Transmission Expansion Planning With Wind Power Plant Using Differential Evolution Algorithm

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Abstract

Nowadays modern electric power systems consist of large-scale and highly complex interconnected transmission systems, thus transmission expansion planning (TEP) is now a significant power system optimization problem. The TEP problem is a large-scale, complex and nonlinear combinatorial problem of mixed integer nature where the number of candidate solutions to be evaluated increases exponentially with system size. In recent years differential evolution algorithm (DE) procedures have been attracting significant attention from the researchers as such procedures have been found to be extremely effective in solving power system optimization problems. In this paper, the TEP problem has been investigated in static form. In addition, one cases of the static TEP problem, without generation resizing, have also been investigated. The proposed method has achieved solutions with good accuracy, simple implementation and satisfactory computation time. The analyses have been performed within the mathematical programming environment of MATLAB using DE a detailed comparison has also been presented.

Keywords— *AC power flow, Differential Evolution, Garver's 6 bus system and Transmission Expansion Planning.*

Introduction

Electric energy is the most popular form of energy because it can be transported easily at high efficiency and reasonable cost. Nowadays the real-world electric power systems are large-scale and highly complex interconnected transmission systems. An electric power system can be subdivided into four major parts that are generation, transmission, distribution and load [1-3]. The purpose of a transmission system is to transfer electric energy generating units at various locations to the distribution systems that ultimately supply the load. Transmission lines that also interconnect neighboring utilities permit economic power dispatch across regions during normal conditions as well as the transfer of power between regions during emergency. Over the past few decades, the amount of electric power energy to be transferred from generation sites to major load areas has been growing dramatically. Due to increasing costs and the essential need for reliable electric power systems, suitable and optimal design methods for different sections of the power system are required. Transmission systems are a major part of any power system therefore they have to be accurately and efficiently planned. In this report, electric power transmission systems are studied with regard to optimizing the transmission expansion planning (TEP) problem [2]. Electric power transmission lines are initially built to link remote generating power plants to load centers, thus allowing power plants to be located in regions that are more economical and environmentally suitable. As systems grew, meshed networks of transmission lines have emerged, providing alternative paths for power flows from generators to loads that enhance the reliability of continuous supply. In regions where generation resources or load patterns are imbalanced, transmission interconnection eases the requirement for additional generation [5]. Additional transmission capability is justified whenever there is a need to connect cheaper generation to meet growing load demand or enhance system reliability or both.

Problem formulation

In general, transmission expansion planning problem can be mathematically formulated by using DC power flow model, which is a nonlinear mixed-integer problem with high complexity, especially for large-scale real-world transmission networks. There are several alternatives to the DC model such as the transportation, hybrid and disjunctive models.

The objective of transmission expansion planning is to minimize investment cost while satisfying operational and economic constraints. In this research, the classical DC power flow model is applied to solve the TEP problem. Mathematically, the problem can be formulated as follows.

$$\min v = \sum_{(i,j)\in w} c_{ij} n_{ij} \qquad (1)$$

where v, cij and nij represent, respectively, transmission investment cost, cost of a candidate circuit for addition to the branch i-j and the number of circuits added to the branch i-j. Here is the set of all candidate branches for expansion.

Problem constraints

The objective function represents the capital cost of the newly installed transmission lines, which has some restrictions. These constraints must be included into mathematical model to ensure that the optimal solution satisfies transmission planning requirements. These constraints are described as following

Kirchoff's current law

This optimization is constrained by Kirchhoff's current law, which requires that the total power flowing into a node must be equal to the total power flowing out of the node:

$$A^o F_p^o - P_p + D_p = 0 \quad \forall p = 1,....,np \qquad (2)$$

where A^o is the node–branch incidence matrix for the intact system(initial network), F_p^o is the vector of transmission line flows for the intact system during demand period p, Pp is the vector of nodal generations for demand period p, and Dp is the nodal demand vector for period p.

Kirchoff's voltage law

The Kirchhoff's voltage law implies the constraint that relates flows and injections

$$F_p^o = H^o\left(P_p - D_p\right) \quad \forall p = 1,....,np \qquad (3)$$

where, H^o is the sensitivity matrix for the intact system.

Transmission line flows

The thermal constraints on the transmission line flows have also to be satisfied:

$$-T \le F_p^o \le T \qquad \forall p = 1,....,np \qquad (4)$$

where, T is the vector of transmission line capacities, and p corresponds to each one of the np periods in the load duration curve. It should be noted that the constraints in equations (2) to (4) have been derived using a dc power flow formulation neglecting losses.

Output of the generators

The optimization must respect the limits on the output of the generators

$$P^{\min} \le P_p \le P^{\max} \quad \forall p = 1,....,np \qquad (5)$$

where, Pmin is the vector of minimum nodal generations and Pmax is the vector of maximum nodal generations.

Differential evolution algorithm

DE is a population-based stochastic search algorithm that works in the general framework of evolutionary algorithms. The various operations of DE are initialization, mutation, crossover and selection.

Initialization

The first step of DE optimization process is initialization of population. In initialization process all candidates are randomly generated as a real valued number within its corresponding feasible bounds using the expression

$$X_{ij}^{G} = X_i^{\min} + rand_i[0,1] \times (X_i^{\max} - X_i^{\min}) \qquad (6)$$

i =1, 2,….D and j=1,2,…NP

where, NP is number of population and D is number of decision parameter of the problem. $X_i^{\min}$ and $X_i^{\max}$ are the lower and upper bounds of the decision parameter i, respectively. randi [0, 1] represents a uniformly distributed random value in the range (0,1).

Mutation

During mutation, three random vectors are selected from current population. The mutation is carried out on randomly selected vector X_{r1}^{G} with the difference of two other randomly selected vectors X_{r2}^{G} and X_{r3}^{G}. The mutation vector is generated using equation (7).

$$V_i^{G} = X_{r1}^{G} + F \times (X_{r2}^{G} - X_{r3}^{G}) \qquad (7)$$

where F is scaling factor, which is typically chosen from within the range [0, 1].

Crossover

The next step of DE optimization process is crossover. In this step, by applying crossover operation between target vector and mutant vector a trial vector $U_i^{(G)}$ is created according to a selected probability distribution

$$U_i^{(G)} = U_{j,i}^{(G)} = \begin{cases} V_{j,i}^{(G)} & if \quad rand_j(0,1) \le CR \\ X_{j,i} & otherwise \end{cases} \qquad (8)$$

The crossover constant CR is a user-defined value (known as the “crossover probability”), which is usually selected from within the range [0, 1]. The crossover constant controls the diversity of the population and aids the algorithm to escape from local optima. randj is a uniformly distributed random number within the range (0, 1).

Selection

Selection is the final operation of DE procedure. This operator compares the fitness of the trial vector and the corresponding target vector and selects the one that provides the better solution. This selected vector is then treated as target vector for next iteration.

$$X_i^{(G+1)} = \begin{cases} U_i^{(G)} & if \quad f(U_i^{(G)}) \le f(X_i^{(G)}) \\ X_i^{(G)} & otherwise \end{cases} \qquad (9)$$

Implentation of DE to TEP

Primal Static Transmission Expansion Planning

The general fitness function of the static TEP problem can be formulated as follows:

$$F_s = \frac{1}{O_s(x) + w_1 p_1(x) + w_2 p_2(x)} \qquad (10)$$

Fs(X) and Os(X) are fitness and objective functions of the static TEP problem, respectively. P1(X) and P2(X) are equality and inequality constraint penalty functions respectively. X denotes individual vector of decision variables. 1 and 2 are penalty weighting factors, which are set to “0.5” in this study. For the static TEP problem, the objective and penalty functions are as follows.

$$O_s = V(X) = \sum_{(ij)\in\Omega} c_{ij} n_{ij} \tag{11}$$

$$P_1(X) = \sum_{k=1}^{nb} \left| d_{kB_k} \theta_{kk} \right| \tag{12}$$

$$P_2(X) = \sum_{l=1}^{nc} \mu_1 \tag{13}$$

µl is the penalty coefficient of the l-th inequality constraint. c is an inequality constraint constant that is used if an individual violates that inequality constraint. In this study, c is set to 0.5. nb and nc represent the number of buses in transmission system and the number of considered inequality constraints, respectively.

Simulation results

This section presents the details of the simulation study carried out on Garver’s 6 bus system for transmission expansion planning using proposed approach. The data for Garver’s 6 bus system are given in appendix. The simulation studies were carried out by developing program on MATLAB R2013a and MATPOWER 4.1 software.

It consists of 5 buses in which 3 buses are load bus and 2 buses are generator bus. The data for generator, load and branch data are given in appendix. Figure 1 shows power flow result for existing network and Figure 2 shows network with future loads and generating units. The existing power system with future loads and new generation is shown in Figure 2. Each load is assumed to be four times the present values. Two 120 MW units have been added at bus 3 and new bus 6 with three new units each have capacity of 120 MW,240 MW, 240 MW respectively has been established.

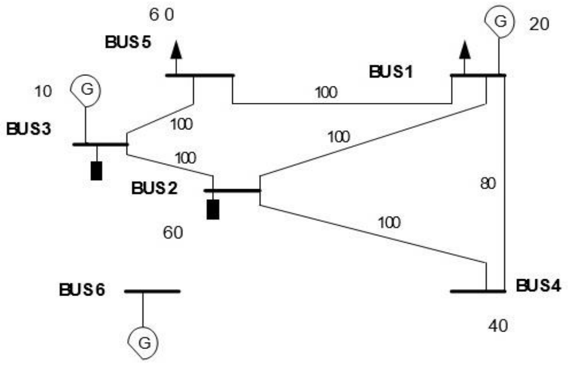

Figure 1. Generation and transmission system

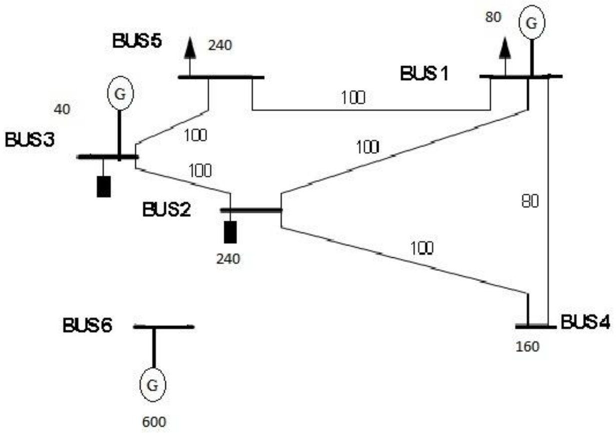

Figure 2. Network with future loads and generating units

Table 1. NETWORK POWER FLOW RESULT

Branch #	From Bus	To Bus	From Bus P(MW)	Injection Q(MVAr)	To Bus P(MW)	Injection Q(MVAr)	LOSS P(MW) Q(MVAr)	
1	1	2	16.24	1.38	-16.00	-0.41	0.241	0.96
2	1	4	22.99	2.65	-22.26	0.26	0.729	2.92
3	1	5	14.90	-0.21	-14.80	0.61	0.101	0.40
4	2	3	-62.05	-1.08	63.86	8.33	1.811	7.25
5	2	4	18.04	1.50	-17.74	-0.26	0.308	1.23
6	3	5	46.14	4.36	-45.20	-0.61	0.938	3.75
						Total	4.128	16.51

Table 2. NETWORK WITH FUTURE LOADS AND GENERATING UNITS POWER FLOW RESULT

Branch #	From Bus	To Bus	From Bus P(MW)	Injection Q(MVAr)	To Bus P(MW)	Injection Q(MVAr)	LOSS P(MW) Q(MVAr)	
1	1	2	144.94	-11.99	-125.76	88.73	19.185	76.74
2	1	4	107.07	-35.78	-89.73	105.14	17.339	69.36
3	1	5	216.93	34.29	-195.05	53.21	21.875	87.50
4	2	3	-81.86	50.90	85.62	-35.85	3.763	15.05
5	2	4	-8.09	-46.42	9.88	53.61	1.798	7.19
6	3	5	37.96	46.49	-36.38	-40.20	1.573	6.29
						Total	65.534	262.13

Table 3. SYSTEM EXPANSION USING DE

S.NO	NEW LINE ADDED	NO OF PARALLEL PATH	COST×103 (US$)
1	2-6	2	60
2	3-5	2	40
3	4-6	3	90
4	5-6	1	61
TOTAL COST			251

Table 4. SYSTEM EXPANSION USING POWER FLOW RESULTS

Branch #	From Bus	To Bus	From Bus P(MW)	Injection Q(MVAr)	To Bus P(MW)	Injection Q(MVAr)	LOSS P(MW) Q(MVAr)	
1	1	2	-2.79	15.54	3.02	-14.63	0.226	0.90
2	1	4	-22.99	15.72	24.05	-11.50	1.056	4.22
3	1	5	43.02	15.72	-42.17	0.98	0.842	3.37
4	2	3	6.58	2.38	-5.78	42.47	0.802	3.21
5	2	4	-30.19	-39.26	31.16	-2.97	0.970	3.88
6	2	6	-109.70	6.85	119.90	14.72	10.196	38.24
7	2	6	-109.70	23.52	119.90	14.72	10.196	38.24

8	3	5	43.59	23.52	-42.69	-9.36	0.903	3.61
9	3	5	43.59	12.97	-42.69	-9.36	0.903	3.61
10	3	5	43.59	12.97	-42.69	-9.36	0.903	3.61
11	4	6	-71.74	4.82	75.83	10.54	4.096	15.36
12	4	6	-71.74	4.82	75.83	10.54	4.096	15.36
13	4	6	-71.74	4.82	75.83	10.54	4.096	15.36
14	5	6	-69.76	27.09	77.71	5.22	7.947	32.32
						Total	47.233	181.2

Network with wind loads and generating units power flow results

The existing power system with future loads and new generation is shown in Figure 3. Each load is assumed to be four times the present values. Two 120 MW units have been added at bus 3 and new bus 6 with three new units each have capacity of 120 MW,240 MW, 240 MW respectively has been established. Figure 3 shows power flow result for existing network future load and generation. Figure 3 infers that it satisfies power flow equation but the first three lines are overloaded to alleviate this overload the system to be expanded.

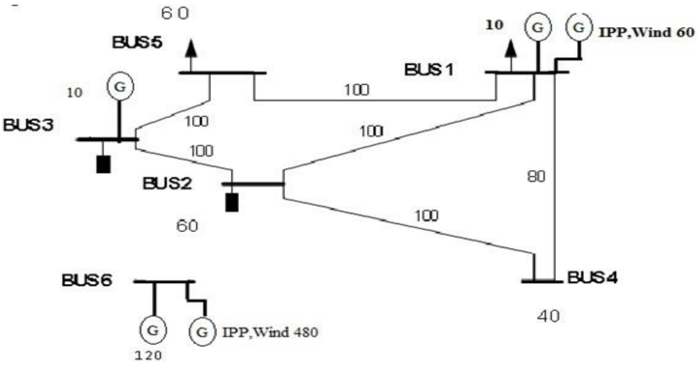

Fig. 3 Power flow result for existing network future load and generation

SYSTEM EXPANSION WITH WIND USING DE

S.NO	NEW LINE ADDED	NO OF PARALLEL PATH	COST×103 (US$)
1	2-6	2	80
2	3-5	2	60
3	4-6	3	100
4	5-6	1	81
TOTAL COST			321

The achieved results of Graver's system using proposed approach are presented in Table VII. These results are then discussed as follows:

In this case, the optimal solution of the static TEP problem was found by DE. The investment cost of this optimal solution equals to v = $251,000 with the following topology: n2-6 = 2, n3-5 = 2 and n4-6 = 3, n5-6 = 1

From the results it is identified that all overloaded are alleviated and new lines power flow limit are also within the limit.

NETWORK WITH FUTURE LOADS AND GENERATING UNITS POWER FLOW RESULT

Branch #	From Bus	To Bus	From Bus P(MW)	Injection Q(MVAr)	To Bus P(MW)	Injection Q(MVAr)	LOSS P(MW)	Q(MVAr)
1	1	2	144.94	-11.99	-125.76	88.73	19.185	96.74
2	1	4	107.07	-35.78	-89.73	105.14	17.339	100.36
3	1	5	216.93	34.29	-195.05	53.21	21.875	97.50
4	2	3	-81.86	50.90	85.62	-35.85	3.763	15.05
5	2	4	-8.09	-46.42	9.88	53.61	1.798	17.19
6	3	5	37.96	46.49	-36.38	-40.20	1.573	20.29
						Total	62.563	347.13

NETWORK WITH FUTURE LOADS AND GENERATING UNITS POWER FLOW RESULT

Branch #	From Bus	To Bus	From Bus P(MW)	Injection Q(MVAr)	To Bus P(MW)	Injection Q(MVAr)	LOSS P(MW)	Q(MVAr)
1	1	2	-2.79	15.54	3.02	-14.63	0.226	0.90
2	1	4	-22.99	15.72	24.05	-11.50	1.056	4.22
3	1	5	43.02	15.72	-42.17	0.98	0.842	6.37
4	2	3	6.58	2.38	-5.78	42.47	0.802	6.21
5	2	4	-30.19	-39.26	31.16	-2.97	0.970	3.88
6	2	6	-109.70	6.85	119.90	14.72	20.196	38.24
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8	3	5	43.59	23.52	-42.69	-9.36	0.903	7.61
9	3	5	43.59	12.97	-42.69	-9.36	0.903	3.61
10	3	5	43.59	12.97	-42.69	-9.36	0.903	3.61
11	4	6	-71.74	4.82	75.83	10.54	10.096	20.36
12	4	6	-71.74	4.82	75.83	10.54	4.096	20.36
13	4	6	-71.74	4.82	75.83	10.54	4.096	15.36
14	5	6	-69.76	27.09	77.71	5.22	7.947	37.32
						Total	67.233	201.2

Conclusion

Cost-effective transmission expansion planning (TEP) is a major challenge for electrical power system optimization as its main objective is to obtain the optimal expansion plan that meets technical requirements while offering economical investment. In this paper, the TEP problem has been investigated in static form. In addition, one cases of the static TEP problem, without generation resizing, have also been investigated. The proposed method has achieved solutions with good accuracy, simple implementation and satisfactory computation time. The analyses have been performed within the mathematical programming environment of MATLAB using DE a detailed comparison has also been presented. The simulation results have shown demonstrated the good compromise between the effectiveness and computational efforts of the proposed method.

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