A method to enhance system loadability in the presence of ramp-rate limits using optimization

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***Abstract*—At present, because of the continuous increase in demand for electricity, it is necessary to reschedule the active power generations of generators and other system control parameters such as generation voltages, tap settings of the transformers, reactive power injected by the shunt compensators. To accomplish this task, it is necessary to perform optimal power flow solution methodology by considering loadability index as an objective function. The proposed OPF problem is solved while satisfying system constraints such as equality, in-equality constraints and ramp-rate limits. The proposed methodology is tested on standard IEEE-30 bus and real time Indian-62 bus test systems.**

***Index Terms*—Loadability index; Optimal power flow; PSO; ramp-rate limits.**

I. Introduction

THE Optimal Power Flow (OPF) is a popularly used method in electrical power system for effective controlled operation and proper planning towards meeting the load growth subjected to meeting various objectives. The chief necessity of the optimization of the power flow is to estimate the proper combination of the controllable parameters like voltage and real power generation at generator buses, tap setting of the transformers in transmission lines, value of compensating capacitors towards minimization of the specific objective functions. A problem with more number of controllable parameters makes the system non-linear and discontinues. So, traditional solution methodologies failed to give an optimized global solution.

A detailed methodology to identify and optimal number and its optimal location to install multiple series devices were presented in [1]. The proposed methodology uses the differential evolution algorithm to identify optimal parameter settings to enhance the system loadability subjected to various system constraints. The device control parameters are adjusted, so that the device installation cost was minimized without any violation of system thermal and voltage limits. In this paper, the convergence characteristic of the proposed methodology is compared with the existing genetic algorithm.

The loadability of power system is enhanced more by placing shunt devices in an optimal location [2]. In this, the optimal location is identified based on worst case reactive power margin as an index. It is also identified that, the effect of increase of active power demand on a given system. The FACTS controller is used to enhance the voltage stability under most critical conditions of power system. The device location is identified using multi-objective optimization problem by considering device installation cost, highest load voltages, maximum worst case reactive power margin and minimized real power losses.

There are various optimization algorithms in the literature [3-5] concentrates in finding a methodology to increase the reactive loading margin to increase the loadability on a given system based on non-linear and non-convex optimization techniques. The results obtained through this can be implemented directly in real time power system operation, planning and management. But, because of this methodology larger systems can’t be handled in the presence of some of the pertinent constraints or some of the smaller disturbances.

II. Problem Formulation

In its general form, the OPF problem can be mathematically represented as

$$\text{Minimize} \quad f(x,u) \tag{1}$$

$$\text{subjected to} \quad g(x,u)=0 \quad h_{min} \le h(x,u) \le h_{max} \tag{2}$$

where

$f(x,u)$ is the objective function
x is the vector of dependent variables
u is the vector of independent or control variables
$g(x,u)$ represents equality constraints
$h(x,u)$ represents inequality constraints.

The OPF solution determines a set of optimal variables to achieve a certain goal such as minimum generation cost, power loss etc., subjected to all the equality and inequality constraints. The dependent variables are slack bus active power, load bus voltage magnitudes and its angles, generators reactive powers and line flow limits. The independent variables consist of continuous and discrete variables. The continuous variables are active powers of all generators, except slack bus and generator voltages. The discrete variables are tap settings of regulating transformers and reactive power injections.

A. Loadability enhancement

This objective is used to maximize the system loadability that can be described as

$$\text{Loadability} = \lambda(x,u)$$

Where, λ can be considered as a constant factor at each load, the real and reactive power balance equations as follows:

$$\sum_{\forall i} \mathrm{P_{G,i}} - \sum_{\forall j} (1+\lambda)\mathrm{P_{Load,j}} - \sum_{\forall k} \mathrm{P_{Losses,k}} = 0 \quad --(3)$$

$$\sum_{\forall i} \mathrm{Q_{G,i}} - \sum_{\forall j} (1+\lambda)\mathrm{Q_{Load,j}} - \sum_{\forall k} \mathrm{Q_{Losses,k}} = 0 \quad --(4)$$

$P_{Load,j}$ and $Q_{Load,j}$ are the real and reactive power loads at j^{th} bus under base case condition (λ=0), $P_{Losses,k}$ and $Q_{Losses,k}$ are real and reactive power losses in k^{th} transmission line

III. CONSTRAINTS

The following constraints are considered for the formulated loadability index:

A. *Equality constraints*

These constraints are usually load flow equations described as

$$P_{Gk} - P_{Dm} - \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \cos(\theta_{km} - \delta_k + \delta_m) = 0 \quad (5)$$

$$Q_{Gk} - Q_{Dm} + \sum_{m=1}^{NB} |V_k||V_m||Y_{km}| \sin(\theta_{km} - \delta_k + \delta_m) = 0 \quad (6)$$

where, 'PGk, PDk' are the active and reactive power generations at kth bus, 'PDm, QDm' are the active and reactive power demands at mth bus, 'NB' is number of buses, |Vk|, |Vm| are the voltage magnitudes at kth and mth buses, 'δk, δm' are the phase angles of voltages at kth and mth buses, |Ykm|, θkm are the bus admittance magnitude and its angle between kth and mth buses.

B. *In-equality constraints*

Generator bus voltage limits:

$$V_{G_i}^{\min} \le V_{G_i} \le V_{G_i}^{\max}; \qquad \forall i \in N_G$$

Active Power Generation limits:

$$P_{G_i}^{\min} \le P_{G_i} \le P_{G_i}^{\max}; \qquad \forall i \in N_G$$

Transformers tap setting limits:

$$T_i^{\min} \le T_i \le T_i^{\max}; \qquad i = 1,2,..., n_t$$

Capacitor reactive power generation limits:

$$Q_{Sh_i}^{\min} \le Q_{Sh_i} \le Q_{Sh_i}^{\max}; \qquad i = 1,2,....., n_C$$

Transmission line flow limit:

$$S_{l_i} \le S_{l_i}^{\max}; \qquad i = 1,2,....,N_{line}$$

Reactive Power Generation limits:

$$Q_{G_i}^{\min} \le Q_{G_i} \le Q_{G_i}^{\max}; \qquad \forall i \in N_G$$

Load bus voltage magnitude limits:

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1,2,...., N_{load}$$

C. *Ramp-rate limits*

The constraints of the ramp-rate limits, the operating limits of the generators are restricted to operate always between two adjacent periods forcibly. The ramp-rate constraints are

$$\max\left(P_{G_i}^{\min}, P_i^0 - DR_i\right) \le P_{G_i} \le \min\left(P_{G_i}^{\max}, P_i^0 + UR_i\right) \qquad (7)$$

Where, P_i^0 is ith unit power generation at previous hour. DRi and URi are the respective down and up ramp-rate limits of ith unit.

Finally the above proposed problem is more generalized to solve in-equality constraints can be given as

$$FC_{aug} = FC + R_1\left(P_{g,slack} - P_{g,slack}^{\lim}\right)^2 +$$
$$R_2 \sum_{i=1}^{N_{Load}} \left(V_i - V_i^{\lim}\right)^2 + R_3 \sum_{i=1}^{NG} \left(Q_{G_i} - Q_{G_i}^{\lim}\right)^2 + R_4 \sum_{i=1}^{N_{line}} \left(S_{l_i} - S_{l_i}^{\max}\right)^2$$

Where, R1, R2, R3 and R4 are the penalty quotients having large positive value. The limit values are defined as

$$x^{\lim} = \begin{cases} x^{\max}, & x > x^{\max} \\ x^{\min}, & x < x^{\min} \end{cases}$$

Here 'x' is the value of Pg,slack, Vi, QGi.

IV. PARTICLE SWARM OPTIMIZATION

Particle swarm optimization conducts its search using a population of particles [6]. Each particle in PSO changes its position according to new velocity and the previous positions in the problem space.

Because of the advantages of the PSO, like simple concept and implementation mechanism, handling of control parameters, finding procedure of the global best solution is chosen to implement the defined solution methodology.

In PSO, the particle velocity and the position in (k + 1)th iteration is updated using Eq's (8) and (9)

$$V_j^{k+1} = \omega . V_j^k + C_1.\mathrm{rand1}().\left(P_{best,j} - X_j^k\right) + C_2.\mathrm{rand2}().\left(G_{best} - X_j^k\right) \quad --(8)$$

$$X_j^{k+1} = X_j^k + V_j^{k+1} \qquad \forall \; j = 1,2,3, \ldots \ldots .. n \quad --(9)$$

where k is the iteration count, C_1 and C_2 are acceleration coefficients, rand1 and rand2 are uniformly distributed random numbers in [0 1]. $P_{best,j}$ is the best position found by the particle j so far, G_{best} is the position among all particles. Here, the second part is a cognitive part and has its own thinking and memory. The third term is the social parameter on which the particle changes its velocity. 'ω' is the inertia weight and can be calculated as follows

$$\omega^{k+1} = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{k_{max}} \mathrm{X}\, k \quad --(10)$$

Equations (8) and (9) have three tuning parameters ω, C_1 and C_2 that greatly influence the PSO algorithm performance. The value of 'ω' was proposed linearly with time from a value of 1.4–0.5 [7]. As such global search starts with a large weight value and then decreases with time to favor local search over global search [8]. In this paper, the methodology to find values for the tuning parameters and the procedure of updating dynamic inertia weight is implemented [9]. Because this provides a balance between global and local explorations, thus it needs less number of iterations to get an optimal solution.

V. RESULTS AND ANALYSIS

In this paper, the proposed methodology is tested on standard IEEE-30 bus and real time Indian-62 bus test systems.

A. *Example-1*

IEEE-30 bus system with six generators and forty one transmission lines is considered. For this system, there are eighteen control variables which include six active power generations, voltage magnitudes at the generator buses, four tap changing transformers and two shunt compensators.

The proposed PSO method is applied to enhance the system loadability in terms of loadability index (LBI). The OPF results without and with ramp-rate limits is tabulated in Table.1. From this table, it is observed that, with ramp-rate limits, the LBI value is decreased when compared to without ramp-rate limits, because of the restriction on the generation limits. It is also observed that, with ramp-rate limits, the total generation and there by the losses are decreased. It is also observed that, with ramp-rate limits, all generators are following up ramp-ramp rates and operating towards the maximum limits.

The convergence characteristics for this system are shown in Fig.1. From this figure, it is observed that, with ramp-rate limits, the convergence characteristics starts with least LBI value and reaches final best value in more number of iterations when compared to without ramp-rate limits.

TABLE.1. OPF RESULTS FOR IEEE-30 BUS SYSTEM

S. No	Control parameters		PSO method: Without ramp	PSO method: With ramp
1	Real power Generation (MW)	P_{G1}	191.5725	191.3162
		P_{G2}	71.44415	60.92791
		P_{G5}	26.74206	37.4621
		P_{G8}	27.53891	20.82313
		P_{G11}	19.17439	18.01952
		P_{G13}	39.75898	31.96162
2	Generator voltages (p.u.)	V_{G1}	0.994579	0.995106
		V_{G2}	0.954897	0.951124
		V_{G5}	1.020647	1.018445
		V_{G8}	1.024984	0.97265
		V_{G11}	1.069023	1.027857
		V_{G13}	1.019682	0.95582
3	Transformer tap setting (p.u.)	T_{6-9}	1.079453	0.993226
		T_{6-10}	0.935159	0.982288
		T_{4-12}	0.995611	1.023472
		T_{28-27}	0.996235	0.981584
4	Shunt compen-sators (MVAr)	$Q_{C,10}$	17.73998	19.96386
		$Q_{C,24}$	9.974653	25.4465
5	Total generation (MW)		376.231	360.5105
6	Loadability Index value		0.27265	0.22086
7	Total power loss (MW)		15.56197	14.51874

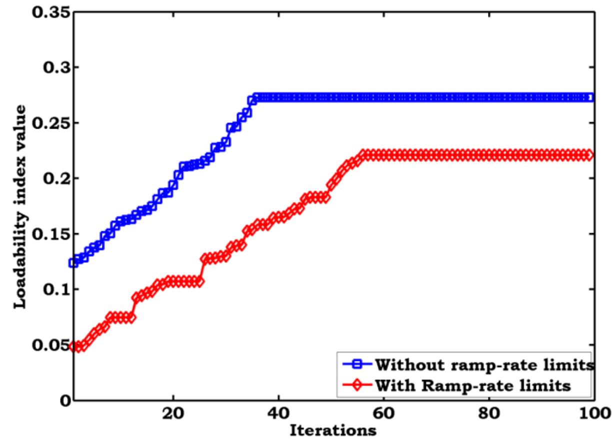

Fig.1. Convergence characteristics for IEEE-30 bus system

B. *Example-2*

Indian-62 bus system with nineteen generators and eighty nine transmission lines is considered. For this system, there are forty nine control variables which include nineteen active power generations, voltage magnitudes at the generator buses and eleven tap changing transformers.

The proposed PSO method is applied to enhance the system loadability in terms of loadability index (LBI). The OPF results without and with ramp-rate limits is tabulated in Table.2. From this table, it is observed that, with ramp-rate limits, the LBI value is decreased when compared to without ramp-rate limits, because of the restriction on the generation limits. It is also observed that, with ramp-rate limits, the total generation and there by the losses are decreased. It is also observed that, with ramp-rate limits, all generators are following up ramp-ramp rates and operating towards the maximum limits.

The convergence characteristics for this system are shown in Fig.2. From this figure, it is observed that, with ramp-rate limits, the convergence characteristics starts with least LBI value and reaches final best value in more number of iterations when compared to without ramp-rate limits.

TABLE.2. OPF RESULTS FOR INDIAN-62 BUS SYSTEM

S. No	Control parameters		PSO method: Without ramp	PSO method: With ramp
1	Real power generation (MW)	P_{G1}	239.6913	209.7653
		P_{G2}	243.1453	290.3295
		P_{G5}	239.7306	240.3831
		P_{G9}	19.67439	14.45717
		P_{G14}	55.06454	55.86526
		P_{G17}	215.161	233.3357
		P_{G23}	55.67213	53.87244
		P_{G25}	397.6957	383.1104
		P_{G32}	387.4799	367.4594
		P_{G33}	37.65914	29.62417
		P_{G34}	58.31195	95.09657
		P_{G37}	52.1666	52.94868
		P_{G49}	55.71522	57.5207
		P_{G50}	64.48154	44.34852
		P_{G51}	208.4096	212.864
		P_{G52}	60.56444	68.53704

		P_{G54}	56.98987	42.85103
		P_{G57}	80.80202	81.96427
		P_{G58}	434.9643	429.8396
2	Generator voltage (p.u.)	V_{G1}	1.027855	1.022486
		V_{G2}	0.953624	0.954798
		V_{G5}	0.993696	1.031245
		V_{G9}	0.967484	0.999745
		V_{G14}	1.053488	1.051939
		V_{G17}	0.981228	1.023414
		V_{G23}	1.061056	1.064648
		V_{G25}	0.98619	1.073156
		V_{G32}	0.951915	1.011652
		V_{G33}	0.999307	1.020475
		V_{G34}	0.952791	1.010738
		V_{G37}	1.000647	1.06867
		V_{G49}	0.906455	0.988475
		V_{G50}	1.020354	0.998049
		V_{G51}	1.010082	0.974192
		V_{G52}	1.025753	0.917227
		V_{G54}	1.000492	0.97625
		V_{G57}	1.028013	0.985201
		V_{G58}	1.025356	0.958169
3	Transformer tap seting (p.u.)	T_{1-14}	1.014861	1.000736
		T_{14-15}	0.991726	0.991063
		T_{4-14}	1.011281	1.021079
		T_{13-14}	1.048804	1.055815
		T_{12-13}	1.084999	1.007707
		T_{14-19}	1.074778	1.038005
		T_{14-18}	1.050766	0.963666
		T_{14-16}	1.008427	0.997982
		T_{48-54}	0.995237	1.0795
		T_{48-50}	1.023992	0.99426
		T_{49-48}	0.986976	1.003414
4	Total generation (MW)		2963.379	2954.173
5	Loadability Index value		0.2180	0.1401
6	Total power loss (MW)		55.37943	52.17288

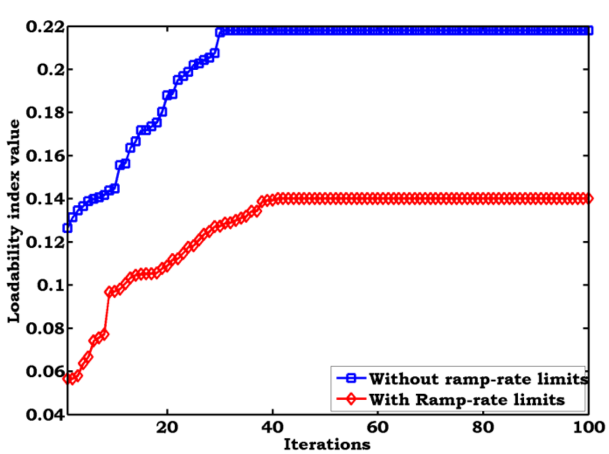

Fig.2. Convergence characteristics of Indian-62 bus system

VI. CONCLUSION

In this paper, optimal power flow solution methodology has been successfully applied to enhance the system loadability. The proposed problem has been solved while satisfying equality, in-equality constraints and ramp-rate limits. The effect of ramp-rate limits has been analyzed on standard IEEE-30 bus and Indian-62 bus test systems.

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