Optimal Reactive Power Dispatch Incorporating Solar Power Using Jaya Algorithm

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Abstract Optimal reactive power dispatch (ORPD) is the most functional part of reactive power dispatch technique, by which an effective solution of power flow can be befitted and the system parameters can be arranged in such a value, so that network power losses could be minimized. The ORPD problem can be solved as a single-objective as well as multi-objective optimization problem with the help of various conventional techniques as well as modern developed techniques like differential evolution, particle swarm optimization, genetic algorithm, Jaya algorithm, etc. This paper is an attempt to minimize transmission line power losses by introducing solar energy sources in addition to the existing conventional sources to power network system along with adjusting the reactive power controlled parameter without violating technical equality constraints and inequality constraints. The proposed designed model has been analyzed for IEEE 14-bus and IEEE 30-bus test systems by using Jaya algorithm. The simulation result with comparing others' existing result with and without the inclusion of solar energy has shown that the proposed designed model is effective and profitable for planning an interconnected reliable power system network.

Keywords Differential evolution · Genetic algorithm · Jaya algorithm · ORPD · Particle swarm optimization (PSO) · Photovoltaic (PV) · Renewable energy · Solar energy

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1 Introduction

Economical operation on power system network has two objectives, one is active power regulation and another is reactive power dispatch. Both the objectives can be improved by introducing renewable sources to the system. Nowadays, renewable sources play an important role on the performance of interconnected power system. They not only minimize harmful green house gas emissions and dependency on fossil fuel but also reduce long-term generation cost of electric power. This article will also show the importance of renewable sources to minimize the active power losses in the system. An interconnected power system is modeled with the help of IEEE 14-bus and IEEE 30-bus test system and is analyzed with ORPD problem by using Jaya algorithm. Jaya algorithm is simple yet powerful optimization algorithm, which is based on the objective that the solution finding out from a problem should be the best solution and should avoid the worst solution. The main objective is to improve the performance of the power system by introducing renewable sources to the system along with controlling the reactive power flow and hence minimizing transmission losses and increasing reliability of the system. The ORPD equation has been formulated with considering the injection of renewable unit to the system, and the best solutions of controlled parameter value (i.e., generator bus voltage, tap changer of transformer, reactive power source) have been found out using Jaya algorithm without violating the equality constraints and inequality constraints. Hence, the best solution for minimizing active power losses has been evaluated. More emphasis is given in the generation of power using renewable energy along with conventional sources in order to reduce the generation cost and to preserve the non-replenishable sources for high demand period. There is an increasing penetration of renewable energy in the system. Thus, in this paper, the solar energy has been incorporated into the IEEE bus test system where the power output from photovoltaic (PV) arrays are integrated along with the existing thermal power to the generator bus in order to minimize the transmission line power loss in the system [1–5].

2 Problem Formulation

2.1 The ORPD Problem

The objective of the ORPD problem is minimization of active power loss, and it is solved by determining the optimal location of the control variables without the violation of any constraints. The objective function of the problem is expressed as follows [3]:

$$\text{Min } P_{\text{loss}} = \sum_{k \in \text{NL}} g_l (V_a^2 + V_b^2 - 2V_a V_b \cos \delta_{ab}) \tag{1}$$

where P_{loss} is the total active power loss in the transmission lines, NL denotes number of transmission lines, g_l depicts conductance of branch l, V_a, V_b are magnitude of the bus voltages the ath and bth buses, respectively, and δ_{ab} is the phase difference between these voltages. There are few equality constraints given below [6]:

$$P_{Ga} - P_{Da} - V_a \sum_{b=1}^{\text{NB}} V_b[G_{ab} \cos \theta_{ab} + B_{ab} \sin \theta_{ab}] = 0 \tag{2}$$

$$Q_{Ga} - Q_{Da} - V_a \sum_{b=1}^{\text{NB}} V_b[G_{ab} \sin \theta_{ab} + B_{ab} \cos \theta_{ab}] = 0 \tag{3}$$

where NB denotes the number of buses, P_{Da} and Q_{Da} are the active and reactive load demands of bus a. P_{Ga} and Q_{Ga} are the active and reactive powers generated at the ath bus, respectively. G_{ab} and B_{ab} are the conductance and susceptance the between ath and bth buses, respectively.

There are few inequality constraints given below [6]:

The inequality constraints of the independent variables are:

$$V_{Ga}^{\min} \leq V_{Ga} \leq V_{Ga}^{\max}; \quad a = 1, \ldots, N_{\text{GB}} \tag{4}$$

$$Q_{Ca}^{\min} \leq Q_{Ca} \leq Q_{Ca}^{\max}; \quad a = 1, \ldots, N_{\text{SC}} \tag{5}$$

$$T_a^{\min} \leq T_a \leq T_a^{\max}; \quad a = 1, \ldots, N_{\text{T}} \tag{6}$$

where $V_{Ga}^{\min}$ and $V_{Ga}^{\max}$ are the maximum and minimum generator voltages of the ath bus, respectively. $Q_{Ca}^{\min}$ and $Q_{Ca}^{\max}$ are the maximum and minimum reactive power injection of the ath shunt compensator, respectively, and $T_a^{\min}$, $T_a^{\max}$ are the maximum and minimum tap settings of the ath transmission line, respectively. N_{GB} is the total number of generator buses, N_{SC} is the number of shunt compensators and N_{T} is the number of tap-changing transformers. The inequality constraints of the dependent variables are:

$$V_{La}^{\min} \leq V_{Li} \leq V_{Li}^{\max}; \quad i = 1, \ldots, N_{\text{LB}} \tag{7}$$

$$Q_{Gi}^{\min} \leq Q_{Gi} \leq Q_{Gi}^{\max}; \quad i = 1, \ldots, N_{\text{C}} \tag{8}$$

$$S_{Li} \leq S_{Li}^{\max}; \quad i = 1, \ldots, \text{NL} \tag{9}$$

where $V_{La}^{\min}$ and $V_{La}^{\max}$ are the minimum and maximum voltages of the load bus a, respectively. $Q_{Ga}^{\min}$ and $Q_{Ga}^{\max}$ are the minimum and maximum reactive power generations of the ath generator bus, respectively. $S_{La}^{\max}$ depicts the maximum apparent power flow in the ath line and NLB denotes the number of load buses.

2.2   Inclusion of PV Unit to the System

In this paper, the study is done by considering the PV unit to be situated at the generator buses and their active power outputs are added to the power output of the conventional generators situated at the generated buses of the standard systems. The power output of the solar PV arrays are determined by using the simplified method of estimating the output of the PV modules under different operating conditions.

2.3   Performance Prediction Model of PV Array

The factors that are mostly responsible for the performance of a PV array are the temperature of the PV module (T) and solar irradiance (E) of the area. The electrical characteristics which are important for the operation of PV array are open-circuit voltage (V_{oc}), short-circuit current (I_{sc}), the peak power output (P_{max}) and fill factor (FF) [7].

$$I_{sc} = I_{sc0}\left(\frac{E}{E_0}\right)^x \tag{10}$$

where E_0 is the solar irradiance and I_{sc0} is the short-circuit current of the PV module under E_0. I_{sc} is the short-circuit current of the PV module under the solar irradiance E. The nonlinear effects on the photocurrent are indicated by the exponential term x. The open-circuit voltage V_{oc} under a given condition is given by

$$V_{oc} = \frac{V_{oc0}}{1 + y \ln \frac{E_0}{E}}\left(\frac{\tau_0}{\tau}\right)^z \tag{11}$$

where V_{oc0} is the open-circuit voltage of the PV module when exposed to normal solar irradiance at temperature τ_0, y is a coefficient of technology-specific of PV module technology which is dimensionless and z is used for considering all the nonlinear effects of voltage and temperature. Fill factor FF is dimensionless and it helps in measuring the deviation of the actual I–V characteristic from the ideal one. The equation for calculating FF is given below:

$$FF = FF_0\left(1 - \frac{R_s}{V_{oc}/I_{sc}}\right) \tag{12}$$

where R_s is the series resistance, FF_0 is the ideal fill factor of the PV module and v_{oc} is the normalized value of open-circuit voltage to the thermal voltage. FF_0 and v_{oc} are given by

$$FF_0 = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{1 + v_{oc}} \tag{13}$$

$$v_{oc} = \frac{V_{oc}}{nK\tau/e} \tag{14}$$

where n is the ideality factor and it ranges between 1 and 2, e is the charge of an electron (1.6×10^{-19} C) and K is the Boltzmann constant (1.38×10^{-23} J/K). The maximum power output of the PV module is given by

$$P_{max} = FF \cdot V_{oc} \cdot I_{sc} \tag{15}$$

If there are N_S number of series and N_P number of parallel PV modules and P_M be the module power output, then the array power output is given by

$$P_A = N_P \cdot N_S \cdot P_M \tag{16}$$

2.4 Calculated Power Output of PV Array

The active power output from the PV array is calculated using the following parameters from Table 1 [7]. The location chosen in this problem is Srinagar, India, and data is taken from the year 2012 [8]. The calculated power output of the PV array is 348.35 kW.

In this paper, the model of each PV unit has been considered to have 10 modules in both series and parallel and generates around 348.35 kW of power. A total of 20 units can be combined to generate a power of 6.967 MW of power at a particular generator bus. Thus, this power from the PV system is combined to that of the power from the thermal generators at all the generator buses of the system.

Table 1 Values of the different parameters of PV array

Parameters	Values	Parameters	Values
x	1.21	E	192.917 W/m^2
y	0.058	V_{oc0}	21 V
z	1.15	I_{sc0}	6.5 A
n	1.5	R_s	0.012 Ω
τ_0	298 K	N_P	10
τ	288 K	N_S	10
E_0	1000 W/m^2		

3   Implementation of Jaya Algorithm

The Jaya algorithm is a metaheuristic algorithm developed by Rao [9] to solve the objective functions of stochastic optimization techniques. The objective of the algorithm is to proceed toward the best solution and keep avoiding the worst solution. The algorithm keeps on updating the values of the control variables wherever it obtains a better solution compared to the previous iteration. Let $f(x)$ be an objective function which needs to be minimized. Let 'v' be the number of design variables (i.e., $a = 1$, 2, …, m) and i be a particular iteration for which the number of candidate solutions be 'c' (i.e., population size, $b = 1, 2, …, c$). Let $f(x)_{\text{best}}$ and $f(x)_{\text{worst}}$ be the best and worst solutions of the function $f(x)$ and the candidates obtaining the best and worst solutions be recorded as the best and the worst candidates, respectively. Let value of the ath variable be $A_{a,b,i}$ for the ath candidate in the ith iteration. The modified value is represented as:

$$A'_{a,b,i} = A_{a,b,i} + r_1\big(A_{a,\text{best},i} - \big|A_{a,b,i}\big|\big) - r_2(A_{a,\text{worst},i} - \big|A_{a,b,i}\big|) \qquad (17)$$

where $A_{a,\text{best},i}$ is the best candidate value of the ath variable and $A_{a,\text{worst},i}$ is the worst value of the ath variable. $A'_{a,b,i}$ is the updated value of $A_{a,b,i}$ and r_1 and r_2 are two random numbers in the range [0, 1].

3.1   Effectiveness of Jaya Algorithm

The Jaya algorithm has proved to be a superior algorithm over many metaheuristic algorithms in determining the optimal solution of the active power loss in the ORPD problem like PSO, DE, ABC and DE-ABC [10]. Here, the Jaya algorithm is used to determine the active power loss in the transmission lines by incorporating the solar energy into the system, and then, it is comparing with the results of those from the actual system without PV.

4   Simulation Results

The ORPD problem is solved using the Jaya algorithm for minimization of the objective function of active power loss. The algorithm is tested on IEEE 14-bus and IEEE 30-bus test system for two different cases for each system. In the first case, the active power output is considered to be delivered only from the conventional generators and then the real power losses are calculated for the ORPD problem using both PSO and Jaya algorithms. In the second case, the bus data of the systems are modified by adding the active power output from the PV blocks to the power output from the generators at the generator buses. Again, the real power losses are

calculated for the ORPD problem using both PSO and Jaya algorithms, and the results are compared. The results for both cases applying the two algorithms are compared, and the results are given below.

4.1 IEEE 14-Bus Test System

There are 5 generators in IEEE 14-bus test system which are situated at buses 1, 2, 3, 6 and 8 where bus 1 is the slack bus and the others are the PV buses. It has 20 numbers of branches with 3 branches (4–7, 4–9 and 5–6) having tap-changing transformers connected to them. The initial active power loss of the transmission line of the network for the base case is 13.49 MW [11]. The load flow for the system is run by taking the line data and bus data from [12]. The case studies for the test system are as follows:

Case 1:

The number of control variables considered for this case is 10 and their details are listed below [13]:

(a) 5 numbers of generator voltages at the PV buses 1 (slack bus), 2, 3, 6 and 8. Their range is [0.9, 1.1] p.u.
(b) 3 numbers of tap-changing transformers connected in the lines between (4–7, 4–9 and 5–6). Their range is within [0.9, 1.1] p.u.
(c) 2 numbers of static VAR compensators (SVCs) situated at buses 9 and 14. Their range is [0, 0.18] p.u.

Here, the power from the PV unit is not included in the system.

Case 2:

In this case, the control variables and their limits were kept unchanged, only the active power output from PV system has been added to the generator bus data along with the power of the thermal generators. A total of 6.967 MW power is added to all the generator buses (1, 2, 3, 6 and 8) individually.

The ORPD problem has been solved for all the cases using both PSO and Jaya algorithms and their results along with the comparison of the convergence characteristics for both the cases are shown in Table 2 and Fig. 1, respectively.

4.2 Effectiveness of PV on ORPD for Minimization of Active Power Loss and Voltage Deviation

The results obtained from Table 2 and Fig. 1 prove that the penetration of solar power has reduced the active power loss in the system largely, and specifically, the results from Jaya algorithm depict the superiority of the algorithm in determining

**Table 2** Comparative results of IEEE 14-bus test system

Control variables (p.u.)	PSO (without PV system, case 1)	Jaya (without PV system, case 1)	PSO (with PV system, case 2)	Jaya (with PV system, case 2)
V_{G1}	1.1	1.1	1.1	1.1
V_{G2}	1.1	1.0973	1.1	1.0973
V_{G3}	1.0634	1.0609	1.0634	1.0609
V_{G6}	1.0408	1.1	1.0412	1.1
V_{G8}	1.1	1.1	1.1	1.1
T_{4-7}	1.0865	1.0093	1.0884	1.0093
T_{4-9}	1.0661	0.9442	1.0682	0.9442
T_{5-6}	1.1	0.9969	1.1	0.9969
Q_{sc9}	18	18	18	18
Q_{sc14}	18	18	18	18
Total P_{loss} (MW)	12.4023	12.3215	10.0773	9.9389

Fig. 1 Convergence characteristics of PSO and Jaya algorithms for power loss for both the cases on the IEEE 14-bus test system
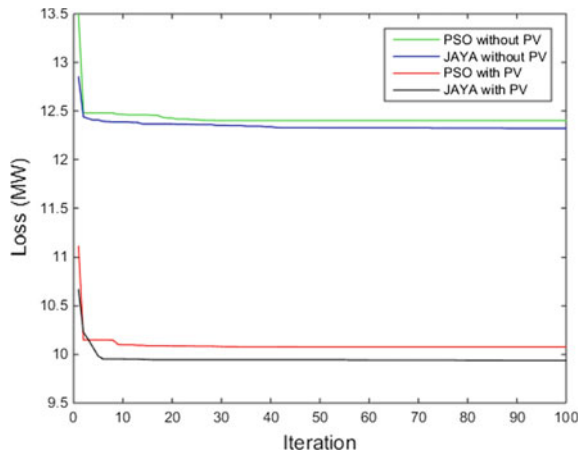
the optimal solution over PSO. Since, the PV cannot deliver reactive power, but its contribution in active power in the lines helps in reducing the voltage deviation in the buses as shown in Fig. 2 and thus improves the voltage profile of the system. Thus, Jaya algorithm has the ability to successfully reduce the power loss as well as the voltage deviation in the buses to a greater extent compared to PSO.

Fig. 2 Convergence characteristics of PSO and Jaya algorithms for voltage deviation for both the cases on the IEEE 14-bus test system
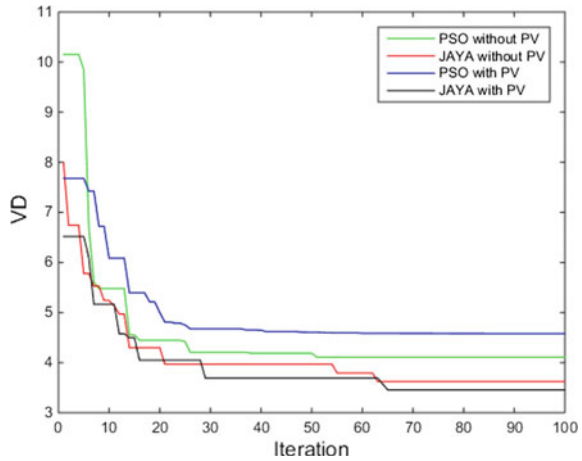
4.3 IEEE 30-Bus Test System

The standard IEEE 30-bus test system comprises of total of 6 generators that are situated at the buses 1, 2, 5, 8, 11 and 13 out of which bus 1 is the slack bus and the others are PV buses. There are 41 numbers of branches in which 4 numbers of adjustable transformers are connected in branches (6–9, 6–10, 4–12 and 28–27). The load flow for the system is run by taking the line data and bus data from [11]. Initially, transmission line active power loss is 17.8984 MW for the base case [11]. The two case studies for the test system are as follows:

Case 1:

The number of control variables considered in this particular case for the optimization problem is 12. The variables along with their limits are listed below [13]:

(a) 6 numbers of generator voltages at the PV buses 1 (slack bus), 2, 5, 8, 11, 13. Their range is [0.9, 1.1] p.u.
(b) 4 numbers of tap-changing transformers connected in the lines between (6–9, 6–10, 4–12 and 28–27). Their range is within [0.9, 1.1] p.u.
(c) 2 numbers of static VAR compensators (SVCs) situated at buses 10 and 24. Their ranges are [0, 0.2] p.u. and [0, 0.04] p.u., respectively.

Here, the power from the PV unit is not included in the system.

Case 2:

The control variables in this case has been kept unchanged along their limits. Here, only the active power output from the PV system is included along with the power of the thermal generators in the generator bus data. A total of 6.96 MW power is added to all the generator buses (1, 2, 5, 8, 11 and 13) individually. Both PSO and Jaya algorithms are used to solve the ORPD problem of minimization of active power

losses of the transmission lines. The results along with the convergence characteristics compared for both the cases are shown in Table 3 and Fig. 2, respectively.

The results obtained from Table 3 and Fig. 3 for the above-mentioned cases imply that the addition of power from the solar energy has helped in reducing the active power losses in the transmission lines to a great extent. Thus, the penetration of the solar energy in the system helps in getting a better result of the ORPD problem. Moreover, the convergence characteristics prove that Jaya is superior in determining

Table 3 Comparative results of IEEE 30-bus test system

Control variables (p.u.)	PSO (without PV system, case 1)	Jaya (without PV system, case 1)	PSO (with PV system, case 2)	Jaya (with PV system, case 2)
V_{G1}	1.1	1.1	1.1	1.1
V_{G2}	1.0976	1.0953	1.0976	1.0953
V_{G5}	1.1	1.0555	1.1	1.0555
V_{G8}	1.0463	1.0921	1.0463	1.0921
V_{G11}	1.1	1.1	1.1	1.1
V_{G13}	1.1	1.0985	1.1	1.0985
T_{6-9}	1.0997	1.0460	1.0997	1.0460
T_{6-10}	1.1	0.9	1.1	0.9
T_{4-12}	1.08	0.9758	1.08	0.9758
T_{28-27}	1.0263	0.9535	1.0263	0.9535
Q_{sc10}	0.2	0.2	0.2	0.2
Q_{sc24}	0.04	0.04	0.04	0.04
Total P_{loss} (MW)	**16.1872**	**16.029**	**12.7176**	**12.5347**

Fig. 3 Convergence characteristics of PSO and Jaya for both the cases on the IEEE 30-bus test system
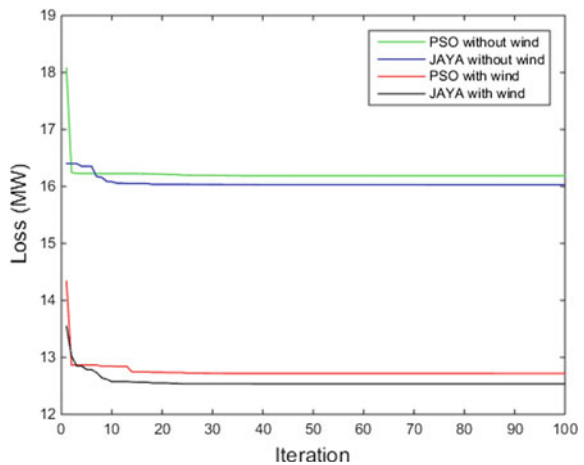
the optimal solution to the problem and also minimizes the objective function largely compared to the other mentioned algorithm in the literature.

5 Conclusion

In this paper, the output from the PV system is added with that of the initial output from the conventional thermal generators of the respective standard systems. The results from the solutions of the ORPD problem from the case studies prove that the transmission line power loss is reported to be lower when the solar power is integrated to the system compared to that of the result when there is no intervention of solar power into the system. Thus, the penetration of additional renewable energy (solar energy in this paper) in the system helps in reducing the power loss in the transmission lines in the ORPD problem. On the other hand, the Jaya algorithm seems to have minimized the objective function largely compared to the other reported algorithm and thus is much more efficient, consistent and superior in determining the optimal solutions to the objective function. In other terms, it is a better choice compared to PSO in finding out the optimal values of control variables in the ORPD problem and thus optimizing the problem faster when tested on the different case studies for the standard IEEE 14- and 30-bus test systems.

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