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Optimum Power Flow by using Interior Point Optimization Method

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Abstract

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The electric power industry is mainly responsible to ensure the high-quality, reliable, and economical operation of power systems by defining the limits and constraints of power system equipment. This paper uses the interior-point method to solve the nonlinear OPF problem. This method adjusts optimum values of OPF control variables, including the generator's active and reactive power output, with the objective function of minimizing total system losses. The interior-point method has been analyzed on a standard IEEE-14 bus test system using optimum power flow/unit commitment tools of DIgSILENT/Powerfactory. The analyses are conducted for alternating current (AC) power flow analysis and optimum power flow analysis, which represent Case 1 and Case 2, respectively. The results indicate that the total losses of the power system are reduced from 13.39 MW to 2.31 MW with the proposed algorithm.

Keywords: optimum power flow, optimization methods, interior point method, power system network

1. Introduction

Power system engineers concentrate on OPF which provides an efficient solution for power system planning and operation. The main objective of OPF is to minimize operational costs and power system losses with reliable and uninterruptible electricity [1]. To maintain reliable and uninterruptible electricity, OPF should satisfy all equality constraints: the bus real and reactive power balance, the set points of generator voltage, the megawatt interchange of area, and inequality constraints. The constraints consist of the flow limits of the transmission line/transformer, active and reactive power limits of the generator, and the bus voltage magnitudes [2].

In this paper, the OPF problem is solved using the interior point method in optimum power flow/ unit commitment tools of DIgSILENT/Powerfactory to minimize total system losses. The proposed method is implemented in the IEEE-14 bus. To illustrate the performance of the optimization algorithm, the obtained results are compared with the AC power flow case. The main contributions of the present research are explained as follows:

- The interior point optimization method for the OPF problem is applied to minimize power system losses in DIgSILENT/Powerfactory
- The application to the standard IEEE test system is performed. Thus, the capability of the proposed method is acquired.
- Technical and economic objective functions for the tested power system are explained.

The paper is organized as follows: In section two, the methodology of OPF is presented. In section three, the OPF study of the IEEE-14 bus system is realized using interior-point and AC optimization methods. In section four, the results are compared for the IEEE-14 bus system. Finally, a brief conclusion is presented in section five.

2. Optimum Power Flow

In the literature, gradient-based method [3], nonlinear and quadratic programming [4], linear programming (LP) [5] and interior-point methods (IPM) [5]–[7], Genetic algorithm (GA) [1]–[8], glowworm swarm optimization[9], sine cosine algorithm [8]–[9], artificial bee colony algorithm [12]–[15], adaptive charged system search algorithm[16], Particle swarm optimization (PSO) [17]–[20], are used to solve OPF problem. Conventional methods such as the gradient-based method or LP are susceptible to points of starting and usually converge local optimum. LP methods are fast but have a disadvantage due to utilizing only linear objective functions. The disadvantage of NLP is that it has a complex algorithm. Methods based on modern optimization techniques such as GA, PSO, artificial be colony algorithm, and sine/cosine algorithm produce better results thanks to the robust and parallel algorithm for the OPF problem.

The OPF techniques are realized to determine the optimum operating state of the power system satisfying all operational and physical constraints. OPF is defined as complex nonlinear mathematical programming. The OPF problem involves some controllable variables to get desired operating conditions [20]. The main objective of OPF is to ensure specific objectives, such as minimizing losses and generator costs by optimizing control variables. The OPF problem can be mathematically stated as follows:

$$\text{minimize: } f\ (x,u) \tag{1}$$

$$\text{subject to: } g(x,u)=0 \tag{2}$$

$$h(x,u)\leq 0 \tag{3}$$

where f(x,u) is the total losses function of the power system which needs to be optimized, g(x,u)=0 is the equality constraint presenting the load flow equation, h(x,u)≤0 is the inequality constraint presenting state variable limit. The "u" vector comprises of independent variables or control variables, and the "x" vector consists of dependent variables or state variables. State variables are shown in (1).

$$[x]^T = [V_{L1} \ldots . V_{LN}, P_{G1}, S_{L1} \ldots .. S_{LM}] \tag{4}$$

V_{L1}: bus voltage

P_{G1}: slack bus active power

S_L: transmission line loading

Control variables are shown in (5)

$$[x]^T = [P_{G1} \ldots P_{GZ}, Q_{G1} \ldots .. Q_{GZ}] \tag{5}$$

P_G: generator active power

Q_G: generator reactive power

Z: number of total generators

N: number of buses

M: number of transmission line

P: number of transformers

2.1 Equality Constraint:

Active and reactive power balance usually describes as the equality constraints at each load bus as shown in (6) and (7).

$$\sum P_s=0 \tag{6}$$

$$\sum Q_s=0 \tag{7}$$

where "s" is net power injection, P_s and Q_s describe net active and reactive power injection at *s*th bus

2.2 Inequality Constraint:

In the OPF, inequality constraints express the upper and lower limit of all variables: generator active and reactive power, bus voltage, transformer tap ratings, and transmission line flow. These constraints are given in from (7) to (12)

$$P_{Gkmin} \leq P_{Gk} \leq P_{Gkmax} \qquad \text{k=1}\cdots\cdots\text{Z} \tag{8}$$

$$Q_{Gkmin} \leq Q_{Gk} \leq Q_{Gkmax} \qquad \text{k=:1}\cdots...\text{Z} \tag{9}$$

$$V_{kmin} \leq V_{k} \leq V_{kmax} \qquad \text{k=1}\cdots\cdots\text{N} \tag{10}$$

$$T_{tmin} \leq T_{t} \leq T_{tmax} \qquad \text{t=1}\cdots\cdots.\ \text{P} \tag{11}$$

$$|\emptyset_{ij}| \leq \emptyset_{ijmax} \tag{12}$$

$$|\emptyset_{ji}| \leq \emptyset_{ijmax} \tag{13}$$

P_{Gkmin}: minimum active power limit of the kth generator
Q_{Gkmin}: minimum reactive power limit of the kth generator
P_{Gkmax}: maximum active power limit of the kth generator
Q_{Gkmax}: maximum reactive power limit of the kth generator
V_{kmin}: minimum voltage level limit of kth bus
V_{kmax}: maximum voltage level limit of kth bus
$\emptyset_{ijmax}$: maximum flow limit transmission line
T_{kmin}: minimum tap ratio limit of the kth transformer
T_{kmax}: maximum tap ratio limit of the kth transformer

2.3 Interior Point Method

The basic principle of the IPM is the implementation of a logarithmic barrier function that enables the incorporation of inequality constraints in the objective function. In that way, inequality constraints are indirectly considered. The objective function is updated with a logarithmic function. The barrier function is as follows:

$$f(x,u,z)= f(x,u,z)- z\sum_{k=1}^{n_h} ln\ (-h_k(z)) \tag{14}$$

Where z >0 is the parameter of the barrier. The logarithmic function provides that h(z)<0. For effective minimization of the objective function, z is decreased monotonically to zero. The IPM consists of a five-step process which are initial guess, computing variable directions, updating variables reducing the barrier parameter, and convergence test[21].

3. Optimum power flow study

OPF problem is solved using the interior point method. The results were obtained through IEEE 14 bus test system in DIgSILENT/Powerfactory.

The main parameter of the IEEE 14 bus test system is given in Table I. In the IEEE 14 bus test system, transmission line impedance data are presented as per unit value. It is required that these values must convert the real value to the model transmission line in DIgSILENT/Powerfactory. So these data are converted as real impedance values by taking 100 MVA base power and related bus voltage and are given in Table 2a and Table2b.

Table 1: Parameters of IEEE-14 bus test system

Bus	Bus Voltage (pu)	The angle of bus voltage	Active power of load (MW)	Reactive power of load(MVAR)	Active power of generator(MW)	Reactive power of generator(MVAR)	Shunt Capacitance(pu)
1	1.060	0.0	0.0	0.0	232.4	-16.9	0.0
2	1.045	-4.98	21.7	12.7	40.0	42.4	0.0
3	1.010	-12.72	94.2	19.0	0.0	23.4	0.0
4	1.019	-10.33	48.8	-3.9	0.0	0.0	0.0
5	1.02	-8.78	7.6	1.6	0.0	0.0	0.0
6	1.070	-14.22	11.2	7.5	0.0	12.2	0.0
7	1.062	-13.37	0	0	0.0	0.0	0.0
8	1.090	-13.36	0	0	0.0	17.4	0.0
9	1.056	-14.94	29.5	16.6	0.0	0.0	0.19
10	1.051	-15.10	9	5.8	0.0	0.0	0.0
11	1.057	-14.79	3.5	1.8	0.0	0.0	0.0
12	1.055	-15.07	6.1	1.6	0.0	0.0	0.0
13	1.050	-15.16	13.5	5.8	0.0	0.0	0.0
14	1.036	-16.04	14.9	5	0.0	0.0	0.0

Table 2a: The impedance value of the transmission line and transformer

Line from Bus – to Bus	**Resistance Ω**	**Reactance Ω**	**Susceptance µS**
1-2	3.69	11.268	277.253
1-5	10.289	42.476	258.349
2-3	8.949	37.701	229.994
2-4	11.066	33.578	178.534
2-5	10.846	33.114	181.685
3-4	12.761	32.571	67.213
4-5	2.542	8.019	0
6-11	1.13	2.367	0
6-12	1.463	3.045	0
6-13	0.787	1.551	0
9-10	0.379	1.006	0
9-14	1.513	3.218	0
10-11	0.977	2.286	0
12-13	2.63	2.379	0
13-14	2.0345	4.142	0

Table 2b: The impedance value of the transmission line and transformer

Transformer from bus to bus	**Resistance Ω**	**Reactance (pu)**	**Tap setting value (pu)**
4-7	0	0.20915	0.978
4-9	0	0.55618	0.969
5-6	0	0.25202	0.932
7-8	0	0.17615	0
7-9	0	0.11001	0

Case-1: The IEEE 14 bus test system, established in DIgSILENT/Powerfactory, is shown in Figure. 1. The test system consists of 5 thermal generators, 1 shunt capacitor, and 11 loads. The total load is 259 MW and 73.5 MVAR. In that case study, the AC power flow analysis is carried out. The Newton-Raphson method (power equation) is used as its nonlinear equation solver for AC power flow [22].

Case-2: In that case study, the interior point optimization method is used as its nonlinear equation solver in the optimum power flow/ unit commitment tool of the power factory for the OPF study using the IEEE 14 bus test, which is simulated in Case-1. While control variables of the interior point method are active and reactive power dispatch of the generator, constraints are active and reactive power limits of the generator, branch flow limits, and bus voltage limits.

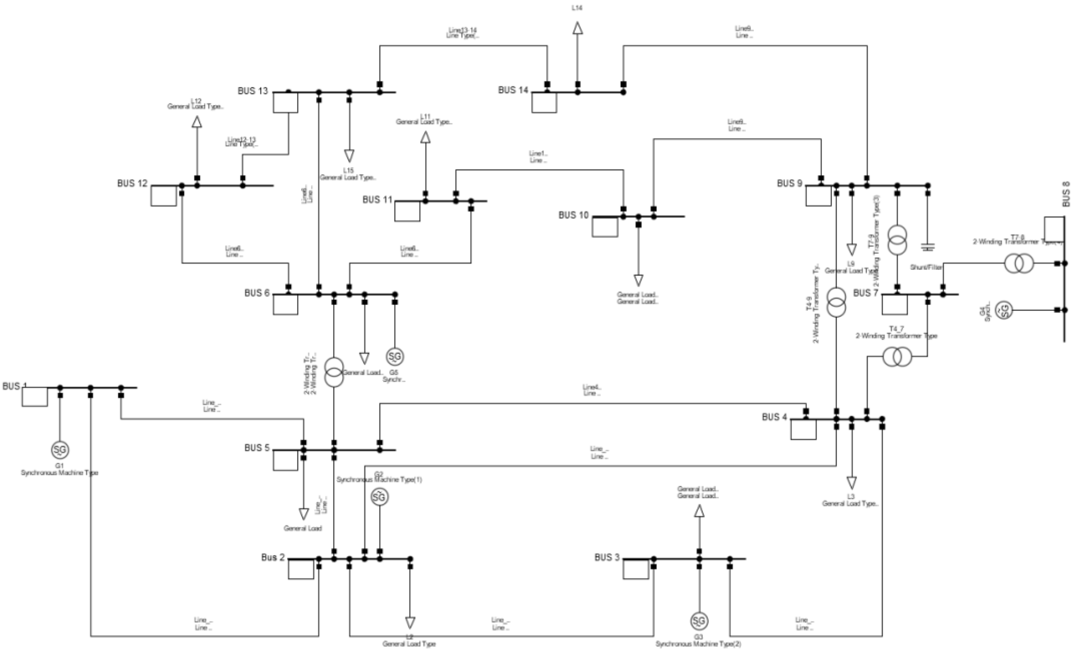

Figure 1: IEEE 14 bus test system in DIgSILENT

4. Result and discussion

The voltage value of buses for Case-1 and Case-2 are given in Table III. According to the optimum power flow case, the nominal voltage values of buses for Bus 5-14 get closer rated bus voltage. The voltage value of Bus-8 is 1.09 pu in case of AC load flow (case-1) which is close upper limit voltage value (1.1 pu). When the OPF is applied to the tested power system, the voltage level of Bus-8 is 1.01 pu. Hence, the power system can be operated more reliably.

Table 3: Bus voltages values

	Case-1		Case-2	
Bus	Bus voltage (pu)	Angle of bus voltage	Bus voltage (pu)	Angle of bus voltage
1	1.060	0.0	1.06	0.0
2	1.045	-4.98	1.05	-0.13
3	1.010	-12.72	1.03	-2.35
4	1.019	-10.33	1.02	-2.81
5	1.02	-8.78	1.02	-2.49
6	1.070	-14.22	1.03	-6.53
7	1.062	-13.37	1.02	-2.16
8	1.090	-13.36	1.01	3.19
9	1.056	-14.94	1.03	-5.10
10	1.051	-15.10	1.02	-5.66
11	1.057	-14.79	1.02	-6.62
12	1.055	-15.07	1.02	-7.29
13	1.050	-15.16	1.01	-7.22
14	1.036	-16.04	1.0	-7.09

The loading level of the transformer is given in Table IV. The transformer loading level depends on produced active power of generators. As the produced active power of generators changed, the transformer loading level altered as shown in Table 4. Thus, Transformers 5-6 and 7-8 have the highest loading levels in Cases 1 and 2, respectively. For both case studies, the transformers are operated within limit values.

Table 4: Transformer loading level

Transformer from bus to bus	Case-1 (%)	Case-2 (%)
4-7	28.43	11.15
4-9	15.3	8.95
5-6	41.92	38.30
7-8	15.91	54.48
7-9	27	47.81

The loading level of generators is given in Figure. 2. The loading level of Generator 2-4 increased in case of OPF (case-2). Generators 1 and 3 have the highest loading levels in Case-1 and Case-2, respectively. All generators are operated within limit values.

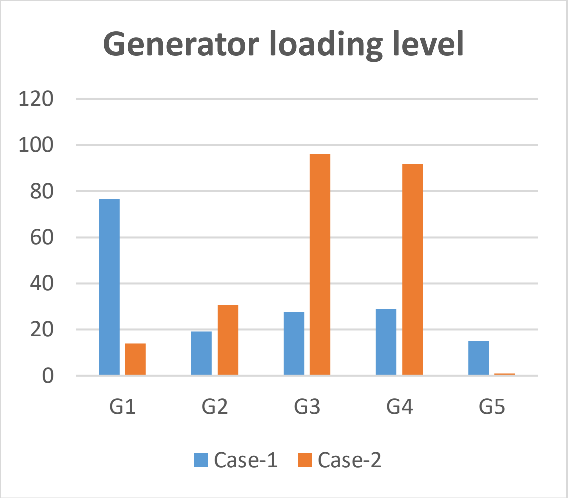

Figure 2: Generator loading level

The loading level of transmission lines is given in Table V. When OPF is applied to the power system, the active power of generators is changed, and it affects the transmission line loading level as shown in Table 5. The loading level of Line_1-2, Line_1-5, and Line_2-3 are significantly decreased in case-2 thanks to OPF. So, the overloading of the transmission line can be prevented in case of load increase.

Table 5: Transmission line loading

Name	**Case-1 %**	**Case-2 %**
Line_10-11	3.87	5.05
Line_12-13	1.68	1.32
Line_13-14	5.59	3.17
Line_4_5	62.34	13.24
Line_6-11	7.58	5.16
Line_6-12	7.63	7.20
Line_6-13	17.8	15.52
Line_9-10	6.42	12.82
Line_9-14	9.58	14.18
Line_1-2	74.59	10.57
Line_1-5	71.38	27.79
Line_2-3	70.18	21.58
Line_2-4	53.76	30.82
Line_2-5	39.83	28.72
Line_3-4	23.86	9.9

Total active power, total reactive power, and total losses are given in Table VI for both cases. The total losses of the tested power system decreased from 13.39 to 2.31 MW thanks to OPF. The total produced active power of generators is reduced. Hence the power system can be operated economically.

Table 6: Comparison of results

Parameter	Case-1 (MW)	Case-2 (MW)
Total active power generation	272.39	261.31
Total load	259	259
Total losses	13.39	2.31

5. Conclusion

In this paper, a general overview of the OPF problem is presented. A standard mathematical formulation containing the formulation of the OPF problem as well as the objectives and constraints are represented. The interior point method has been successfully applied to the standard IEEE-14 bus test system to minimize total system losses. The AC power flow and OPF which uses the interior method optimization method are simulated using the optimum power flow/unit commitment tool of DIgSILENT/Powerfactory. The results are compared in terms of losses, loading of generator and transmission lines, and bus voltages. The total system losses are reduced from 13.39 MW to 2.31 MW. For future work, IPM can be implemented in real power systems thanks to simplicity to minimize total system losses. Also, metaheuristic methods, genetic algorithms, particle swarm optimization, and ant colony optimization can be applied to solve multi-objective optimization problems that include OPF and the economical operation of the power system.

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Contribution of Researchers

Conceptualization, Y.Y. and Ö.Ç.; methodology, Y.Y. and Ö.Ç.; software, Y.Y.; validation, Y.Y., Ö.Ç. and A.T: writing original draft preparation, Y.Y., Ö.Ç and A.T; writing review and editing, A.T. and K.Ç.B, supervision, A.T. and K.Ç.B; All authors have read and agreed to the published version of the manuscript.”

Conflicts of Interest

We have no conflicts of interest to disclose.

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