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Sub-transmission Expansion Planning with Attendance of Wind Farms

Mohammad Hossein Abedi* , **Mohammad Sadegh Sepasian***, **Davood Farokhzad****
*Department of Electrical and Computer Engineering, Power and Water University of Technology
** Iran Grid Management Company

ABSTRACT

The energy from fossil-fuelled units is considered to be replaced gradually with renewable sources like wind energy. In this study we propose a new method for expansion planning of sub-transmission system with attendance of wind farms. Using wind energy associated with the conventional expansion planning needs a proper model for uncertainty of wind farms. The proposed method comprises two stages. In the first stage, a probabilistic model for wind farm output power is developed using Markov reliability model. In the second stage, genetic algorithm is used to find the optimal number of wind turbines in windward substations and best configuration of lines among the candidate ones. Evaluation of the method has been done on a typical sub-transmission system and the results confirmed that using this procedure has much more profits including economical, fossil-fueled energy saving and reliability benefits.

Keywords: *expansion planning, wind farm, Markov reliability model, sub-transmission system, genetic algorithm*

NOMENCLATURE

ns	Number of substations
n_{ij}	Number of new circuits at corridor i-j
cl_{ij}	The cost of line installed in corridor i-j ($)
fs	Number of wind farm power steps
nw	Number of windward substations
p_{ki}	Probability of kth power level of ith wind farm
C_{ti}	Transformer installation cost at ith substation
n_{tik}	Number of transformers installed at ith substation in kth power level
C_{si}	Substation installation cost at ith new substation
S_{ksi}	Capacity of substation installed at ith new substation in kth power level
C_w	Wind turbine installation cost ($)
n_{iw}	Number of wind turbines at ith substation
h	Horizon year
nu	Number of transmission substations
nl	Number of load levels
P_{idt}^{G}	Imported power to sub-transmission system from ith transmission substation in dth load level in tth year (MW).
P_{iwt}	Imported wind power to sub-transmission system from ith substation in tth year (MW).
T_d	Duration of dth load level (hr).
K_{dt}^{G}	Electricity price of the transmission system in the load level d in tth year ($/MW-hr)
K_{wt}	Operational cost of wind farm including the cost of maintenance and reparation in tth year ($/MW-hr)
rfl	Reserve factor for line

$P_{ij,d}$	Flowing power at corridor i-j in the load level of d (MW).
$P_{ij}^{\max}$	Maximum capacity of corridor i-j (MW).
rfs_i	Reserve factor for ith substation
S_{si}	Capacity of ith substation (MW).
P_{si}	Loading of ith substation (MW).
n_{ij}^{0}	Number of existing circuits at corridor i-j.
$n_{ij}^{\max}$	Maximum permissible number of circuits at corridor i-j.
$n_{w\ \max}$	Maximum number of wind turbines in wind farm
P_i^G	Active power of ith substation (MW).
P_i^D	Load demand of ith substation (MW).

1. INTRODUCTION

Sub-transmission system is part of an electric power transmission network which is between transmission and distribution networks and connects energy sources in the extra high voltage transmission network to medium voltage load points. As the consumption of the loads increases, the existing sub-transmission network must be expanded to remain adequate and be able to reliably feed the distribution network [1]. The aim of sub-transmission system expansion planning (SSEP) is to propose network fortification and new installations to minimize the total cost in the horizon year with adequate reliability [2]. Over the last few years, several researches are done on network expansion. A multi-stage procedure and GA (Genetic Algorithm) is used in [3] for routing the feeders and locating the substations; the minimum expansion cost is obtained considering constraints such as voltage drop, feeders' capacity and radial configuration of network. [4] uses GA to choose new substations among the candidate ones and to upgrade the existing substations. The loads have been regarded as fuzzy to model the uncertainty in the load forecast and for the sake of long-term planning. In [5] mathematically model of the effects of distributed generation on expansion planning of sub-transmission system is obtained which gives the optimal capacity of substations; optimal location and capacity of distributed generations as well as optimal configuration of sub-transmission lines using GA and Linear Programming (LP).

On the other hand, higher fuel costs, tax credits, and better wind turbine generator technology at megawatt scale have hipped up considerable interests in wind power [6]. Contribution of wind energy to electrical power generation has grown rapidly in many power systems. Wind turbine generators have reached a size of 5 MW and wind farms are planned at a size of more than 500 MW [7]. Some studies of using wind energy in power systems have recently been addressed [8-12]. The effects of distributed wind turbines at a wind farm are studied in [8]. In [9] output power correlation of distant wind farms for different periods of time is discussed. Long-term social benefits of wind energy have been estimated in [10]. A frequency and duration based approach is utilized to model a wind farm as a multistate conventional unit, where the probability and transition rates of each state can be calculated using the wind regime data of wind farm and wind turbine characteristics [11]. [12] proposes a method to evaluate a wind farm project unifying cost reduction in transmission system losses, load delivery point interruption and generating units operation while respecting composite system reliability analysis in the presence of wind power.

This paper intends to develop a new method for network expansion planning with aim of extracting optimal energy from windward substations. First, Analytic approach using Markov reliability model has overcome difficulties associated with calculating wind farm probabilistic output power. The effects of using wind farms on the SSEP have been evaluated. Problem description and mathematical modeling of the method is discussed in section IV and V respectively. This problem has been modeled from viewpoint of electric companies as a static planning. In the proposed objective function the fix and variable costs and constraints including reliability ones related to the network and operation of substations and wind farms are considered.

Solution algorithm of the problem is described in section VI. The optimal number of wind turbines and also the optimal configuration of lines for supplying the load of sub-transmission system are determined so that the total cost of expansion plan is minimized. The proposed objective function and its constraints, compose an optimization problem which is solved using genetic algorithm (GA) and linear programming (LP). At last in sections VII and VIII, the effectiveness of the proposed method is shown by its application on a typical sub-transmission system and the results are compared with SSEP without using the wind energy.

2. WIND POWER ANALYSIS

2.1 Wind Turbine Output Power Model

The output power of the wind turbines depends on the wind speed characteristics as well as on the availability of the electrical generator. These factors are given by the turbine manufacturer, designated as power curve of the turbine [11]. The wind unit starts delivering electrical output at the cut-in speed and reaches the rated output at a wind speed called the rated speed. The electrical output is held constant at the rated value for further increases in wind speed by suitably control up to the cut-out speed, beyond which the unit is shutdown for safety reasons. Between the cut-in and the rated speeds, the relationship between the wind speed and the electrical output is non-linear due to the combined effects of aero-turbine and generator characteristics [6]. Mathematical expression of "speed-power" curve is given by

$$P_t = \begin{cases} 0 & 0 \le v < V_{ci} \\ \left[A + B \times v + C \times v^2\right] \times P_r & V_{ci} \le v < V_r \\ P_r & V_r \le v < V_{co} \\ 0 & V_{co} \le v \end{cases} \qquad (1)$$

Where A, B, and C are constants and determined based on parameters of wind turbine. A typical V80-2MW wind turbine electrical output curve is shown in Fig. 1 with cut-in, rated, and cut-out speeds of 4, 15, and 25 m/s, respectively [13].

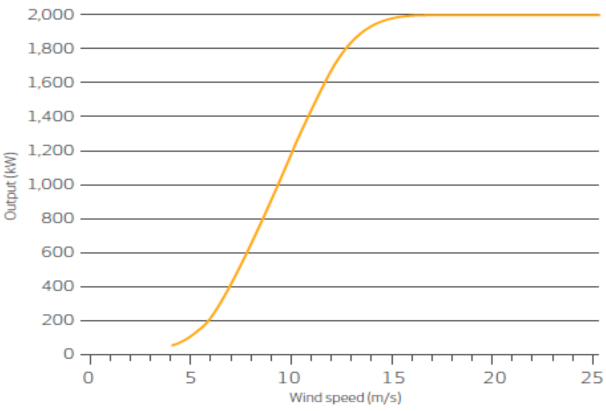

Fig. 1. Power curve of V80-2 MW Turbine

Each unit's FOR is assumed to be 4%. Output power of the turbine can be split into finite states e.g. 0, 0.5, 1, 1.5, and 2MW steps. After turning statistical data of wind speed to power outputs, the probability of each state is calculated on basis of abundance of them. Table I Shows power levels and probability of each state for a high speed wind statistical data with 11m/s mean speed. Number of steps depends on the required model accuracy.

Table I. Probability of each output power level for a single wind turbine

State	Output Power Level	Probability
1	$0 \le P_t \le 0.25$	0.42250
2	$0.25 \le P_t \le 0.75$	0.09721
3	$0.75 \le P_t \le 1.25$	0.06350
4	$1.25 \le P_t \le 1.75$	0.06444
5	$1.75 \le P_t$	0.35225

2.2 Wind Farm Output Power Model

A wind farm consists of various identical wind turbines. Wind farm Markov model associated with N_t turbines considering FOR of single turbines is shown in Fig. 2. λ_{ij} is the transition rate (in occurrences per hour). The transitions rates between some states are not shown completely for the sake of clarity. After merging identical states, we can calculate probability of new power levels for wind farm. Table II gives probability amounts of 5 state power levels for a wind farm containing $N_t = 10$ turbines.

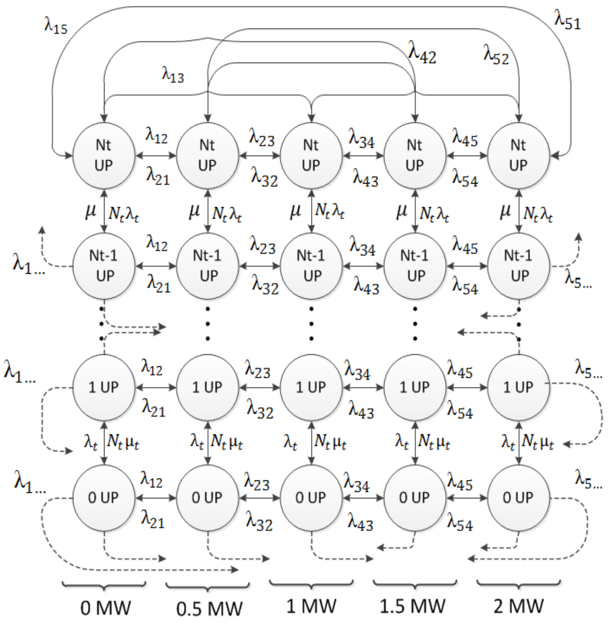

Fig. 2. Markov model for output power of a wind farm containing N_t wind turbines

Table II. Probability of Each Output Power Level for a wind farm

State	Output Power Level	Probability
1	$0 \le P_t \le 2.5$	0.42250
2	$2.5 \le P_t \le 7.5$	0.09761
3	$7.5 \le P_t \le 12.5$	0.06710
4	$12.5 \le P_t \le 17.5$	0.08102
5	$17.5 \le P_t$	0.33176

3. PROBLEM DESCRIPTION

3.1 Components of Expansion Planning Cost

Providing demanded energy to supply system load with minimum total cost is the aim of sub-transmission expansion planning considering wind farms with respect to the constraints of the problem as reliability ones. Unknowns of the problem contain:

- Expanded capacity of existing substations
- Installed capacity of new substations
- Number of wind turbines in windward substations
- Capacity and location of new lines

These costs are divided into two parts. First part is fixed or investments cost such as land, transformer, line construction and wind turbine installation cost. The second part is variable costs including operation and maintenance costs of wind farm and also the cost of purchased power from the upward grid (Transmission network) [5].

3.2 Load Duration Curve Model

The model of system load is necessary to be known because the state of operation must be determined. Thus this model might not be their peak value but annual load variation must be considered. The substations' loads are modeled as three-level linear approximation of load duration curve (LDC) according to Fig. 3. Load forecasting studies can propose such curve from annual consumption precedence of system [14].

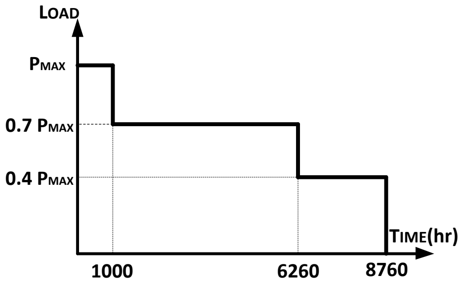

Fig. 3. Load-Duration Curve for substations' load

4. MATHEMATICAL MODELING AND CONSTRAINTS

4.1 Problem Variables

As noted, the participation degree of transmission network and wind farms in supplying system load must be determined. So there are three types of variables: Amount of supplied power by transmission network and wind farms in each load level; the size of wind farms and the new lines to be constructed.

4.2 Objective Function

Here is the mathematical model of the expansion planning problem:

$$OF = LC + SEC + SIC + WFIC + WFOC + EC \qquad (2)$$

Different parts of objective function are as follows:

4.2.1 Line Cost

The first part of the objective function indicates the cost of new lines construction between existing or new substations including sub-transmission or transmission substations.

$$LC = \sum_{i,j=1}^{ns} cl_{ij}.n_{ij} \qquad (3)$$

The cost of each line depends on its impedance, capacity, length and number of circuits.

4.2.2 Substation Expansion Cost

To calculate the cost of new transformers which are added to the existing substations we have:

$$SEC = \sum_{k=1}^{fs} \sum_{i \in nw} p_{ki}.C_{ti}.n_{tik} \qquad (4)$$

The effect of wind farm probability output power can be observed in decreasing number of transformers in the relevant substation.

4.2.3 Substation Installation Cost

The cost of installing new substation including transformers, equipment and land cost is given by:

$$SIC = \sum_{k=1}^{fs} \sum_{i \in nw} p_{ki} \, C_{si} \, . S_{ksi} \qquad (5)$$

Wind farm impact is considered such as previous part.

4.2.4 Wind Farm Installation Cost

The following is the cost related to installing wind farm at windward substations which depends on number of the wind turbines.

$$WFIC = \sum_{i \in nw} C_w \, n_{iw} \qquad (6)$$

4.2.5 Electricity Cost

By summing the cost of active power electrical energy which flows from transmission network in different load levels during the horizon year we have:

$$EC = \sum_{t=1}^{h} \sum_{i=1}^{nu} \sum_{d=1}^{nl} P_{idt}^{G} T_d K_{dt}^{G} \qquad (7)$$

4.2.6 Wind Farm Operating Cost

Approximately all of the cost of this part belongs to maintenance and reparation of wind turbines and other equipments [15].

$$WFOC = \sum_{t=1}^{h} \sum_{i \in nw} P_{iwt} K_{wt} \qquad (8)$$

4.3 Problem Constraints

The complete model of the problem requires series of constraints to be considered, including the following:

4.3.1 Reliability Limits

Deterministic Security Criterion (N-1) is applied to the lines, to prevent substations from islanding. Also loading of the lines in all levels must be less than maximum limit considering reserve factor for the lines.

$$\left| P_{ij,d} \right| \le (1 - rfl) \left| P_{ij}^{\max} \right| \qquad (9)$$

The next reliability constraint is that loading of each substation must be lower than maximum limit. To guarantee the reliability of substation loading, the reserve factor for the substations must be considered.

$$0 \le P_{si} \le (1 - rfs_i) S_{si} \quad i = 1, 2, \ldots, ns \quad S_{si} \in \Omega_i \qquad (10)$$

Where Ω_i is the set of installable capacities on the ith substation. When there is only one transformer is installed in the substation, reserve factor definition is not effective. Therefore, the possibility of single contingency on the transformers is regarded.

4.3.2 Line Construction Limit

Number of lines to be installed between substations must be fewer than maximum allowable lines in each corridor.

$$0 \le n_{ij} + n_{ij}^{0} \le n_{ij}^{\max} \qquad i, j = 1, 2, .., ns \qquad (11)$$

4.3.3 Substation Capacity Limit

Because of technical or geographical constraints there is a capacity limit to expand or install substations

$$0 \le S_{si} \le S_{si}^{\max} \qquad , i = 1, 2, \ldots, ns \qquad (12)$$

4.3.4 Wind Farm Size Limit

Margins of wind farm size obey following inequality in (13). Upper limit of wind farm size is due to the restrictions on equipment and land size, but the lower limit is used to prorate the cost between turbines.

$$n_{w \min} \le n_{iw} \le n_{w \max} \qquad iw \in nw \qquad (13)$$

5. PROBLEM SOLUTION ALGORITHM

GA is a random search method that can be used to solve non-linear systems of equations and to optimize complex problems [16]. The principle of this algorithm is according to the selection of individuals. It does not need a good initial estimation to solve the problem. In other words, the solution of a complex problem can be started from weak initial estimations and then be corrected in an evolutionary process of fitness. The standard genetic algorithm manipulates the binary strings that may be the solutions of the problem [17]. In the present study which deals with integer variables, we should use the decimal codification genetic algorithm (DCGA) instead of binary ones [18]. The chromosome includes two parts as shown in Fig. 4. First section indicates the value of ith gene which expresses the number of wind turbines on the ith substation. The value of each gene in the second part is the number of circuits of sub-transmission lines in the relative corridor.

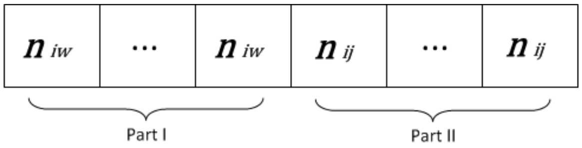

Fig 4. The structure of the chromosome

By decoding part I the optimal capacity and cost of expansion or installing the substations and also the number and cost of wind turbines corresponding to the windward substations are calculated. Decoding part II represents cost of installed new lines.

As we know operation cost of wind farms belongs to just maintenance and reparation. There is no way other than performing a linear programming to find out optimal power generation of wind farms and power purchased from the transmission network. Participation degree of wind farms in providing the energy of sub-transmission system must be determined. In order to find out this, in each iteration of GA, a linear programming optimization is performed. the linear objective function (LOF) which should be minimized, is sum of transmission network electricity cost and wind farm operating cost.

$$LOF = EC + WFOC \tag{14}$$

Subject to

$$P_i^G - P_i^D - \sum_{j=1}^{ns} P_{ij} = 0 \tag{15}$$

$$P_{ij} = \frac{\theta_i - \theta_j}{X_{ij}} \tag{16}$$

$$\left|P_{ij,d}\right| \le (1-rfl)\left|P_{ij}^{\max}\right| \tag{17}$$

As it is shown in (15) and (16), DC load flow is used to find out the power passing through the lines. Fig. 5 represents the proposed method in a flowchart.

6. NUMERICAL RESULTS

The proposed method is applied to the test system which its one-line diagram is shown in Fig. 6 in order to demonstrate its efficiency. The system includes nine substations at voltage of 63 kv. Three of them are the new installed ones, and have to be connected to the network. There are two high voltage transmission substation feeding the sub-transmission system at voltage 230/63 kv.

As mentioned before, the loads are given in three levels. The existing and candidate capacities of lines are 25 and 50 MVA, which are connected to sub-transmission and transmission substations. The mean speed of wind at the 5th, 7th and 8th substations is 8, 11 and 14m/s, respectively.

Other required test data are indicated in Table III.

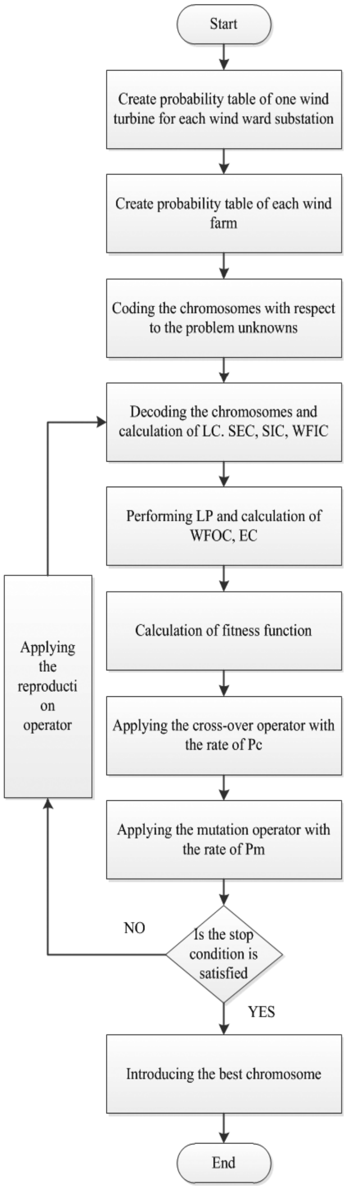

Fig. 5. The flowchart of the proposed approach

Table III. Economic data for the test

Parameter	Value
Electricity price in the first load level in first year of study ($/MW-hr)	50
Electricity price in the second load level in first year of study ($/MW-hr)	30
Electricity price in the third load level in first year of study ($/MW-hr)	20
Installation cost of one wind turbine ($)	1,000,000
Operational cost of wind farm ($/MW-hr)	5
Horizon year	10

Inflation rate (%)	10

To compare the effect of wind farms on the costs of expansion planning, two case studies are designed as follows:

1) Sub-transmission expansion planning in which the whole load are fed by transmission network

2) Sub-transmission expansion planning with attendance of wind farms which some of the loads are supplied by wind energy.

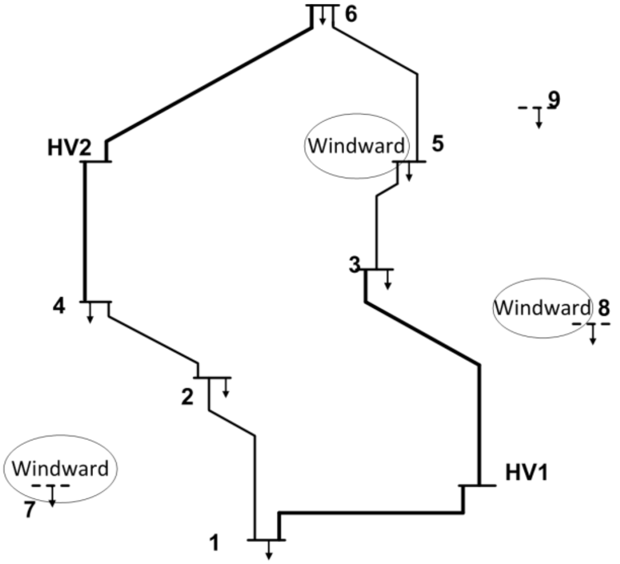

Fig. 6. The one-line diagram of the test network remarking windward substations

The test results including wind farm sizes and constructed lines are indicated in tables IV and V. It could be seen that the number of wind turbines in the bus which has better wind regime and more average wind speed, are more than others. Furthermore in the second case, the number of constructed line circuits, are less than the first one. Table VI compares the expansion planning cost between two cases. Because of supplying a part of demanded energy by wind farms, the capacity of substations which has to be expanded or installed, is decreased in the second case. The most important part of planning cost, related to the operational cost during the horizon year, is decreased very much for the sake of wind energy used in the system. Considering the total cost, the expansion planning of sub-transmission system with attendance of wind farms is much more economical.

Table IV. wind farm size at windward substation

Substation name	Capacity of wind farms (MW)
5	9
7	12
8	15

Table V. Constructed lines in two cases

Case 1			Case 2		
From bus	To bus	Capacity (MVA)	From bus	To bus	Capacity (MVA)
1	7	2×25	2	4	1×25
2	4	1×25	4	7	2×25
4	HV2	1×50	4	HV2	1×50
5	9	1×25	5	9	1×25
5	HV2	1×50	5	HV2	1×50
6	9	1×25	8	9	1×25
8	HV1	2×50	8	HV1	1×50

Table VI. Cost Comparison Between Two Cases

Parameter (M$)	**Case1**	**Case 2**
Existing Substations Expansion Cost	1.68	1.60
New Substations Installation Cost	16.5	14.22
Lines Construction Cost	32.17	29.1
Wind Farm Installation Cost	0	36
Total Operation Cost	438.34	369.53
Total cost	488.69	450.45

7. CONCLUSION

The presence of the wind has noticeable economic benefits for electrical companies. In this paper, the impact of wind energy as a new option for supplying the load of system, on the expansion planning of sub-transmission system was modeled mathematically and evaluated. The proposed model was expressed by an optimization problem and solved using genetic algorithm and the linear programming. The results for application of the proposed method on the test network showed that the use of wind farms in the expansion planning of sub-transmission system provides more economical plans and more fossil-fueled energy savings.

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