Network Investment Planning for High Penetration of Wind Energy under Demand Response Program

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Abstract— **The role of demand response becomes more crucial when there is a large penetration of intermittent renewable energy sources into the electrical grid. Flexible demand can be arranged to follow intermittent generation balancing demand and supply. Moreover, the transmission network where renewable energy resources are accommodated can constrain the capacity of green energy sources due to congestion or other operational problems. In this paper, a probabilistic approach using Monte Carlo simulation is proposed for transmission investment planning along with demand response schedule considering high penetration of wind energy resources. This work mainly aims to answer two questions i) What are the optimum transmission capacities? ii) With which consumers should the system operator negotiate to set load curtailment contracts? Several load levels for each of which consumers may have different load curtailment bids are taken into account. Also, the volatile nature of wind power is modeled in the form of normal distribution probability density functions. The correlation between outputs of wind farms exposed by a similar wind regime is considered. The transmission planning problem is modeled in the framework of a linear optimization problem. Furthermore, a nonlinear optimization process is used to analyze Monte Carlo results and calculate the most probable optimum amount of load curtailment at each bus. The whole approach is tested on the IEEE 24 bus test system.**

Keywords- Demand response, *optimal Transmission network expansion, Correlation, Mote Carlo Simulation.*

I. INTRODUCTION

One of the key challenges facing the world community is to minimize the amount of CO_2 generated in the production of electricity since CO_2 is thought to be a chief cause of global warming and hence climate change. In this regard, the European Commission has brought in a new legislation ordering that 20% of European Union's (EU's) energy consumption must be supplied from renewable energies by 2020[1] . For example the UK, as a member of the EU, has launched a move to dramatically increase the contribution of renewable energies to the total energy consumption from around 2% in 2008 to 15% by 2020 [2]. Among all renewable energy resources wind energy industry has been flourishing so that a significant proportion of future green energy has been planned to come from wind.

The majority of sites where wind power can be harnessed are far from the load centers, so these sites eventually should be connected to transmission network. A plan for integrating a considerable number of wind power plants distributed all over the network is usually associated with transmission network expansion planning. Transmission network plays a crucial role in facilitating the high penetration of wind energy resources. A transmission network suffering from network congestion or other security problems can simply impose a barrier to full exploitation of wind energy resources and consequently the future generation mix target will be unachievable. Transmission expansion, however, is a problematic issue due to difficulties in obtaining the right of way for constructing new overhead lines as well as the costly nature of these projects. Therefore, the main challenge is to find a transmission expansion plan requiring the minimum investment to both accommodate the future generation mix and meet security criteria.

Volatile available power is the main feature distinguishing wind energy from other conventional energy resources. Also, unlike conventional power plants which centrally generate a large amount of power, wind farms relatively generate less power, but they are distributed over the transmission network. Correlation between outputs of wind farms are another feature singling out the wind energy as a different energy source.

All aforementioned differences pose a need for a different approach for transmission network planning when a considerable amount of wind energy resources is integrated into the network. Obviously, conventional deterministic methods [3][4] which are traditionally used for transmission planning are no longer appropriate to deal with uncertainties stemming mainly from wind power intermittency. Instead, probabilistic approaches such as Monte Carlo [5], Fuzzy logic [6] and analytical methods [7] can be deployed to solve the problem. In this work, every wind farm's output is modeled in the form of a probability density function. Also, Monte Carlo simulation (MCS) is deployed to simulate a large number of possible generation scenarios with consideration of wind farms' outputs PDFs as well as correlation between wind farms' outputs.

Technology advancements along with new incentive policies

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facilitate demand response programs which are meant to enhance the active participation of consumers in the power system. Demand response programs can even be conceived as an alternative to generation and transmission expansion [8]. In a power system with a high level integration of intermittent energy resources, demand response can be an effective option to deal with a varying generation regime. Technically speaking, responsive demands enhance the flexibility of a network. Wind power can be accurately predicted for the next thirty minutes to an hour that gives operators enough time to either re-dispatch the generators or employ demand response options. To date, different demand response programs which generally can be categorized into price-based and incentive-based programs have been introduced to consumers [9]. In this paper, an incentive-based demand response program is taken into account the fact that consumers are willing to curtail the load providing their bid is accepted.

In this paper, a probabilistic approach using MCS is proposed to find the most probable optimal transmission network expansion along with optimum load curtailment schedule so that the proposed network is able to securely accommodate a high integration of wind energy. Due to the fact that consumers bid differently for the load curtailment in the course of the year, several load levels are considered as well as different bids for load curtailment at each load level for any bus.

The remainder of the paper organized as follows. In the next section, the problem formulations as well as all models used in this study are introduced. Numerical studies are produced in section III where the proposed algorithms are tested on the IEEE 24 bus test system. Some concluding remarks finally are made in section IV.

II. PROBLEM FORMULATION

In this work, the main aim is to find the optimal transmission network capacity along with the optimum generation dispatch as well as the amount of load curtailments which should be allocated to particular buses at particular load levels. In this section, conventional formulation of the transmission planning problem is introduced first, then assumptions, constraints and the whole methodology for solving the problem are elaborated.

A. *Conventional transmission planning problem*

The transmission investment planning problem is formulated in the framework of DC load flow which has been extensively deployed to solve the transmission planning problem [5][10]. In the framework of DC load flow, the transmission planning problem is a linear minimization which usually consists of two terms as shown by (1)

$$\underset{G_i^j, P_{\max i}}{Minimize} : \sum_{j=1}^{Np} D_j . \sum_{i=1}^{Ng} C_i . G_i^j + \sum_{i=1}^{N_l} T_{ci} . l_i . (P_{\max i} - P_{existing\_i}) \qquad (1)$$

Where:

D_j Duration of the load level j (hour)

C_i Incremental cost of generator i (€/MWh)

G_i^j Power generated by generator i at load level j (MW)

T_{ci} Annuitized investment cost of line i (€/km.MW.year)

l_i Length of transmission line i (km)

$P_{\max i}$ Capacity of candidate transmission line i (MW)

$P_{existing\_i}$ Existing capacity of line i (MW)

N_l Number of candidate transmission lines

N_p Number of load levels

N_g Number of generators

In the above optimization problem $P_{\max i}$, G_i^j are decision variables. The first term represents the generation cost while the second term represents the transmission investment.

The problem formulated in (1) is subject to Kirchhoff's first and second laws as formulated in (2) and (3), respectively.

$$\sum_{\forall i \in N_{gk}} G_i^j + \sum_{\forall i \in N_{lk}} P_i^j - L_k^j = 0 \quad k = 1,..., N_b \qquad (2)$$

$$P_i^j - \frac{(\theta_k^j - \theta_l^j)}{X_i} = 0 \quad i = 1,..., N_l \qquad (3)$$

Where

P_i^j Power flowing in transmission line i at load level j (MW)

L_k^j Load demand at bus k for load level j (MW)

N_{gk} Set of generators connected to bus k

N_{lk} Set of lines connected to bus k

N_b Number of buses

θ_k^j Voltage angle of bus k at load level j (radian)

X_i Reactance of transmission line i (p.u.)

Also, power system components' limits which are upper and lower limits on generation units as well as thermal ratings of transmission lines should be respected, as equated in (4) and (5)

$$G_{\min i} \le G_i^j \le G_{\max i} \quad i = 1,..., N_g \qquad (4)$$

$$-P_{\max i} \le P_i^j \le P_{\max i} \qquad i = 1,..., N_l \qquad (5)$$

The "N-1" security criterion should also be respected. Due to the fact that generators' outputs cannot usually change immediately generations' outputs are assumed to be similar for both intact and contingent network at the same load level. Therefore the whole optimization problem described above is subject to Kirchhoff's laws as well as power system components' limits for contingent networks as shown with (6) to (8).

$$\sum_{\forall i \in N_{gk}} G_i^j + \sum_{\forall i \in N_{lk}, i \neq c} P_i^{j(c)} - L_k^j = 0 \quad k = 1, \ldots, N_b \tag{6}$$

$$P_i^{j(c)} - \frac{\left(\theta_k^{j(c)} - \theta_l^{j(c)}\right)}{X_i} = 0 \qquad i = 1, \ldots, N_l \tag{7}$$

$$-P_{\max i} \leq P_i^{j(c)} \leq P_{\max i} \qquad i = 1, \ldots, N_l \tag{8}$$

$P_i^{j(c)}$ is the power following in the line i at load level j when a line c trips.

B. Wind power modeling and correlation

The main characteristic which makes wind power different from other conventional power plants is the intermittent nature of wind. New technologies allow forecasting of the changes in the wind speed for thirty minutes to an hour in advance, so system operator in a power system with a high integration of wind energy has enough time to optimally re-dispatch generation units or schedule a change in consumption in order to balance supply and demand. For planning purposes, wind speed is usually modeled with a Weibull probability density function (PDF), this model along with technical characteristic of the wind farm can be used to estimate the actual power output of wind farm [11]. In this work, however, just for the sake of simplicity a normal distribution for the wind farm's power output is assumed, as considered in [12]. A normal distribution which is usually described by an expected value (σ) and variance (ν) as shown by (9).

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{(x-\nu)^2}{2\sigma^2}} \tag{9}$$

In practice, however, the expected value as well as variance for a particular wind farm varies in the course of the. Therefore, for a practical approach, different wind characteristics are considered for every load level.

Another distinguishing feature of wind energy resources is the correlation between outputs of wind farms which are in the area with the same wind regime. In this work, a correlation matrix for wind resources is taken account so that the impact of level of correlation on the transmission planning problem and load curtailment schedule is investigated.

C. Demand Response

There is a high potential for flourishing demand response programs especially in the presence of high penetration of wind energy. Demand response, simply, can be a good substitution for power supply shortages when wind does not blow or even sometimes encourage consumers to consume more if an extra supply exists. Demand response programs embraces diverse strategies such as peak shifting, peak shaving, direct load curtailment control, price-based response etc [13]. In this work, the main focus is on direct load curtailment control program that system operator has a contractual authority to curtail the demand at the particular buses where when the system experience power supply shortage, overload or any other violence in the power system. Demand response programs should be considered in the stage when generation expansion or transmission expansion is planned so that a trade-off can be made between investment and demand response expenses. Therefore the cost of load curtailment should be incorporated into original transmission planning's objective function introduced by (1), the new objective function is as follows.

$$\underset{G_i^j,\, P_{\max i}}{Minimize} : \sum_{j=1}^{Np} D_j . \sum_{i=1}^{Ng} C_i . G_i^j + \sum_{i=1}^{N_l} T_{ci} . l_i . (P_{\max i} - P_{existing\_i}) + \sum_{j=1}^{Np} D_j . \sum_{i=1}^{Nb} B_i^j . DR_i^j \tag{10}$$

Where

DR_i^j is the load curtailment at bus i at load level j (MW)

B_i^j the consumer's bid for one MWh load curtailment at bus i at load level j (€/MWh)

In practice, it is hard to estimate the bid (B_i^j) in which consumers wish to join demand response program. There are some surveys and studies conducted to calculate the interruption cost of different types of consumers. The offer for load curtailment, however, should be higher than the amount covering consumers' interruption cost in order to encourage consumers for participation in demand response program. Moreover, in a real life scenarios interruption cost for a particular consumer may vary based on its actual load demand in different time of the year. Therefore, in this study, different bids are associated with each load level.

In order to incorporate responsive demand into the transmission planning problem, the power balance constraint which was introduced with (2), should be rewritten as presented with (11), also (12) expressing the boundary of load curtailment is introduced to the problem.

$$\sum_{\forall i \in N_{gk}} G_i^j + \sum_{\forall i \in N_{lk}} P_i^j - L_k^j + DR_k^j = 0 \quad k = 1, \ldots, N_b \tag{11}$$

$$0 \leq DR_k^j \leq L_k^j \tag{12}$$

D. Methodology

MCS is employed so that the transmission planning problem is solved for many different scenarios which are randomly generated taking into account the probability distribution function of wind generations as well as the correlation between wind farms. In this study, 2000 random generation scenarios are taken into account, so 2000 solutions for transmission expansion problem are proposed along with 2000 different load curtailment programs. Next, the statistical analyses as well as an optimization process are conducted to figure out the most probable optimum transmission capacity along with demand response action considering all those 2000 outcomes. This analysis, in the first stage, aims to find the most matched PDFs fitting to MCS's results for both transmission capacities and load curtailments. Based on the MCS's results transmission capacities are modeled in form of normal distribution functions whose expected values propose the required transmission capacities.

Load curtailments for each bus at any load level, however, are modeled with exponential distribution functions. In order to determine the most probable optimum load curtailments, an optimization should be carried out as explained in the following.

Step 1: A cumulative distribution function (CDF) for the total load curtailment at each load level is fitted into the MCS's results. The actual total load curtailment at load level j (LC^j_{total}) is calculated based on the aforementioned CDF as well as the degree of certainty (α) about total load curtailment which is usually set by the system planners. The relation between actual total load curtailment and degree of certainty can mathematically be expressed by (13).

$$\alpha = f^j_{total}(LC^j_{total}) = 1 - e^{LC^j_{total}/\mu} \qquad (13)$$
$$\therefore LC^j_{total} = \mu.Ln(1-\alpha)$$

Where $f^j_{total}()$ is the CDF for total load curtailment at load level j, and LC^j_{total} is the only argument of this function, μ is a parameter of CDF. In this work, a degree of certainty of 95% is assumed.

Step 2: A CDF is fitted to the MCS's results for load curtailment at each bus at any load level. It can be shown by (14).

$$\alpha^j_i = f^j_i(LC^j_i) = 1 - e^{LC^j_i/\mu^j_i} \qquad (14)$$

$f^j_i()$ the CDF for load curtailment at bus i at load level j, μ^j_i is the parameter of CDF. α^j_i is the probability of the need for the load curtailment less than LC^j_i at bus i at load level j.

Step 3: the best LC^j_i is determined through an optimization procedure so that the summation of all α^j_i is maximized while the summation of all load curtailments at load level j should be equal to LC^j_{total} which is calculated by (14). This problem can be formulated as follows.

$$\text{Maximize } \sum_{i=1}^{Nb} \alpha^j_i \qquad (15)$$

Subject to

$$\sum_{i=1}^{Nb} LC^j_i = LC^j_{total} \qquad (16)$$

$$\alpha^j_i = f^j_i(LC^j_i) \qquad (17)$$

III. Numerical Studies

The proposed algorithm is tested on the IEEE 24 bus test system which is shown in Fig 1. For every bus a load curve with ten load levels is considered. In Table I and Table II the original load and the percentage of load along with its duration at each load level are given, respectively.

Also, at each load level different PDFs for wind farms are assumed as shown in Table III. As can be seen in Table II the demands at load level 4 and 6 are equal so are load level 5 and 7. In Table III, however, different characteristics for wind farms at equal load levels are considered. The reason for that is to consider the fact that two identical load levels may represent the demands in two different times of the year when the wind regimes are different.

Every line except bus7-bus8 is considered as credible line outage.

TABLE I. THE ORIGINAL LOAD IN THE IEEE 24 BUS TEST SYSTEM

Bus #	Load (MW)	Bus #	Load (MW)
1	108	13	265
2	97	14	194
3	180	15	317
4	74	16	100
5	71	17	0
6	136	18	333
7	125	19	181
8	171	20	128
9	175	21	0
10	195	22	0
11	0	23	0
12	0	24	0

TABLE II. THE LOAD AND DURATION AT EACH LOAD LEVEL

Load level	1	2	3	4	5	6	7	8	9	10
Percentage of original load (%)	100	90	80	70	60	70	60	50	40	30
Duration (Hours)	400	500	600	800	800	1000	1000	1200	1200	1250

TABLE III. THE PDF CHARACTERISTICS OF WIND FARMS AT EACH LOAD LEVEL

	Load level									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Expected Value (σ)	30	30	35	35	35	20	20	20	20	20
Variance (v)	10	10	10	10	10	5	5	5	5	5

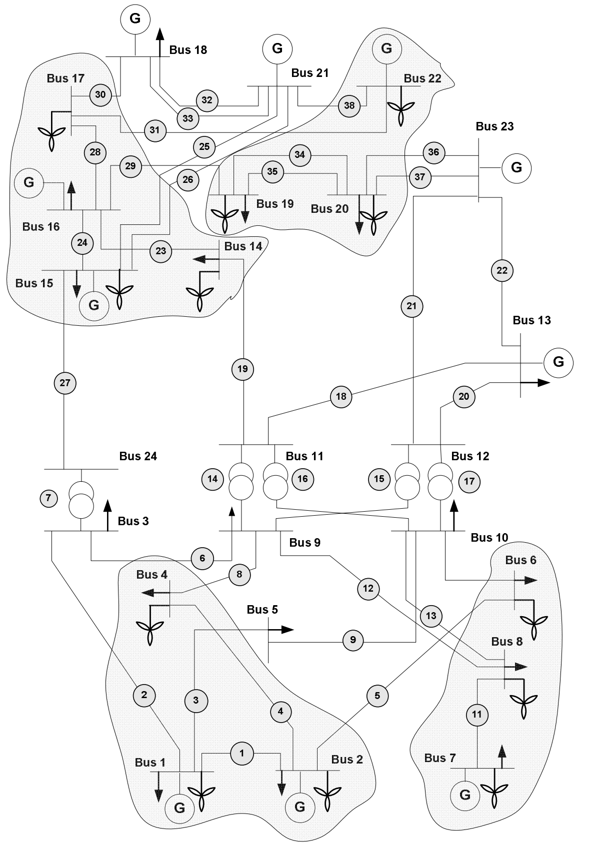

Figure 1. The schematic diagram of IEEE 24 bus test system

The consumers' bids for load curtailment at any load level, also, are produced in Table IV, and it is assumed that all consumers bid identically.

The wind plants capacities are set in a way that almost 20% of energy consumption comes from wind. The wind generation cost is simply neglected in order to achieve that level of wind integration whereas by using the proposed approach around 80% of total energy is economically dispatched among other generation types. The generation costs and maximum capacities of non-wind generations are shown in Table V.

TABLE IV. BIDS FOR LOAD CURTAILMENT AT EACH LOAD LEVEL

Load Level	1	2	3	4	5	6	7	8	9	10
Price (€/MWh)	65	65	65	55	55	55	50	50	45	45

TABLE V. GENERATION INFORMATION FOR THE 24 BUS NETWORK

Bus #	Generation Cost (€/MWh)	Max Capacity (MW)	Bus #	Generation Cost (€/MWh)	Max Capacity (MW)
1	45.2	200	18	35	300
2	45.2	150	21	35	300
13	51.2	300	22	51.2	300
15	50	150	23	40	300
16	40	150	23	45.2	300

Two studies are conducted so that, first, the optimal transmission capacities along with optimum load curtailments and generation dispatch are calculated while the wind energy resources are completely uncorrelated. Secondly, the same study is carried out but four uncorrelated wind regions in each of which wind farms have a 0.9 correlation are taken into account. Regions are shaded in the Fig. 1. From this point onwards these two studies are named Case I and Case II, respectively.

In this particular study, the best distribution which may be fitted to the optimal transmission capacities resulted from MCS with 2000 random scenarios is normal distribution. Therefore for every of 38 transmission lines shown in Fig. 1, a normal distribution PDF is estimated. The mean value of these normal distribution PDFs are the transmission capacities which are proposed for the transmission reinforcement plan. For both Case I and Case II, the optimal transmission capacities securely allowing 20% penetration of wind energy are illustrated in Fig. 2. As can be seen, in both cases almost the same transmission capacities are required. Therefore, in these particular cases, correlation between wind energy resources has a negligible effect on the transmission investment. Nonetheless, the amount of load curtailments is affected by correlation as discussed later in this section.

In the Fig. 3 the CDFs for total load curtailment in both cases are shown. In order to meet a 95% degree of certainty, 127 MW total load curtailment at the load level one (peak load) has to be planed if wind energy resources are uncorrelated – CASE I – whereas in the CASE II 148 MW load shed through demand response program should be scheduled.

MCS's results show there are five out of twenty four buses where negotiation for the demand response contract needs to be conducted. μ , the only parameter of the CDF of load shedding at each of those five buses is given in Table VI for Case I and Case II. Also, the optimal amount of load curtailment which is one of the facets in the demand response contracts is calculated by deploying the optimization procedure formulated with (15). These results are presented in Table VI. Also, Table VI shows the probability of the need for less than calculated amount of load curtailment at a particular bus. For example, in Case I, at bus 3 the optimal load curtailment at peak load is 18 MW. With a likelihood of 97%, however, this amount is the maximum load curtailment which is required at bus 3.

As shown in Table VI, different load curtailment programs are required for Case I and Case II although the demand response program should apply to the same buses in either case. It is expected that for the correlated wind energy resources a greater load curtailment is required as if wind does not blow in a region simply all wind turbines within that region are affected, so a considerable drop in available power resources occurs. The simulation, also, show the same fact as for Case II a more 21 MW load curtailment than Case I should be planned.

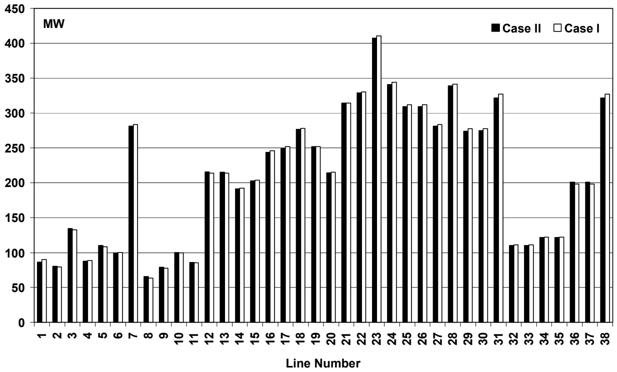

Figure 2. Optimum transmission capacities in Case I and Case II

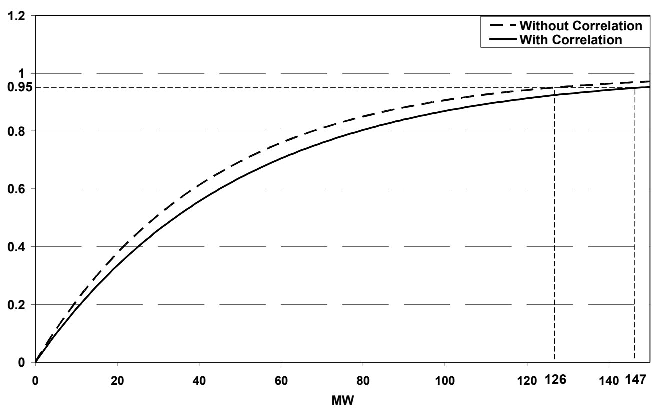

Figure 3. The CDF of total load curtailment in Case I and Case II

TABLE VI. THE OPTIMUM LOAD CURTAILMENT PROGRAM FOR CASE I AND CASE II

	Case I			Case II		
	μ CDF	*curtailed load (MW)*	*Probability*	*μ CDF*	*curtailed load (MW)*	*Probability*
Bus 3	0.05	18	0.98	0.06	23	0.98
Bus 6	0.08	27	0.96	0.07	26	0.97
Bus 7	0.18	44	0.91	0.17	48	0.93
Bus 8	0.05	19	0.97	0.05	20	0.98
Bus 10	0.05	19	0.97	0.09	31	0.96
Total Load curtailment (MW)		127			148	

IV. CONCLUSION

Responsive demand has the potential to play a crucial role in the next generation of more flexible and smarter power grids. In a power system with considerable amount of intermittent energy resources such as wind energy, demand response programs can be deployed to balance demand and supply in real time. Demand response programs can even substitute for generation and transmission network expansion. Therefore, the best time to consider demand response options is at the planning stage as some over investments may be averted.

In this paper, demand response was incorporated into the transmission planning problem for systems with a high penetration of wind energy. A probabilistic model for wind power was considered taking account of the correlation between wind farms exposed to the same wind regime. A probabilistic approach was proposed to find the most probable optimum plan for transmission investment as well as the load curtailment schedule. The effect of correlation between wind farms was also investigated. The proposed method was run on IEEE 24 bus system with 10 load levels and 37 credible line outages. Also, a probabilistic model for wind plants was considered. The optimum amount of transmission capacities were calculated as well as the optimum load curtailment schedule. Also, as results showed, the proposed method is able to determine the probability of the need for a particular amount of load curtailment at the particular bus. These results can give planners a practical insight of the shape and size of the transmission network of the future as well as required corrective actions in the presence of large amount of wind energy.

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