Constrained Power Loss Minimization of DC Microgrid Using Particle Swarm Optimization

S. Angalaeswari and K. Jamuna

Abstract The optimal power flow has been considered as the important issue in the power system network. There are many ways to optimize the power flow out of which power loss minimization and voltage profile improvement are considered as the efficient ways. The power loss minimization for distributed system has been performed with particle swarm optimization (PSO) algorithm and the results are compared with forward/backward load flow method. The analysis is also performed with and without addition of renewable sources. The results show that the inclusion of DG at various buses reduces the power loss and improves the voltage magnitude profile

Keywords Microgrid · Distributed generation · Particle swarm optimization (PSO)

1 Introduction

The power generation from any country plays a vital role in improving the economy of that country. The maximum amount of power has been produced from conventional sources over long period of time. To satisfy the power demand and to make the world pollution free, the power sectors turn toward the nonconventional sources for the past one decade. When the renewable sources are placed nearer to the consumer, it greatly reduces the transmission loss and reduces the power electronic interfacing devices.

The sources that are located near to the load distribute the power to the load with the minimum distance and minimum effort; hence they are called as distributed

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S.C. Satapathy et al. (eds.), *Proceedings of the International Conference on Data Engineering and Communication Technology*, Advances in Intelligent Systems and Computing 468, DOI 10.1007/978-981-10-1675-2_38

energy sources. The cluster of distributed generators, energy storage devices, and loads are called as microgrids [1]. The microgrid is the best alternate solution for the conventional grid. The microgrid can be operated with public distribution grid in grid connected mode, or islanded mode, or transition mode. The microgrid can deliver power to the local loads more efficiently and reliably. If the power from the distributed generators in the microgrid is more than the load connected, the excess power can be given to the grid. Otherwise, the loads in the microgrid usually take power from the grid [2].

Even though the microgrid gives the reliable power to the consumers, the maximum efficiency from the sources is less due to the intermittent source availability of the nonconventional energy sources. From the available sources, the real power taken from the source to the load can be maximized using any optimization techniques. The best method to maximize the power flow is to minimize the real and reactive power losses in the system, thereby improving the voltage profile in the system. This paper is presented as follows: Sect. 2 gives the modeling of wind turbine, solar cell, and the fuel cell. Section 3 discusses the particle optimization algorithm which is used for minimization of the real power loss by considering the bus voltage limits as inequality constraint. Section 4 provides the load flow algorithm used in radial distribution system. Section 5 discusses the results of bus voltage and real power loss obtained from IEEE 33 bus system before and after introducing PSO. Section 6 gives the conclusion of the paper.

2 Modeling of Distributed Generators

The main advantages of distributed generators (DG) are transmission capacity relief, distribution capacity relief, grid improvement, improved grid asset utilization and increased reliability, reactive power (VAR) support, energy and load management, and voltage support.

3 Modeling of Wind Turbine

Wind energy is one of the most available and exploitable forms of nonconventional energy. The wind velocity will not be constant all the time. The maximum power extracted from the wind turbine has been estimated at around 59 % and it has been taken as Betz's limit [3].

(i) Area of the rotor (A) is given as

$$A = \frac{\pi d^2}{4}. \tag{1}$$

where d = diameter of the rotor.

(ii) Tip speed ratio λ is given as

$$\lambda = \frac{2\pi RN}{v_{\infty}}. \tag{2}$$

where R = radius of the swept area in m, N = rotational speed in revolutions per second and v_{∞} = wind speed without rotor interruption in m/s

(iii) Torque coefficient is calculated from

$$C_T = \frac{Cp}{\lambda}. \tag{3}$$

C_p is assumed as 35 %.

(iv) The aerodynamic torque is calculated as

$$T_m = \frac{1}{2}\rho C_T \pi R^3 V\infty^2. \tag{4}$$

where ρ = air density $\approx 1.225\,\text{kg/m}^3$ at 15 °C and at normal pressure.

(v) The power available in the wind is given by

$$P_m = \frac{1}{2}\rho CpAV\infty^3. \tag{5}$$

4 Modeling of Solar Cell

A mathematical model is developed for the solar cell. The equivalent model of a solar cell is considered from Ref. [4]. There are many ways to represent the equivalent circuit of solar cell. Every circuit differs from others by the number of circuit components. In this paper, the single diode equivalent circuit is considered which includes current source in parallel with a diode, resistance R_s, and a shunt resistance R_{sh}. In the ideal condition, the R_s is very small, almost equal to zero and the R_{sh} is very large, almost equal to infinity. Then the current is given by the following equation: [using Kirchhoff's current Law] [5]

$$I = N_p I_{ph} - Np_{Id} \tag{6}$$

$$Iph = \{I_{sc} + k_1(T_c - T_{ref})\}\frac{\lambda}{1000}. \tag{7}$$

$$Id = Is\left[e^{\frac{qU}{NskTcA}} - 1\right]. \tag{8}$$

Table 1 Specifications of solar cell

I, *Id*	Output current from the solar cell, diode current in A
Iph, *Isc*	Current generated due to light illumination, short-circuit current (3.27)A
k_1	Cell's short-circuit current temperature coefficient, 0.0017A/°C
Tc, *Tref*	Cell temperature(350 K), reference temperature (301.18)K
λ, *Is*	Solar radiation, 1500 W/m^2, module saturation current, A
q, *U*	Electric charge of electron, 1.6 * 10^{-19} C, V_{oc}, voltage of PV cell, 400 V
k, *A*	Boltzmann constant, 1.38 * 10^{-23} J/K, p–n junction's ideality factor, 1.5
I_{rs}	Module reverse saturation current, 2.0793 * 10^{-6} A
E_g	Band gap energy of the semiconductor, 1.1 eV
N_s, N_p	Number of solar cells in series (800), in parallel (40)

$$Is = Irs\left[Tc/Tref\right]^3 e^{\left[\frac{qEg\left[\left(\frac{1}{Tref}\right)-\left(\frac{1}{Tc}\right)\right]}{kA}\right]}. \tag{9}$$

The power produced by the solar cell is (Table 1)

$$P = UI. \tag{10}$$

5 Modeling of Fuel Cell

Fuel cells are classified as power generators that can operate continuously when the fuel and oxidant are supplied. The reversible PEM (Poly ethylene membrane) fuel cell model is used in this paper. The theoretical cell voltage of the cell is given as [6]

$$U_{th} = -\frac{\Delta G}{nF}. \tag{11}$$

The theoretical (reversible) standard voltage is

$$U_0 = -\frac{\Delta G_0}{nF}. \tag{12}$$

$$\Delta G = \Delta H - T\Delta S. \tag{13}$$

The theoretical thermal voltage is given as

$$thermal = -\frac{\Delta H}{nF}. \tag{14}$$

Table 2 Specifications of fuel cell

ΔG, ΔH	Change in Gibbs energy, J/mol, change in enthalpy, −286 J/mol,
ΔS	Change in entropy, −0.1634 J/K/mol
n, F	Number of electrons per mole (2), Faraday's constant(96485.309 C/mol)
R, T	Universal gas constant(8.31451 J/K/mol), cell operating temperature, K
aH_2O,	Activity of species $H_2O \approx 1$
aH_2	Activity of species H_2 according to pressure, (1-thermal)0.8
$aO_2{}^{1/2}$	Activity of species O_2 according to pressure, (1-U_{th})0.2
I, Ns	Current from fuel cell (100)A, number of fuel cell stack(150)

The free energy can be expressed as

$$\Delta G = \Delta G_0 + RT \ln\left[\frac{aH_2O}{aH_2 \times aO_2{}^{1/2}}\right]. \tag{15}$$

The theoretical cell voltage is obtained as follows:

$$Uth = U_0 - \frac{RT}{nF} \ln\left[\frac{aH_2O}{aH_2 \times aO_2{}^{1/2}}\right]. \tag{16}$$

$$\text{Equivalent cell voltage} = 1.2297 + (T - 298.15)\frac{\Delta S_0}{nF} + \frac{RT}{nF} \ln\left[\frac{aH_2 \times aO_2{}^{1/2}}{aO_2^{3/2}}\right]. \tag{17}$$

The power generated = Ns × Equivalent cell voltage × I (Table 2).

6 Power Loss Minimization Using FW/BW Load Flow Method

The power loss is calculated on IEEE 33 bus system [7]. Since the nature of the system is radial, the normal load methods cannot be applied. The following assumptions are made in the considered system: (i) balanced radial distribution network for three phases; (ii) the system can be represented by the equivalent single-line diagram; and (iii) line charging capacitances are neglected at the distribution voltage levels [8].

In Fig. 1, V_i is the voltage at the sending end at an angle of δ_i; V_j is the voltage at the receiving end at an angle of δ_j; Z_{ij} is the series impedance of the transmission line; R_{ij} is the resistance of the line; and X_{ij} is the reactance of the line.

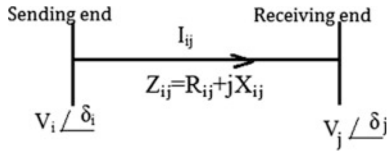

Fig. 1 Equivalent circuit of transmission line

The current flow in the transmission line can be calculated [7, 9] as

$$I_{ij} = \frac{V_i\angle\delta_i - V_j\angle\delta_j}{Z_{ij}}. \tag{18}$$

The real power and reactive power losses can be determined from the following equations:

$$P_{Lij} = r_{ij}\frac{Pij^2 + Qij^2}{Vj^2}. \tag{19}$$

$$Q_{Lij} = x_{ij}\frac{Pij^2 + Qij^2}{Vj^2}. \tag{20}$$

P_{ij}, Q_{ij} is the real, reactive power flowing in the line.

Algorithm for forward/backward load flow method:

1. Assume the flat initial voltages at all nodes for the first iteration.
2. Start with end node, and the node current can be computed using the following equation:

$$Iij = \left(\frac{Si}{Vi}\right)^*. \tag{21}$$

   * in Eq. (21) indicates the conjugate of the $\left(\frac{Si}{Vi}\right)$.
3. By applying KCL, the branch current from node i to node j can be calculated using the following equation in the backward sweep:

$$I_{i,i+1} = I_{i+1} + \sum \text{Currents in branches flowing away from node } i+1. \tag{22}$$

4. The voltage at ith bus(node) is computed by the following equation in the forward sweep mode:

$$V_i = V_{i+1} + (I_{i,i+1} \times Z_{i,i+1}). \tag{23}$$

5. The load current is updated with the new voltages and the real and reactive power loss is calculated. Repeat the above steps till the voltage difference between the successive iteration is less than the tolerance level.

7 Implementation of Particle Swarm Optimization (PSO)

PSO was first introduced by James Kennedy and Russell Eberhart in the year 1995. Particle swarm optimization is an optimization tool which is used to determine the optimum value of the objective function based on the particles position and velocity. Each individual in this algorithm is taken as particles and this particles move from the current position to new one by searching the optimum path. In every iteration, this particle identifies the best path to move from its current position from its own experience and its nearby particles movement. The direction of a particle is given as a set of nearby particles and its own experience [10].

Algorithm for PSO:

- Step 1 Set the iteration count k as 0. Randomly generate NP particles, their initial position, and initial velocities.
- Step 2 Evaluate the loss for each and every particle. If the voltage limits are satisfied, set the current position as particle best PB. Among all the particles, which one is having the minimum loss is considered as global best (GB). Otherwise, initialization should be repeated.
- Step 3 Increment the Iteration count k = k + 1.
- Step 4 Update the speed and update the current position.
- Step 5 The particle best can be updated if $fi(Xi^k) < fi(PBi^{k-1})$ then $PBi^k = Xi^k$ else $PBi^k = PBi^{k-1}$.
- Step 6 The global best can be calculated as $f(GB^k) = \min\{fi(PBi^k)\}$ If $f(GB^k) < f(GB^{k-1})$ then $GB^k = GB^k$ else $GB^k = GB^{k-1}$.
- Step 7 If the iteration reaches the maximum defined, then stop, or else go to step 3.

Flowchart: (Fig. 2).

8 Simulation Results

In an optimal power flow, the values of some or all of the control variables have to be determined so as to optimize the objective function. In this paper, the objective function is to minimize the real power loss in a radial distribution network (RDN) using PSO method. The algorithm is implemented on the IEEE 33 bus system. The bus voltages and the real power loss are calculated for the following three cases: (i) without PSO and without DGs; (ii) with PSO without DGs; and (iii) with PSO and DGs. For the analysis, the voltage limits considered are 0.95–1.05.

Case (i) Power Loss without PSO and without DGs (Load flow Analysis)

The real power loss has been calculated for IEEE 33 bus system by conducting forward/backward load flow analysis. Initially, the voltages at all buses are assumed with flat value of $1\angle 0°$. Then the load flow has been conducted by considering the

Fig. 2 Flowchart of particle swarm optimization

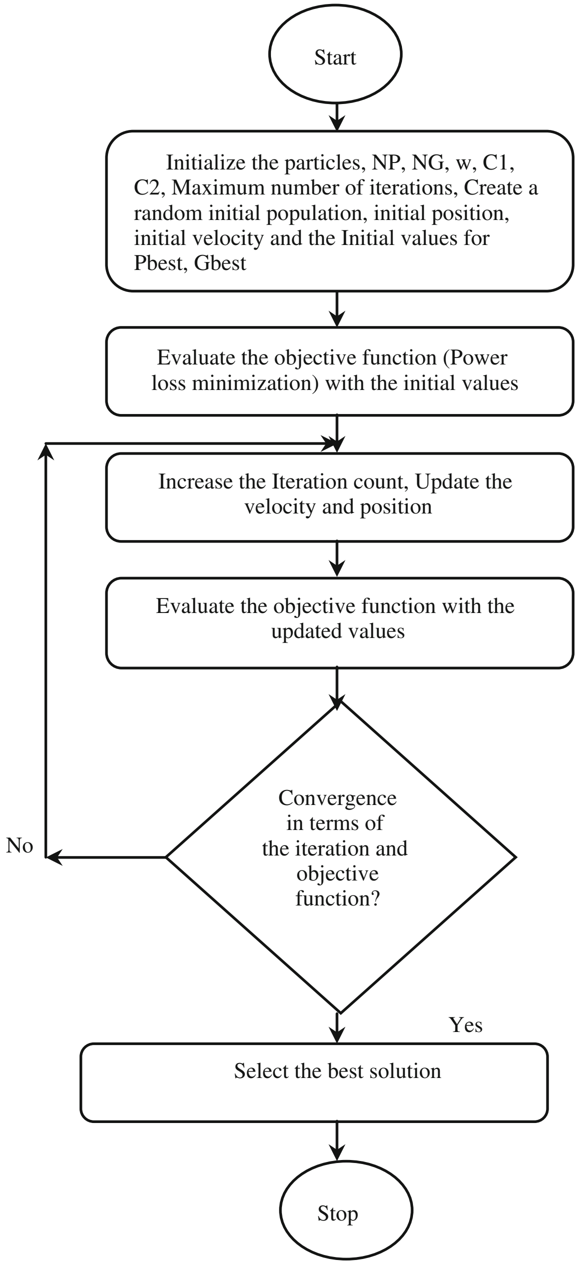

Table 3 Result of voltage magnitude profile for load flow (FBS method) and PSO without DG

Bus no	Voltage in p.u[a] without PSO and DGs (load flow)	Voltage in p.u[a] with PSO and without DGs	Bus no	Voltage in p.u[a] without PSO and DGs (load flow)	Voltage in p.u[a] with PSO and without DGs	Bus no	Voltage in p.u[a] without PSO and DGs (load flow)	Voltage in p.u[a] with PSO and without DGs
1	1.0000	1.0000	12	0.9177	0.9911	23	0.9793	0.9832
2	0.9970	0.9965	13	0.9115	0.9632	24	0.9726	0.9500
3	0.9829	0.9770	14	0.9092	0.9800	25	0.9693	0.9500
4	0.9754	0.9860	15	0.9078	0.9721	26	0.9475	0.9934
5	0.9679	0.9888	16	0.9064	0.9703	27	0.9450	0.9900
6	0.9495	0.9695	17	0.9044	0.9510	28	0.9335	0.9603
7	0.9459	0.9826	18	0.9038	0.9639	29	0.9253	0.9620
8	0.9323	0.9500	19	0.9965	0.9924	30	0.9218	1.0500
9	0.9260	0.9595	20	0.9929	0.9500	31	0.9176	0.9500
10	0.9201	0.9590	21	0.9922	0.9805	32	0.9167	0.9657
11	0.9192	0.9971	22	0.9916	0.9670	33	0.9164	0.9931

[a]p.u-per unit

constraints. The bus voltages are given in Table 3. The real power loss calculated from the load flow is 210.9 kW.

Case (ii) Power Loss with PSO and without DGs

The objective function of minimizing the real power loss has been determined by particle swarm optimization method in the radial network with the voltage constraints. The voltages are being improved by this algorithm. Even though this

Table 4 Result of voltage magnitude profile for PSO without and with DG

Bus no	Voltage in p.u[a] PSO without DGs	Voltage in p.u[a] PSO with DGs	Bus no	Voltage in p.u[a] PSO without DGs	Voltage in p.u[a] PSO with DGs	Bus no	Voltage in p.u[a] PSO without DGs	Voltage in p.u[a] PSO with DGs
1	1.0000	1.0000	12	0.9911	0.9911	23	0.9832	0.9833
2	0.9965	0.9965	13	0.9632	0.9637	24	0.9500	0.9500
3	0.9770	0.9770	14	0.9800	0.9804	25	0.9500	0.9500
4	0.9860	0.9860	15	0.9721	0.9725	26	0.9934	0.9970
5	0.9888	0.9889	16	0.9703	0.9705	27	0.9900	0.9900
6	0.9695	0.9699	17	0.9510	0.9532	28	0.9603	0.9609
7	0.9826	0.9843	18	0.9639	0.9643	29	0.9620	0.9625
8	0.9500	0.9500	19	0.9924	0.9925	30	1.0500	1.0500
9	0.9595	0.9600	20	0.9500	0.9500	31	0.9500	0.9500
10	0.9590	0.9594	21	0.9805	0.9807	32	0.9657	0.9665
11	0.9971	0.9971	22	0.9670	1.0204	33	0.9931	0.9963

[a]p.u-per unit

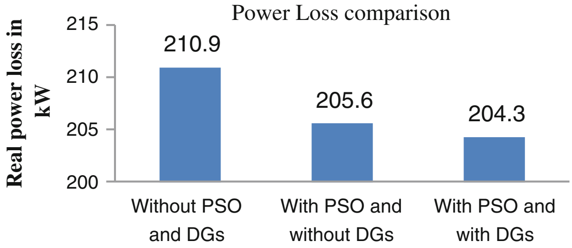

Fig. 3 Comparison of real power loss

algorithm gives unique result for every run due to the selection of random numbers in the velocity, the real power loss is always less than the value obtained from normal load flow. The average real power loss determined by this method is 205.6 kW. The voltage profile is given in Table 4.

Case (iii) Power loss with PSO and with DGs

In the third case, the distributed generators of three sources are considered. The DGs are placed randomly at three buses in the network. A wind turbine is connected at bus 32. Solar panel of series and parallel combinations is connected at bus 21. Fuel cell stack is connected at bus 25. The ratings of all DGs are calculated from the given specifications. After introducing DGs in the network, the real power loss has been reduced to 204.3 kW. The voltage profile is also improved a lot (Fig. 3).

9 Conclusion

In this paper, the real power loss has been minimized using PSO which has maximized the power flow of the network. Due to the introduction of the DG at specified buses, the power losses have been further reduced. The implementation of PSO algorithm and the incorporation of DG in the system reduce the real power loss from 2.51 % (Reduction in real power loss of PSO compared to load flow) to 3.12 % (Reduction in real power loss of PSO and DGs compared to load flow). Hence, the power flow is also maximized.

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