Comparative Analysis on Security-Constrained Optimal Power Flow Using Linear Sensitivity Factors-Based Contingency Screening

Darshan B. Rathod and Rinkesh A. Jain

Abstract Security-Constrained Optimal Power Flow (SCOPF) is a significant tool used for analysis of power system operation and planning. This paper presents a solution of SCOPF considering critical contingencies simulated on IEEE 30-bus system. The main objective of the presented work is to minimize the total generation cost. An interior point algorithm has been used to find out a feasible and optimal solution with minimum computational time for secured power system operation. Contingency screening for SCOPF formulation has been accomplished with the help of Linear Sensitivity Factors (LSFs) obtained from the Z-bus algorithm. Comparative analysis has been carried out for the results obtained with those of other techniques published in the literature for same test cases.

Keywords Contingency screening · Interior point algorithm · LSFs · Optimal power flow (OPF) · SCOPF

1 Introduction

SCOPF plays a major role in the power system economic operation and security study. Minimization of generation cost without breaching security constraints is a challenging task for power system analyst in a large interconnected power system having many threats under normal and stressed conditions. SCOPF is an extension of OPF, wherein OPF problem is augmented to consider contingency cases such as line outage, generation outage, or important outage of any important components of power system to attain an operating point which is secure and optimal [1]. Thus SCOPF problem is highly constrained, nonlinear, and non-convex problem of the power system [2]. With increasing the size of network and more contingencies to

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be considered, SCOPF problem becomes more complex and computational time increases. The overall SCOPF problem has been based on two types of security analysis; steady state and dynamic security [3]. In steady-state security-based SCOPF, the system operators monitor the power flow with stimulating contingencies to analyze any case of overload and voltage violations.

Network designers and system operators typically rely on the use of conventional methods, including Newton's method [4], quadratic programming [4], interior point method [5], etc., to solve OPF/SCOPF problem. Recently, many meta-heuristic algorithms are proposed to solve power system problems. They have a good performance in finding the global optimum solution but require more computational time as well as are not adaptive to online interface of the dynamical behavior of power system. That is why still conventional OPF algorithms are widely used due to computational efficiency and strong theoretical background [6].

This paper is organized as follows: Sect. 2 presents a summary of SCOPF problem formulation. Contingency screening is carried out in Sect. 3. Section 4 shows results of SCOPF for IEEE 30-bus test system.

2 SCOPF Problem Formulation

SCOPF problem deals with adjusting controlling parameters of the system to acquire optimal solution while considering security. But one concern that needs to be taken care of is while acquiring optimal solution of SCOPF the security of power system is not violated [1]. That means, if there is any outage occurs during operation, the system can somehow manage the condition and stay intact even after outage.

For ensuring the security of the system, contingency constraints for critical contingencies should be identified and SCOPF problem is to be formulated. Some possible controllable parameters are:

- Generator MW outputs.
- Generator voltages.
- Transformer tap ratio.
- Switched capacitor settings.

SCOPF can be implemented by first formulating OPF. For OPF problem, the objective function is generation cost to be minimized can be given by Eq. (1).

$$f = \sum_i \mathrm{K}_i(\mathrm{P}_{\mathrm{Gi}}) \tag{1}$$

where K_i is the cost function for generating P_{Gi} power at the respective bus. A quadratic generation cost function is considered and given by Eq. (2).

$$f(\mathrm{P}_{\mathrm{Gi}}) = \mathrm{a}_{\mathrm{i}}\mathrm{P}_{\mathrm{Gi}}^2 + \mathrm{b}_{\mathrm{i}}\mathrm{P}_{\mathrm{Gi}} + \mathrm{c}_{\mathrm{i}} \tag{2}$$

The solution must satisfy constraints at the pre-contingency state and constraints at the post-contingency state.

Equality Constraints at Pre-Contingency

The active and reactive power balance equations in the pre-contingency case are given by Eqs. (3) and (4).

$$\sum_{i=1}^{NG} P_{Gi}^{0} - \sum_{j=1}^{NLoad} (P_{Load\,j}) - P_{Loss}^{0} = 0 \tag{3}$$

$$\sum_{i=1}^{NG} Q_{Gi}^{0} - \sum_{j=1}^{NLoad} (Q_{Load\,j}) - Q_{Loss}^{0} = 0 \tag{4}$$

Equality Constraints at Post-Contingencies

The active and reactive power balance equations in the post-contingency case are given by Eqs. (5) and (6).

$$\sum_{i=1}^{NG} P_{Gi}^{k} - \sum_{j=1}^{NLoad} (P_{Load\,j}) - P_{Loss}^{k} = 0 \tag{5}$$

for $k = 1,2, \ldots K$

$$\sum_{i=1}^{NG} Q_{Gi}^{k} - \sum_{j=1}^{NLoad} (Q_{Load\,j}) - Q_{Loss}^{k} = 0 \tag{6}$$

for $k = 1,2, \ldots K$

Inequality Constraints

Inequality constraints such as limit on voltage at generator bus, limit on real power generation and transformer tap ratio limit must be taken into consideration. Limits on control variables are given by:

Limit on voltage at generator bus is given by Eq. (7).

$$V_i^{min} \le V_i \le V_i^{max}\text{ , for } i = 1, \ldots, N \tag{7}$$

Limit on real power generation is given by Eq. (8).

$$P_{Gi}^{min} \le P_{Gi} \le P_{Gi}^{max}\text{ , for } i = 1, \ldots, NG \tag{8}$$

Transformer tap ratio limit is given by Eq. (9).

$$a_i^{min} \le a_i \le a_i^{max}\text{ , for } i = 1, \ldots, NT \tag{9}$$

Functional constraints

Functional constraints such as limit on voltage at PQ bus, reactive power generation limit, line overflow limit, etc., are also considered for SCOPF problem.

Limit on voltage at PQ bus is given by Eq. (10).

$$\mathrm{V}_{\mathrm{PQ}i}^{\min} \leq \mathrm{V}_{\mathrm{PQ}i} \leq \mathrm{V}_{\mathrm{PQ}i}^{\max}, \text{ for } i = 1, \ldots, \mathrm{N} \tag{10}$$

Line overflow limit is given by Eq. (11).

$$\mathrm{S}_i^{\min} \leq \mathrm{S}_i \leq \mathrm{S}_i^{\max}, \text{ for } i = 1, \ldots, \mathrm{N} \tag{11}$$

Reactive power generation limit is given by Eq. (12).

$$\mathrm{Q}_i^{\min} \leq \mathrm{Q}_i \leq \mathrm{Q}_i^{\max}, \text{ for } i = 1, \ldots, \mathrm{NG} \tag{12}$$

3 Contingency Screening

The contingency screening analysis is carried out using LSFs based on Z-bus [7]. LSFs approximate the change of branch power flow depending on the shift of generation or outage of any other branch. These factors are of two types

- Line Outage Distribution Factor (LODF) [8].
- Generation Shift Factor (GSF) [8].

3.1 LODF Using Z-Bus

For simulating outage of branch, it is convenient to calculate LODF. This factor illustrates the change of power flow in the line ij when the outage of line mn occurred.

LODF is represented in Eq. (13).

$$\mathrm{L}_{ij,mn} = \frac{\Delta \mathrm{P}_{ij}^{mn}}{\mathrm{P}_{mn}^{0}} \tag{13}$$

LODF using Z-bus method is given by Eq. (14).

$$\mathrm{L}_{ij,mn} = -\frac{\mathrm{Z}_a}{\mathrm{Z}_c}\left[\frac{(\mathrm{Z}_{im} - \mathrm{Z}_{in}) - (\mathrm{Z}_{jm} - \mathrm{Z}_{jn})}{\mathrm{Z}_{th,mn} - \mathrm{Z}_a}\right] \tag{14}$$

where lower index mn shows outage line and ij shows line whose post-outage power flow is to be checked, Z_a = impedance of outage line, Z_c = impedance of line under consideration, $\mathrm{Z}_{im}, \mathrm{Z}_{in}, \mathrm{Z}_{jm}, \mathrm{Z}_{jn}$ are off-diagonal elements of Z-bus.

Post-outage power flow in line *ij* due to outage of line *mn* is given by Eq. (15).

$$P'_{ij} = P_{ij} + L_{ij,mn} P^0_{mn} \tag{15}$$

3.2 GSF Using Z-Bus

For simulating outage of generator, it is convenient to calculate GSF. This factor describes the change of power flow in the line ij rely on the change of generation in the bus m. GSF represented in Eq. (16).

$$K^m_{ij} = \frac{\Delta P_{ij}}{\Delta P_m} \tag{16}$$

This factor gives approximation in-line flow due to change in generation on particular bus. GSF using Z-bus method is given by Eq. (17).

$$K_{ij,m} = \frac{Z_{im} - Z_{jm}}{Z_c} \tag{17}$$

where *m* shows bus whose generation is to be changed and *ij* shows line whose post-outage power flow is to be checked, Z_c = impedance of line under consideration, Z_{im}, Z_{jm} are off-diagonal elements of Z-bus.

Post-outage line flow in line *ij* due to change in generation at bus *m* is calculated by Eq. (18).

$$P'_{ij} = P^0_{ij} + K_{ij,m}\ \Delta P_m \tag{18}$$

4 Results and Discussions

Simulation of IEEE 30-bus standard test system is carried out for OPF and SCOPF as per loading conditions considered in [9]. Formulation of Z-bus is done using step-by-step method and from Z-bus LSFs are calculated. MATPOWER 6.0 toolbox [10] has been used to obtain OPF and SCOPF solution. The objective function considered here is minimization of the total generation cost. The line data and bus generation data for IEEE 30-bus system is taken from [9]. Two different cases are simulated and the results have been analyzed.

1. OPF and SCOPF case considering seven critical outages/contingencies.
2. OPF and SCOPF case considering a generator outage.

Table 1 Details for case 1

Control parameters		Line outages
Generator bus voltage	VG1, VG2, VG5, VG8, VG11, VG13	1, 2, 4, 5, 7, 33, 35
Generator active power injection	PG2, PG5, PG8, PG11, PG13	

Table 2 Details for case 2

Control parameters		Generator outage
Generator bus voltage	VG1, VG2, VG5, VG8, VG11, VG13	13
Generator active power injection	PG2, PG5, PG8, PG11, PG13	

4.1 Case 1

Here, OPF-base case and SCOPF problem are simulated for IEEE 30-bus system using MATPOWER. For SCOPF case, total of seven critical line outages obtained from LSFs are chosen as shown in Table 1. For secure and reliable operation of power system without violation of any security constraint, a generation rescheduling needs to be done. The test results are shown in Table 3 and that reveals due to rescheduling the cost of generation gets increased.

4.2 Case 2

Here, outage of generator at bus 13 is simulated using MATPOWER and details of case 2 is given in Table 2. By observing results of generator outage case, generation cost is increased compared to line outage case.

The control parameter's value for the optimal solution obtained in both the cases has been shown in Table 3. Rated line data for both cases are considered to be their maximum line flow limits.

Total generation cost of OPF and SCOPF for both the cases are represented in Fig. 1. As seen from Fig. 1, generation cost for SCOPF case is little more than OPF case.

Active power generation at different buses is shown in the Fig. 2. This graph gives comparative results of both OPF and SCOPF case for case 1 for active power generation. Comparative study of test case 1 with gradient method is given in Table 4.

A comparative study of other algorithms available in the literature for OPF and SCOPF has been given in Tables 5 and 6. Comparison shows that IPM gives better performance compared to other methods found in literature.

Table 3 Control parameters for both cases

Optimal control variable	Case 1		Case 2	
	OPF	SCOPF	OPF	SCOPF
PG2	48.87	58.45	50.24	62.49
PG5	21.52	24.12	21.95	25.07
PG8	22.23	35.99	25.52	41.32
PG11	12.27	16.52	13.34	18.7
PG13	11.36	14.23	0	0
VG1	1.06	1.058	1.06	1.06
VG2	1.042	1.044	1.043	1.044
VG5	1.015	1.009	1.015	1.012
VG8	1.02	1.025	1.018	1.023
VG11	1.082	1.062	1.06	1.06
VG13	1.071	1.093	1.041	1.044
Losses (MW)	9.456	7.263	9.879	7.426
Fuel cost ($/h)	802.2	812.1	805.98	818.86

Fig. 1 Representation of total cost for test cases

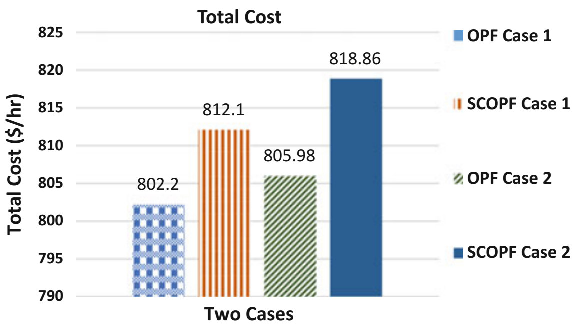

Fig. 2 Representation of active power generation for case 1

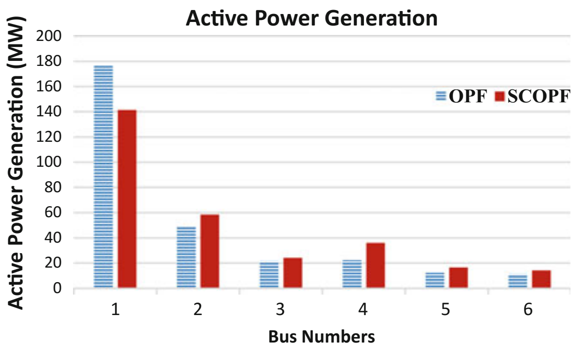

Table 4 Comparative study of test case 1

Optimal Solution	OPF		SCOPF	
	IPM	Gradient [1]	IPM	Gradient [1]
PG2	48.87	48.84	58.45	57.56
PG5	21.52	21.51	24.12	24.56
PG8	22.23	22.15	35.99	35
PG11	12.27	12.14	16.52	17.93
PG13	11.36	12	14.23	16.91
VG1	1.06	1.05	1.06	1.05
VG2	1.042	1.038	1.044	1.033
VG5	1.015	1.011	1.009	1.005
VG8	1.02	1.019	1.025	1.023
VG11	1.06	1.09	1.06	1.09
VG13	1.06	1.09	1.06	1.08
Losses (MW)	9.456	9.48	7.263	7.11
Fuel cost ($/h)	802.2	802.4	812.1	813.74

Table 5 Comparative results of test case 1—OPF

Technique	Fuel cost ($/h)
IPM	802.2
Gradient [1]	802.4
EP [11]	802.907
TS [11]	802.502
TS/SA [11]	802.788
ITS [11]	804.556
IEP [11]	802.465
SADE_ALM [12]	802.404
pSADE_ALM [12]	802.405

Table 6 Comparative results of test case 1—SCOPF

Technique	Fuel cost ($/h)
IPM	812.1
Gradient [1]	813.74
SADE_ALM [12]	834.54
pSADE_ALM [12]	826.97

5 Conclusion

This paper presents, a method for the solution of security-constrained OPF problem using IP algorithm. The results of the different cases of the IEEE 30-bus test system show the potential of the suggested method for the SCOPF problem. LSFs based contingency screening technique using Z-bus is very fast and fairly accurate for further SCOPF implementation. By observing all the results, it can be concluded that the cost of generation in SCOPF is found to be little more than that of OPF in order to make the system secure. This extra cost is a difference between the security and economy operation. Interior point method's convergence time is less. Thus, this method satisfies the basic necessity of having a very fast static assessment of power system security.

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