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Optimal Control Strategy to Alleviate Line Congestion in Power System using Bus Power Rescheduling

Journal of Electrical Systems

The Line flow limit is one of the major challenges faced by electric utilities. The prevailing load conditions cause congestion in transmission line. A decisive control action is essential to relieve the congestion by allowing the power to flow in a different route in the same system. The rerouting of power is possible by controlling the generation at a bus or controlling the load in such a way that the power is rerouted through the other lines present in the power system. In this paper, an attempt has been made to relieve the congestion using a sensitivity based direct method and Genetic algorithm (GA) based optimization technique, wherein the power flows in the transmission lines are maintained within the security limits by using both generation shifting and load control. GA is used to calculate the amount of generation and load control required for congestion management in the system. The results of the sensitivity based direct method for congestion management are compared with the results of GA based congestion management technique by implementing both the proposed methods on IEEE 5 bus system and IEEE 30 bus systemwith a congested line. The effectiveness of each algorithm is also analyzed by applying the techniques on hardware of reduced order model of IEEE 5 bus system. It is found that GA based method is able to alleviate the overloads in transmission line more effectively than the direct method.

Keywords: Congestion management, power flow sensitivity index, Sensitivity based direct method, shifting of generation, Genetic Algorithm based optimal method.

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1. Introduction

Transmission lines are getting congested due to continuous increase in demand and generation capacity augmentation on the power system without addition of new transmission lines. In the competitive market environment electrical utilities try to operate the transmission lines near to their stability and loadability margin. Since the available resources are dwindling and severe environmental issues are faced by the utilities, optimal utilization of available transmission lines became essential. Though enhancement of transmission infrastructure gives solution, it is not feasible due to monetary and right of way issues. Control of power flowing through the transmission lines is an essential option available to a power system operator. By this technique effective utilization of the available transmission line is possible. When line outages occur with congested transmission lines the system will be pushed towards black out state. So a control algorithm which relieves the congestion in transmission lines utilizing the existing control devices in a coordinated manner is required. In addition to all these solution should be achievable, economically feasible, reliable and also applicable in the existing power system environment.

An exhaustive overview of literature has been carried out by the authors on congestion management. Based on the literature review it is found that managing the congestion during

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planning level and real time are the first and second stages of congestion management respectively. Congestion management using reconfiguration of transmission grid based on deterministic approach [1], concurrent handling of two constraints with several uncertainties are utilised in [2] and optimal power flow in transmission lines on the basis of least congestion cost is presented in [3]. Congestion management by providing information to transmission provider and system user about the effect of power transaction on transmission lines is proposed in [4]. Congestion management in deregulated environment is modeled as multi-objective optimization problem in [5], where multiple objectives such as cost of congestion management, voltage and transient stability margin are considered while solving the problem. Nodal prices are varied depending on the transmission line congestion in the power system in [6], analytical formulation which accounts for measures to relieve congestion by grid expansion and re-dispatch is considered in [7] and Flexible AC transmission system (FACTS) devices is considered for managing congestion in [8].

Congestion management techniques adopted by various researchers is reviewed in [9]. It discusses about Locational Marginal Pricing and available transmission capability based congestion management, safe operation of power system and proper congestion management in real time. Congestion management is realised by cost free as well as non cost free methods. Cost free methods include changing the network structure, use of transformer as well as series FACTS devices, etc. Resheduling generation and load reduction are the non-cost free methods available for congestion management. Direct method and optimal method are available in real time for congestion management. Congestion is removed in optimal methods by using inclusive load model and FACTS devices. Since congestion leads to blackout state in power system, the operator has to give quick solution to the problem for operating power system in secured state. So congestion management requires an effective, efficient and direct method for finding the solution.

In direct method for removing congestion based on sensitivity of a particular line with that of the increase in bus power injection and contribution of each and every bus for management of congestion is reported in [10]. Algorithms based on linearised relation between line current and bus injected power are developed to remove congestion in transmission line by [11]. The terminal buses of overloaded line is considered for effective management of congestion in [12] while generation rescheduling and load curtailment to be adopted for managing congestion usage ofsuper decoupled load flow method is proposed in [13]. Rescheduling generation and load shedding using local optimisation for removing line overloads is considered in [14].The location of series compensator such as thyristor Controlled Series Capacitor for operating the power system in secured state using sensitivity matrix is proposed in [15]. Power flow control by varying line reactance is proposed in [16] where step change in line reactance is considered to remove congestion which is difficult to implement in real time power systems. Reliability is improved by placing a capacitor suitably in a system using genetic algorithm (GA) is proposed in [17].

Sensitivity based direct method of congestion management involving generation shifting and load curtailment is attempted in this paper. The proposed algorithm is tested on IEEE 5 bus system and IEEE 30 bus system through generation rescheduling and load curtailment in simulation and hardware. Congestion management requires Generation rescheduling along with load curtailment at optimal levels,so it is also proposed, that these be optimised using GA. This paper also provides a comparison of performances of the proposed two methods viz., the direct method and the optimal method in relieving the congestion.

The rest of the paper is organized as follows. Concept behind the development of congestion management algorithm is presented in the section 3. Section 4 presents the test system for verifying the proposed congestion management algorithm. Section 5 presents implementation and comparison of the algorithms in simulation to relieve congestion of IEEE 5 bus system and IEEE 30 bus system. The hardwaretesting is done on IEEE 5 bus system. The paper is concluded in section 6.

2. Notation

The notation used throughout the paper is stated below.

P_{ij}	real power flow between bus i and bus j
$V_i \angle \delta_i$	complex voltage at bus i
$V_j \angle \delta_j$	complex voltage at bus j
X_{net}	net effective line reactance offered by line 1 and 2
δ_{ij}	phase angle difference between bus i and j
P_{lm}	the power flowing in the line
m	the branch line number in the power system under consideration. Its value varies from 1 to b
N	the total number of buses present in the power system
P_n	the nodal power injected at the nth bus
ΔP_i	Sending end bus power injections
ΔP_j	receiving end buspower injections
ΔP_{inj}	power injection at the buses
S_{mn}	Sensitivity matrix
B_l	is the line admittance matrix of the power system under consideration having a dimension of b×b
A	is the branch node incidence matrix of the power system under consideration having a dimension of b× N
B	is the imaginary part of nodal admittance matrix of dimension N × N

3. Congestion management algorithm

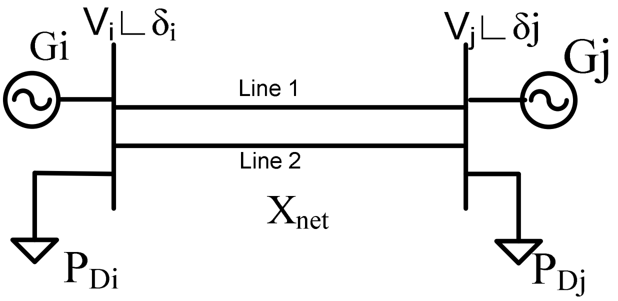

Figure 1. Two bus system

Management of congestion involves control of real power flow in power system. Reliable and secured power supply involves keeping the line flows within the maximum limit. For the two bus system shown in Figure 1Power flowing from bus i to bus j is given by [15].Equation (1) indicates that line power flow can be controlled by controlling magnitude and angles of bus voltages as well as reactance of the line.

$$P_{ij} = \frac{|V_i| * |V_j| \sin \delta_{ij}}{X_{net}} \tag{1}$$

The net power flow can also be varied by changing the bus power by generation shifting and load shedding [18]. For line reactance control, series compensation is used. In this paper, sensitivity based direct method and GA based optimisation method are proposed to relieve congestion. Both the methods deploy generation shifting, and load shedding to relieve congestion.

3.1 Sensitivity Index Based Direct Method

Sensitivity based direct method of congestion management yields solution in straight forward manner without iteration in a single step with the analytical support. DC power flow equation [15] is used to calculate the power flowing through line"m" of an N bus power system is computed as

$$P_{lm} = \sum S_{mn} * P_n \tag{2}$$

S_{mn} is the Sensitivity matrix [15] calculated by equation (3). It relates line power flow with injected power at a particular bus. It's order is b x N.

$$S_{mn} = B_1 A B^{-1} \tag{3}$$

The system is said to be congested if P_{lm} of any line violates its limit. To relieve the congestion, the bus power at sending end or receiving end of the line which is congested has to be varied. The bus power can be varied by changing the generation or load in that bus. The change in bus power required to relieve congestion in buses i and j is computed using equation (4) which is derived from equation (2).

$$P_{lm(\max)} = \left(\sum_{n=1, n=i, j}^{N} S_{mn} * P_n \right) + (S_{mi} * (P_i + \Delta P_i)) + (S_{mj} * (P_j + \Delta P_j)) \tag{4}$$

Maximum power flow limit is $P_{lm(\max)}$ for the overloaded line. To satisfy the equality constraint of the system, the power change should be

$$\Delta P_i = -\Delta P_j = \Delta P_{inj} \tag{5}$$

Where ΔP_i and ΔPj are the power injections at the sending and receiving end buses of the transmission line which is congested. The only unknown variable in the equation (4) is "ΔPi", which is the amount of shift in generation and load shedding that must be done on the bus i for congestion management in the overloaded line "m".

3.2 GA Based Optimal method

Optimisation technique is used to minimise the quantum of generation relocation and load shedding required in the different buses with prevailing power flow to keep all the transmission lines within the security limits. The objective function for the optimal method is

Objective function:

$$\min \sum_{j=1}^{N} \left|\Delta P_j\right| \tag{6}$$

Subjected to equality constraint

$$P_{lm(\max)} = \sum\nolimits_{n=1}^{N} S_{mn}\left(P_n + \Delta P_n\right) \tag{7}$$

and

$$\sum_{j=1}^{N} \Delta P_j = 0 \tag{8}$$

and, inequality constraint

$$P_{jmin} \leq P_j + \Delta P_j \leq P_{jmax} \tag{9}$$

In this work, the objective function given in equation (6) is considered to be the fitness function. The population size, string length, crossover probability and mutation probability are considered to be 10, 20, 0.8 and 0.05 respectively for GA. Roulette wheel is used for parent selection. Best fitness equal to average fitness is considered to be the stopping criterion. The number of variables is N i.e., considering all the N buses of the power system.

4. Problem formulation

The validity of the sensitivity based direct method and GA based optimisation method are tested in simulation using Standard IEEE 5 bus system shown in Figure 2. Table 1 gives the line data of the five bus system.

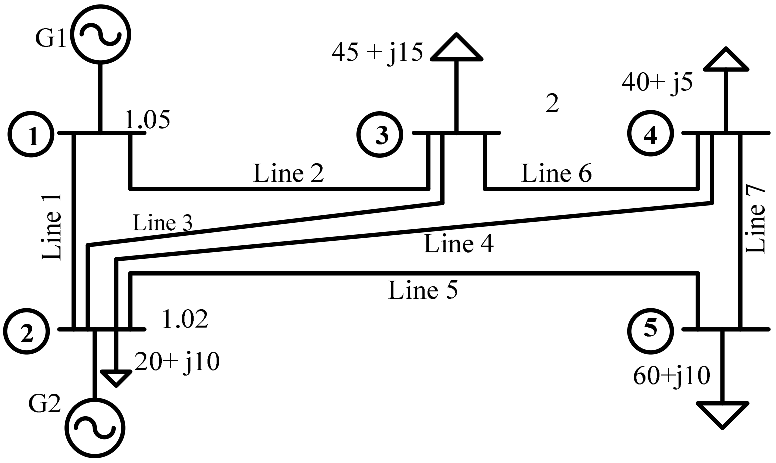

Figure 2. IEEE Five bus system

Table 1 : Line data of the of IEEE 5 bus system

Line (bus tobus)	Series Impedance R+jX (p.u)	Line charging Y/2 (p.u)	PowerLimit (MW)
1-2	0.02+j0.06	j0.030	100
1-3	0.08+j0.24	j0.025	50
2-3	0.06+j0.18	j0.020	50
2-4	0.06+j0.18	j0.020	50
2-5	0.04+j0.12	j0.015	50
3-4	0.01+j0.03	j0.010	50
4-5	0.08+j0.24	j0.025	50

Later, for further verification the algorithms are applied to a scaled down hardware model of IEEE 5 bus system which is available in the power systems laboratory. The developed system shown in Figure 3 is scaled down from 100kV, 100MVA down to 400V, 3kVA.Table 2 gives the line data of the five bus system.

Table 2 :Line data of the of scaled down model of IEEE 5 bus system

Line	Series ImpedanceR+jX (Ω)	Power flow limit(W)
1-2	0.878+j2.634	1200
1-3	3.579+j10.738	250
2-3	2.689+j8.0698	300
2-4	2.689+j8.0698	300
2-5	1.783+j5.35	250
3-4	0.459+j1.3784	250
4-5	3.600+j10.801	250

(a) front Panel (b) backside view

Figure 3. Scaled down model of IEEE 5 bus system

5. Implementation of Control Algorithm

The congestion management algorithms proposed in section 3is implemented both in simulation and hardware model of the IEEE 5 bus system presented in section 4 and the same algorithm is applied in simulation to IEEE 30 bus system [19].

5.1. Simulation results and discussion

The line flows of the IEEE 5 bus system are computed using equation (2). The sensitivity matrix (S_{mn}) in equation (2) is calculated using the line data given in Table 1 and equation (3). S_{mn}matrix of IEEE 5 bus system is given in equation (10). To implement the algorithm, the transmission line of the IEEE 5 bus system is overloaded through proper selection of bus power. In this paper, three different conditions viz., (i) line 2 overload, (ii) line 1 overload and (iii) line 5 overload are created by choosing suitable bus powers.

$$S_{mn} = \begin{bmatrix} 0.5857 & -0.2571 & -0.0428 & -0.0857 & -0.2000 \\ 0.2143 & 0.0571 & -0.1572 & -0.1143 & -0.0000 \\ 0.0905 & 0.1619 & -0.1953 & -0.1238 & 0.0666 \\ 0.1080 & 0.1651 & -0.1206 & -0.1968 & 0.0444 \\ 0.1872 & 0.2158 & 0.0730 & 0.0349 & -0.5109 \\ 0.1048 & 0.0191 & 0.4476 & -0.4380 & -0.1334 \\ 0.0128 & -0.0158 & 0.1270 & 0.1651 & -0.2891 \end{bmatrix} \quad (10)$$

The algorithms are then implemented in the overloaded system to relieve congestion.

Case (i) Line 2 Overload of IEEE 5 bus system

The generation at bus 1 is set to 145 MW and generation at bus 2 is set to 40 MW respectively. The real power demand at bus 2, bus 3, bus4 and bus 5 are maintained at 11 MW, 84 MW, 45 MW and 45 MW respectively. DC load flow analysis using equation (2) is carried out and presented as equation (11).The algorithms are then implemented in the overloaded system to relieve congestion.

$$\begin{bmatrix} 93.92 \\ 51.08 \\ 36.80 \\ 37.44 \\ 48.69 \\ 3.86 \\ 3.69 \end{bmatrix} = \begin{bmatrix} 0.5857 & -0.2571 & -0.0428 & -0.0857 & -0.2000 \\ 0.2143 & 0.0571 & -0.1572 & -0.1143 & -0.0000 \\ 0.0905 & 0.1619 & -0.1953 & -0.1238 & 0.0666 \\ 0.1080 & 0.1651 & -0.1206 & -0.1968 & 0.0444 \\ 0.1872 & 0.2158 & 0.0730 & 0.0349 & -0.5109 \\ 0.1048 & 0.0191 & 0.4476 & -0.4380 & -0.1334 \\ 0.0128 & -0.0158 & 0.1270 & 0.1651 & -0.2891 \end{bmatrix} * \begin{bmatrix} 145 \\ 29 \\ -84 \\ -45 \\ -45 \end{bmatrix} \quad (11)$$

The power flowing in line 2 is 51.08 MW during this condition. The maximum power flow limit in the line2 is 50 MW. So the line 2 power is equated to its maximum value. The equations (4) and (5) are used for calculating the change in power injection required at bus 1 and bus 3 which arebusesto which line 2 is connected.

$$[50.00] = [0.2143 \quad 0.0571 \quad -0.1572 \quad -0.1143 \quad 0] * \begin{bmatrix} 145 + \Delta P_{inj} \\ 29 \\ -84 - \Delta P_{inj} \\ -45 \\ -45 \end{bmatrix} \quad (12)$$

The $\Delta P_{inj}$is calculated for this case using the direct method as -2.009 MW. So the load at bus 3 is reduced by 2.009MW from 84 MW to 81.0991 MW with a corresponding reduction in generation at bus 1 by the same magnitude of 2.009 MW from 145 MW to 142.991 MW. The power changes in buses are tabulated in Table 3. The power flow in different lines due to these changes in power is presented in Table 4. From Table 4, it is evident that the line 2 congestion is alleviated by the direct method.

Further, the congestion issue is solved using GA as explained in section 2.2. The convergence plot of the GA and changes in power at all buses are presented in Figure 4.

Table 3 : Bus power injections for solving the line 2 overload in case (i)

	ΔP_1 (MW)	ΔP_2 (MW)	ΔP_3 (MW)	ΔP_4 (MW)	ΔP_5 (MW)
DirectMethod	-2.9009	0	2.9009	0	0
Optimalmethod	-2.899	0	2.895	0.003	0

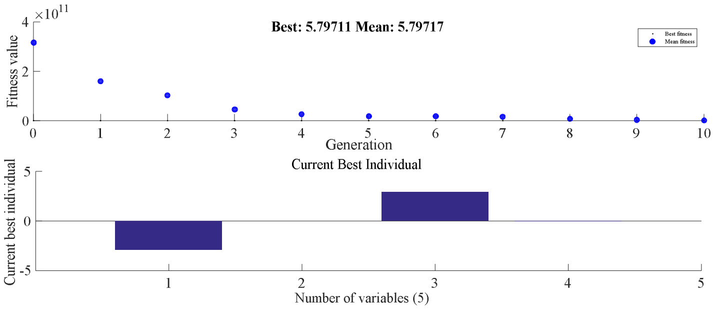

Figure 4. Convergence plot of GA based optimisation for case (i)

Table 4: Line flows during base case, direct method and optimal method for case (i)

	Line 1 (MW)	Line 2 (MW)	Line 3 (MW)	Line 4 (MW)	Line 5 (MW)	Line 6 (MW)	Line 7 (MW)
BaseCase	93.92	51.08	36.80	37.44	48.69	3.86	-3.69
Direct Method	92.10	**50.00**	35.97	36.77	48.36	4.86	-3.36
Optimal Method	92.10	**50.00**	35.97	36.77	48.36	4.86	-3.36

It is found from Figure 4 that there is a need to reduce load by 2.895 MW and 0.003 MW at bus 3 and bus 4 respectively along with reduction in generation at bus 1 by 2.899 MW. The change in power injection required is tabulated in Table 3. Power flows in the various lines are computed using equation (2) and tabulated in Table 4. The power flows in various lines are presented as bar chart in Figure 5 for ease of comparison.

From Table 4 and Figure 5, it is evident that both direct method and GA optimization method relieve congestion in the transmission line effectively.For comparison the power flow in various lines are shown as bar chart in Figure 5.

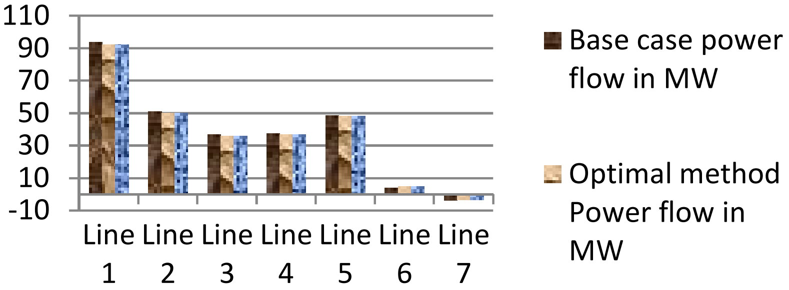

Figure 5. Line flows during base case, direct method and optimal method for case (i)

Case (ii) Line 1 overloadof IEEE 5 bus system

In this case load at bus 2, bus 3, bus 4, bus 5 are maintained at 60 MW, 30 MW, 40 MW and 50 MW respectively, Generation at bus 1 is 140 MW and that at bus 2 is 40 MW. Line flows are calculated using equation (2) and presented in equation (13). It is found that the power flowing in line 1 is 101.8520 MW, whereas its limit is 100 MW. The ΔP_{inj} required to remove the excess power flow of 1.85 MW is calculated again using equation(4) and (5) as presented in equation (14).

$$\begin{bmatrix} 101.8520 \\ 38.1480 \\ 16.91 \\ 21.09 \\ 43.85 \\ 25.05 \\ 6.15 \end{bmatrix} = \begin{bmatrix} 0.5857 & -0.2571 & -0.0428 & -0.0857 & -0.2000 \\ 0.2143 & 0.0571 & -0.1572 & -0.1143 & -0.0000 \\ 0.0905 & 0.1619 & -0.1953 & -0.1238 & 0.0666 \\ 0.1080 & 0.1651 & -0.1206 & -0.1968 & 0.0444 \\ 0.1872 & 0.2158 & 0.0730 & 0.0349 & -0.5109 \\ 0.1048 & 0.0191 & 0.4476 & -0.4380 & -0.1334 \\ 0.0128 & -0.0158 & 0.1270 & 0.1651 & -0.2891 \end{bmatrix} * \begin{bmatrix} 140+\Delta P_{inj} \\ -20-\Delta P_{inj} \\ -30 \\ -40 \\ -50 \end{bmatrix} \tag{13}$$

$$[100] = [0.5857 \quad -0.2571 \quad -0.0428 \quad -0.0857 \quad -0.2000] * \begin{bmatrix} 140+\Delta P_{inj} \\ -20-\Delta P_{inj} \\ -30 \\ -40 \\ -50 \end{bmatrix} \tag{14}$$

The values of ΔP_{inj} required is found to be -2.1974 MW so load shedding of 2.1974 MW is proposed at bus 2 with a decrease in generation of 2.1974 MW at bus 1 in this method. The change in bus power and the line flows are presented in Table 5 and 6 respectively. Power flow in line 1 got reduced to 100 MW with this change calculated using direct method. GA is applied for this case also to reduce the power flow in line 1 to 100MW. Figure 6 shows the convergence plot and values of the variable. The result obtained from GA is tabulated in Table 5.

Table 5: Bus power injections for solving the line 1 overload in case (ii)

	ΔP_1 (MW)	ΔP_2 (MW)	ΔP_3 (MW)	ΔP_4 (MW)	ΔP_5 (MW)
DirectMethod	-2.1974	2.1974	0	0	0
Optimalmethod	-2.201	2.132	0	0	0.068

Load shedding of 2.132MW and 0.068MW at bus 2 and bus 5 respectively along with decrease in generation of 2.201 MW at bus1 relives congestion and line 1 power flow is reduced to 100MW. It is provided in Table 6.

Table 6: Line flows during base case, direct method and optimal method for case (ii)

	Line 1 (MW)	Line 2 (MW)	Line 3 (MW)	Line 4 (MW)	Line 5 (MW)	Line 6 (MW)	Line 7 (MW)
Base case	101.85	38.15	16.91	21.09	43.85	25.05	6.15
Direct method	**100.00**	37.80	17.07	21.21	43.91	24.86	6.09
Optimal method	**100.00**	37.80	17.06	21.21	43.86	24.85	6.07

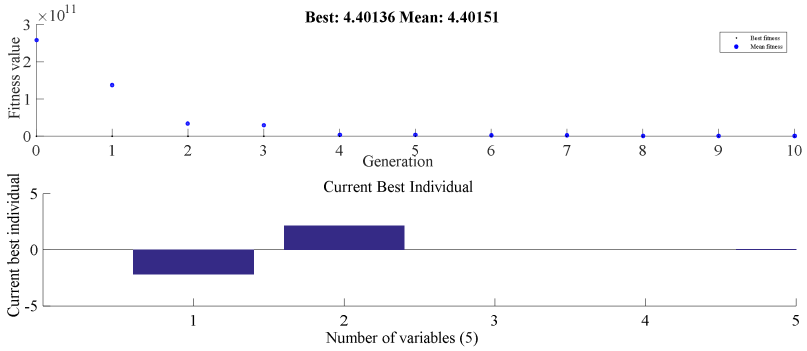

Figure 6. Convergence plot of GA based optimisation for case (ii)

For comparison, the power flow in all the lines for base case, direct method and GA based optimal methods are presented as bar chart in Figure 7.

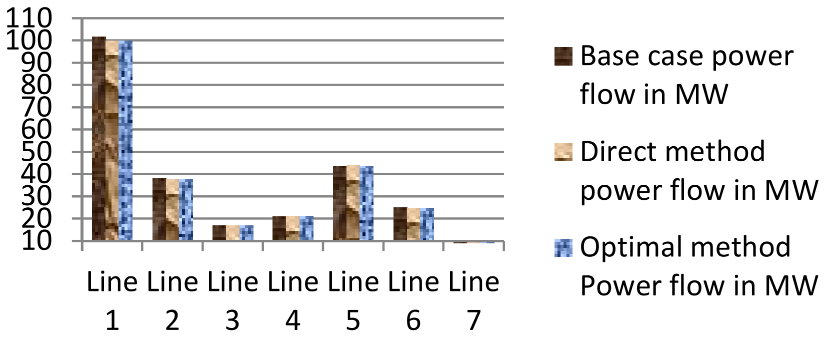

Figure 7. Line flows during base case, direct method and optimal method for case (ii)

Case (iii) Line 5 overloadof IEEE 5 bus system

Load at bus 2, bus3, bus 4, bus 5 is maintained at 4 MW, 31 MW, 80 MW and 72 MW respectively. The generation at bus 1 and bus 2 is scheduled to 147 MW and 40 MW respectively. Power flow for this case is calculated using equation (2) and presented in equation (15).

$$\begin{bmatrix} 99.43 \\ 47.57 \\ 30.30 \\ 38.11 \\ \mathbf{67.02} \\ 46.86 \\ -4.98 \end{bmatrix} = \begin{bmatrix} 0.5857 & -0.2571 & -0.0428 & -0.0857 & -0.2000 \\ 0.2143 & 0.0571 & -0.1572 & -0.1143 & -0.0000 \\ 0.0905 & 0.1619 & -0.1953 & -0.1238 & 0.0666 \\ 0.1080 & 0.1651 & -0.1206 & -0.1968 & 0.0444 \\ 0.1872 & 0.2158 & 0.0730 & 0.0349 & -0.5109 \\ 0.1048 & 0.0191 & 0.4476 & -0.4380 & -0.1334 \\ 0.0128 & -0.0158 & 0.1270 & 0.1651 & -0.2891 \end{bmatrix} * \begin{bmatrix} 147 \\ 36 \\ -31 \\ -80 \\ -72 \end{bmatrix} \tag{15}$$

During this situation power flow in the line 5 is 67.02 MW. Power flow limit in the line 5 is 50 MW. The change in bus power at bus 2 and 5 are computed using direct method as shown in equation (16). The line flows are given in equation (17). Thesolution of change in bus powers and the line power flows are tabulated in Table 7 and 8 respectively. The change in bus power at bus 2 and 5 are increasing the load by 23.4168 MW and decrement load by 23.4168 MW respectively.

$$[50.00]=[0.1872 \quad 0.2158 \quad 0.0730 \quad 0.0349 \quad -0.5109]*\begin{bmatrix}147\\36+\Delta P_{inj}\\-31\\-80\\-72-\Delta P_{inj}\end{bmatrix} \tag{16}$$

Table 7:Bus power injections for solving the line 5 overload in case (iii)

	ΔP_1 (MW)	ΔP_2 (MW)	ΔP_3 (MW)	ΔP_4 (MW)	ΔP_5 (MW)
Direct Method	0	-23.4168	0	0	23.4168
Optimal method	-6.634	-16.74	-0.335	-0.044	23.754

This relives the congestion in line 5 from 67.0170 MW to 50 MW. Meanwhile, the line 1 power flow is increased to 100.7622 MW from 99.4251 MW. This is above the line limit of 100 MW. The solution provided by direct method relieves congestion in line 5 but congested the line 1. Therefore, direct method fails to give suitable solution for the entire congestion problem

$$\begin{bmatrix}100.76\\46.24\\28.06\\35.28\\50.00\\43.29\\-1.42\end{bmatrix}=\begin{bmatrix}0.5857 & -0.2571 & -0.0428 & -0.0857 & -0.2000\\0.2143 & 0.0571 & -0.1572 & -0.1143 & -0.0000\\0.0905 & 0.1619 & -0.1953 & -0.1238 & 0.0666\\0.1080 & 0.1651 & -0.1206 & -0.1968 & 0.0444\\0.1872 & 0.2158 & 0.0730 & 0.0349 & -0.5109\\0.1048 & 0.0191 & 0.4476 & -0.4380 & -0.1334\\0.0128 & -0.0158 & 0.1270 & 0.1651 & -0.2891\end{bmatrix}*\begin{bmatrix}147\\36\\-31\\-80\\-72\end{bmatrix} \tag{17}$$

The ΔP_{inj}required at different buses is provided in Table 7. The line power flow due the bus power changes are furnished in Table 8. GA is applied to solve the same problem. The convergence plot and the optimal vales obtained are presented in Figure8.

Table 8:Line flows during base case, direct method and optimal method for case (iii)

	Line 1 (MW)	Line2 (MW)	Line3 (MW)	Line4 (MW)	Line5 (MW)	Line6 (MW)	Line7 (MW)
Base case	99.43	47.57	30.30	38.11	67.02	46.86	4.98
Direct method	**100.76**	46.24	28.06	35.28	**50.00**	43.29	-1.42
Optimal method	**95.11**	45.26	28.64	35.73	**50.00**	42.55	-1.75

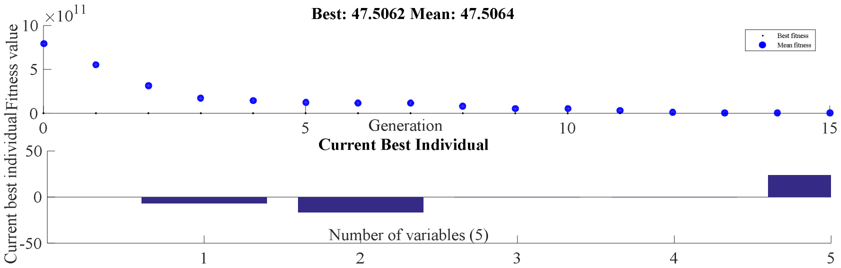

Figure 8. Convergence plot of GA based optimisation for case (iii)

Table 7 shows that, decrease in generation of 6.634 MW at bus 1 and 16.74 MW at bus 2 along with increase in load of 0.335 MW at bus 3, 0.044 MW at bus 4 and reduction in load of 23.754 MW at bus 5 relieves the congestion in line 5 from 67.017 MW to 50 MW. The bar chart of power flows for the base case, direct method and GA is presented to Figure 9 for comparison.

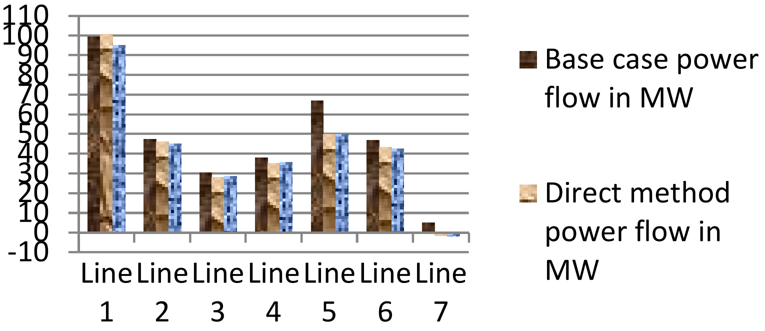

Figure 9. Line flows during base case, direct method and optimal for case (iii)

It is found that GA based optimal method of congestion management is able to relieve congestion without congesting the other lines which is not possible by the direct method.

Case (iv) Line 20 overload in IEEE 30 bus system

The direct method and GA based optimal method are tested in IEEE 30 bus system [19] and the results are presented in this section. S_{mn} matrix is developed for the IEEE 30 bus system using data provided in [19]. The maximum power flow limit for various lines is presented in table 9.

In the IEEE 30 bus system Load at bus 2 to bus 30 is maintained at21.7 MW, 2.4 MW, 7.6 MW, 94.2 MW, 0 MW, 22.8 MW, 30 MW, 0 MW, 5.8 MW, 0 MW, 11.2 MW, 0 MW, 6.2 MW, 148.7 MW, 3.5 MW, 9 MW, 3.2 MW, 9.5 MW, 2.2 MW, 17.5 MW, 0 MW, 3.2 MW, 8.7 MW, 0 MW, 3.5 MW, 0 MW, 0 MW, 2.4 MW, 10.6 MW respectively. The generation at bus 1 and 2 is 383.9 MW and 40 MW respectively. The line flow for this condition is computed using equation (2). Table 10 shows that the power flow in line 20 is found to be 20.77 MW which is above the capacity of 20 MW.

Table 9: Line flow limits for various transmission lines in the IEEE 30 bus system

Line Number	1	2	3,11, 14,18	4 to 7,15	8,22, 30 to 35,37	9,10, 12, 23 to 26, 36,41	13,16, 27 to 29, 38 to 40	17	19 to 21
Line flow limit (MW)	500	200	100	150	40	50	25	27	20

Table 10: Line flows during base case, direct method and optimal method for case (iv)

	Line 17 (MW)	Line 18 (MW)	Line 19 (MW)	Line 20 (MW)	Line 21 (MW)	Line 22 (MW)	Line 23 (MW)
Base Case	26.97	84.74	-8.69	20.77	-12.19	-20.04	-23.24
Direct Method	27.40	84.40	-8.73	**20**	-12.23	-20	-23.20
Optimal Method	**27.00**	83.59	-8.65	**19.98**	-12.42	20.04	23.01

Using direct method, the change in power injection required at starting bus 14 and ending bus 15 of congestedline 20 are calculated using equation (4) and (5) and is presented in table 11.

Table 11: Bus power injections for solving the line 20 overload in case (iv)

	ΔP_{12} (MW)	ΔP_{13} (MW)	ΔP_{14} (MW)	ΔP_{15} (MW)	ΔP_{16} (MW)	ΔP_{17} (MW)	ΔP_{18} (MW)
Direct Method	0	0	-1.2004	1.2004	0	0	0
Optimal method	-0.8320	-0.36578	-0.8156	2.0639	-0.26484	-1.50E-05	-0.2243

Increase in demand by 1.2004 MW at bus 14 and decrease the demand by 1.2004 MW in bus 15 relieves the congestion in line 20. Meanwhile, the power flowing in line 17 is increased to 27.4004 MW from 26.9728 MW. This is above the line limit of 27 MW. The solution provided by direct method relieves congestion in line 20 but congested the line 17. Therefore, direct method fails to give suitable solution.

Hence, this congestion problem is solved using GA based optimization technique andΔP_{inj}required at significant buses is given in Table 11. The convergence plot and the optimal vales obtained are presented in Figure 10.The power flow in significant lines due the bus power changes are furnished in Table 10. The bar chart of power flows for the base case, direct method and GA is presented to Figure 11 for comparison.

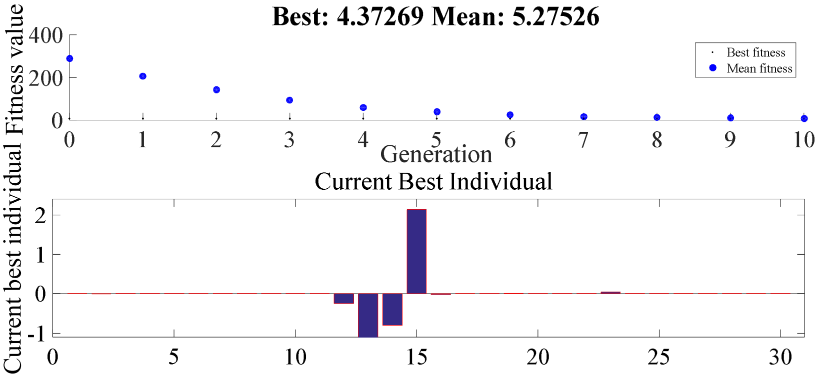

Figure10. Convergence plot of GA based optimisation for case (iv)

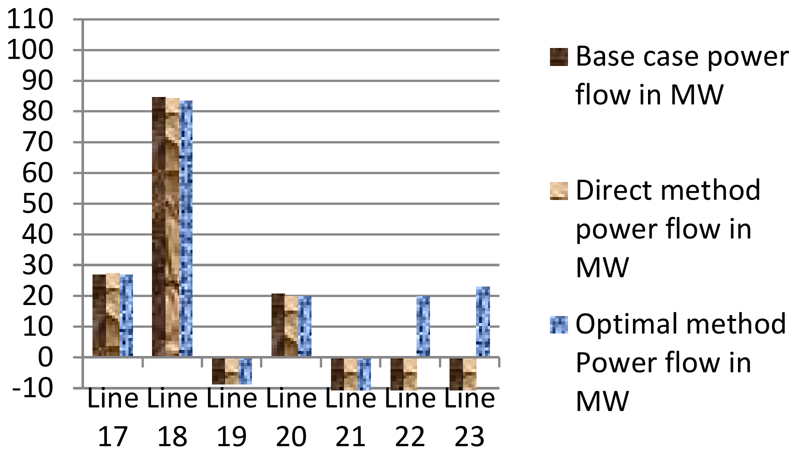

Figure 11. Line flows during base case, direct method and optimal for case (iv)

It is found that GA based optimal method of congestion management is able to relieve congestion in all the four cases without congesting the other lines which is not possible by the direct method.

5.2. Experimental results and discussion

A scaled down hardware model of IEEE 5 bus system explained in section 3 is used for validating the proposed algorithms. The sensitivity matrix for hardware model computed using the line reactance furnished in Table 2 is given in equation (18). Bus 1 of hardware model of IEEE 5 bus system is connected to the grid, Lab alternator supplies 250W to Bus 2.

$$S_{mn} = \begin{bmatrix} 0.5875 & -0.2580 & -0.0422 & -0.0862 & -0.2011 \\ 0.2125 & 0.0580 & -0.1578 & -0.1138 & 0.0011 \\ 0.0910 & 0.1614 & -0.1961 & -0.1232 & 0.0670 \\ 0.1086 & 0.1647 & -0.1199 & -0.1979 & 0.0445 \\ 0.1880 & 0.2160 & 0.0738 & 0.0348 & -0.5125 \\ 0.1034 & 0.0194 & 0.4461 & -0.4370 & -0.1319 \\ -0.0120 & 0.0160 & -0.1262 & -0.1652 & 0.2875 \end{bmatrix} \tag{18}$$

Load connected at bus 2, 3, 4 and 5 are 379.4W, 102.4W, 502.2W and 129.5W respectively. The calculated values of power flow for this load condition is given in equation (19).

$$\begin{bmatrix} 615.17 \\ 249.45 \\ 131.10 \\ 178.52 \\ 175.99 \\ 277.78 \\ 46.21 \end{bmatrix} = \begin{bmatrix} 0.5875 & -0.2580 & -0.0422 & -0.0862 & -0.2011 \\ 0.2125 & 0.0580 & -0.1578 & -0.1138 & 0.0011 \\ 0.0910 & 0.1614 & -0.1961 & -0.1232 & 0.0670 \\ 0.1086 & 0.1647 & -0.1199 & -0.1979 & 0.0445 \\ 0.1880 & 0.2160 & 0.0738 & 0.0348 & -0.5125 \\ 0.1034 & 0.0194 & 0.4461 & -0.4370 & -0.1319 \\ -0.0120 & 0.0160 & -0.1262 & -0.1652 & 0.2875 \end{bmatrix} * \begin{bmatrix} 865 \\ -129.4 \\ -102.4 \\ -502.2 \\ -129.5 \end{bmatrix} \tag{19}$$

The power flows in lines are measured and furnished in Table 12 as the base case. The computed and measured value matches well. It is also found that power flow in line 6 is 278W, which is greater than the limit of 250W. Sensitivity based direct method is applied to reduce the overloading.

Table 12: Line flows during base case, direct method and optimal method for case (v)

	Line 1 (W)	Line2 (W)	Line3 (W)	Line4 (W)	Line5 (W)	Line6 (W)	Line7 (W)
Base case	614.5	249.5	132	179	177	278	46
Direct method	614	251.5	134	176	175	**250**	45
Optimal method	614	**250**	133	175.5	175	**250**	45

By setting the power flow in the transmission line at 250W, ΔP_{inj} is calculated using equation (20).

$$[250.00] = [0.1034 \quad 0.0194 \quad 0.4461 \quad -0.4370 \quad -0.1319] * \begin{bmatrix} 865 \\ -129.4 \\ -102.4 + \Delta P_{inj} \\ -502.2 - \Delta P_{inj} \\ -129.5 \end{bmatrix} \tag{20}$$

According to direct method, ΔP_{inj} required for reducing the power flow in line 6 to 250 W is 31.7065 W. The power injection required at various buses have been obtained and given in Table 13.

Table 13: Bus power injections for solving the line 5 overload in case (v)

	ΔP_1 (MW)	ΔP_2 (MW)	ΔP_3 (MW)	ΔP_4 (MW)	ΔP_5 (MW)
DirectMethod	0	0	-31.7065	31.7065	23.4168
Optimalmethod	-2.409	0	-29.984	32.394	0

Load in bus 3 is then increased by 31.7065 W and correspondingly 31.7065 W is reduced at bus 4. The change is implemented in the hardware model by shifting a load of 32 W from bus 4 to bus 3. The power flows measured in all the lines have been tabulated in Table 12. It is found that the congestion is shifted from line 6 to line 2. It is therefore concluded that direct method failed to provide solution in this case.

GA based optimisation procedure is then used to calculate ΔP_{inj} at various buses in the hardware model. The convergence plot and optimal values are given in Figure 12. The ΔP_{inj} required in each bus is given in Table 13. Reduction in generation at bus 1 by 2.409W, increase in load at bus 3 by 29.984 W and reduction in load at bus 4 by 32.394 W are furnished by GA.The power changes suggested have been implemented in the hardware. Fine adjustment in power has been achieved through load rheostat. The power flow in each line is measured and tabulated in Table 12.

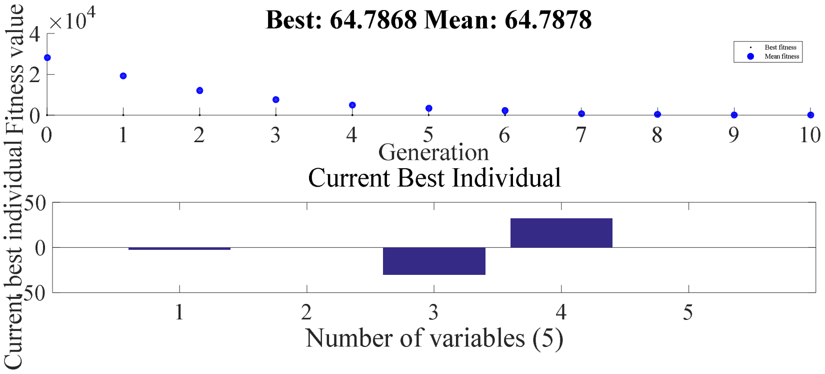

Figure 12. Convergence plot of GA based optimisation for scaled down IEEE 5 bus system

Now Line 6 power flow is reduced to 250W. Power flows in all other lines are within the stipulated limit. The comparison of the measured line flows is presented in Figure 13.It proves that GA based optimization method is superior to the direct method in congestion management.

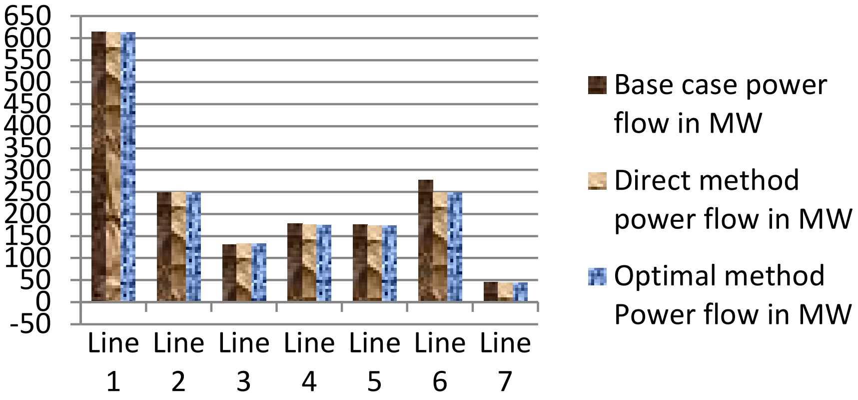

Figure 13. Line flows during base case, direct method and optimal method

6. Conclusion

This paper proposed two algorithms to relieve congestion in power transmission lines: (i) sensitivity based direct method and (ii) GA based optimal method. The proposed methods are validated on IEEE 5, IEEE 30 bus system by simulation and the same is validated in hardware model of IEEE 5 bus system. The direct method provides analytical solution in a single step by changing load and generation only at the starting and ending bus of the overloaded line. Whereas, the GA based optimal method takes few iteration for convergence towards the optimal solution with power changes in many of the buses. Both the methods are found to relieve congestion in most of the system conditions. But the direct method failed to yield solution in a three cases as it takes care only of one line without considering the other lines. In case of the optimal method it considers line flow limits of all the transmission lines at a time. This makes the GA based optimal method to be more effective than sensitivity based direct method in relieving congestion on transmission lines.

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