission lines the probabilities of its failure are ever increasing. Blackouts have become quite a frequent occurrence worldwide in recent times. Hence, development of an effective system for management of contingency is the biggest issue of today's world.

Contingency severity calculation is one of the most important aspects of power system reliability. Although, dynamic security assessment is also being performed [1], but ensuring the security of the power system in static condition still remains the primary objective of power system engineers. Several methods have been used for static contingency analysis in the literature, namely, combinatory linear sensitivity and

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Peer review under responsibility of Ain Shams University.

Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2015.11.004

eigenvalue analysis [2], artificial neural network based method [3], and analytical hierarchy process based method [4]. The traditional method for contingency analysis, although lengthy, is still the most accurate method of severity assessment. During system disturbances, system stability becomes vulnerable and there is a high risk of moving toward global instability or total collapse or blackout if preventive actions are not taken quickly. Facts devices provide good solution to various power system issues including congestion and contingency provided the devices have been optimally placed and tuned in the system. Many computational intelligence methods viz., Cat Swarm optimization [5], artificial bee colony and gravitational search algorithm [6], Differential Evolution [7], and Improved Teaching Learning based technique [8] have been applied for optimal placement and tuning of UPFC. Moazzami et al. [9] have presented a strategy for blackout prevention in a power system using parallel FACTS devices and a combination of corrective actions. Roselyn et al. [10] have used multi-objective rescheduling with FACTS devices using Genetic Algorithm for improvement of voltage stability. Some researchers have also used index based methods such as voltage stability Index [11] and composite index [12] for optimal location of FACTS devices such as TCSC.

Traditionally PV and QV curves have been used in the industries for the voltage stability analysis. But these curves require selection of precise buses for analysis. Unless problems already exist, the choice of buses could omit the problematic buses. Also, PV curves show the behavior of system bus voltages only when the system is under stressed condition. Hence, it is not a good tool for power system planning issues. Index based method for optimal placement of FACTS devices is found to be very accurate and at the same time uses very less computational time. It is equally suited for both static and dynamic analysis of the system. When the load on the transmission systems increases the problem of line overload and voltage collapse both are an issue of major concern. Therefore, it is necessary to consider the combination of a voltage stability index and a line overload index for assessing the actual system stress under contingency condition. Line stability index has major advantages that it is easy to compute, computational cost is less, and identification of weak buses by this method is very easy. Metaheuristic methods have shown good success in tuning FACTS devices. Differential evolution developed by Storn is a very simple and accurate method and has very less computation time [13]. Out of all FACTS devices IPFC is considered to be most flexible, powerful and versatile as it employs multiple VSCs with a common DC link. IPFC has the capability of compensating multitransmission line. It can regulate both real and reactive power flow along with real power transfer in between lines [14]. Optimal placement and sizing of IPFC for contingency management are expected to provide good solution to the post-contingency issues.

In this paper, an off-line long term investment strategy for placement of IPFC is being proposed for protection of power system against contingency. The line which has the highest probability of severity is proposed to be the optimal location for IPFC placement. Two separate indices have been combined to form a Composite Severity Index (CSI) to evaluate line overloads and bus voltage violations. Real Power Performance Index (PI) is employed for the measurement of line overloads in terms of real power flow. Line Stability Index (L_{mn}) has been used for voltage stability assessment. The IPFC is placed on the line which is repeated most frequently on the severity list for the various outages. Thereafter, the IPFC is tuned for a multi objective function using Differential Evolution. The results obtained have been compared with a state of art method, Genetic Algorithm. The multi-objective function chosen is the reduction of real power loss, voltage deviation, security margin and capacity of installed IPFC. The load on the system is increased by 10% and 25% respectively in order to observe the performance of IPFC in stressed conditions. The proposed method is implemented and tested on an IEEE 14 and 57 bus system.

2. Proposed Composite Severity Index

2.1. Real Power Performance Index

Severity of loading on the system for normal and contingency condition can be determined from Real Power Performance Index [15]. It is given by Eq. (1):

$$\mathrm{PI}_{ij} = \sum_{m=1}^{N_L} \frac{w_m}{2n}\left(\frac{P_{lm}}{P_{lm}^{\max}}\right)^{2n} \tag{1}$$

where

P_{lm} is the real power flow,

${P_{lm}}^{\max}$ is the rated real power capacity of line m,

n is the exponent,

w_m is a real non-negative weighting factor which may be used to show a relative importance of the lines, and

N_L is the total number of lines in the network.

PI will have a small value when all the line loads are within limits and takes a high value during overloads. Thus, PI is a good measure of line overloading. 'n' is used for normalization. Since, a composite index is being used, so, in order to keep the values of both indices in the same range, the value of n is chosen to be 1. Equal importance has been given to all lines. Hence, the value of weighting factor, w_m is designated as 1. The overall PI of the system is the sum of PI's of all lines and is given by Eq. (2):

$$\text{Overall PI} = \sum_{\forall L} \mathrm{PI} \tag{2}$$

where L is the no. of lines in the system.

2.2. Line Stability Index

Line Stability Index (L_{mn}) is a voltage collapse proximity indicator [11,16]. Let us consider a single line of an interconnected system. The power flow at the sending end and receiving end is given in Eqs. (3) and (4):

$$S_r = \frac{|V_s||V_r|}{Z}\angle(\theta - \delta_1 + \delta_2) - \frac{|V_r|^2}{Z}\angle\theta \tag{3}$$

$$S_s = \frac{|V_s|^2}{Z}\angle\theta - \frac{|V_s||V_r|}{Z}\angle(\theta + \delta_1 - \delta_2) \tag{4}$$

From the above equations, the active and reactive power is given in Eqs. (5) and (6):

$$P_r = \frac{|V_s||V_r|}{Z}\cos(\theta - \delta_1 + \delta_2) - \frac{|V_r|^2}{Z}\cos\theta \quad (5)$$

$$Q_r = \frac{|V_s||V_r|}{Z}\sin(\theta - \delta_1 + \delta_2) - \frac{|V_r|^2}{Z}\sin\theta \quad (6)$$

Let, $\delta_1 - \delta_2 = \delta$ in Eq. (6)

$$V_r = \frac{V_s\sin(\theta-\delta) \pm \{[V_s\sin(\theta-\delta)]^2 - 4ZQ_r\sin\theta\}^{0.5}}{2\sin\theta} \quad (7)$$

In order to obtain real values of V_r,

$$[V_s\sin(\theta-\delta)]^2 - 4ZQ_r\sin\theta \geqslant 0 \quad (8)$$

Let $Z\sin\theta = x$, we have

$$[V_s\sin(\theta-\delta)]^2 - 4xQ_r \geqslant 0 \quad (9)$$

Or

$$\mathrm{L_{mn}} = \frac{4xQ_r}{[V_s\sin(\theta-\delta)]^2} \leqslant 1 \quad (10)$$

$\mathrm{L_{mn}}$ is the stability index of that line.

Thus, as long as the system is stable, the value of the stability index is less than 1. When the value of the index increases beyond 1, the system loses stability and moves toward voltage collapse. Using this technique the lines in the system which are under stressed condition can be identified. $\mathrm{L_{mn}}$ index is given in Eq. (11):

$$\mathrm{L_{mn}} = \frac{4xQ_r}{[V_m\sin(\theta-\delta)]^2} \quad (11)$$

where

$$\delta = \delta_m - \delta_n \quad (12)$$

$$\theta = \tan^{-1}(X/R) \quad (13)$$

where
θ is the angle between voltage and current,
X is the reactance of line between bus m and n,
R is the resistance of line between bus m and n,
δ_m voltage phase angle of bus m,
δ_n voltage phase angle of bus n,
Q_n is the reactive power at bus n,
V_m is the voltage magnitude at bus m.

The overall $\mathrm{L_{mn}}$ of the system is given by (14):

$$\text{Overall } \mathrm{L_{mn}} = \sum_{\forall L} \mathrm{L_{mn}} \quad (14)$$

2.3. Composite Severity Index (CSI)

PI gives an estimate of line overloads in terms of apparent power. $\mathrm{L_{mn}}$ 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 PI and $\mathrm{L_{mn}}$ values of all the lines for a particular line outage, the composite severity index is calculated as given in (15):

$$\mathrm{CSI} = w_1 \times \mathrm{PI} + w_2 \times \mathrm{L_{mn}} \quad (15)$$

where

$$w_1 + w_2 = 1 \quad (16)$$

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 importance of the indices. In this study, the equal weightage has been given to both the indices. The overall CSI of the system is given by Eq. (17):

$$\text{Overall CSI} = \sum_{\forall L} \mathrm{CSI} \quad (17)$$

The generalized procedure for placement of IPFC using CSI for any given bus system is shown in flowchart given in Fig. 1.

3. Tuning of IPFC for multi-objective function

An objective function is formulated to find the optimal size of IPFC which minimizes the total active power loss, total voltage deviations, and security margin with the usage of minimum value of installed IPFC.

3.1. Objective function

A multi objective function formulated is given in Eq. (18):

$$Min\ F = Min \sum_{i=1\ to\ 4} w_i f_i \quad (18)$$

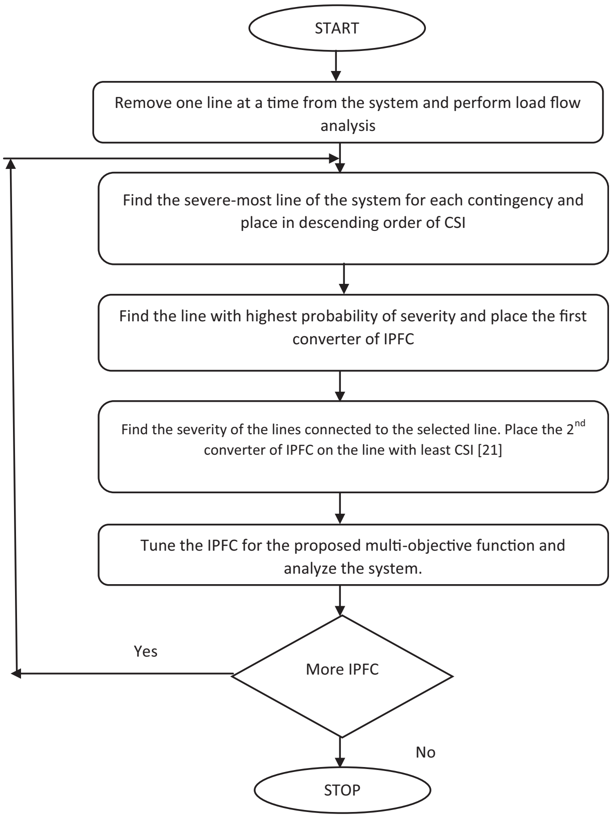

Figure 1 Generalized procedure for tuning and placement of IPFC using CSI. (See above-mentioned references for further information.)

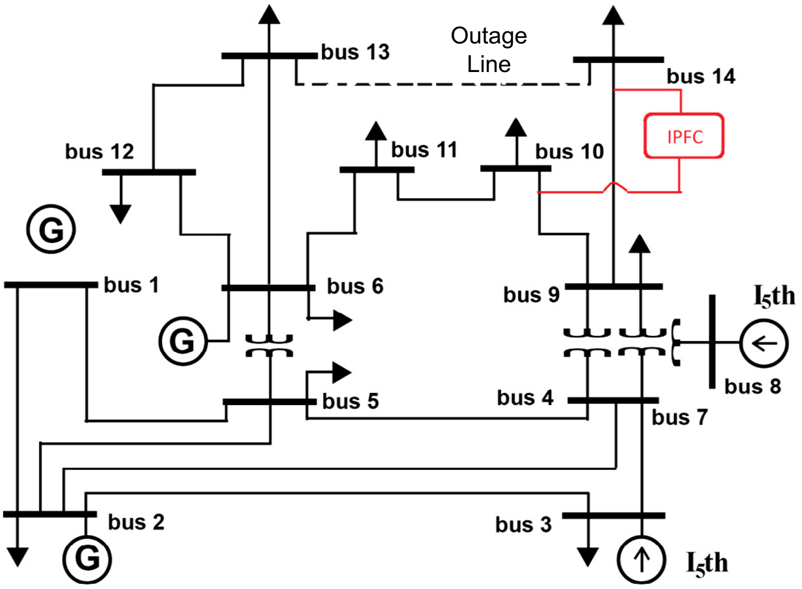

Figure 2 IEEE 14 bus test system with outage in line 13–14 and IPFC placement on line connected between buses 9–14 and 9–10.

Table 1 Index values of lines after contingency analysis of IEEE 14 bus system for normal loading.

S. No.	Line outage		Severe line		PI (p.u.)	Severe line		L_{mn} (p.u.)	Severe line		CSI (p.u.)
	From bus	To bus	From bus	To bus		From bus	To bus		From bus	To bus	
1	13	14	9	14	0.6516	9	14	1.195	9	14	0.6276
2	5	6	4	5	0.571	13	14	0.6195	4	5	0.6707
3	2	3	4	5	0.5117	9	14	0.5053	4	5	0.5116
4	2	4	4	5	0.465	9	14	0.5029	4	5	0.4646
5	7	9	4	9	0.3964	4	9	0.7462	4	9	0.4089
6	6	12	9	14	0.3029	9	14	0.5796	9	14	0.2968
7	6	11	13	14	0.2896	13	14	0.5613	13	14	0.2888
8	12	13	9	14	0.2815	9	14	0.5402	9	14	0.2758
9	4	7	9	14	0.2746	9	14	0.5269	9	14	0.2648
10	4	5	9	14	0.2698	9	14	0.5183	9	14	0.2605
11	10	11	9	14	0.2602	13	14	0.5042	13	14	0.2577
12	3	4	9	14	0.2614	9	14	0.5032	9	14	0.2568
13	4	9	9	14	0.2631	9	14	0.507	9	14	0.2566
14	2	5	9	14	0.2598	9	14	0.5001	9	14	0.2554
15	9	10	9	14	0.2565	9	14	0.4938	9	14	0.2529
16	1	5	9	14	0.2565	9	14	0.4943	9	14	0.2525

where

$$w_1 + w_2 + w_3 + w_4 = 1 \tag{19}$$

$w_1 = w_2 = w_3 = w_4 = 0.25$.

w_1, w_2, w_3, and w_4 are the weighting factors of the individual objective functions. The weighting factors are used to reflect the relative importance of the objective functions. In this study, equal preference has been given to all the objective functions. Hence, value of each weight is taken as 0.25, such that there sum is equal to unity.

3.1.1. Reduction of loss

The expression for reduction of active power loss [17] is given in Eqs. (20) and (21):

$$\mathit{Minimize} \quad f_1(x) = \sum_{n=j,k}^{lk} P_{loss} \tag{20}$$

$$\begin{aligned} P_{loss} = {} & (|V_i|^2 G_{in} - |V_i||V_n|[G_{in}\cos\theta_{in} + B_{in}\sin\theta_{in}] \\ & - |V_i||V_{sein}|[G_{in}\cos\theta_{sein} + B_{in}\sin\theta_{sein}]) + (|V_i|^2 G_{in} \\ & - |V_i||V_n|[G_{in}\cos\theta_{ni} + B_{in}\sin\theta_{ni}] - |V_n||V_{sein}|[G_{in} \\ & \times \cos\theta_{sein} + B_{in}\sin\theta_{sein}]) \end{aligned} \tag{21}$$

where lk is the number of transmission lines, $V_i = V_i\angle\theta_i$ and $V_n = V_n\angle\theta_n$ are the voltages at the end buses i and n $(n = j, k)$.

$V_{sein} = V_{sein}\angle\theta_{sein}$ $(n = j, k)$ is the series injected voltage source of nth line, se stands for series, G_{in} and B_{in} are the transfer conductance and susceptance between bus i and n $(n = j, k)$ respectively. The magnitude and phase angle of the series injected voltage of V_{seij} and V_{seik} are determined optimally.

Table 2 Index values of lines after contingency analysis of IEEE 14 bus system for 110% and 125% loading.

S. No.	Line outage		Severe line		CSI (110%) (p.u.)	Severe line		CSI (125%) (p.u.)
	From bus	To bus	From bus	To bus		From bus	To bus	
1	13	14	9	14	0.6718	9	14	0.7621
2	5	6	4	5	0.6948	4	5	0.9080
3	2	3	4	5	0.6270	4	5	0.8364
4	2	4	4	5	0.5387	4	5	0.7259
5	7	9	4	9	0.4279	4	9	0.4704
6	6	12	9	14	0.2998	9	14	0.4975
7	6	11	13	14	0.2968	13	14	0.3149
8	12	13	9	14	0.2781	9	14	0.2821
9	4	7	9	14	0.2674	9	14	0.2721
10	4	5	9	14	0.2636	9	14	0.2687
11	10	11	13	14	0.2679	13	14	0.2818
12	3	4	9	14	0.2586	9	14	0.2620
13	4	9	9	14	0.2587	9	14	0.2624
14	2	5	9	14	0.2576	9	14	0.2609
15	9	10	9	14	0.2536	9	14	0.2566
16	1	5	9	14	0.2534	9	14	0.2569

Table 3 CSI of lines connected to line 9–14 for 13–14 contingency.

S. No.	From bus	To bus	CSI (p.u.)
1.	9	10	0.0374
2.	9	4	0.2388
3.	9	7	0.2151

3.1.2. Minimization of voltage deviation

To have a good voltage performance, the voltage deviation at each bus must be made as small as possible. The Voltage Deviation (VD) [18] can be expressed by Eq. (22):

$$f_2(x) = \min(VD) = \min\left(\sum_{k=1}^{Nbus} |V_k - V_k^{ref}|^2\right) \tag{22}$$

V_k is the voltage magnitude at bus k.

3.1.3. Minimization of security margin

This objective function depends on the static voltage stability and investigates how the risk of voltage collapse is alleviated [19]. The security margin of a system can be expressed as follows in Eq. (23):

$$SM = \frac{\sum_{j\in J_L} S_j^{\lim} - \sum_{j\in J_L} S_j^{initial}}{\sum_{j\in J_L} S_j^{\lim}} \tag{23}$$

where J_L = A set contains all load buses.

Since minimization is the objective of optimization, the objective function in Eq. (23) is rewritten in Eq. (24):

$$f_3(x, u, z) = 1 - SM = \frac{\sum_{j\in J_L} S_j^{initial}}{\sum_{j\in J_L} S_j^{\lim}} \tag{24}$$

3.1.4. Minimization of total capacity of installed IPFC

The total capacity of the installed IPFC [20] required is formulated as in Eq. (25):

$$f_4(x) = \min\left(PQ_1^2 + PQ_2^2\right) \tag{25}$$

where PQ: capacity of each VSC of IPFC

$$PQ_1^2 + PQ_2^2 = \left(Vse_{ij}\left(\frac{\overline{V_i - Vse_{ij} - V_j}}{Z_{ij}}\right)\right)^2 + \left(Vse_{ik}\left(\frac{\overline{V_i - Vse_{ik} - V_k}}{Z_{ik}}\right)\right)^2 \tag{26}$$

The above multi-objective function is subjected to the following constraints.

3.2. Equality constraints

$$P_{gi} + P_i - P_{Di} = \sum_{j=1}^{n} V_i V_j Y_{ij} \cos(\theta_{ij} + \delta_j - \delta_i) \quad \forall i \tag{27}$$

$$Q_{gi} + Q_i - Q_{Di} = \sum_{j=1}^{n} V_i V_j Y_{ij} \sin(\theta_{ij} + \delta_j - \delta_i) \quad \forall i \tag{28}$$

3.3. Inequality constraints

$$V_i^{\min} \leqslant V_i \leqslant V_i^{\max} \quad \forall i \in \text{load bus} \tag{29}$$

$$S_{in}(V, \delta)| \leqslant S_{in}^{\max} \tag{30}$$

3.4. IPFC constraints

$$V_{se}^{\min} \leqslant V_{se} \leqslant V_{se}^{\max} \tag{31}$$

$$\theta_{se}^{\min} \leqslant \theta_{se} \leqslant \theta_{se}^{\max} \tag{32}$$

where S_{in} is the power injected by the IPFC converters.

4. Results and discussion

4.1. IEEE 14 bus test system

An IEEE 14 bus test system given in [22] has 4 generator buses, 9 load buses and 20 transmission lines as seen in Fig. 2. Bus 1 is the slack bus. Bus numbers 2, 3, 6, and 8 are the generator buses. The remaining buses are load buses. System base MVAR is 100. The resistance and inductive reactance of the coupling transformers are taken as 0.001 p.u. The voltage magnitude of the two converters of the IPFC is taken in the range $0 \leqslant Vse \leqslant 0.1$ and the angle is taken in the range $-\Pi \leqslant \theta_{se} \leqslant \Pi$. Only load buses have been considered for IPFC placement.

Contingency analysis has been performed on IEEE 14 bus system for normal, 110% and 125% loading. The most severe line corresponding to every outage is identified and tabulated along with the details of the index values in Table 1, in descending order of CSI. The result of contingency analysis for 110% and 125% loading has been given in Table 2. It is observed from the CSI values that line 9–14 has the highest probability of severity for normal and increased loading conditions. Also it is observed that line 13–14 outage is the severemost of all the outages causing severity of line 9–14. Hence the line 9–14 is chosen for the placement of 1st converter of the IPFC. Three lines have been connected with the line 9–14 through a common bus. The CSI values of these lines for line 13–14 outage are given in Table 3. It is observed that the line connected between buses 9 and 10 has the least CSI of 0.0374 p.u, hence is the healthiest line. Hence the second converter of IPFC is chosen to be placed on line 9–10. Thus further analysis is done for line 13–14 contingency with IPFC placement at 9–14 and 9–10.

After placement, the IPFC is tuned using DE and GA. DE has two parameters, namely, step size (F) and crossover probability (CR). The effect of variation of these parameters on the objective functions has been shown in Fig. 3. It is observed that although computation time is maximum for step size equal to 0.1, the objective of minimization is better achieved for a smaller step size. It is also observed that for $F = 0.1$ minimal values of objective are obtained at CR = 0.3. Hence these values of parameters have been chosen for the analysis. Similarly, the value of GA parameters is taken as given in Table 4.

Various parameters of the system are studied for three different system conditions – without contingency, with contingency at line 13–14, with optimal placement of IPFC, and

Table 4 Genetic algorithm parameters for IPFC tuning.

Algorithm	Parameter	Value
Differential evolution	Step size (F)	0.1
	Cross over probability (CR)	0.3
Genetic algorithm	Population size	20
	Maximum generations	50
	Stall gen. limit	100
	Time limit	300

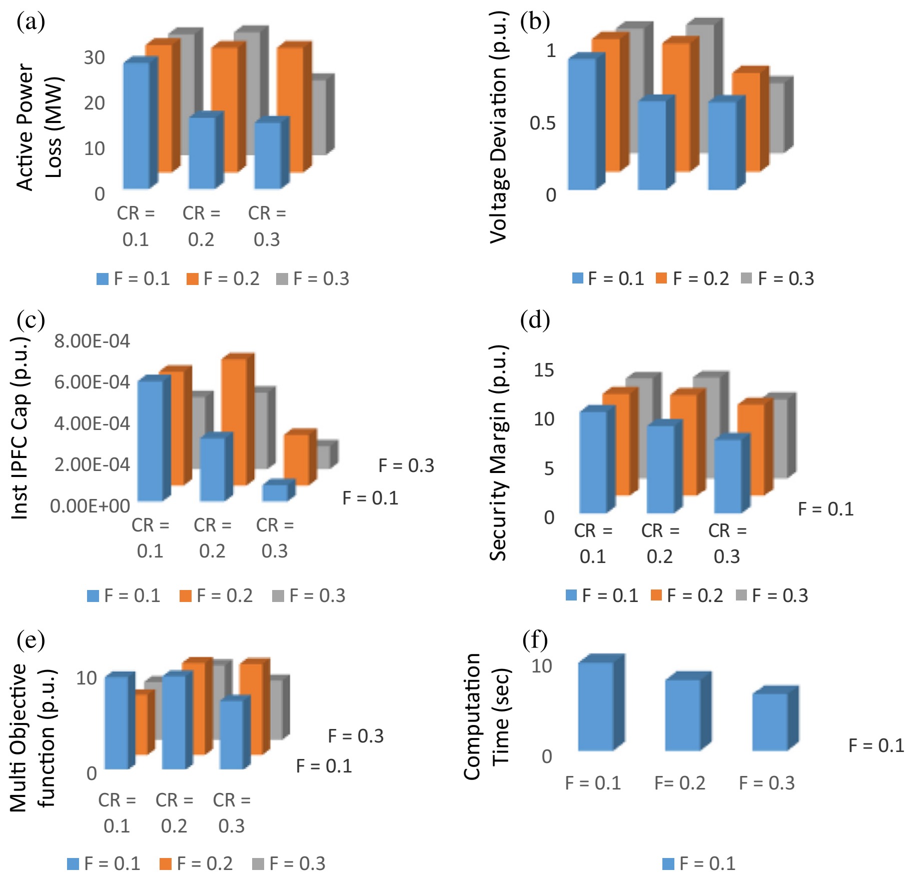

Figure 3 System parameters vs. CR and F (a) active power loss, (b) voltage deviation, (c) installed IPFC capacity, (d) security margin, (e) multi-objective function and (f) computation time.

Table 5 Comparison of results without contingency, with contingency and with optimal placement of IPFC at 9–14 and 9–10 for normal load.

S. No.	Parameter	Without contingency	With contingency at 13–14	With optimal placement of IPFC	With GA tuned IPFC	With DE tuned IPFC
1.	Active power loss (MW)	22.5451	29.2832	22.266	18.148	14.555
2.	Reactive power loss (MVAR)	82.1714	109.3464	74.518	67.281	55.809
3.	PI of severe line (p.u.)	0.01	0.0601	0.0398	0.0225	0.0334
4.	L_{mn} of severe line (p.u.)	0.5162	1.195	0.7358	0.5095	0.2385
5.	CSI of severe line (p.u.)	0.2581	0.6276	0.3878	0.2660	0.1359
6.	Cap. of inst. IPFC	–	–	0.0073	1.1866e−4	8.0255e−5
7.	Security margin (p.u.)	9.2219	10.1456	8.7642	8.7527	7.4466
8.	Voltage deviation (p.u.)	0.6961	1.0793	0.6024	0.5795	0.6014
9.	Overall RPPI (p.u.)	5.4014	5.7877	5.4874	4.9100	4.6343
10.	Overall L_{mn} (p.u.)	3.6631	4.7253	3.0393	3.0279	1.7555
11.	Overall CSI (p.u.)	4.5324	5.2566	4.2635	3.9690	3.1949

Table 6 System parameters for increased loading for different system conditions for IEEE 14 bus system.

Percent load	Parameters	w/t contingency	With contingency	With optimal placement	DE tuned
110% load	Active power loss (MW)	26.313	34.510	24.468	20.492
	Reactive power loss (MVAR)	97.658	130.289	80.938	74.899
	Voltage deviation (p.u.)	0.7412	1.1617	0.6088	0.5466
	Inst. IPFC (p.u.)	–	–	0.0089	9.1820e−5
	Security margin (p.u.)	9.9619	11.0028	9.0750	8.6421
	Overall CSI (p.u.)	5.2439	6.12	4.5046	4.16
125% load	Active power loss (MW)	32.828	43.825	32.406	22.879
	Reactive power loss (MVAR)	124.49	167.177	109.313	93.821
	Voltage deviation (p.u.)	0.8176	1.3078	0.5891	0.4816
	Inst. IPFC (p.u.)	–	–	0.0086	1.4466e−4
	Security margin (p.u.)	11.0972	12.3459	10.5599	9.7208
	Overall CSI (p.u.)	6.4991	7.6858	5.9524	5.0516

optimal tuning of IPFC. The results have been tabulated in Table 5 for normal loading. The parameters taken into consideration are active power loss, reactive power loss, overall L_{mn}, overall CSI, overall PI, voltage deviation, capacity of installed IPFC, security margin, L_{mn}, PI, and CSI of line 9–14. The active and reactive power loss of the healthy system (without contingency) is found to be 22.5451 MW and 82.1714 MVAR respectively. With the outage of line 13–14, it is observed that the active and reactive power loss of the system is increased to 29.2832 MW and 109.3464 MVAR. After placement of IPFC in the line 9–14 and 9–10, the active and reactive power loss of the system reduced to 22.266 MW and 74.518 MVAR respectively. It is observed that when the IPFC is tuned using GA the losses are reduced to 18.148 MW and 67.281 MVAR respectively. After tuning the IPFC using DE the active and reactive power loss of the system is reduced to 14.555 MW and 55.809 MVAR respectively. Similarly, DE is found to be more efficient in minimizing the other objective function values. It is observed that contingency in line 13–14 increases the severity of the line 9–14 as given by PI, L_{mn} and CSI values. Optimal placement and tuning of IPFC at the proposed location reduces the value of the indices to pre-contingency state. The overall CSI of the system reduces from 5.2566 p.u. to 4.2635 p.u. after the placement of IPFC. Tuning the IPFC using GA decreases the CSI to 3.9690 p.u. The value of CSI with DE tuned IPFC is 3.1949 p.u. Thus, DE is found to be tuning the IPFC much more effectively in comparison with GA. Hence, further detailed analysis is done using DE only.

The different system conditions at increased loading have been studied in Table 6. Security margin is a measure of overall congestion of the system. It is observed that as the load increases the security margin of the system increases. But with optimal placement and tuning of IPFC the security margin of the system decreases almost to the pre-contingency state of the system. Similarly, there is a considerable reduction in the values of other system parameters such as active power loss, reactive power loss and voltage deviation after placement and tuning of IPFC. Thus the effectiveness of IPFC placement and tuning to improve the post-contingency state of the system even in increased loading condition has been witnessed. Tuning of IPFC is also found to decrease the capacity of installed IPFC to a good extent for all loading conditions. Therefore, an overall improvement in system parameters is obtained with a minimalistic use of IPFC.

Table 7 Indices of severe lines under increased loading conditions for IEEE 14 bus system.

Loading	Line No.	CSI w/t contingency (p.u.)	CSI with contingency (p.u.)	CSI with opt. IPFC (p.u.)	CSI with DE tuned IPFC (p.u.)
(Normal load)	9–14	0.2507	0.6276	0.3878	0.1359
	1–5	0.3972	0.4409	0.3512	0.2821
	4–5	0.1809	0.2124	0.2112	0.2027
	2–4	0.2308	0.2593	0.2501	0.1476
	2–3	0.3152	0.3262	0.3253	0.2821
110% Load	9–14	0.2598	0.6718	0.3923	0.2648
	1–5	0.4907	0.5430	0.3845	0.3841
	4–5	0.2200	0.2570	0.3852	0.2467
	2–4	0.2597	0.2946	0.2255	0.2086
	2–3	0.3752	0.3899	0.3698	0.3568
125%	9–14	0.2629	0.7621	0.4421	0.0266
	1–5	0.6474	0.7043	0.5280	0.4658
	4–5	0.2887	0.3356	0.5273	0.2577
	2–4	0.3213	0.3854	0.2898	0.2561
	2–3	0.4979	0.5409	0.4793	0.4397

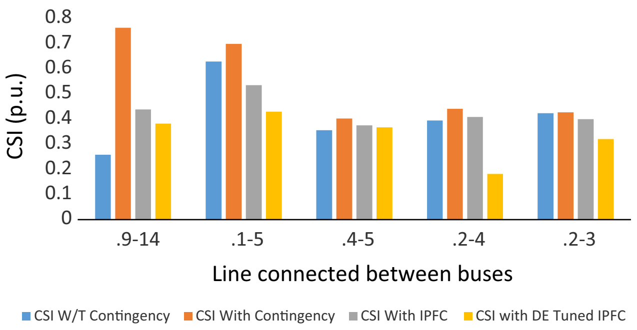

Figure 4 CSI of lines at 125% load without contingency, with contingency and with IPFC for IEEE 14 bus system.

The CSI of a few congested lines for different loadings has been presented in Table 7. It is observed that after optimal placement and tuning of IPFC, the congestion in the line gets reduced to a good extent for different system conditions. The CSI values of a few lines for 125% load for all the three system conditions have been shown graphically in Fig. 4. The voltage profile of the 14 bus system for normal load has been given in Fig. 5. It observed that the voltage at the buses is nearly equal to unity after optimal placement and tuning of IPFC.

4.2. IEEE 57 bus test system

In IEEE 57 bus system given in [23], bus no. 1 is considered as a slack bus and bus nos. 2, 3, 6, 8, 9, 12 are considered as PV buses while all other buses are load buses. This system has 80 interconnected lines as shown in Fig. 6.

The details of the most severe lines for each outage with respect to PI, L_{mn} and CSI have been given in Table 8. It is observed that line 24–25 has the highest probability of severity

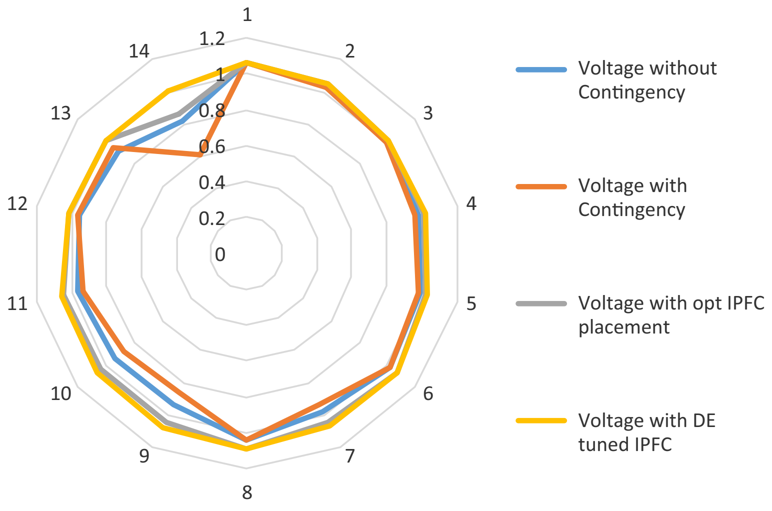

Figure 5 Comparison of voltage profile without contingency, with contingency, and with optimal placement of IPFC under normal loading.

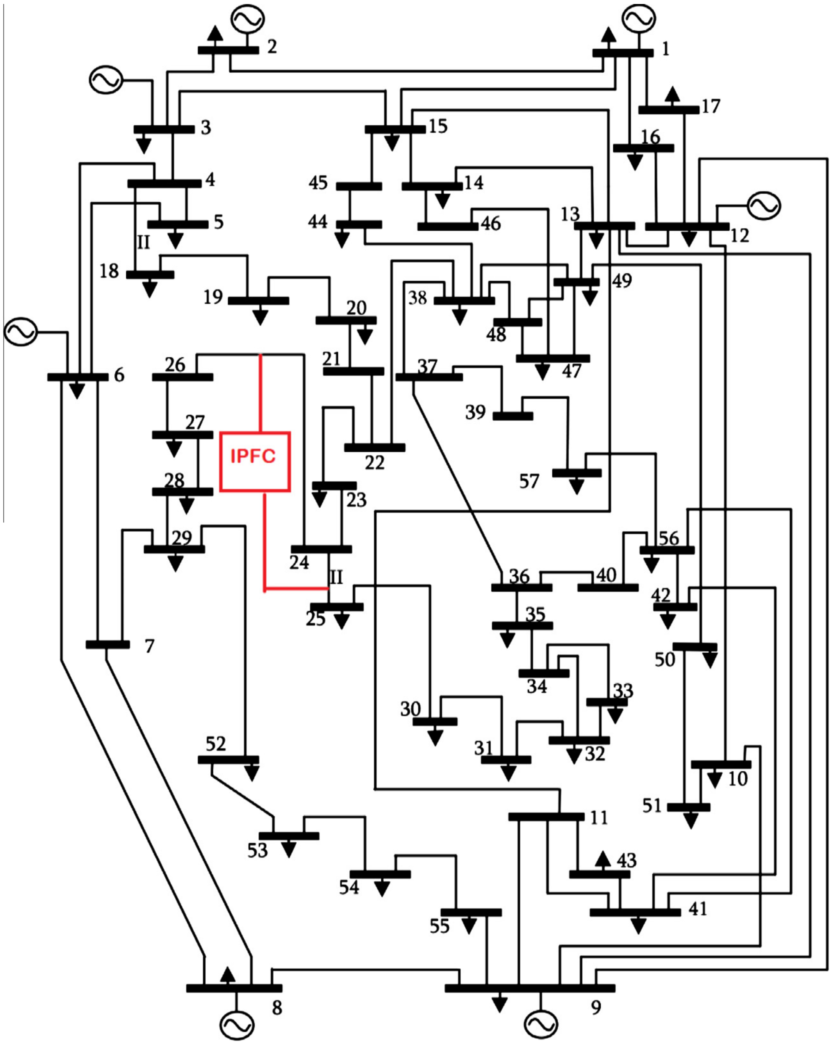

Figure 6 IEEE 57 bus test system for line 1–2 contingency with IPFC installed at line connected between buses 24–25 and 24–26.

for various line outages. The maximum CSI of line 24–25 is 0.901 p.u. for line 9–13 contingency. Thus, 9–13 contingency is considered to be the severe-most contingency. Hence, line 24–25 is chosen for the placement of the 1st converter of the IPFC. Line 24–25 is connected to lines 24–26, 24–23, and 25–30 through a common bus. From Table 9, it is observed that for line 9–13 contingency, the value of CSI for line 24–26 is 0.0299 p.u, which is minimum of all CSIs. Hence, line connected between buses 24–26 is chosen for the placement of the 2nd converter of the IPFC. Thus further analysis is done for line 9–13 contingency with IPFC placement on the lines 24–25 and 24–26.

Various parameters of the system are studied for three different system conditions at normal load – without contingency, with contingency at line 9–13 and with optimal placement of IPFC. The results have been tabulated in Table 10. The parameters taken into consideration are active power loss, reactive power loss, security margin, voltage deviation, capacity of installed IPFC, overall L_{mn}, overall CSI, overall PI, L_{mn}, PI, and CSI of line 24–25. It is observed that contingency in the line 9–13 increases the values of the system parameters. The active and reactive power loss of the system without contingency was 58.708 MW and 226.075 MVAR respectively. After the outage of line 9–13, the active and reactive power loss increased to 61.074 MW and 235.556 MVAR respectively. Placement of IPFC at the severe location reduces the losses to 47.403 MW and 163.894 MVAR respectively. Tuning of IPFC using GA reduces the active and reactive power loss to 47.104 MW and 161.628 MVAR respectively. Tuning of IPFC using DE reduces the losses to 41.241 MW and 157.081 MVAR respectively. The CSI of line 24–25 under normal condition is 0.1164 p.u. After contingency in line 24–25 the CSI of the line increased to 0.9010 p.u. When the IPFC is placed at the proposed location the CSI of the line reduces to 0.1879 p.u. When the IPFC is tuned using GA the CSI of line 24–25 is reduced to 0.1397 p.u., while DE tuned IPFC reduces the CSI of the line to 0.1391 p.u. Similarly it is observed that, placement and tuning of IPFC at the proposed location reduces the other system parameters to a good extent. Also, DE is found to be a more effective tool for tuning IPFC in comparison with GA. Hence, further analysis has been done using only DE for tuning the IPFC.

Table 8 Index values of lines after contingency analysis of IEEE 14 bus system.

S. No.	Line outage		Severe line		PI (p.u.)	Severe line		L_{mn} (p.u.)	Severe line		CSI (p.u.)
	From bus	To bus	From bus	To bus		From bus	To bus		From bus	To bus	
1.	9	13	7	29	0.4865	24	25	1.7737	24	25	0.901
2.	4	18	7	29	0.491	24	25	1.7568	24	25	0.8925
3.	4	18	7	29	0.491	24	25	1.7555	24	25	0.8915
4.	13	15	14	15	0.7389	24	25	1.7239	24	25	0.8759
5.	1	17	14	15	0.6329	24	25	1.7223	24	25	0.8751
6.	1	16	14	15	0.5981	24	25	1.7145	24	25	0.8712
7.	3	4	14	15	0.6296	24	25	1.7139	24	25	0.8704
8.	14	15	13	15	0.4905	24	25	1.7015	24	25	0.8647
9.	12	17	7	29	0.4872	24	25	1.6907	24	25	0.8592
10.	12	16	7	29	0.4862	24	25	1.6853	24	25	0.8565
11.	9	10	7	29	0.4834	24	25	1.6766	24	25	0.8521
12.	9	12	7	29	0.4826	24	25	1.6697	24	25	0.8486
13.	52	53	7	29	0.333	24	25	1.6468	24	25	0.8372
14.	49	50	7	29	0.4738	24	25	1.6331	24	25	0.8302
15.	13	14	13	15	0.4926	24	25	1.6058	24	25	0.8165
16.	1	2	7	29	0.4472	24	25	1.5992	24	25	0.813
17.	2	3	7	29	0.448	24	25	1.5985	24	25	0.8127
18.	5	6	7	29	0.4771	24	25	1.5959	24	25	0.8115
19.	4	6	7	29	0.4538	24	25	1.5957	24	25	0.8113
20.	6	8	7	29	0.4593	24	25	1.5939	24	25	0.8104
21.	36	40	7	29	0.4761	24	25	1.5605	24	25	0.7935
22.	6	7	7	29	0.5078	24	25	1.5427	24	25	0.7849
23.	4	5	7	29	4561	24	25	1.5363	24	25	0.7814
24.	3	15	7	29	0.4866	24	25	1.5221	24	25	0.7741
25.	47	48	7	29	0.45	24	25	1.5031	24	25	0.7647

Table 9 CSI of lines for 9–13 contingency.

S. No.	From bus	To bus	CSI (p.u.)
1	24	23	0.0910
2	24	26	0.0299
3	25	30	0.1551

The system parameters for 110% and 125% load for different system conditions have been studied and the results have been presented in Table 11. The CSI values of a few lines for different loads have been presented in Table 12. It is observed that with placement and tuning of IPFC, the losses in the system and the congestion in the line get reduced to a good extent. The CSI values of the lines for 125% load for all the three system conditions have been shown graphically in Fig. 7. The voltage profile of the 57 bus system for normal load has been given in Fig. 8. Although IPFC is a series connected device, placement of the device at the proposed location compensates the voltage of the buses to an adequate level.

Table 10 Comparison of results without contingency, with contingency and with optimal placement of IPFC at 24–25 and 24–26.

S. No.	Parameter	Values in different system state				
		Without contingency	With contingency at 9–13	With optimal placement of IPFC	GA tuned IPFC	DE tuned IPFC
1.	Active power loss (MW)	58.708	61.074	47.403	47.104	41.241
2.	Reactive power loss (MVAR)	226.075	235.556	163.894	161.628	157.081
3.	PI of severe line (p.u.)	0.0296	0.0283	0.0042	0.0053	0.0052
4.	L_{mn} of severe line (p.u.)	0.2032	1.7737	0.2962	0.2741	0.2728
5.	CSI of severe line (p.u.)	0.1164	0.9010	0.1879	0.1397	0.1391
6.	Voltage deviation (p.u.)	10.1691	10.7521	6.9110	6.4663	6.3960
7.	Cap. Of inst. IPFC (p.u.)	–	–	0.0039	1.2008e−4	1.1974e−4
8.	Security margin (p.u.)	29.3497	29.5946	26.0063	25.6328	24.4165
9.	Overall RPPI (p.u.)	15.1572	15.2828	14.5635	15.7011	14.4268
10.	Overall L_{mn} (p.u.)	19.69	20.9010	9.1757	8.5191	8.1868
11.	Overall CSI (p.u.)	17.4236	18.0919	11.8696	12.1101	11.3068

Table 11 System parameters for increased loading for different system conditions for IEEE 57 bus system.

% load	Parameters	w/t contingency	With contingency	With optimal placement	DE tuned
110% load	Active power loss (MW)	59.989	62.247	59.882	59.192
	Reactive power loss (MVAR)	231.139	232.065	221.465	221.19
	Voltage deviation (p.u.)	6.8099	6.9749	6.9474	6.9017
	Inst. IPFC (p.u.)	–	–	5.1587e−5	1.5207e−7
	Security margin (p.u.)	29.7098	29.7839	29.1906	28.6457
	Overall CSI (p.u.)	14.9237	14.9517	14.2442	14.1289
125% load	Active power loss (MW)	99.721	100.625	98.902	94.746
	Reactive power loss (MVAR)	375.397	378.557	360.019	350.603
	Voltage deviation (p.u.)	7.8710	7.9736	7.6950	7.1544
	Inst. IPFC (p.u.)	–	–	1.5254e−4	1.8868e−5
	Security margin (p.u.)	36.0105	36.0753	36.3128	34.8870
	Overall CSI (p.u.)	22.8687	23.0264	23.0201	22.4437

Table 12 Indices of severe lines under increased loading conditions for IEEE 57 bus system.

Loading	Line No.	CSI w/t contingency (p.u.)	CSI with contingency (p.u.)	CSI with opt. IPFC (p.u.)	CSI with DE tuned IPFC (p.u.)
Normal	3–4	0.2932	0.2995	0.2596	0.1994
	4–5	0.1164	0.1162	0.107	0.104
	1–16	0.4463	0.5093	0.4713	0.4681
	5–6	0.1873	0.431	0.3575	0.3326
110%	3–4	0.4683	0.4865	0.485	0.4847
	4–5	0.1359	0.1366	0.1135	0.1135
	1–16	0.6798	0.7551	0.7389	0.7386
	5–6	0.1904	0.3729	0.3312	0.331
125%	3–4	0.9063	1.1714	1.0017	0.9895
	4–5	0.1447	0.149	0.1415	0.1411
	1–16	1.2705	1.3654	1.3149	1.3044
	5–6	0.2314	0.3518	0.301	0.2951

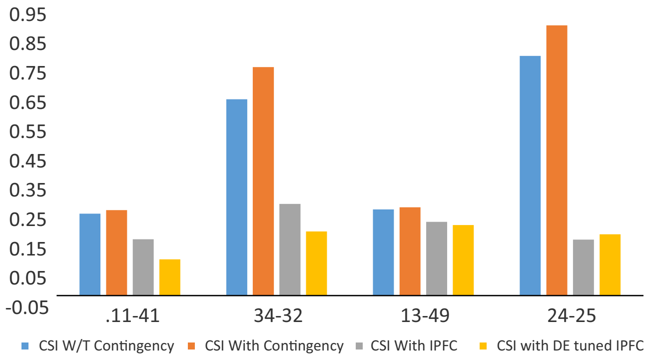

Figure 7 CSI of lines at 125% load without contingency, with contingency and with IPFC for IEEE 57 bus system.

5. Conclusion

Consistent system operation is a very important criterion of the modern power systems. Load flow control using multi-faceted IPFC device can maintain a reliable system operation even in the event of contingencies. Proper placement and tuning of the costly device is necessary for its effective utilization.

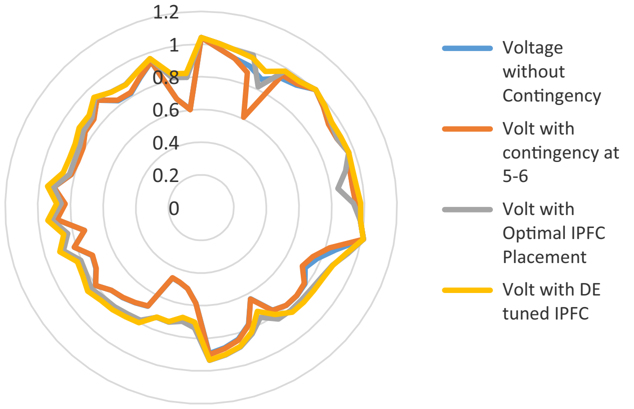

Figure 8 Voltage profile without contingency, with contingency, and with optimal placement of IPFC for normal loading.

- An approach for contingency estimation on the basis of probability of severity has been proposed.
- The severe lines for different line outages are identified and ranked in descending order of CSI for both the test systems. It is observed from the results that for some contingencies

voltage instability may be a more severe issue while in other cases line overloading may pose a greater threat. Since, CSI has the ability to predict the overall severity of the line, it is found to be a more preferable index in comparison with single indices PI and L_{mn}.

- The 1st converter of IPFC is chosen to be placed on the line with highest probability of severity. The 2nd converter is placed on the healthiest line that has a bus in common with the chosen line. It has been established that placement of IPFC effectively reduces line overload, improves voltage stability and reduces the active and reactive power loss of the system. It also reduces the voltage deviation and hence enhances the voltage profile of the system. It has been observed that the voltage deviation, overall PI, L_{mn} and CSI of the system are reduced to the pre-contingency level.
- The IPFC parameters have successfully been tuned using DE for the multi-objective function. Comparison of the results with GA proves the effectiveness of the proposed method. Improvement in security margin reduces congestion in the line. Reduction in losses improves the power transfer capability of the system. Reduction in voltage deviation improves the voltage stability of the system.

Appendix. A

Bus data for IEEE 14 bus system.

Bus No.	Type	V	Theta	P_{Gi}	Q_{Gi}	P_{Li}	Q_{Li}	$Q_{\min}$	$Q_{\max}$
1	1	1.060	0	0	0	0	0	0	0
2	2	1.045	0	40	42.4	21.7	12.7	−40	50
3	2	1.010	0	0	23.4	94.2	19.0	0	40
4	3	1.0	0	0	0	47.8	30.9	0	0
5	3	1.0	0	0	0	7.6	10.6	0	0
6	2	1.070	0	0	12.2	11.2	7.5	−6	24
7	3	1.0	0	0	0	0.0	0.0	0	0
8	2	1.090	0	0	17.4	0.0	0.0	−6	24
9	3	1.0	0	0	0	29.5	16.6	0	0
10	3	1.0	0	0	0	9.0	5.8	0	0
11	3	1.0	0	0	0	3.5	10.8	0	0
12	3	1.0	0	0	0	6.1	10.6	0	0
13	3	1.0	0	0	0	13.5	50.8	0	0
14	3	1.0	0	0	0	14.9	50.0	0	0

Bus data for IEEE 57 bus system.

Bus No.	Type	V	Theta	P_{Gi}	Q_{Gi}	P_{Li}	Q_{Li}	$Q_{\min}$	$Q_{\max}$
1	1	1.04	0	0	0	0	0	−200	300
2	2	1.01	0	0	−0.8	3	188	−17	50
3	2	0.985	0	40	−1	41	121	−10	60
4	3	1	0	0	0	0	0	0	0
5	3	1	0	0	0	13	114	0	0
6	2	0.98	0	0	0.8	75	12	−8	25
7	3	1	0	0	0	0	0	0	0
8	2	1.005	0	450	62.1	150	22	−140	200
9	2	0.98	0	0	2.2	121	26	−3	9
10	3	1	0	0	0	5	2	0	0
11	3	1	0	0	0	0	0	0	0
12	2	1.015	0	310	128.5	377	24	−150	−155
13	3	1	0	0	0	18	2.3	0	0
14	3	1	0	0	0	10.50	5.30	0	0
15	3	1	0	0	0	22	5	0	0
16	3	1	0	0	0	43	3	0	0
17	3	1	0	0	0	42	8	0	0
18	3	1	0	0	0	27.2	9.8	0	0
19	3	1	0	0	0	3.3	0.6	0	0
20	3	1	0	0	0	2.3	1	0	0
21	3	1	0	0	0	0	0	0	0
22	3	1	0	0	0	0	0	0	0

Appendix. A (*continued*)

Bus No.	Type	V	Theta	P_{Gi}	Q_{Gi}	P_{Li}	Q_{Li}	$Q_{\min}$	$Q_{\max}$
23	3	1	0	0	0	6.3	2.1	0	0
24	3	1	0	0	0	0	0	0	0
25	3	1	0	0	0	6.3	3.2	0	0
26	3	1	0	0	0	0	0	0	0
27	3	1	0	0	0	9.3	0.5	0	0
28	3	1	0	0	0	4.6	2.3	0	0
29	3	1	0	0	0	17	2.6	0	0
30	3	1	0	0	0	3.6	1.8	0	0
31	3	1	0	0	0	5.8	2.9	0	0
32	3	1	0	0	0	1.6	0.8	0	0
33	3	1	0	0	0	3.8	1.9	0	0
34	3	1	0	0	0	0	0	0	0
35	3	1	0	0	0	6	3	0	0
36	3	1	0	0	0	0	0	0	0
37	3	1	0	0	0	0	0	0	0
38	3	1	0	0	0	14	7	0	0
39	3	1	0	0	0	0	0	0	0
40	3	1	0	0	0	0	0	0	0
41	3	1	0	0	0	6.3	3	0	0
42	3	1	0	0	0	7.1	4	0	0
43	3	1	0	0	0	2	1	0	0
44	3	1	0	0	0	12	1.8	0	0
45	3	1	0	0	0	0	0	0	0
46	3	1	0	0	0	0	0	0	0
47	3	1	0	0	0	29.7	11.6	0	0
48	3	1	0	0	0	0	0	0	0
49	3	1	0	0	0	18	8.5	0	0
50	3	1	0	0	0	21	10.5	0	0
51	3	1	0	0	0	18	5.3	0	0
52	3	1	0	0	0	4.9	2.2	0	0
53	3	1	0	0	0	20	10	0	0
54	3	1	0	0	0	4.1	1.4	0	0
55	3	1	0	0	0	6.8	3.4	0	0
56	3	1	0	0	0	7.6	2.2	0	0
57	3	1	0	0	0	6.7	2	0	0

- The system loading has been increased to 110% and 125% load and the performance of the system has been studied. The IPFC has been found to alleviate the overall performance of the system at all loadings for both IEEE 14 bus and 57 bus systems.

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