Optimal Setting of Interline Power Flow Controller for Congestion and Contingency Management

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Abstract - The effect of outages in transmission lines and generator units can be predictable for stable and reliable operation of power system through contingency assessment. Hence, contingency assessment is an important task for stable and effective operation of power system. In this paper, a method of placement of interline power flow controller (IPFC) based on the probability of severity has been proposed. Contingency ranking of lines has been done using Composite Severity Index which is a probabilistic based strategy for the placement of IPFC. IPFC is placed on the line with highest probability of severity during the occurrence of different outages. Thereafter, the size of the IPFC was optimized using cuckoo search algorithm. The proposed methodology has been applied on the IEEE 14 bus system data and results presented. The system overall CSI, active and reactive power were reduced by 7.31%, 10.17% and 14.46% respectively. The results show that optimal placement of IPFC effectively reduces line congestion, improves voltage stability and reduces the active and reactive power loss of the system.

Keyword- Power Flow, line utilization factor, severity index, Contingency Management

1 INTRODUCTION

Demand in power is growing at an alarming rate as a result of increase in population and industrialization worldwide. Therefore, a highly modernized power system is expected to cater for the growing demands of power wherever required, with acceptable quality and costs. In order to accommodate this increase in demand, more generation plants are being installed. The installation of new generation plants, however, necessitates the expansion of existing transmission network. Moreover, control constraints on the expansion of the transmission network leads to the reduction of stability margins and increase in the risks of repeated outages and blackouts (Vassell, 1991). Despite the increase in generation and transmission capacity, load demand continues to increase to proportions that cause extreme stress on existing transmission line which often manifests as voltage collapse due to the shortage of reactive power delivered at the load centres (Jun and Akihiko, 2006).

Around the world, increase in the occurrence of blackout or complete failure is becoming worrisome. Reliable operation of power system under both normal and contingency situation is highly desirable in today’s complex electrical networks. Hence contingency severity calculation is very important in power system planning and thus critical to power system reliability. There are various steady state and dynamic contingency ranking methods used for contingency screening of disturbances in system instability to avoid total collapse or blackout. When disturbance occurs in power system, system stability becomes vulnerable and if preventive measures are not taken quickly there is a high risk of total system collapse. In other to avert system collapse, detection and control measures have to be put in place (Karami et al., 2007).

Different solutions have been developed to minimise the effect of system disturbances and thus prevent system collapse. One of such solutions is the application of Flexible Alternate Current Transmission System (FACTS) devices in modern power systems. FACTS technology is regarded as one of emerging technologies for power system security improvement. Steady state problems and transient stability enhancement can be achieved when using FACTS devices for power system secure operation. There are various types of FACTS devices such as Static Synchronous Series Compensator (SSSC), Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), Interline Power Flow Controller (IPFC) and Unified Power Flow Controller (UPFC) (Hingorani and Gyugi, 2000). Of these types, the IPFC is considered to be the most flexible, powerful, and versatile as it employs at least two Voltage Source Converter (VSCs) with a common DC link. Hence, IPFC has the capability of compensating multi-transmission lines. (Wei et al., 2004; Jayasankara et al., 2010).

Proper positioning and tuning of FACTS devices in the power system is a big concern in the industry as their effectiveness varies with position in a power system and it is the focus of this paper. This concern is being addressed in different ways by a lot of researchers using conventional and heuristic methods. Jun and Akihiko (2006) presented an optimal power flow (OPF) control in electric power systems incorporating IPFC. Karami et al. (2007) addressed the problem of voltage security and congestion management in power system under heavy loading utilizing STATCOM and Real Genetic Algorithm for optimal tuning. Patil and Karagi (2017) reviewed developments in the area of optimal placement of different FACTS devices in a deregulated environment. They presented detailed discussions on objective functions and the different optimization techniques applied by researchers in recent times. Charan and Parimi (2018) investigated the effectiveness of IPFC in controlling the power flow while maintaining the voltage profile in a 400kV power system network. Rajagopalan et al., (2018) optimally located IPFC in order
to minimise power losses on a 5 Bus power system using Bees Algorithm.

In this paper, long term investment approach for placement and tuning of IPFC is proposed for protecting power system against contingency. The line with the highest probability of severity is proposed to be the optimal location for IPFC placement. Thereafter, cuckoo search algorithm is used for tuning the IPFC. Cuckoo Search algorithm is a heuristic approach for non-differentiable and nonlinear continuous functions. It converges quickly and does not require many control variables and is versatile and easy to use (Yang and Deb, 2009). Two different indices; Line Utilization Factor (LUF) and Fast Voltage Severity Index (FVSI) have been combined to develop a Composite Severity Index (CSI) to assess line overloads and bus voltage violations. LUF is used to measure line overloads in terms of both real and reactive power while FVSI has been employed for voltage contingency ranking. Both indices are merged to develop a Composite Severity Index, which is used to obtain a precise estimate of overall stress on the line. It is proposed that the IPFC should be placed on the line which appear more frequently on the severity list of CSI for the different outages. Cuckoo search algorithm is used to tune the IPFC to minimize its size and therefore cost. The proposed method is implemented and tested on an IEEE 14 bus system which is shown in Figure 1. The line data and bus data for IEEE 14 bus system is shown in Table 1 and Table 2 respectively. The results have been presented and discussed in section 3.

2 MODELLING OF THE IPFC

IPFC consists of at least two back to back DC-AC converters connected by a common DC link (Zhang, 2003). The basic model of the IPFC consists of three buses i, j and k. Two transmission lines are connected with the bus i in common. The equivalent circuit of the IPFC with two converters is represented in Figure 2. V_i, V_j, V_k are complex voltages at bus i, j, k respectively. Each of these voltages is characterized by a magnitude and phase angle. V_se_in, is the complex controllable series injected voltage source. It shows the series compensation of the series converter. V_se_in is given by the following:

\[ V_{se_{in}} = V_{se_{in}}(\theta_{se_{in}}) \]

where \( n = j, k \). \( Vse_{in} \) and \( \theta se_{in} \) are the magnitude and angle of Vse_in. Zse_in is the series transformer impedance. \( Pse_{in} \) is the active power exchange of each converter via the common DC link. \( P_i \) and \( Q_i \) as given in Eqsns. (2) and (3) are the sum of the active and reactive power flows leaving the bus i. The IPFC branch active and reactive power flows leaving bus n are \( P_{ni} \) and \( Q_{ni} \) and the expressions are given in Eqsns. (4) and (5). \( I_{j_i}, I_{k_i} \) are the IPFC branch currents of branch j - i and k - i leaving bus j and k, respectively.

\[ P_i = V_i^2 g_{ii} - \sum_n V_n [g_{iin} \cos(\theta_i - \theta_n) + b_{in} \sin(\theta_i - \theta_n)] - \sum_n V_n V_{se_{in}} [g_{iin} \cos(\theta_i - \theta_{se_{in}}) + b_{in} \sin(\theta_i - \theta_{se_{in}})] \]  
\[ Q_i = -V_i^2 b_{ii} - \sum_n V_n [g_{iin} \sin(\theta_i - \theta_n) + b_{in} \cos(\theta_i - \theta_n)] - \sum_n V_n V_{se_{in}} [g_{iin} \sin(\theta_i - \theta_{se_{in}}) + b_{in} \cos(\theta_i - \theta_{se_{in}})] \]  
\[ P_{ni} = V_e^{\ast} g_{mn} - \sum_n V_n (g_{in} \cos \theta_{in} + b_{in} \sin \theta_{in}) - V_e V_{se_{in}} (g_{in} \cos (\theta_i - \theta_{se_{in}}) + b_{in} \sin (\theta_i - \theta_{se_{in}})) \]  
\[ Q_{ni} = -V_e^{\ast} b_{mn} - \sum_n V_n (g_{in} \sin \theta_{in} - b_{in} \cos \theta_{in}) - V_e V_{se_{in}} (g_{in} \sin (\theta_i - \theta_{se_{in}}) + b_{in} \cos (\theta_i - \theta_{se_{in}})) \]

where \( n = j, k \).

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

\[ Re(V_{se_{in}} I_{j_i}^{\ast} + V_{se_{in}} I_{k_i}^{\ast}) = 0 \]

where superscript * means complex conjugate.

2.1 LINE UTILIZATION FACTOR

Line Utilization Factor (LUF) is an index used for determining the congestion of the transmission lines. (Akanksha, 2015) It is given by

\[ LUF_{ij} = \frac{MVA_{ij}}{MVA_{ij_{max}}} \]

where; LUF_{ij} is line utilization factor of the line connected to bus i and bus j. \( MVA_{ij_{max}} \) is maximum MVA rating of the line between bus i and bus j. \( MVA_{ij} \) is actual MVA rating of the line between bus i and bus j.

LUF estimate the percentage of line being utilized and is an efficient method to estimate the congestion in a line. The overall LUF of the system is given by:

\[ OverallLUF = \sum LUF \]

Where, \( L \) is the number of line in the system.
2.2 FAST VOLTAGE STABILITY INDEX

Fast Voltage Stability Index (FVSI) is a line-based voltage stability indicator given by the following equation:

\[ FVSI_{ij} = \frac{z_{ij} G_{ij}}{v_{ij}^2} \]

where,
\[ Z = \text{line impedance} \]

Symbols ‘i’ and ‘j’ represent the sending and receiving buses respectively.

\[ X_{ij} = \text{line reactance} \]

\[ Q = \text{reactive power at the receiving end} \]

\[ V_{i} = \text{sending end voltage} \]

The value of FVSI that is evaluated close to 1 indicates that the particular line is close to its instability point which may lead to voltage collapse in the entire system. To maintain a secure condition, the value of FVSI should be maintained well less than 1. The overall FVSI of the system is given by:

\[ \text{OverallFVSI} = \sum_{ij} FVSI \]

2.3 COMPOSITE SEVERITY INDEX

After obtaining the LUF and FVSI values of all the lines for a specific line outage, the composite severity index is calculated as follows:

\[ CSI_{ij} = w_1 \times LUF_{ij} + w_2 \times FVSI_{ij} \]

where, \( w_1 \) and \( w_2 \) are the weighting factors of both indices for line i-j. Equal weightage of 0.5 was given to the two indices, therefore the sum of \( w_1 \) and \( w_2 \) is equal to unity. The overall CSI of the system is given as:

\[ \text{OverallCSI} = \sum_{ij} CSI \]

2.4 OPTIMAL TUNING OF IPFC

To find the optimal size of IPFC, a multi objective function is formulated. The objective functions are:

- minimization of the active power loss, total voltage deviations, security margin and usage of minimum value of installed IPFC.

Since there are four objective functions, weighing factors are used to reflect the relative importance of the objective function. But in this study equal preference is given to all the objective functions and is taken to be 0.25.

The multi objective function is:

\[ \min F = \min \sum_{i=1}^{n} w_i f_i \]

where, \( w_1, w_2, w_3, w_4 \) are the weighing factors
\[ w_1 + w_2 + w_3 + w_4 = 1 \]
\[ w_1 = w_2 = w_3 = w_4 = 0.25 \]

The formulation for each objective function is provided as follows:

2.4.1 Minimization of the active power loss

\[ \min f_1(x) = \min \sum_{i=1}^{n} P_{\text{loss}} \]

\[ P_{\text{loss}} = \{|V_i|^2 G_{ii} - |V_i||V_j||G_{ij}| \cos \theta_{ij} + B_{in} \sin \theta_{in}| + VIVJs \sin Gicos \theta + Bini \sin \theta i + VI\Gj - VIV\Gjcos \theta + Bini \sin \theta i - VIVj Sin Gicos \theta + Bini \sin \theta i \]

where:
\( ik \) is the number of transmission lines,
\( V_i = V_i(\theta_i) \) and \( V_n = V_n(\theta_n) \) are voltages at the end buses i and n (\( n = j, k \)),
\( V_{\sin} = V_{\sin}(\theta_{\sin}) \) is the series injected voltage source of \( n \)th line.
\( G_{in} \) and \( B_{in} \) are the transfer conductance and susceptance between bus i and n respectively.

The magnitude and phase angle of the series injected voltages \( V_{aij} \) and \( V_{vik} \) are determined optimally.

2.4.2 Minimization of voltage deviation

It is necessary to minimize the voltage deviation at each bus to the smallest possible value in other to have a good voltage performance. The appropriate equation can be expressed as:

\[ \min f_2(x)(x) = \min (VD) = \min \left( \sum_{k=1}^{n} (v_k^0 - v_{k}^r)^2 \right) \]

where \( V_k \) is the voltage magnitude at bus k.

2.4.3 Minimization of security margin

This function depends on the static voltage stability and shows whether the chance of voltage collapse is reduced. The security rate of a system according to the critical state can be expressed as follows:

\[ SM = \frac{\sum_{i=1}^{n} (S_{i}^\text{init})}{\sum_{i=1}^{n} S_{i}^\text{init}} \]

where; \( J_L \) = A set containing all load buses

SM has a value between 0 and 1 for a system with stable operating condition. SM = 0 at the voltage stability limit. A negative value of SM means the system cannot supply the initial load. Thus, the nearer the value of SM is to 1, the more stable the system is. It is therefore a maximization function. Since minimization is the aim of the multi-objective function, the objective function for SM can be rewritten as:

\[ f_3(x, u, z) = 1 - \frac{1}{\sum_{i=1}^{n} S_{i}^\text{init}} \]

2.4.4 Minimization of total capacity of installed IPFC

The minimum total capacity of the installed IPFC required for mitigating the overload on the transmission lines can be expressed as follows:

\[ f_4(x) = \min (PQ_1^2 + PQ_2^2) \]

where PQ denotes capacity of each VSC of the IPFC.

\[ PQ_1^2 + PQ_2^2 = (Vse_i \left( \frac{V_i - V_{\sin} - V_j}{z_{ij}} \right))^2 + (Vse_k \left( \frac{V_i - V_{\sin} - V_k}{z_{ik}} \right))^2 \]

The objective functions are subject to the following constraints:

i. Equality constraints

\[ P_{\text{gi}} + P_{\text{di}} = \sum_{i=1}^{n} V_i |V_i| \cos (\theta_i + \delta_i - \delta_i) \quad \forall i \]

\[ Q_{\text{gi}} + Q_{\text{di}} = \sum_{i=1}^{n} V_i |V_i| \sin (\theta_i + \delta_i - \delta_i) \quad \forall i \]

ii. Inequality constraints

\[ V_{i}^\text{min} \leq V_{i} \leq V_{i}^\text{max} \quad \forall i \in \text{load bus} \]

\[ S_{ij}(V, \delta) \leq S_{ij}^\text{max} \quad \forall i, j \]

iii. IPFC constraints
2.5 APPLICATION OF CUCKOO SEARCH ALGORITHM FOR IPFC PLACEMENT

Cuckoo search algorithm is based on the brood parasitic behaviour of some cuckoo species along with the Levy flight behaviour of some birds and fruit flies (Yang and Deb, 2009). Cuckoo Search considers three rules:

1) Each cuckoo lays one egg at a time, and puts its egg in the randomly chosen nest;
2) The best nests for good quality of eggs will be transferred to the next generations;
3) The number of available host nests is set at fixed value. The probability of discovery of the cuckoo egg by the host bird is considered as \( P_a \in [0, 1] \).

In this case, the host bird can either throw the egg away or abandon the nest to build a new nest. In summary, it can be presumed that each egg in a nest denotes a solution, and a cuckoo egg stands for a new solution. The goal is to use the new and potentially superior solutions (cuckoos) to replace a not so good solution in the nests. The algorithm as applied in this work is provided in Figure 3.

![Cuckoo Search Algorithm flow chart](image)

**Fig. 3: Cuckoo Search Algorithm flow chart.**

3 RESULTS AND DISCUSSION

IEEE 14 bus test system has 4 generator buses, 9 load buses and 20 transmission lines. Bus 1 is the slack bus. Bus number 2, 3, 6, 8 are the generator buses while other buses are load buses. Line data IEEE 14 bus system is provided in Table 3. Hence, outages on line 13 – 14 was used as the contingency. The CSI for all the lines was computed considering three scenarios. First scenario is that of the existing system without contingency also known as the base case. Second is the system after subjection to contingency and third is the system with contingency plus the application of optimally tuned IPFC. The CSI for these three scenarios is provided in Table 3.

**Table 1. Line data IEEE 14 bus system**

| Line No | From Bus | To Bus | R (p.u.) | X (p.u.) | \( G_b \) (p.u.) | \( B_b \) (p.u.) |
|---------|----------|--------|----------|----------|-----------------|-----------------|
| 1       | 1        | 2      | 0.01938  | 0.05917  | 0.0264          | 1               |
| 2       | 2        | 3      | 0.04699  | 0.11979  | 0.0219          | 1               |
| 3       | 2        | 4      | 0.05811  | 0.17632  | 0.0187          | 1               |
| 4       | 1        | 5      | 0.05403  | 0.22030  | 0.0246          | 1               |
| 5       | 2        | 5      | 0.05695  | 0.17388  | 0.017           | 1               |
| 6       | 3        | 4      | 0.06701  | 0.17103  | 0.0173          | 1               |
| 7       | 4        | 5      | 0.01335  | 0.04211  | 0.0064          | 1               |
| 8       | 5        | 6      | 0.25202  | 0.0932   | 0               | 1               |
| 9       | 4        | 7      | 0.20912  | 0.57846  | 0.978           | 1               |
| 10      | 7        | 8      | 0.17615  | 0.986    | 0               | 1               |
| 11      | 4        | 9      | 0.55618  | 0.969    | 0               | 1               |
| 12      | 7        | 9      | 0.11001  | 0.864    | 0               | 1               |
| 13      | 9        | 10     | 0.03181  | 0.0845   | 0               | 1               |
| 14      | 6        | 11     | 0.09498  | 0.1989   | 0               | 1               |
| 15      | 6        | 12     | 0.12291  | 0.25581  | 0               | 1               |
| 16      | 6        | 13     | 0.06615  | 0.13027  | 0               | 1               |
| 17      | 9        | 14     | 0.12711  | 0.27038  | 0               | 1               |
| 18      | 10       | 11     | 0.08205  | 0.19207  | 0               | 1               |
| 19      | 12       | 13     | 0.22092  | 0.19988  | 0               | 1               |
| 20      | 13       | 14     | 0.17093  | 0.34802  | 0               | 1               |
Different performances of the system were calculated for the three scenarios mentioned. The results have been provided in Table 5. The performances taken into consideration are active power loss, reactive power loss, and overall CSI value. The active and reactive power losses of the base case are found to be 15.7578 MW and 68.3483 MVAR respectively as shown in Table 5. With the outage of line 13-14, it is observed that the active and reactive power losses of the system increased to 25.5347 MW and 97.8797 MVAR as calculated from the optimization algorithm. After placement and tuning of IPFC on the lines 7 - 9 and 9 - 10, the active and reactive power losses of the system reduced to 22.266 MW and 74.518 MVAR respectively as calculated from the optimization algorithm. The loss profiles with IPFC installed show considerable reduction in losses for lines 9 to 18 as seen in Figures 6 and 7. Placement of IPFC at the proposed location reduces the values of CSI and overall CSI to levels lower than the pre-contingency levels as shown in Table 3 and Table 5. Reduction in CSI values mean that the lines concerned are now less vulnerable to congestion in the event of a contingency. The implication of these results is that optimal placement and tuning of IPFC reduces the congestion in the line considerably. It also mitigates active and reactive power losses in the system during a contingency. The voltage profile of the IEEE 14 bus system for the three scenarios is provided in Figure 4. It can be observed that the system voltage profile improves with the optimal placement of IPFC.

It can be observed from Table 3 that the line connected between the buses 7 - 9 is most vulnerable as compared to other lines because it has a CSI of 0.7510. Hence the line 7 - 9 is chosen for the placement of the first converter of the IPFC. Further analysis was carried out on the three lines connected with the line 7-9 through a common bus (i.e. lines 9 – 14, 9 – 10 and 9 – 4). The CSI values of these lines for an outage on line 13 - 14 have been given in Table 4. It can be observed that the line connected between buses 9 - 10 has the lowest CSI value. Hence, it is the healthiest line. Therefore, the second converter of the IPFC is chosen to be placed on this line.
the active and reactive power loss of the system. It also reduces the voltage deviation and hence enhances the voltage profile of the system. These improvements are expected to lead to increased power quality and efficiency in power delivery.

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Table 5. Comparison of results at various system state with optimal placement of IPFC at 7 - 9 and 9 - 10

| Parameter Description | Without Contingency | With Contingency At 13-14 | With Optimal placement of IPFC |
|-----------------------|---------------------|--------------------------|-------------------------------|
| Active Power Loss (MW) | 15.7578             | 25.5347                  | 23.6684                       |
| Reactive Power Loss (MVAR) | 68.3483         | 97.8797                  | 87.9245                       |
| CSI of Line 7 - 9 | 0.7510               | 0.8277                   | 0.7277                         |
| Overall CSI | 7.8307               | 8.9872                   | 7.5974                         |

4 CONCLUSION

This work presents the application of optimal placement and tuning of IPFC to manage overload and contingency problem in a transmission line system. The active power, reactive power and overall CSI for the power transmission line used in this study have been reduced by 7.31%, 10.17% and 14.46% respectively. These results show that optimal placement of IPFC effectively reduces line congestion, improves voltage stability and reduces...