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THE IMPACT OF RENEWABLE GENERATION ON SYSTEM LOCATIONAL MARGINAL PRICE AND TOTAL SYSTEM LOSSES

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ABSTRACT: Wind generation is one of the most mature and cost-effective resources among different types of the renewable energy technology. Large-scale wind generation projects have been commissioned around the world and are much more coming on stream in the nearest future. Because of its high degree intermittency, its effect on system operation needs to be investigated especially in a market environment. One of the key elements for investigation is the cost aspect of energy in a power system with increasing penetration of wind generation.

This paper investigates the impacts of wind generation on system locational marginal price and total system losses considering different penetration levels and dispersion of wind generation in the network.

Index Terms: Wind generation, Penetration levels, Locational Marginal Price, Optimal Power flow, Loss sensitivities, System losses.

1. INTRODUCTION

The need to reduce environmental pollution from the conventional generation has increased the interest in generating electricity from renewable sources such as sunlight, wind and tidal waves which are naturally replenished. One of the main advantages of the electricity generation from renewable sources is that it produces little or no harmful emissions, which minimises their impact on the environment, and the primary energy source will not be depleted.

Wind generation is considered a promising and encouraging alternative for the power generation because of its tremendous environmental and social benefits, together with public support and government incentives [1]. Wind, however, is an intermittent and diffuse source of energy, as wind speed is highly variable and the site is specific. This variable and stochastic nature of the wind brings a lot of issues with respect to the system operation. Hence, the need to evaluate the impact of wind generation on the system Locational Marginal Price (LMP) and total system losses, considering the penetration levels and locations, is discussed in this paper.

However, because of the intermittent nature of wind power and the requirement for reduction of harmful gases from power production, wind power is considered as a base load unit, and hence power from wind is always connected to the system. One of the drivers for this paper is used to determine the effect of wind power on the system LMP as well as the system losses. This paper is organised as follows: Section 2 describes an overview of Locational Marginal Price; Section 3 describes Optimal Power Flow (OPF) and LMP calculations. A modified 30-bus test system is used as described in Section 4 and the results are presented in Section 5. Section 6 presents the conclusions from the results.

2. LOCATIONAL MARGINAL PRICE (LMP)

Locational Marginal Price is the marginal cost of serving the next MW load at a location while considering the network constraints. LMP was first implemented in New Zealand in 1997 followed by some US markets [3] such as Pennsylvania-New Jersey-Maryland in 1998, New York ISO in 1998, New England ISO in 2003 as well as CAISO in 2002 [4]. However, according to [5], LMP was introduced even earlier in some Latin American countries such as Chile in 1982, Argentina in 1992, Peru in 1993 and Bolivia in 1994. One of the main reasons why LMP is used is because it provides an efficient price signal to market participants regarding the usage, the generation and the investment. In another word, generators have incentives to locate in constrained areas with high marginal costs while loads have the incentives to locate in unconstrained areas with low marginal costs. In order to relieve the congestion, both generators and loads have the incentives for transmission investment because LMP prices directly reflect the opportunity cost of transmission between locations.

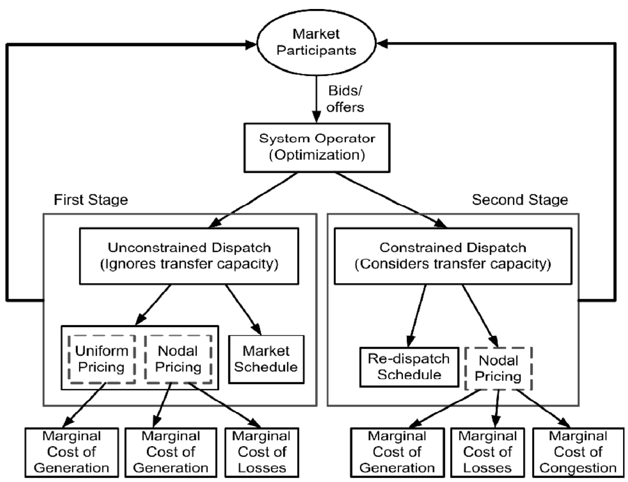


Figure 1: Nodal Pricing Mechanism

LMP can be distinctively divided into two stages which are the unconstrained and the constrained dispatch as shown in Figure 1. Basically all the market participants will submit their bids and offers to the independent system operator (ISO) and these bids determine the market clearing price by placing the marginal generators bids and offers in an ascending order accordingly until it meets the total system load subject to security limits. In economic terms, the market clearing point is the point of intersection between the supply and the demand curves as illustrated as point A in Figure 2.

Ignoring the line resistance and the grid limitations, the first stage (i.e., economic dispatch) of the unconstrained dispatch shown in Figure 1 gives a uniform marginal price throughout the network. However, in a practical case, the nodal price at one bus differs from the next one and thus prices vary by location due to losses. In the presence of transmission constraints, the second stage (i.e., system redispatch) will be carried out to relieve the network of congestion by 'constraining off' some generators on the grid and 'constraining on' some generators in order to secure the balance between the supply and the demand to make the operation feasible. Hence, the LMP prices will not be uniformed but vary by locations reflecting the effects of energy, the losses and the congestion in the system.

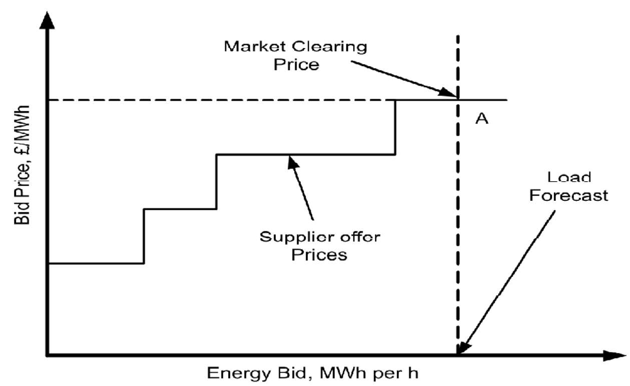


Figure 2: Market Settlement in Single Auction Power Pools

3. OPTIMAL POWER FLOW AND LOCATIONAL MARGINAL PRICE

Locational marginal price is formulated using a security constrained optimal power flow (OPF) dispatch. It was developed in the early 1960s as an extension of the conventional economic dispatch to determine the optimal settings for control variables while respecting various network and equipment constraints [6]. Generally, an OPF problem is to determine the most efficient-cost generation output from all available resources while minimising the operating cost, the subject to power flow equations and the network constraints.

OPF functionally combines the power flow and the economic dispatch with the objective of minimising operating cost, taking into account equality and inequality constraints. This optimisation approach is applied to spot pricing theory to the dispatch generation and the load in an economic manner where suppliers submit bids to the pool operator, and the economic dispatch results are determined. Suppliers are then paid a price according to their bus prices, and correspondingly consumers pay according to their bus prices. The OPF problem for real power can be expressed as: [7, 8]

$$\text{Min} \sum_{k=1}^{N} C_{gen,k}(P_{gen,k}) \tag{1}$$

$$S.t \quad \sum_{Gen} P_{gen,k} = \sum_{load} P_{load,k} + \sum_{Transfer} P_{Transfer} \tag{2}$$

$$P_{gen,k}^{\min} \le P_{gen,k} \le P_{gen,k}^{max} \tag{3}$$

$$g_{line,l} \le g_{line,l}^{max} \tag{4}$$

The symbols P represents the real power and the suffixes *gen,k; load,k* represent the output of generator and the load demand at node k respectively. The suffix *Transfer* represents the power transfer. The symbol $g_{line,l}$ represents the transmission line flow at line l, and the superscripts *min* and *max* represent the minimum and maximum limit of the corresponding variables respectively. The generator cost function model at bus k, is given as

$$C_{gen,k}(P_{gen,k}) = (a + bP_{gen,k} + cP_{gen,k}^2) \times \text{FuelCost} \tag{5}$$

where a, b and c are the cost coefficients with their units in MBtu/h, MBtu/MWh and MBtu/MW²h respectively. The equality constraint in Equation (2) is the active power balance equation, where the total supply is equal to the total demand plus system losses. The inequality constraint in equations (3) and (4) corresponds to the active power generation limits and line flow limits of the system. The generator cost function at bus k is given in equation (5). Fuel cost is expressed in £/MBtu and it varies depending on the fuel used by a generator. It is set equal to £1/MBtu in the simulations for this paper.

The objective function in a centralized dispatch is to minimize the system operating cost subject to equality and inequality constraints. Hence, the Lagrange-Kuhn-Tucker function of the real power OPF problem can be written as:

$$L = \sum_{k=1}^{N} C_{gen,k}(P_{gen,k}) + \sum_{k=1}^{N} \lambda_k \left[\sum_{Gen} P_{gen,k} - \sum_{load} P_{load,k} - \sum_{Transfer} P_{Transfer} \right] + \sum_{l=1}^{nl} \mu_l \left[g_{line,l} - g_{line,l}^{\max flow} \right] + \sum_{k=1}^{N} \pi_k^{\max} \left[P_{gen,k} - P_{gen,k}^{\max} \right] + \sum_{k=1}^{N} \pi_k^{\min} \left[P_{gen,k}^{\min} - P_{gen,k} \right] \tag{6}$$

Where:

$C_{gen,k}(P_{gen}, k)$ = the energy bid function of bus k;

λ_k = the Lagrange multiplier for the marginal value of the active power balance constraint at bus k;

$\pi_k^{\max}$ = the Kuhn-Tucker multiplier of upper limit of active power at bus k;

$\pi_k^{\min}$ = the Kuhn-Tucker multiplier of lower limit of active power at bus k;

μ_l = the Marginal cost of transmission constraint at line l;

$P_k^{\max}$ = the upper limit of active power injection at bus k

$P_k^{\min}$ = the lower limit of active power injection at bus k.

Applying Karush-Kuhn-Tucker (KKT) condition [9], the LMP can be expressed as follows:

$$\lambda_k = \lambda_k^{energy} + \lambda_k^{loss} + \lambda_k^{cong} \tag{7}$$

$$\text{or} \quad \lambda_k = \lambda_0 - \lambda_0 \frac{\partial P_{Loss}}{\partial P_k} - \sum_{l=1}^{nl} \mu_l T_{l,k} \tag{8}$$

where:

λ_k = marginal price or Locational Marginal Price at bus k;

λ_0 = Lagrange multiplier associated to the power balance equation (which is the cost of energy component i.e., λ_k^{energy});

λ_k^{loss} = marginal cost of loss component at bus k;

λ_k^{cong} = marginal cost of congestion component at bus k;

$\frac{\partial P_{Loss}}{\partial P_k}$ = real power loss sensitivity factor at bus k denoted as L_k;

μ_l = vector of Lagrange multipliers associated to network constraints on line l;

$T_{l,k}$ = sensitivity factor of the network at bus k due to network constraints on line l.

The OPF in the above section is reinforced by the inclusion of voltage limit constraints and reactive power equation. The Locational Marginal Price at each bus is calculated using the standard OPF formulation of the PowerWorld™ simulator package.

The Lagrange multipliers determined from the solution of the optimum power flow provide important economic 'information' regarding the power system. A Lagrange multiplier can be interpreted as the derivative of the objective function with respect to enforcing the respective constraint. Therefore, the Lagrange multipliers associated with enforcing the power flow Equations of the OPF can be interpreted as the marginal cost of providing additional energy (£/MWh) to that bus in the power system, also known as locational marginal price. The LMP can be decomposed into three components which are the cost of energy, the cost of marginal losses and the cost of marginal congestion to reflect the effects of system marginal cost, loss compensation and congestion management respectively as well as voltage support. These components (i.e., energy, loss and congestion) are all important cost terms in the deregulated electricity market and can be forwarded to the generators and the consumers as control signals to regulate the level of their generation and consumption.

4. TEST SYSTEM AND SIMULATION PROCEDURE.

Using a modified IEEE30-bus test system [2], the impact of penetration levels of wind generation is studied and investigated particularly on the system LMP and the total system losses using PowerWorld™ simulator package [10]. The modified test system consists of six generators, forty one branches and twenty one loads as shown in Figure 3, and all the branch parameters are given in Table 1.

The modified test system is analysed using AC Optimal Power Flow (OPF) as described in Section 3. It is also assumed that the pool market uses single auction market settlement strategies (see Figure 1) with the objective function to minimise the total cost of real power production. The generator cost parameters for the test system are shown in Table 2. The voltage p.u. value for each generator is set at 1.05p.u.

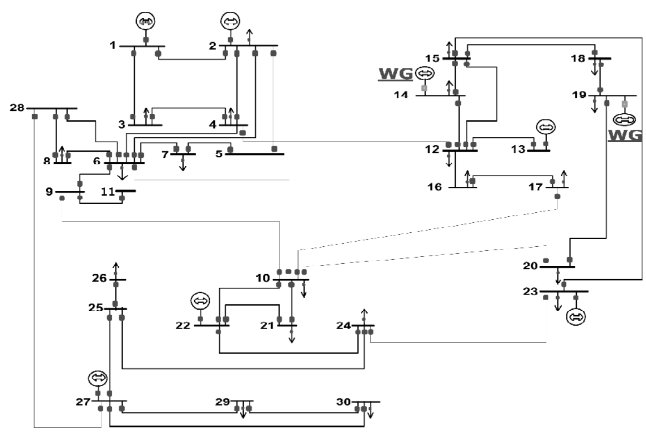


Figure 3: One Line Diagram of Modified IEEE 30-bus System

In this simulation, the marginal cost of wind farm is set equal to half of the minimum marginal cost of the existing generator in the network to reflect the subsidy enjoyed by renewable generation.

The location of the wind farms is studied and investigated on bus #14 and bus #19 with the assumption that there is similar wind regime in these areas. A wide range of case studies from 0% to 35% of wind penetration are carried out to analyze the impact of wind power on the system LMP and on the system real power losses. The analysis of the system LMP and system losses is viewed from two different perspectives: the first one is the level of wind penetration (i.e., 0% to 35%) and the second one is dispersion of wind generation (i.e., single and multiple locations).

Using the time step simulation option in the PowerWorld™ simulator, the wind generator output and the system loads are dynamically

Table 1
Branch Parameters for IEEE 30-Bus Test System

From Bus	To Bus	R/pu	X/pu	BCAP/pu	Line Limit/MVA	From Bus	To Bus	R/pu	X/pu	BCAP/pu	Line Limit/MVA	From Bus	To Bus	R/pu	X/pu	BCAP/pu	Line Limit/MVA
1	2	0.0192	0.0575	0.0264	180	28	8	0.0640	0.2000	0.0214	100	17	16	0.0820	0.1930	0.0000	100
1	3	0.0452	0.1852	0.0204	150	9	10	0.0000	0.1100	0.0000	100	18	19	0.0639	0.1292	0.0000	100
2	4	0.0570	0.1737	0.0184	150	9	11	0.0000	0.2080	0.0000	50	19	20	0.0340	0.0680	0.0000	150
2	5	0.0472	0.1983	0.0209	100	10	17	0.0320	0.0850	0.0000	100	22	21	0.0120	0.0240	0.0000	100
2	6	0.0581	0.1763	0.0187	150	10	20	0.0940	0.2090	0.0000	150	22	24	0.1150	0.1790	0.0000	100
3	4	0.0131	0.0379	0.0042	100	10	21	0.0350	0.0750	0.0000	100	24	23	0.1320	0.2700	0.0000	100
4	6	0.0119	0.0414	0.0045	100	10	22	0.0727	0.1499	0.0000	100	25	24	0.1890	0.3290	0.0000	100
4	12	0.0000	0.2560	0.0000	150	12	13	0.0000	0.1400	0.0000	100	26	25	0.1270	0.1900	0.0000	100
5	7	0.0460	0.1160	0.0102	100	14	12	0.1230	0.2560	0.0000	150	27	25	0.1090	0.2090	0.0000	100
7	6	0.0267	0.0820	0.0085	100	15	12	0.0660	0.1300	0.0000	100	28	27	0.0000	0.3960	0.0000	100
8	6	0.0120	0.0420	0.0045	100	12	16	0.0950	0.1990	0.0000	100	27	29	0.1100	0.1075	0.0000	100
6	9	0.0000	0.2080	0.0000	100	15	14	0.2210	0.2000	0.0000	150	27	30	0.1600	0.3015	0.0000	100
6	10	0.0000	0.5560	0.0000	100	15	18	0.1070	0.2190	0.0000	100	29	30	0.1200	0.2265	0.0000	100
28	6	0.0170	0.0600	0.0065	100	23	15	0.1000	0.2020	0.0000	150						

Table 2
Generator's Cost Parameters

Gen. No.	*Generator Cost Co-efficient* $b\,/\,MBtu\,/\,MWh$	P_{min}/MW	P_{max}/MW
#1	12	14.0	280.0
#2	10	10.0	200.0
#13	15	5.0	100.0
#22	14	6.5	130.0
#23	13	7.0	140.0
#27	11	7.5	150.0

varied half hourly to reflect the actual system response. The corresponding results of the system LMP and the system losses on the penetration and dispersion of wind were recorded and discussed in Section 5. A one year data shows similar trend, hence all the results and discussions in the following section are based on one-month load and the wind generation profile for ease of presentation.

5. RESULTS AND DISCUSSIONS

This section presents the simulation results on a modified IEEE 30-bus test system. The wind generator is connected to bus #14 and bus #19 separately for penetration levels from 5% to 35% with an interval of 5%, and then each is connected each to bus #14 and bus #19 simultaneously with a combination of different penetration levels for a month using half-hourly loads and wind farm output data.

As mentioned in Section 4, half-hourly data for loads and wind generation are used for each of the simulation runs and the results on the system LMP, and the total system losses are recorded and discussed in the following sections. The same load profile is used for all wind penetration levels and locations of the wind generation so as to reduce the effect of load changes, while comparing the impact of wind penetration levels and dispersion.

5.1 Single Wind Farm Location on system LMP

The examination of the one-month and half hourly variability of the system with and without wind penetration provides the most insight. Table 3 tabulates the minimum and maximum system LMPs when wind generation is connected at bus 14 and bus 19. Table 3 shows that the system LMPs reduces at the location where the wind generation is connected. That's why the minimum value of system LMPs reduces with the increasing of penetration of wind at that location where the wind generation is connected. It also shows that at certain locations, there is a possibility that the system LMP could be higher than before the wind is connected. This result highlights an important fact that placement of wind generation could reduce as well as increase the overall system LMP as given in Table 3, together with a comparison between when wind is connected at bus #14 and bus #19 respectively.

Figure 4(a) and 4(b) show the LMP plots for the system when the wind generator (WG) is connected to bus #14 and bus #19 respectively, up to a wind penetration level of 35%. There is no much appreciable change on all buses except where the WG is connected. It can also be observed that as the penetration level is increased, the effect on the minimum LMP is evidently reducing the LMP at the buses where the WG is connected. It is observed from Table 1 that the minimum LMP drops to £3.15/MWh at 35% wind penetration, compared to £9.49/MWh at the base case. However, there is a slight increase in the maximum LMP from £16.99/MWh at base case to £17.38/MWh at 25% wind penetration.

5.2 Multiple Wind Farm Location on System LMP

In the multiple locations scenario, wind generation is connected to buses #14 and #19 simultaneously at different penetration levels from 0% to 35% with an interval of 5% to study the system LMPs. Table 4 shows the minimum and maximum LMPs for buses 14 and 19 when the WG is connected to both buses at the same time and points, but at different combination of the penetration levels. Base case values (no wind generation connected) are also shown for comparison purposes.

Table 3
Min and Max LMP with Wind Generator

% of Wind Penetration	Wind at Bus #14 Min LMP /£/MWh	Max LMP /£/MWh	Variation Over Min LMP	Wind at Bus #19 Min LMP /£/MWh	Max LMP /£/MWh	Variation over Min LMP
0%	9.49	16.99	79.0%	9.49	16.99	79.0%
5%	8.92	17.06	91.3%	9.19	16.88	83.7%
10%	8.20	17.11	108.7%	8.69	16.91	94.6%
15%	7.30	17.47	139.3%	7.93	16.91	113.2%
20%	5.84	17.08	192.5%	6.75	16.84	149.5%
25%	5.05	17.38	244.2%	6.20	16.92	172.9%
30%	4.17	17.32	315.3%	5.18	16.98	227.8%
35%	3.15	17.15	444.4%	4.41	16.81	281.2%

Table 4
Min and Max LMP with Multiple Dispersion

% of Combination (G14, G19) (Low, High)	Wind at But #14 & Bus #19 Min LMP /£/MWh	Max LMP /£/MWh	Variation Over Min LMP	% of Combination (G19, G14) (Low, High)	Wind at But #19 & Bus #14 Min LMP /£/MWh	Max LMP /£/MWh	Variation Over Min LMP	% of Total Wind Penetration
BC (0%, 0%)	9.49	16.99	79.0%	BC (0%, 0%)	9.49	16.99	79.0%	0%
C1 (5%, 5%)	8.80	16.97	92.8%	C1 (5%,, 5%)	8.80	16.97	92.8%	10%
C2 (5%, 10%)	8.70	16.88	94.0%	C2 (5%,, 10%)	7.95	17.03	114.2%	15%
C3 (5%, 15%)	7.93	16.80	111.9%	C3 (5%,, 15%)	7.19	17.47	143.0%	20%
C4 (10%, 10%)	8.12	16.79	106.8%	C4 (10%,, 10%)	8.12	16.79	106.8%	20%
C5 (10%, 15%)	7.77	17.04	119.3%	C5 (10%,, 15%)	7.14	16.74	134.5%	25%
C6 (5%, 20%)	6.69	17.06	155.0%	C6 (5%,, 20%)	5.86	16.97	189.6%	25%
C7 (5%, 25%)	6.10	17.06	179.7%	C7 (5%,, 25%)	4.98	17.19	245.2%	30%
C8 (10%, 20%)	6.70	17.07	154.8%	C8 (10%,, 20%)	5.77	16.81	191.3%	30%
C9 (15%, 15%)	6.96	16.80	141.4%	C9 (15%,, 15%)	6.96	16.80	141.4%	30%
C10 (5%, 30%)	5.18	17.06	229.3%	C10 (5%,, 30%)	4.17	16.98	307.2%	35%
C11 (10%, 25%)	6.15	17.11	178.2%	C11 (10%,, 25%)	5.05	16.83	233.3%	35%
C12 (15%, 20%)	6.69	17.08	155.3%	C12 (15%,, 20%)	5.85	16.91	189.1%	35%

The results in Table 4 were plotted as Figures 5(a) and 5(b). They show a similar trend in terms of reducing the LMP at the buses where the wind generation is connected as described in Section 5.1. Higher LMP variations were observed at bus #14 for the same wind penetration levels compared to bus #19. This supports the fact that LMP is a function of the location where the generation is connected and the topology of the network. It also suggests that for a lower LMP where the wind generation is connected for a multiple location scenarios, the wind penetration level is best increased at bus #14 instead of bus #19.

Again, for multiple locations, there is not much appreciable change on all buses except where the WG is connected. It can also be observed that as the penetration level is increasing, the effect on the minimum LMP is

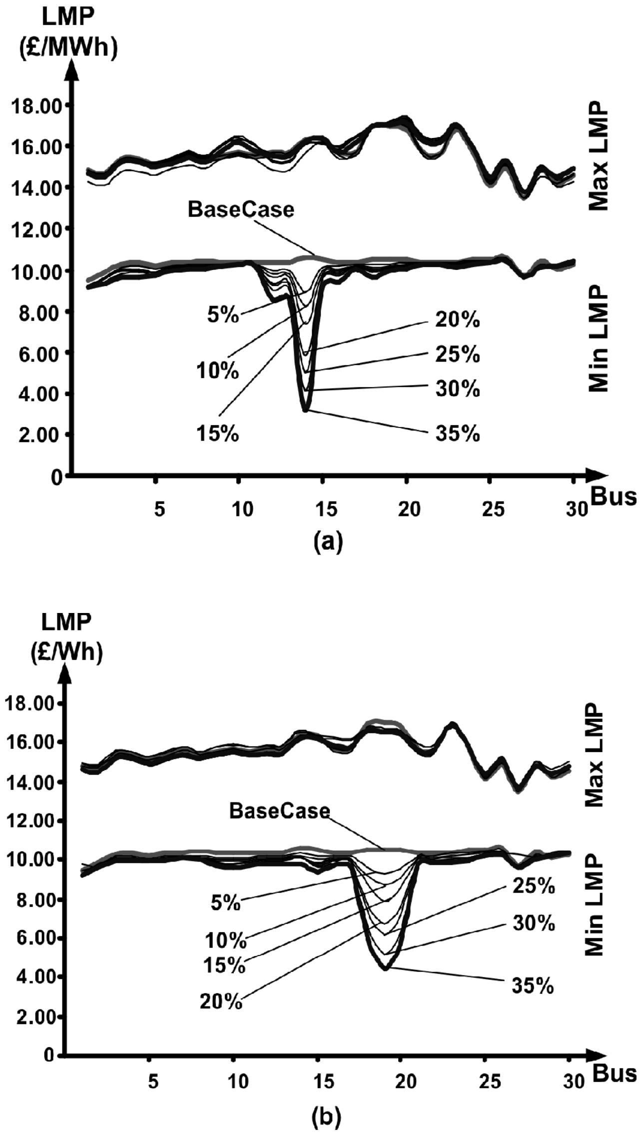
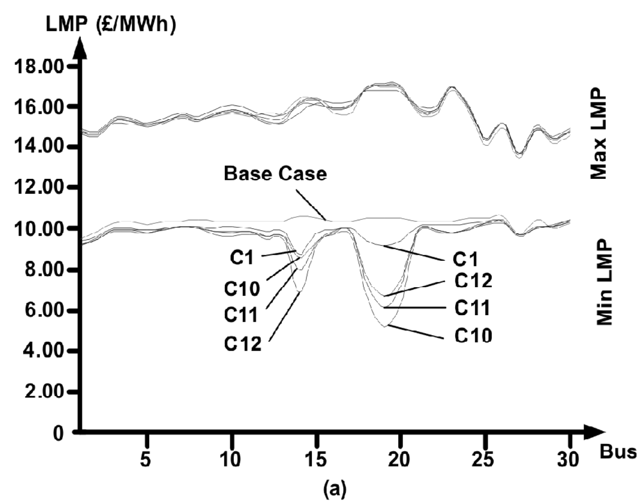


Figure 4: LMP with WG Penetration Level at (a) bus #14 and (b) bus #19



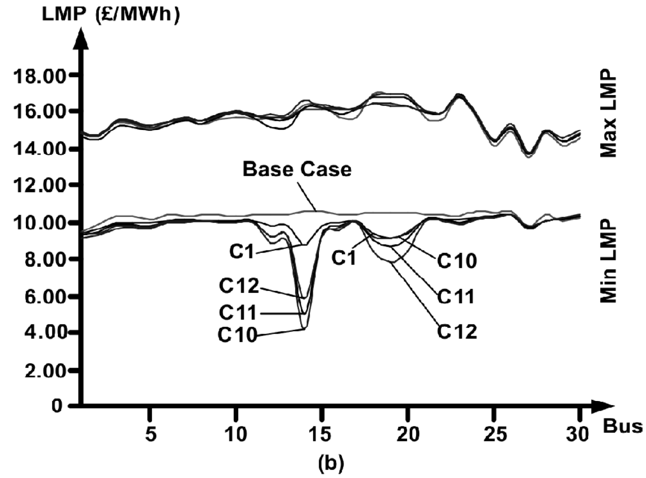


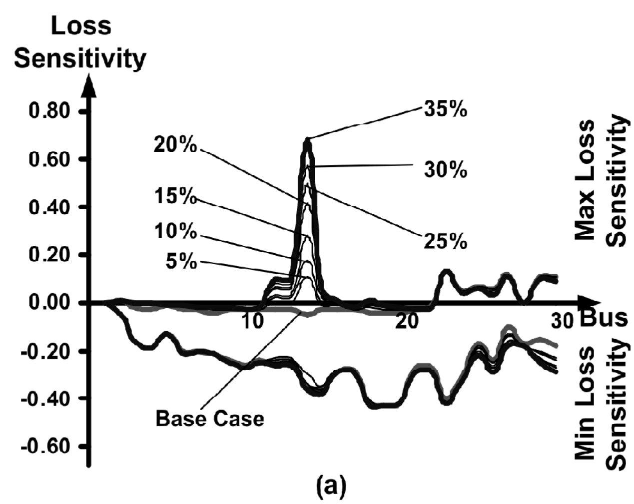
Figure 5: LMP with two WG at (a) bus #14(low) and bus#19(high) (b) bus #19(low) and bus #14(high)

evidently reducing the LMP at the buses where the WG is connected.

5.3 Single Wind Farm Location on system Losses.

Real power loss sensitivity L_k is defined as the change of the total system losses with respect to the real power injection at bus k, $L_k = \dfrac{\partial P_{Loss}}{\partial P_k}$.

Traditionally, loss sensitivities are calculated from the power flow algorithm or the optimal power flow algorithm depending on the selection of system reference bus. The real power loss sensitivity can either be positive (i.e., increase in loss) or negative (i.e., decrease in loss), and its value depends on the location of the angle reference bus.



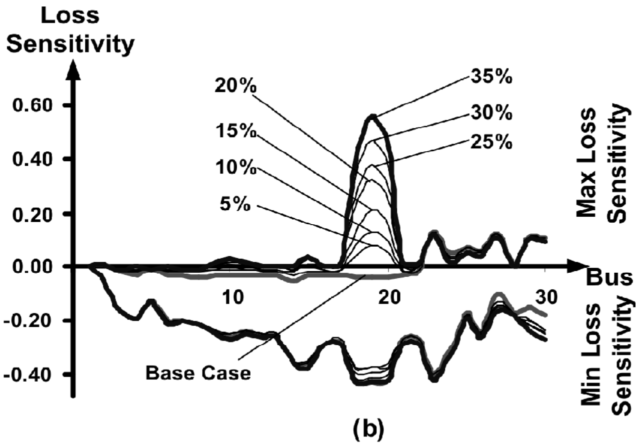


Figure 6: Loss Sensitivities with WG penetration level at (a) bus #14 (b) bus #19

The loss sensitivities were calculated using the system losses recorded from the simulations and recorded in Figure 6, which is a mirror-alike of Figure 4 when the system is unconstrained. It shows that the loss sensitivity where WG is connected increases with the wind penetration level, which implies that higher wind penetration levels will give a higher loss sensitivity where WG is connected.

Table 5 shows the minimum and maximum system loss when WG is connected at bus #14 and bus #19. It shows that the system loss might be reduced as well as increased with different penetration level of WG. This supports the facts that there could be a change in power flow pattern where WG is connected that causes the system loss to increase and decrease with different wind penetration level. This result also suggests that connecting WG at bus #19 is the best location as it greatly reduced the system loss compared to connecting it at bus #14.

It becomes clearer when both locations are compared from the total system loss point of view. Figure 7 shows that with WG connected at bus #19 the loss reduces slightly from 5% to 15% and then it increases steadily with the increase in wind penetration levels. It also shows that the total system losses is lower when WG is connected to bus #19 compared to bus #14.

5.4 Multiple Wind Farm Location on System Loss

Figure 8 shows a mirror-like image of Figure 5 when the system is unconstrained from the loss sensitivity point of view for different case scenarios. Under multiple wind farm dispersions, Figure 8 shows that at the same wind penetration level (e.g. 35%), there could be several case scenarios (e.g. C10, C11 and C12) with different wind penetration levels between bus#14 and bus #19. This will give the utility company a better option to choose at what penetration level and location is optimal with respect to the system losses for locations having a similar wind speeds.

Table 5
Min and Max System Losses with Wind Generator

% of Wind Penetration	*Wind at Bus #14*			*Wind at Bus #19*		
	Min System Loss /MW	*Max System Loss /MW*	*Variation Over Max Sys Loss*	*Min System Loss/MW*	*Max System Loss /MW*	*Variation Over Max Sys Loss*
0%	2.51	51.96	95.2%	2.51	51..96	95.2%
5%	2.63	53.12	95.0%	2.63	52.84	95.0%
10%	3.00	52.61	94.3%	2.84	50.28	94.4%
15%	2.94	52.81	94.4%	2.86	49.90	94.3%
20%	2.51	65.80	96.2%	2.51	52.36	95.2%
25%	2.57	81.35	96.8%	2.58	62.50	95.9%
30%	2.51	104.32	97.6%	2.51	86.66	97.1%
35%	2.54	143.61	98.2%	2.54	112.09	97.7%

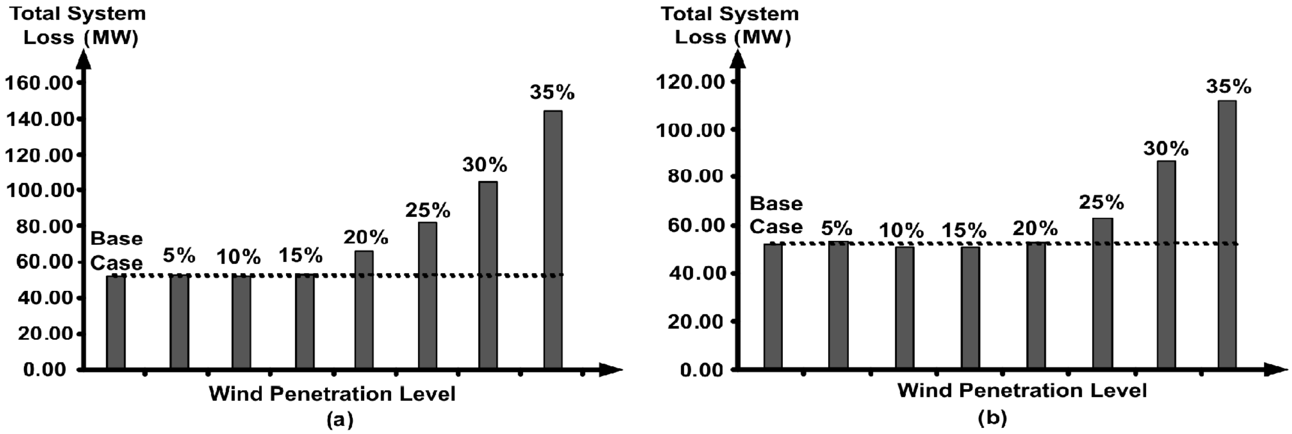


Figure 7: Total System Losses with wind Generation at (a) bus #14 (b) bus #19

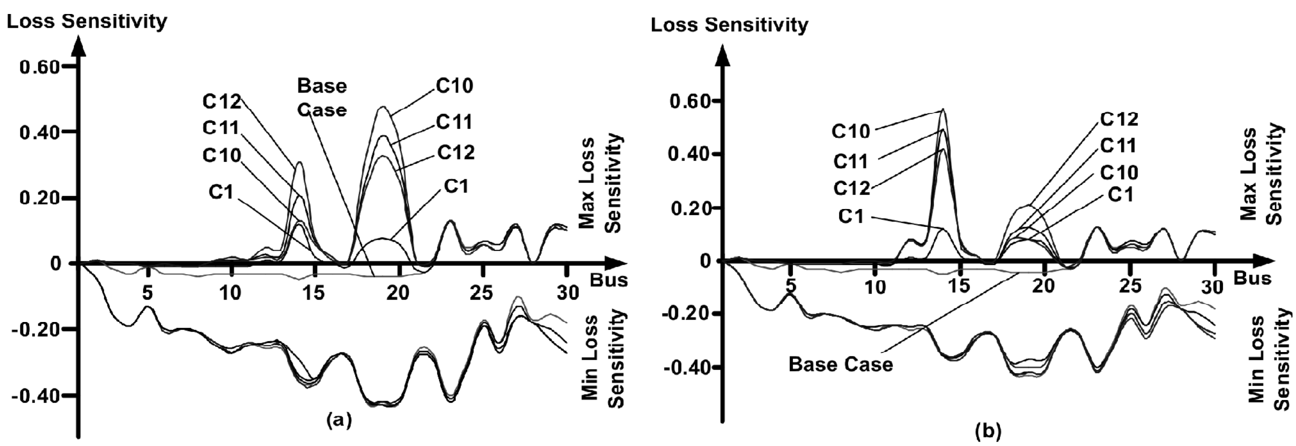


Figure 8: Loss Sensitivities with WG at (a) bus #14(low) and bus #19(high) (b) bus #14(high) and bus #19(low)

Table 6
Min and Max of System Loss with Multiple Dispersion

% of Combination (G14, G19) (Low, High)	*Wind at Bus #14 & Bus #19* Min System Loss/MW	Max System Loss/MW	Variation Over Max Sys Loss	*% of Combination (G19, G14) (Low, High)*	*Wind at Bus #19 & Bus #14* Min System Loss /MW	Max System Loss /MW	Variation Over Max Sys Loss	*% of Total Wind Penetration*
BC (0%, 0%)	2.51	51.96	95.2%	BC (0%, 0%)	2.51	51.96	95.2%	0%
C1 (5%, 5%)	2.63	52.73	95.0%	C1 (5%,, 5%)	2.63	52.73	95.0%	10%
C2 (5%, 10%)	2.98	50.88	94.1%	C2 (5%,, 10%)	3.07	52.22	94.1%	15%
C3 (5%, 15%)	2.89	48.38	94.0%	C3 (5%,, 15%)	2.94	52.38	94.4%	20%
C4 (10%, 10%)	3.01	50.47	94.0%	C4 (10%,, 10%)	3.01	50.47	94.0%	20%
C5 (10%, 15%)	3.40	50.99	93.3%	C5 (10%,, 15%)	3.18	48.96	93.5%	25%
C6 (5%, 20%)	2.63	52.60	95.0%	C6 (5%,, 20%)	2.63	65.80	96.0%	25%
C7 (5%, 25%)	2.92	64.28	95.5%	C7 (5%,, 25%)	2.86	81.90	96.5%	30%
C8 (10%, 20%)	3.08	54.38	94.3%	C8 (10%,, 20%)	2.84	64.37	95.6%	30%
C9 (15%, 15%)	2.94	50.14	94.1%	C9 (15%,, 15%)	2.94	50.14	94.1%	30%
C10 (5%, 30%)	2.63	86.66	97.0%	C10 (5%,, 30%)	2.63	104.32	97.5%	35%
C11 (10%, 25%)	3.12	70.71	95.6%	C11 (10%,, 25%)	2.87	83.58	96.6%	35%
C12 (15%, 20%)	2.95	57.04	94.8%	C12 (15%,, 20%)	2.86	66.36	95.7%	35%

The results presented in Table 6 clearly show that with the same wind penetration levels at buses 14 and 19, increasing wind penetration level at bus #19 does reduce total system losses. It is also observed from Table 4 that with the dispersion of high wind penetration levels at bus #14 and lower wind penetration levels at bus #19 higher total system losses were recorded. This is shown in the third and seventh columns of Table 4, where at the same wind penetration levels, lower wind penetration at bus #14 will give lower total system losses compared to column seven with higher wind penetration level at bus #14.

Figure 9(a) shows the total system loss for multiple dispersion of WG at bus #14(low penetration) and bus #19 (high penetration), and Figure 9(b) shows the total system loss for multiple dispersion of WG at bus #14 (high penetration) and bus #19(low penetration). Both figures show that total system losses can be either higher or lower than the base case scenario. Figure 9(a) shows that case scenario C3 and C10 give the lowest and the highest total system losses with 48.38MW and 86.66MW respectively. Similarly, Figure 9(b) shows that case scenario C9 and C10 give the lowest and the highest total system loss with 50.14MW and 104.32MW respectively. Comparing both figures, we can conclude that to reduce the total system losses, it is best to lower the penetration level at bus #14 and increase the penetration level at bus #19. Both figures also show that there will be an increase and decrease on total system losses with different combination of penetration levels.

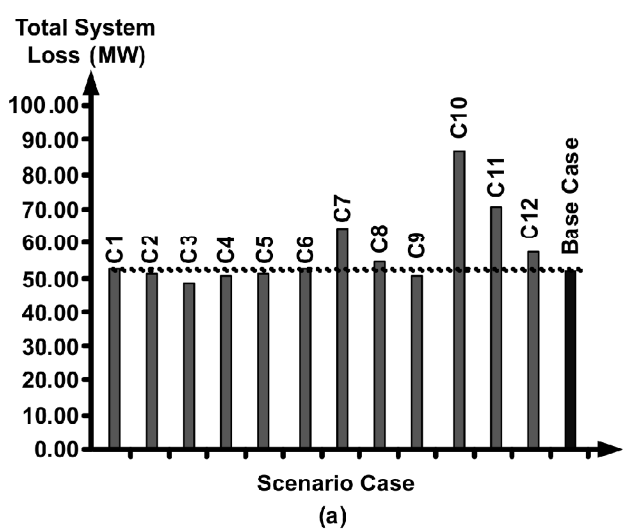


Figure 9: Total System Losses with Multiple Dispersion of WG at (a) bus #14(low) and bus #19(high) (b) bus #19(low) and bus #14(high)

6. CONCLUSIONS

The results analysed show a positive contribution from wind generation in terms of the Locational Marginal Price at buses where the wind plants are connected. This is an advantage for the communities where these wind plants are located because they will pay a lower LMP for the energy demand. Also the results indicate that when the utility has two sites with similar wind characteristics, it could still optimise the location decision based on the impact on the LMP for wind different penetration.

In other words, if the system operator wants to minimize the total system losses with an increase of wind penetration level, then it is advisable, say for the IEEE 30-bus system used here to increase the wind penetration level on bus #19 while reducing the wind penetration level on bus #14.

The results also show that placement of wind generation will increase or decrease the system LMP as well as the total system losses. Hence, it gives an option for the utility in deciding at what penetration level and location WG is optimal with respect to the system LMP and the system losses for locations having a similar wind speeds.

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