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Generator Rescheduling under Congested Power System with Wind Integrated Competitive Power Market

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Abstract: Integration of renewable energy like wind or solar energy creates a huge pressure to the system operator (SO) to ensure the congestion free transmission network under deregulated power market. Congestion Management (CM) with integration of wind farm in double auction electricity market are described in this work to minimize fuel cost, system losses and locational marginal price (LMP) of the system. Location of Wind Farm (WF) is identified based by using Bus sensitivity factor (BSF), which is also used for selection of load bus for double auction bidding (DAB). The impacts of wind farm in congested power system under deregulated environment have been investigated in this work. Modified 39-bus New England test system is used for demonstrate the effectiveness of the presented approach by using Sequential Quadratic Programming (SQP).

Keywords: Double auction bidding (DAB), Congestion Management (CM), Wind Farm (WF), Bus sensitivity factor (BSF), Locational marginal price (LMP), Sequential Quadratic program (SQP).

1. Introduction

The power transmission has been greatly affected after introduction of privatization and deregulation in power sector. The transaction in electricity has increased exponentially due to the competition in power market trading. GENCOs and DISCOs, in the deregulated power market, can independently or in pair transmit power. This may lead to a condition were an unanticipated direction, volume and length of power flow through the transmission networks. Such trade of power may not be accommodated by the present transmission network. As result congestion occurs in the system which may create violation of the system security also. Congestion is usually occurs in modern power system transmission line due to increase in electric power demand or line outage of the system [1].

In [2] optimal bidding strategy of a supplier has been discussed considering double sided bidding. It is very much essential to have maintained security of power system fairly for the continuity of power supply to the consumers with minimum price in deregulated market. Optimal bidding strategy for electricity suppliers under the congestion environment has been discussed in [3]. Bidding strategy is utilized to maximize the profit by using the Refined Immune Algorithm. Electrical market is settled based on the Locational marginal price (LMP) of the system. Optimal GENCOs bidding strategies of electricity market has been established by using Agent-based approach and numerical sensitivity analysis (NSA) technique [4].

The reference [5] describes the bidding strategy in a joint spinning reserve market and day-ahead energy market with integration of micro grid. The optimal cost of energy and spinning reserve bids are obtained by solving the bi-level bidding model using Interior point algorithm. The optimal bidding for the power market is depends on the bidding revenue, expected imbalance and operation cost. Paper [6] presents an auction based market for consumer payment minimization under pool based day-a-head electricity market. A bi-level programming method has been used to characterize locational marginal price. Demand side bidding strategies are applied in electricity market to minimize the cost of purchasing power [7-8]. Flexible AC Transmission System (FACTS) devices like TCSC and SSSC are used to maximize the social welfare in double sided auction market [9].

Wind energy sources have become one of the rapid increasing energy sources in the world. Wind power heavily relies on the environmental conditions, therefore produce unpredictable output power. The reference [10-12] narrates wind and hydro power generation plays an important role in deregulated electricity market. Three bidding strategies are used to formulate the day-ahead bidding model. In the paper [13] author consider the wind energy for congestion management.

The main contribution of this paper is to integrate wind farm considering double auction bidding in power market to minimize the congestion as well as minimize the LMP of the system. With considering the cost function, GENCOs and DISCOs are participating in the pool market and they are maximizing their generation as well as minimizing the overall generation cost of the system. Wind Farm (WF) position in the bus is identified based on the BSF value. In this paper, modified 39-bus New England test system is used as a test system for solving the proposed method.

2. Problem Formulation

The objective function of this problem is to minimize the total fuel cost of thermal generating unit, minimize congestion cost and investment cost of WF connected to the system. Consider N numbers of WF are installed in existing power system network. As a result, the proposed objective function consists of three terms. Mathematically, the objective function of the presented approach is as follows:

$$OF = \sum_{i=1}^{NG} C_i(P_{Gi}) + \sum_{j=1}^{NG} C_j(\Delta P_G) + \sum_{k=1}^{N} C_{WF}(k), \quad (1)$$

where NG is equal to the number of generators, NL is equal to the number of loads, $Ci(P_{Gi})$ is equal to the generating cost of thermal unit, $C_j(\Delta P_G)$ is equal to the congestion cost, C_{WF} is equal to the installation cost of the wind farm.

2.1. Constraint

Following two types of constraints are used in Optimal Power Flow.

2.1.1. Equality Constraint

2.1.1.1. Real Power Balance Equations

$$\sum_{i=1}^{NG} P_{Gi} + P_{WF} - P_{loss} - P_D = 0, \quad (2)$$

$$\sum_{i=1}^{NG} \Delta P_{Gi} = 0, \quad (3)$$

$$P_{loss} = \sum_{J=1}^{TL} G_J \left[|V_i|^2 + |V_j|^2 - 2|V_i||V_j| Cos(\delta_i - \delta_j) \right], \quad (4)$$

where P_G is equal to the active power generation of thermal generating unit, P_{WF} is equal to the total wind power generation of wind farm, P_{loss} is equal to the transmission loss, P_D is equal to the total load, T_L is equal to the number of transmission lines, G_J is equal to the conductance of the line between buses i and j, $|V_i|$ is equal to the voltage magnitude, δ_i is equal to the voltage angle

2.1.1.2. Power Flow Equations

$$P_i - \sum_{k=1}^{BN} |V_i V_k Y_{ik}| Cos(\theta_{ik} - \delta_i + \delta_k) = 0, \quad (5)$$

$$Q_i + \sum_{k=1}^{BN} |V_i V_k Y_{ik}| Sin(\theta_{ik} - \delta_i + \delta_k) = 0, \quad (6)$$

where P_i and Q_i are the injected active and reactive power into the system, BN is equal to the number of buses, Y_{ik} is equal to the bus admittance matrix connected between i^{th} row and k^{th} column, θ_{ik} is equal to the bus admittance matrix connected between i^{th} row and k^{th} column.

2.1.2. Inequality Constraint

2.1.2.1. Bus Voltage Limits

$$V_i^{\min} \le V_i \le V_i^{\max} \qquad i = 1, 2, 3, ...N, \quad (7)$$

where V_i^{min} is equal to the lower limit of bus voltage, V_i^{max} is equal to the upper limit of bus voltage, N is equals the number of buses.

2.1.2.2. Power Limit of Generators

$$Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad i = 1, 2, 3, ...N, \quad (8)$$

$$P_{Gi}^{\min} \le P_{Gi} + \Delta P_{Gi} \le P_{Gi}^{\max} \qquad i = 1, 2, 3, ...N, \quad (9)$$

where PG_i^{min}, PG_i^{max} is equal to the thermal unit minimum and maximum active power limit, QG_i^{min}, QG_i^{max} is equal to the thermal unit minimum and maximum reactive power limit.

2.1.2.3. Security Limit of Transmission Lines

$$\left|MVA\ \ flow_{i,j}^{0}\right| \le MVA\ \ flow_{i,j}^{0}\max_{0}\ \ \ MVA\ \ flow_{i,j}, i \ne j, \quad (10)$$

$$\left|MVA\ \ flow_{i,j}^{k}\right| \le MVA\ \ flow_{i,j}^{k}\max_{k}\ \ \ MVA\ \ flow_{i,j}, i \ne j, \quad (11)$$

where MVA $flow_{ij}$ max_0 and MVA $flow_{ij}$ max_k are represent the maximum power that can flow through the line connecting the buses i & j, during the pre-congestion and post congestion state.

2.1.2.4. Discrete Tap Setting of Transformer

$$T_i^{\min} \le T_i \le T_i^{\max} \qquad i = 1,2,3,......N \qquad (12)$$

2.1.2.5. Ramp Limit of Generators

$$P_{Gi} - P_{Gi}^{\min} = \Delta P_{Gi}^{\min} \le \Delta P_{Gi} \le \Delta P_{Gi}^{\max} = P_{Gi}^{\max} - P_{Gi}, \quad i = 1,2,3......N \qquad (13)$$

where PG_i^{min}, PG_i^{max} is equal to the thermal unit minimum and maximum active power limit.

2.2. Bus Sensitivity Factor (BSF)

Bus sensitivity factor for a congested line is calculated by using following formula [13].

$$BSF_k^l = \frac{\Delta P_{ij}}{\Delta P_k}, \qquad (14)$$

where ΔP_{ij} is equals to the change in real power flow of line k, BSF_k^l is equals to the change in active power flow in the congested line *l* due to active power injection at bus k.

The details derivation of BSF is given in [14].

3. Result and Discussion

The proposed concept has been illustrated on modified 39 bus New England Test System which is having 10 generators and 29 load buses. The data for 39 bus New England system has taken from ref [15]. In the proposed method violation on line 15-16 has been created due to the 14-34 line outages in the system. In this presented approach 50MW of WF power is connected based on the BSF value. It has been found from the reference paper [16] that the investment cost of wind power generator (for 1 MW capacity) is 3.75 $/hr (approx.). So for 50MW wind power cost 187.50 $/hr has been added to the bidding optimal cost of wind power condition. Two most sensitive bus i.e. one positive and one negative bus have been selected for analyzing the proposed method. Out of this two, one sensitive bus is selected for double auction bidding and another one is connected with wind farm. Congestion problem solves by using Sequential Quadratic programming (SQP) approach, which is also used for minimizing the fuel cost of the thermal generating unit.

Based on the bus sensitivity factor, here two cases are analyzed. Firstly, WF connected at bus number 14 and double auction bidding (DAB) at bus number 34 and secondly WF connected at bus number 34 and DAB at bus number 14.

In the present study, violation occurs in L 15-16 due to the line outage L14-34. So the line L15-16 is called congested line. Bus Sensitivity Factor (BSF) is calculated for congested line L 14-34 and some of the selected BSF value is shown in Table 1.

Table 1. Some selected BSF for congested line (15-16).

Bus No.	BSF	Bus No.	BSF
1	0	**22**	0.1543
2	-0.0334	**24**	0.1537
6	0.1547	**26**	0.0307
8	-0.0181	**28**	0.0325
9	0.0332	**30**	0.1539
12	-0.0379	**33**	0.2575
13	-0.0655	**34**	0.4196
14	-0.2536	**35**	0.2326
16	-0.0047	**37**	0.0796
20	0.1943	**39**	0.1538

Firstly, WF connected at bus number 14 and DAB has been done at bus number 34 with a load of 60MW and corresponding optimal power cost and losses are presented in Table 3.

Secondly, wind farm connected at bus number 34 and DAB has been done at bus number 14 with a load of 500MW and corresponding optimal cost and losses are presented in Table 5.

Table 2 shows the power flow through congested line before and after single auction bidding (SAB) and DAB with and without considering WF. From the result, it is seen that that after bidding active power flow through congested line (L 15-16) has reduced from the maximum level to reliable margin.

Table 2. Congested line power flow before and after bidding when WF is connected at bus No. 14.

Power Flow	Before SAB (MVA)	After SAB (MVA)	After SAB with WF (MVA)
L (15-16)	576.92	496.43	496.20
Power Flow	**Before DAB (MVA)**	**After DAB (MVA)**	**After DAB with WF (MVA)**
L (15-16)	576.92	496.43	496.93

Table 3 shows the optimal fuel cost of thermal generating unit with and without considering WF (bus No. 14) for SAB and DAB. From Table 3, it is seen that optimal generation cost with line outage using SAB is 42169.21 $/hr and losses is 54.715 MW, where as optimal generation cost with line outage by using DAB is 41399.62 $/hr and losses is 54.583 MW. From Table 3, it is also seen that optimal generation cost with line outage and with WF by using SAB is 41571.81 $/hr and losses is 52.586 MW, where as optimal generation cost with line outage and with WF by using DAB is 40798.26 $/hr and losses is 52.524 MW.

Fig. 1 shows the locational marginal price with and without considering WF at bus No. 14 and DAB at bus No. 34. It has been seen from Fig. 1 that LMP decreases with integration of WF compare to without WF in both SAB and DAB case.

Table 3. Optimal cost for SAB and DAB with and without presence of WF (bus No. 14) for 14-34 line outages.

Control Variable	Result reported [17]	SAB without line outage	SAB with line outage	SAB with WF and line outage	DAB with line outage	DAB with WF and line outage
PG1 (MW)	604.47	677.00	593.76	609.80	572.80	590.55
PG2 (MW)	646.00	689.42	737.20	715.24	733.09	711.74
PG3 (MW)	715.41	673.21	610.16	619.84	591.88	603.05
PG4 (MW)	652.00	646.73	652.00	648.04	651.41	641.23
PG5 (MW)	508.00	508.00	508.00	508.00	508.00	508.00
PG6 (MW)	687.00	657.45	670.48	658.63	662.30	651.55
PG7 (MW)	580.00	580.00	580.00	580.00	580.00	580.00
PG8 (MW)	564.00	564.00	564.00	564.00	564.00	564.00
PG9 (MW)	667.79	637.50	671.89	655.13	667.08	651.17
PG10 (MW)	674.44	669.10	721.46	698.14	718.26	695.48
Gen Cost ($/h)	41941.34	41932.73	42169.21	41571.81	41399.62	40798.26
Losses (MW)	44.88	48.180	54.715	52.586	54.583	52.524

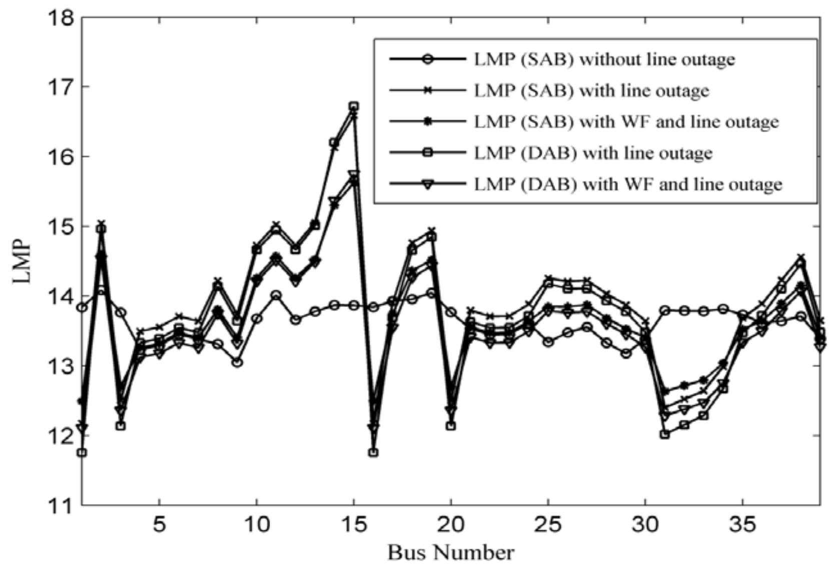

Fig. 1. Locational Marginal Price (LMP) with WF (bus No. 14).

Table 4 shows the power flow through congested line 15-16 before and after SAB and DAB with and without considering WF at bus No. 34. From this Table 4, it is observed that congested line power flow reaches very reliable margin with DAB case compare to SAB case.

Table 5 shows the optimal fuel cost of thermal generating unit with and without considering WF (bus No. 34) for SAB and DAB case. From Table 5, it is seen that optimal generation cost with line outage using SAB is 42169.21 $/hr and losses is 54.715 MW, where as optimal generation cost with line outage by using DAB is 35396.39 $/hr and losses is 40.515 MW. From Table 5, it is also seen that optimal generation cost with line outage and with WF by using SAB is 41713.89 $/hr and losses is 54.647 MW, where as optimal generation cost with line outage and with WF by using DAB is 34975.52 $/hr and losses is 40.085 MW. From the Table 3 and Table 5, it is concluded that, with increasing DAB power, optimal generation cost and losses are reducing. Fig. 2 shows the locational marginal price with and without considering WF at bus No. 34 and DAB at bus No. 14. It has been seen from Fig. 2 that LMP decreases with integration of WF in DAB case compare to SAB case

Table 4. Congested line power flow before and after bidding when WF is connected at bus No. 34.

Power Flow	Before SAB (MVA)	After SAB (MVA)	After SAB with WF (MVA)
L (15-16)	576.92	496.43	496.38
Power Flow	**Before DAB (MVA)**	**After DAB (MVA)**	**After DAB with WF (MVA)**
L (15-16)	576.92	356.77	365.43

Table 5. Optimal cost for SAB and DAB with and without presence of WF (bus No. 34) for 14-34 line outages.

Control Variable	SAB with line outage	SAB with WF and line outage	DAB with line outage	DAB with WF and line outage
PG1(MW)	593.76	576.37	600.28	593.31
PG2(MW)	737.20	733.65	614.23	607.43
PG3(MW)	610.16	594.91	596.70	589.53
PG4(MW)	652.00	651.91	578.05	571.65
PG5(MW)	508.00	508.00	508.00	508.00
PG6(MW)	670.48	663.60	586.13	579.53
PG7(MW)	580.00	580.00	579.97	576.23
PG8(MW)	564.00	564.00	564.00	564.00
PG9(MW)	671.89	667.78	571.64	565.55
PG10(MW)	721.46	718.66	595.74	589.10
Gen Cost($/h)	42169.21	41713.89	35396.39	34975.52
Losses(MW)	54.715	54.647	40.515	40.085

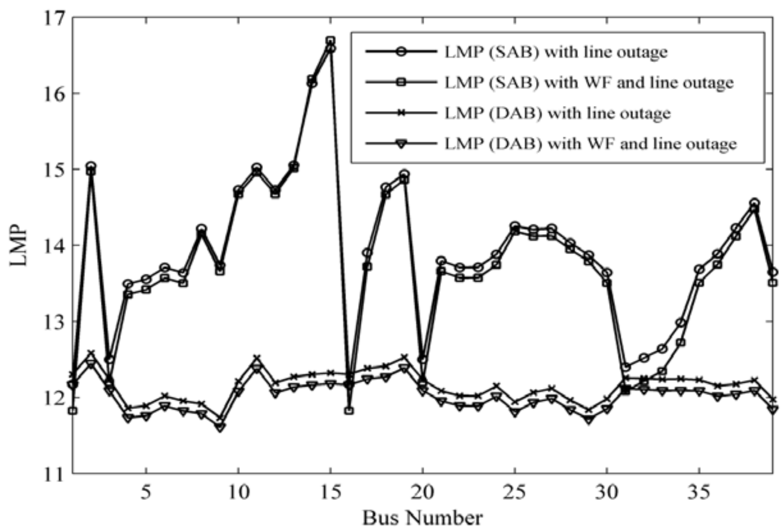

Fig. 2. Locational Marginal Price (LMP) with WF (bus No. 34).

4. Conclusion

The effectiveness of WF integrated competitive power market to alleviate transmission congestion has been investigated in this paper. To mitigate transmission congestion, optimal generation cost and losses are found minimum with DAB with WF integrated system compared to that of SAB with WF integrated system for mitigation transmission congestion. It is also investigates that LMP is minimum with presence of wind farm in the case DAB compared to SAB case. Sequential Quadratic programming (SQP) is used for implementing the proposed method and modified 39 bus New England test system is used for analysis of the proposed approach.

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