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Simultaneous Placements of TCSC and VSCDG for Congestion Management

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***Abstract:** Relieving congestion is a major technical issue in power transmission systems. In this paper, simultaneous placement of Thyristor controlled series capacitors (TCSC) and Voltage source converter based distribution generators (VSC-DG) are used for relieving congestion, minimize system cost and maintain the system in secure state. The system has been analyzed in three stages: (i) first stage, the congestions are made in different transmission network by overload and line outages, (ii) second stage, relieving congestion of transmission lines by using TCSC and VSCDG, where these devices are placed simultaneously at their optimal locations, (iii) comparative cost analysis is done between normal and congested systems. The proposed approach is tested on the 62-bus Indian power system network. The optimal solution of the test systems are obtained by genetic algorithm method and its solutions are compared with primal linear programming. All the results are validated through Power World Simulator and GA toolbox in MATLAB.*

***Keywords:** Restructured Power systems, Network Congestion, Optimal power flow, TCSC and VSCDG.*

I. INTRODUCTION

Electrical power industry across the globe is changing its business as well as its operational mode. The deregulated power utilities are being restructured from last four decades and opened up for private players to introducing competition. Competitive power market creates so many technical problems, out of which the congestion is the major technical problem. This problem is frequently occurring phenomenon in a restructured environment. This problem occur, when the power flow in transmission line reaches maximum limit [1]-[3].The mechanism which is relieved transmission line congestion is called congestion management; it is keeping all line transactions and schedules within limits [4]. Literature survey has been conducted on different congestion management schemes are presented in [5]-[6]. Optimal power flow solution used by different optimization methods on various test bus systems have been discussed [7].

The optimal bidding strategy for generation companies and its risk management in deregulated environment had been presented in [8], the OPF based CM in restructured power system has been presented by the authors [9].

The comparison of primal linear programming (PLP) and fundamentals of linear programming (LP) methods in terms of their application to OPF problems have been described in [10]-[11]. The application of genetic algorithm (GA) and enhanced genetic algorithm (EGA) in order to solve different optimization problems had been analyzed in [12] -[13]. The comparative work of different optimal power flow solutions with heuristic and conventional methods has been presented by the authors [14].The static VAR compensator (SVC) and thyristor controlled series capacitor (TCSC) are shunt and series controlled FACTS device, their modeling and simulation based on controller design for power transfer capability (PTC) and their limits on maximum loadability on transmission line were presented in [15], the dynamic power system stability and grid power control through TCSC have been presented in [16] and the optimal location of TCSC while managing congestion was discussed in [17]. The voltage source converter (VSC) based DG unit modeling and its power flow control has been presented in [19].

In the present work, the proposed method is simultaneous placement of TCSCs and DGs based congestion management method. The objectives of this method are (i) Relieving transmission network congestion (ii) Minimize system cost in terms of real power optimal scheduling and (iii) Finally, maintain the system in secure state. All above objectives are achieved by simultaneously connecting TCSCs and DG units at their optimal locations. The optimal locations of these devices are obtained by real power flow (RPF) and transmission loading relief (TLR) sensitivity index (SI) values. The Indian utility 62 bus and IEEE 118 bus test system are used as test system, which data's has been taken [20]-[21].

II. PROBLEM FORMULATION

A. Objective Function

The transmission congestion management (TCM) has been demonstrated with the traditional spot pricing theory. In this work, the load dispatch center optimally scheduled the real power generating units to meet system demands, while maximizing social welfare and satisfying the system equality and inequality constraints. The objective function of OPF problem is to optimize the steady state performance of a power system; the problem of the pool based market is formulated. The objective function for the generation cost is to minimize the total cost and it can be expressed as follows:

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$$\min\ f(x)=\min(\sum_{i=1}^{N_G}C_i(P_{Gi})-\sum_{i=1}^{N_L}L_i(P_{Li}) \qquad (1)$$

Equation (1) is ssubjected to $Eq(x)=0, Inq(x)\le 0$, where $Inq(x)\&Eq(x)$ are inequality and equality constraints, $f(x)$ is the main objective function of cost and $C_i \& D_i$ are a total cost generation and demand.This cost function is reflects on real power generation of the plant, quadratic function of real power generation at i^{th} bus. The fuel cost of the generators at i^{th} bus can be represented as.

$$f(x)=C_T=\sum_{i=1}^{N_G}\left(a_i+b_iP_{Gi}+c_iP_{Gi}^2\right) \qquad (2)$$

where$C_T\&N_G$ are the total cost of power generation and no. of generating units, $a_i, b_i\&c_i$ are cost coefficient of i^{th} generating a unit of the system. The equality constraints $Eq(x)$are power generation equal to demand plus the losses in the system.

$$P_{gi}-P_{di}=\sum_{j=0}^{N_b}|V_i||V_j||Y_{ij}|\cos(\delta_i-\delta_j-\theta_{ij}) \qquad (3)$$

$$Q_{gi}-Q_{di}=\sum_{j=0}^{Nb}|V_i||V_j||Y_{ij}|\sin(\delta_i-\delta_j-\theta_{ij}) \qquad (4)$$

where N_b is no. of buses, the power flow equations betweeni^{th} toj^{th} buses have been given in (3) & (4).The inequality constraints$Inq(x)$are generator MW & MVAR limits, transmission limits, bus voltages and magnitude limits.

$$P_{Gi}^{\min}\le P_{Gi}\le P_{Gi}^{\max} \qquad (5)$$

$$Q_{Gi}^{\min}=Q_{Gi}\le Q_{Gi}^{\max} \qquad (6)$$

$$V_i^{\min}\le V_i\le V_i^{\max}\ \&\ Tran_{ij}\ge 0 \qquad (7)$$

WhereP_{Gi} &Q_{Gi} are real and reactive power generation limits at i^{th} the bus, V_i is voltage magnitudeat i^{th} bus and $Tran_{ij}$ is the bilateral transaction between i^{th} to j^{th}buses. The OPF based CM problem (1) is incorporated with FACTS and Micro-grid, and it is solved by one classical method (PLP) and one heuristic search method (GA).

B. Simultaneous Placement of TCSCs

In this work, the one of series controlled FACTS device TCSC and the power generating VSC-DG unit are used for relieving transmission line congestion. The modelling of TCSC had given in [14], where the optimal location of this device is obtained from Real Power Flow Sensitivity Index (RPFSI). The Real Power Flow Sensitivity Index (RPFSI) is proposed to find optimal places to incorporate TCSC in the congested system. The severity of the system loading under contingency and normal cases are described by a real power line flow performance index (RPFSI), as given below

$$RPFSI=\sum_{k=1}^{N_L}\frac{w_k}{2n}\left(\frac{P_{Lk}}{P_{Lk}^{\max}}\right)^{2n} \qquad (8)$$

Where$P_{LK}$the real is power flow andP_{LK}^{Max} is the rated capacity of the line- k, n is the exponent, w_k a real non-negative weighting coefficient, which may be used to reflect the importance of the lines and N_L is the no. of lines in the system. The RPFSI factors with respect to the parameters of TCSC can be defined as

$$b_m=\left.\frac{\partial RPFSI}{\partial X_{TCSC.m}}\right|_{X_{TCSC.m}=0} \qquad (9)$$

The sensitivity of RPFSI with respect to TCSC parameter connected between bus-i and bus-j can be written as

$$\frac{\partial RPFSI}{\partial X_{TCSC.m}}=\sum_{k=1}^{N_L}w_kP_{Lk}^3\left(\frac{1}{P_{Lk}^{\max}}\right)^4\frac{\partial P_{Lk}}{\partial X_{TCSC.m}} \qquad (10)$$

The RPFSI values are shown small when all the lines are within their limits under system operating normal condition, which are shown high values when there is overloaded, test systems. Thus, it provides a good measure of severity of the line overloads for a given state of the power system. The TCSC should be incorporated in a transmission line having most minimum RPFSI value to relieve the congestion.

C. Simultaneous Placements of VSCDGs

In this work, the optimal integration of DG unit is obtained from Transmission Loading Relief (TLR) Sensitivity Index. The TLRSI values are determined at all load buses in the system with respect to the congested transmission line. The TLR sensitivity at load bus-$m$with respect to congested line-k (from bus-$i$to bus-j) is$TLRSI_{ij}^m$ given by

$$TLRSI_{ij}^m=\frac{\overline{\Delta P_{ij}}}{\Delta P_m} \qquad (11)$$

Where$\overline{\Delta P_{ij}}$the is extra power flow on the transmission line-k, the excess power can be calculated by

$$\overline{\Delta P_{ij}}=P_{ij}-P_{ij}^{\max} \qquad (12)$$

Where P_{ij} and P_{ij}^{Max} are actual active power flow and maximum active power flow limit of the transmission line-k.The new real power injection with DG at load bus-$m$can be calculated by

$$P_m^{new}=P_m-\frac{TLRSI_{ij}^m}{\sum_{l=0}^{N_L}S_{ij}^l}\overline{\Delta P_{ij}} \qquad (13)$$

where$P_m^{new}$is an actual active power requirement at load bus-m, it can be generated by DG unit, P_m is available active power at the bus-m before DG connected, S_{ij}^l the sensitivity of active power flow on the line-k because of power generation at load bus-m, and N_L is represents the total number of active power demand buses, which are integrated with DG units in the system.

The higher the TLR sensitivity value at load bus shows more the effect of a single MW power transfer at any bus, where the DG unit should be placed on the load buses which should have highest TLR sensitivity index value.

III. TEST RESULTS

To illustrate the effectiveness of the proposed method we have presented illustrative case study on 64 and 118 bus test systems. The model has been implemented and solved with the commercial optimization in POWERWORLD SIMULATOR and MATLAB based GA Toolbox. The Indian utility 62-bus (Tamil Nadu State) system was developed as a test system and analyzed in a restructured environment, where the test system was re-modeled as a pool-based power market model.

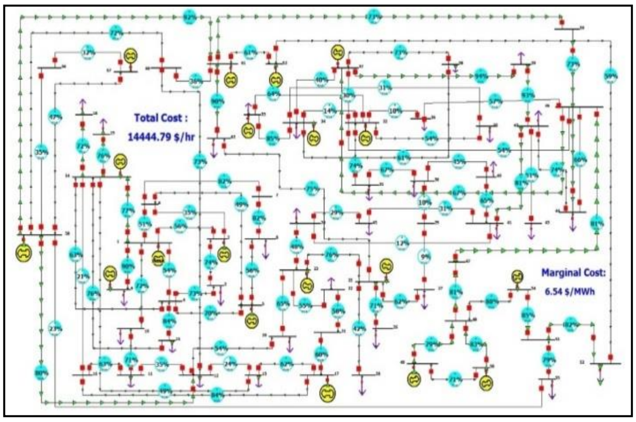

Figure.1 OPF solution of 62-bus is obtained by the PLP method

Fig.1 presents the 62-bus test system. Bus 1 was used as a reference bus, whose adjacent voltage was 1.06p.u.The bus comprised 19-generators, 78-transmission lines, 11-transformers and 33-loads, while the total demand for the system was 2908 MW and 1270 MVAR. Using the system data, as presented in [20], the test was modeled and simulated in the PWS and the OPF solution obtained by the PLP method. The total power generation cost of the system to meet demand 2908 MW is 14444.79 ($/ hr) and the voltage profile of the system is shown within the limits. The generators incremental cost curves are shown in Fig.2.

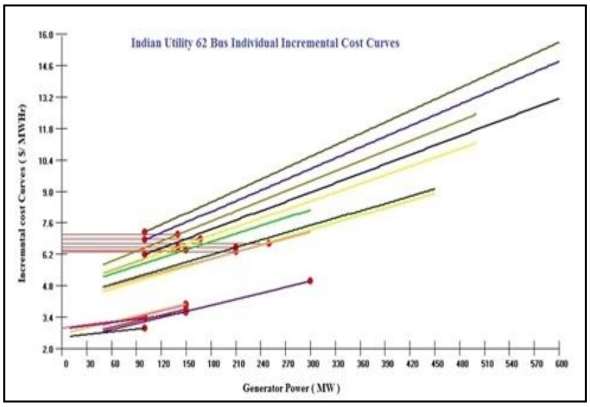

Figure.2 62-bus 19-generators incremental cost curves

Fig.3 shows, the OPF solution of the test system obtained by GA method, where the demand is same as 2908 MW, but the total power generation cost is found to be 14353.40 ($/hr).

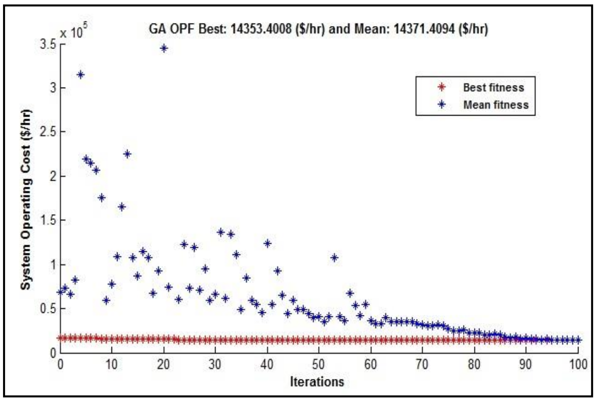

Figure.3 OPF solution of the 62-bus by GA under normal operating condition

It can be noted that, in comparison to PLP-based OPF solution, the GA method gives an additional saving of 91.39 $/hr. Hence, this method is used for further calculations in Subsections ‘A’ and ‘B’.

The congestion in the test system was being created by overloading and line outages (LOs), where the overloading of the system was created by increasing the load at each bus by 25%, while multiple LOs were caused by faults. An OPF-based CM method is proposed for CM using TCSCs and DG units, where the congestion in the network can be relieved by simultaneously placing TCSCs and VSCDG units at their optimal locations. Subsection ‘A’ discusses overloaded systems, while Subsection ‘B’ describes the LO systems.

A. Relieve Congestion in Overloaded 62-bus Test System

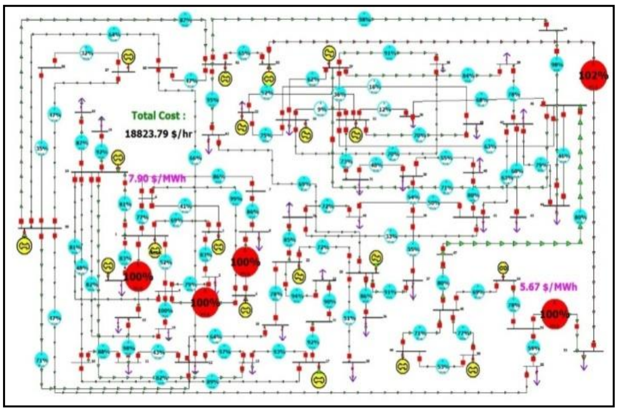

Figure.4 Congested62-bus due to increase load from 2908 to 3489.60 MW-bus

Fig.4 shows, the test system congested due to overload, where the load (20% over loading) increased from 2908 MW to 3489.60 MW.

Table I presents, the lines that were congested due to overloading: namely, line-5, 10, 14, 73 and 76, all of which crossed their maximum MVA limit of 1.0 (p.u).

The maximum MVA limits for all lines in the test systems were specified as 1.0 (p.u), where the congestion costs were reflected on the LMP in different buses, while the total cost of the system increased.

Table I: MVA limits of congested lines in overloaded systems

Line No.	From Bus	To Bus	MVA Limite (p.u)
5	1	10	1.001
10	4	5	1.007
14	5	8	1.010
73	51	53	1.009
76	52	53	1.020

As such, congestion had to be relieved as quickly as possible in order to maintain the system in a stable state. Before relieving the congestion by the simultaneous placement of TCSCs and DG units, calculating the RPFSI and TLRSI values was needed to determine their optimal locations.

Table II: RPFSI and TLRSI values of the overloaded test system

LineNo.	From Bus	To Bus	RPFSI	Load Bus NO.	TLRSI
9	**3**	**4**	**-0.7461**	6	0.004
13	5	6	-0.4433	8	0.319
18	11	16	-0.2971	11	0.237
73	51	53	-0.5218	**53**	**0.583**
82	**58**	**12**	**-0.6154**	**62**	**0.461**

Table II is presents, the RPFSI and TLRSI of the overloaded test systems on congested lines. The transmission line-9 &line-82 (in bold) respectively, had the lowest and second lowest RPFSI values among the selected lines, while load bus-53 & bus-62 (in bold) respectively had the highest and second highest TLRSI values. At these lines and buses, the TCSC and DG units were simultaneously placed in their optimal locations until congestion in the system will be relieved.

The TCSC-1 has been incorporated placed in line-9, which compensated 40% of the line capacity. The reactance of the TCSC-1 is obtained by OPF solution ($X_{TCSC1} = 0.008$ p.u). After placing the TCSC-1 on line-9, the PTC increased from 87.2 to 106.6 MVA. Meanwhile, TCSC 2 was placed in line-82, which compensated 20% of the line capacity. The value of the TCSC-2 reactance was obtained by the solution $X_{TCSC2} = 0.0124$(p.u).After placing the TCSC-2 on line-82, the PTC increased from 138 to 142.34 MVA. The 20 MW DG units were placed at load bus-53, while the 10 MW DG units were placed at load bus-62. After these devices had been placed in the test system, the system was modeled and simulated by the GA method; the solution is presented in Fig.5.

Fig.5 shows the OPF solutions of the test systems using the GA method. From the results, it can be seen that the congestion in all lines were relieved. The total system cost of the congested test system was 18823.79 $/hr (Fig.4) and 18658.06 ($/h) for the uncongested test system (Fig.5).

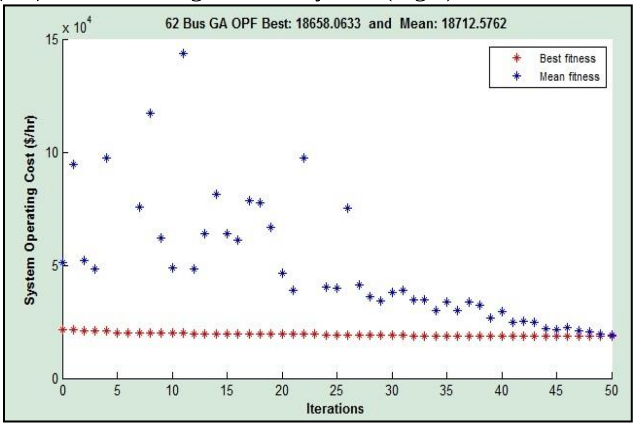

Figure.5 Congestion relieved in an overload test system with TCSCs and DG units by GA

Table III. RPFSI and TLRSI values of the overloaded test system

	Congested	Uncongested
Total Generation	3586.40 (MW)	3561.55 (MW)
Total demand of OL system	3489.20 (MW)	3489.20 (MW)
Total Losses	97.20 (MW)	72.35 (MW)
Total Generation Cost	**18823.79 ($/h)**	**18658.06 ($/h)**

Table III shows, comparison OPF solution between congested and uncongested 62-bus test system under overloaded condition, it can be seen that there was a saving of 165.73 $/hr with the uncongested system.

B. Relieve Congestion in Line Outage 62-bus Test System

Fig.6 presents, the 62-bus test system, which was congested due to LO in line-15 (buses 6-7), line-22 (buses 13-14) and line-83 (buses 58-60), under contingency conditions (cross-marked lines in Fig.6).

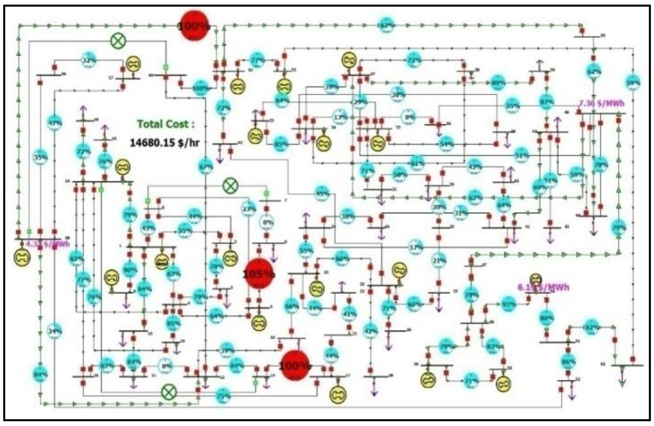

Figure.6 Congested62 bus due to different lines outages

As these lines were unavailable, their power had to be carried by other lines, which caused some of the lines to be congested, as shown in Table 4.

Table IV. MVA limits of congested lines due to Line Outages

Line No.	From Bus	To Bus	MVA Limit (p.u)
14	5	8	1.047
23	13	17	1.001
84	58	61	1.008

Table IV presents, the congested lines due to LOs (red color in Fig.6): namely, Line-14, line-23 and line-84 were congested, all of which crossed their maximum MVA limit of 1.0 (p.u). Meanwhile, the congestion costs were reflected on the LMP in different buses and the total cost of the system increased.

Table V. RPFSI and TLRSI values of the overloaded test system

Line No.	From Bus	To Bus	RPFSI	Load Bus Number	TLRSI
13	5	6	-0.3980	**8**	**0.7513**
24	17	21	-0.2751	12	0.2845
25	**21**	**22**	**-0.6007**	13	0.2669
85	**59**	**61**	**-0.5992**	60	0.3441
88	61	62	-0.4765	**62**	**0.6234**

Table V is presents, the RPFSI and TLRSI values of the congested test system due to LOs. The line-25 and line-85 (in bold) respectively, had the lowest and second lowest RPFSI value among the selected lines, while load bus-8 and 62 (in bold) respectively had the highest and second highest TLRI value. The TCSC and DG units were simultaneously placed in their optimal locations, until they relieved congestion in the system.

TCSC-1 was placed in line-25, which compensated 20% of the line capacity, while the reactance of the TCSC-1is obtained by the solution $X_{TCSC1} = 0.0140$ (p.u).After placing the TCSC-1 on line-25, the PTC increased from 61.4 to 66.03 MVA. TCSC-2 is placed in line-85, which compensated 50% of the line capacity. The value of TCSC-2 reactance is obtained by the solution $X_{TCSC2} = 0.0237$ (p.u). After placing the TCSC on line-82, the PTC increased from 124.8 to 143.90 MVA. The 20 MW DG units were placed at load bus-8, while the 10 MW DG units were placed at load bus-62. After these devices had been placed in the test system, the system was modeled and simulated by the GA method; the solution is presented in Fig.7.

Fig.7 presents the OPF solutions for the test systems using the GA method. From the results, it can be seen that the congestion in all lines was relieved. The total system cost of the congested test system was 14680.15 ($/h) (Fig.6); when compared with the uncongested test system cost of 14471.26 ($/h) (Fig.7).

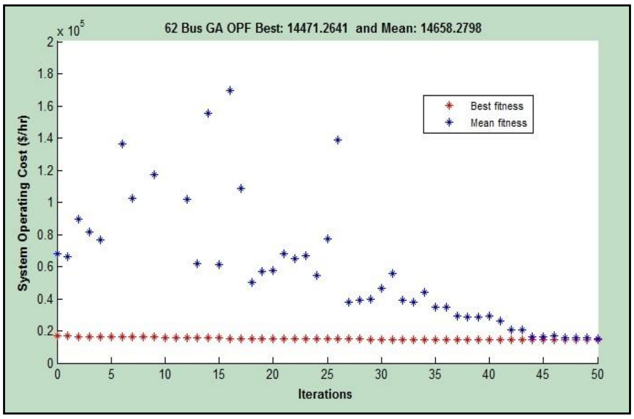

Figure.7 OPF solution for the LO test system after the placement of TCSCs and DGs, as obtained by GA.

After the congestion on the lines (Table 5) had been relieved, it was observed that the MVA limits in these lines were under 0.99 (p.u), while the system was maintained in a secure state.

C. Relieve Congestion in IEEE118-bus Test System

IEEE 118-bus test case represents a simple approximation of the American Electrical Power Systems. This test system contains 19 generators (bold in Fig.8), 35 synchronous condensers, 177 lines, 9 transformers and 91 loads (3698 MW &1438 MVAR), all the required system data have been taken from [21]. The IEEE 118 bus test system, which was congested due to LOs, the line 39 (Buses 17-31), 115 (Buses 70-75) and 173 (Buses 108-109) are outages due to faults (cross-marked green colored lines in Fig.8).As these lines were unavailable, their power has to be carried by other lines, which caused some of the lines to be congested, as shown in Table VI.

Table VI. MVA limits of congested lines due to Line Outages

Line No.	From Bus	To Bus	MVA Limit (p.u)
21	15	17	1.023
57	40	42	1.011
91	60	62	1.050
154	92	100	1.015
180	32	117	1.013

Table VI presents, the congested lines due to LOs (in cross mark Fig.8): these lines have crossed their maximum MVA limit of 1.0 (p.u). Meanwhile, the congestion costs were reflected on the LMP in different buses and the total cost of the system increased.

To relieve the congestions in above mentioned lines by placing TCSCs and DGs simultaneously at their optimal locations, the optimal locations of TCSC and DGs are determined from RPFSI and TLRSI values respectively.

Table VII presents, the RPFSI and TLRSI values of the congested test system due to LOs.Line-23, 48 and 167 (in bold) respectively, have the lowest RPFSI value among the selected lines, which are best lines to incorporate TCSCs.

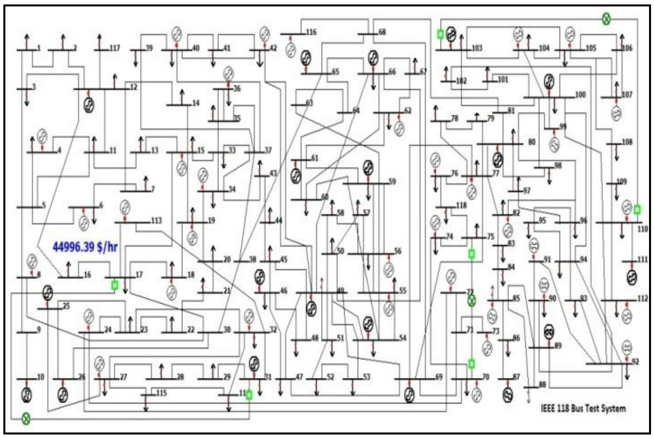

Figure. 8 OPF solution of IEEE 118 bus test system by PLP method

The load buses 45, 74 and 90 (green colored values) have the highest TLRI values, which are best location to connect DGs respectively.

Table VII. RPFSI and TLRSI values for IEEE 118-bus with Line Outages

Line No	From Bus	To Bus	RPFSI	Load Bus No.	TLRSI
23	**17**	**18**	**-0.7217**	27	0.3845
48	**33**	**37**	**-0.6731**	**45**	**0.5587**
67	42	49	-0.4498	**74**	**0.4864**
113	71	73	-0.4312	**90**	**0.6333**
167	**100**	**106**	**-0.5981**	112	0.4091

The TCSCs and DGs units will be placed simultaneously until congestions are relieved all the lines in the system. The simulations result obtains in Fig.8 by PLP and Fig.9 by GA methods after incorporating these devices at their optimal locations. The detailed solution of test systems in terms of real power dispatch, system losses and total power generation cost are tabulated in Table VIII.

Table VIII. Test system results comparative analysis between PLP and GA

	PLP	GA	Real Power (MW)	PLP	GA
Gen.1	411	421	Gen.11	371.7	382
Gen.2	80	80.2	Gen.12	361.29	344
Gen.3	184	194	Gen.13	483.44	498
Gen.4	278	254.4	Gen.14	436.87	417
Gen.5	12	12.01	Gen.15	10.42	10
Gen.6	20	18.63	Gen.16	582.66	592
Gen.7	175	160.05	Gen.17	227.15	206.83
Gen.8	30.5	30	Gen.18	30.9	30
Gen.9	140.6	143	Gen.19	28	26.52
Gen.10	144.3	138			

Method	PLP Method	GA Method
Total Real Power Generation	4007.88 (MW)	3958.45 (MW)
Total Demand	3698 (MW)	3698 (MW)
Total Loss of the System	309.88 (MW)	260.44 (MW)
Total Power Generation Cost ($/hr)	**44996.39($/hr)**	**44255.90($/hr)**

Table VIII shows, the OPF solutions of IEEE 118 bus test system by PLP and GA method respectively. The comparative analysis, it can be seen that the total system cost of the uncongested test system by PLP method is 44996.39 ($/h) and by the GA method is 44255.90 ($/h). It can be observed that the GA method gives the savings of 740.49 ($/h) and minimized system losses.

The GA method takes less time (0.045 seconds) than PLP method time (0.087 seconds) while solving the same problem at 100 iterations. It means the time saved with GA model solution is 0.042 seconds. For the bigger system (thousand buses), this time saved will make an impact in finding the solution sooner.

Finally, the congestions in IEEE 118 bus test system have been relieved, minimized the total system cost and maintained system under secure state.

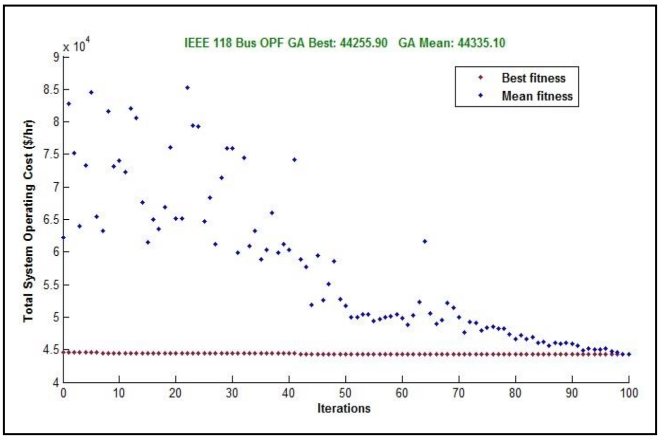

Figure.9 OPF solution of IEEE 118 bus test system by GA method

IV. CONCLUSION

In this paper, the 62-bus and IEEE 118 bus test system were analyzed under both overload and LO conditions. Transmission line congestion is a major technical issue in restructured power systems, particularly against the backdrop of deregulation. CM is the method used to alleviate network congestion problems. The proposed combined FACTS device and MG-based CM method for relieving congestion, as well as minimizing the cost of a system, was implemented on the Indian utility 62-bus power system network. Although this system usually works in a regulated mode, in our work, it was modeled for a pool-based market in a restructured environment.

The congestion of the system has been created by overloading (OL) and line outages (LO), was relieved by the simultaneous placement of multiple TCSC and DG units in the test system. The optimal placement of TCSCs was obtained from the RPFSI values, while the optimal placement of the DG units was obtained from the TLRSI values. The OPF solution for the congested and uncongested test systems was obtained by both the PLP and GA methods. According to the solution, the OPF involving the GA method is highly economical in terms of minimizing losses and costs in the system.

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