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An Analytical And Probabilistic Approach For Reliability/ Cost Assessment Of A Wind Power System

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Abstract

Rapid technological progress, combined with falling costs, a better understanding of financial risk and a growing appreciation of wider benefits, means that renewable energy is increasingly seen as the best solution. Global Renewable energy policies, arising from increasing environmental concerns have set very ambitious targets for wind power penetration in electric power systems all over the world. Modern power system aims to provide reliable as well as cost effective power supply to its consumers. Reliability benefits, environmental benefits and operating cost savings from wind power integration should be compared with the associated investment costs in order to determine optimum transmission facility for wind power delivery.

In this paper an analytical & probabilistic approach for reliability/cost analysis is presented for determining cost-effective transmission line size for wind power delivery. It describes the reliability/cost techniques for determining appropriate transmission line capacity to connect a wind farm to a power grid. The effects of site-specific wind regime, system load, transmission line unavailability, and redundancy on system reliability were studied using a basic system model. The methodology and results shown in this paper should be subsidiary in transmission system planning for delivering wind power to a power system.

Keywords: Wind Power, Reliability, Transmission Capacity, Cost Indices.

Introduction

Renewable energy technologies have grown more robust and more efficient and are increasingly able to generate power even in suboptimal conditions such as low wind speeds. Wind power is the ultimate propitious source of renewable energy, and hence its application in power generation is spreading continuously. Wind power is undergoing the fastest rate of growth of any form of electricity generation in the world. The resource potential is large; with many countries having wind regimes that could serve as a significant energy source. Ambitious goals for wind power development have been set by many countries.

It is reviewed earlier that renewable energy policies, such as the RPS (Renewable Portfolio Standard), have established very resourceful targets for wind power penetration in electric power systems in various parts of the world. Many geographical locations with good wind resources turn into potential sites for large wind farms. It becomes remarkably significant to determine sufficient transmission facility to deliver wind power from these wind farms to the power grid. Wind is a terribly variable energy source, and therefore, transmission system planning for wind delivery is too distinct from conventional transmission planning.

We must do an economic assessment in addition with the reliability assessment in determining suitable transmission facility to deliver wind power from the wind farms to a power grid system. The evaluation of sufficient system facilities is essential in providing adequate and acceptable continuity of supply. Power system reliability can be described by two important attributes: adequacy and security. The two attributes are shown in Figure 1.1.

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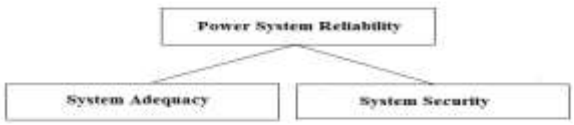

Figure 1.1: Attributes of power system reliability

The ultimate decision on the applicable transmission system will desire a trade off between the system cost and the system reliability. The variation of System Reliability with cost is shown in fig 1.2. Where ΔR = Change in Reliability

ΔC = Change in Cost [5].

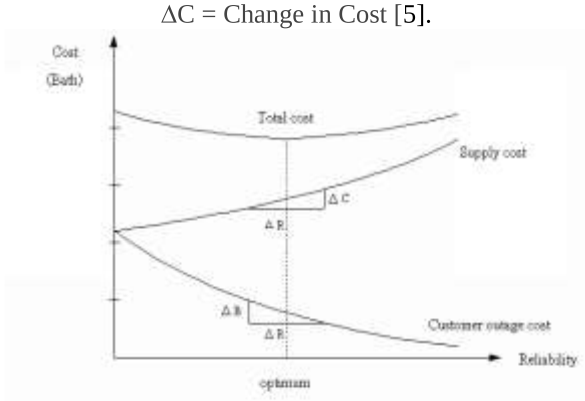

Fig 1.2: Cost vs System Reliability

In this paper an analytical method is presented to determine appropriate transmission line capacity based on its contribution to the overall system risk and associated transmission system cost. The effects of generation, transmission and load parameters on risk based transmission line sizing were studied using the basic system model shown in Figure 1.3

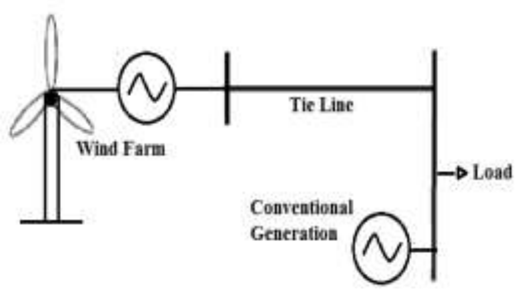

Figure 1.3: Basic system model

1.1 System Data

The system data used for the proposed assessment are described below.

The studies consider a wind farm which is connected to a test power generating system through a transmission line. The wind farm consists of a number of WTG (Wind Turbine Generator) units with cut-in, rated and cutout wind speeds of 14.4, 45 and 90 km/hr respectively. Previous research work [3] has shown that WTG forced outage rate has insignificant impact on the overall system reliability. The forced outage rate of WTG was, therefore, not considered in this studies.

Table 1 shows the mean wind speeds at five different sites. Case studies considering a test wind farm at the different sites were conducted to analyze the adequacy of transmission system for wind power delivery. The Vankusawade Wind Park location is home to large wind farms in Maharashtra, India and is used as the wind farm site in the base case studies.

Tab 1: Average Wind Speed for Vankusawade Wind Park Sites

Location	Site1	Site2	Site3	Site4	Site5
Wind Speed (Km/h)	22.01	19.52	16.78	16.29	14.62

Reliability/ Cost Indices

There are number of benefits associated with utilization of wind energy in a conventional power generation system. Wind power offsets conventional fuel, helps in reducing system down time and also reduces environmental degradation. The reduction in environmental pollution is being estimated under social cost or environmental credits and used in estimating green energy benefits.

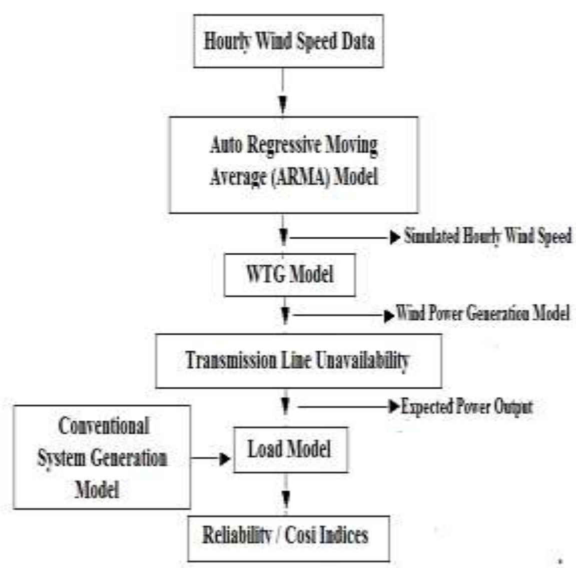

Figure 2.1: Flow chart of evaluation approach.

The investment in transmission line will generally increase linearly with the increase in transmission line capacity. A transmission system

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cost evaluation must be conducted in conjunction with the adequacy studies in order to determine a cost effective line sizing for wind power delivery.

The monetary benefits from the wind delivery system are compared to the investment costs of the transmission system with different power transfer capabilities in order to determine appropriate sizing. All the costs are expressed in Indian Rupees in this paper. The investment cost of 138 kV, 50 MW transmission line is assumed at 66 million (MM) Rupees/km [4]. A linear interpolation was used to estimate the cost per km for transmission lines of various transfer capabilities in this study. The capital investment on the line is spread over an average life of 45 years to obtain annual investment costs.

The conventional fuel offset due to wind application was evaluated assuming the wind sources to be base loaded after the three largest conventional units in the IEEE-RTS (Reliability Test System) . The average fuel cost (FC) of 806.465 Rupees/ MWh was used in the studies considering different types of conventional generating units in the system.

Many governments around the world recognize the environmental benefits and offer financial incentives in various forms to promote wind energy. This study considers a wind power production incentives of 0.55 Rupees/kWh towards wind energy supplied by a wind farm. The value of IEAR (Interrupted Energy Assessment Rate) for the IEEE–RTS system is 210.65 Rupees/kWh [1]. This value was used in this study to evaluate the reduction in the customer interruption costs due to wind application.

The overall cost benefits were calculated using Equation

$$B_W = EES_W \ (FC + WPPI) + IEAR \times \Delta LOEE \quad \text{................. (2.1)}$$

B_W= The Total Benefit from Wind Power
EES_W = Expected Energy Supplied by WTG in MWh,
FC = Average Fuel Cost in Indian Rupees/ MWh,
WPPI =Wind Power Production Incentive,
IEAR = Interrupted Energy Assessment Rate,
ΔLOEE = The Reduction in Loss Of Energy Expectation.

The benefits from wind application were calculated in Indian Rupees considering various system alternatives to determine optimum line sizing.

Effect of Transmission Line Expansion

The amount of wind power delivered to a power system depends on the power transfer capability of the transmission line. There is a certain reliability benefit associated with each additional MW transfer capability in transmission line expansion. The marginal net benefit in expanding the transmission line above 50 MW capacity is shown in Figure 2.2 considering a line length of 100 km. The benefits of connecting wind power through a transmission line were calculated using Equation 2.1. The net benefit is obtained by subtracting the total investment costs from the total benefits from wind power.

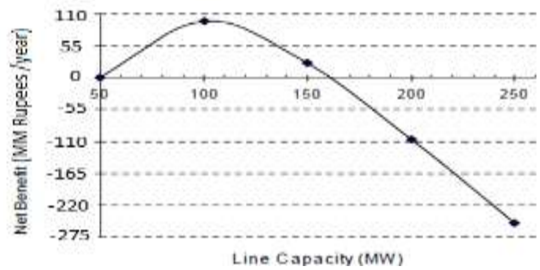

Figure 2.2: Net benefit with transmission line expansion

It can be seen from Figure 2.2 that the net benefit increases as the line capacity is increased from 50 MW. The benefit is maximized at about 100 MW line capacity. It has shown that there was no reliability benefit in expanding the line above 100 MW capacity. It can be seen in Figure 2.2 that the net monetary benefit decreases rapidly as the line capacity is further increased. A line capacity of 160 MW provides the same net benefit as a 50 MW line. The net benefits become negative with further expansion of the tie line. The decision on a particular line capacity should also take into consideration future system expectations. Figure 2.2 shows that the optimum net benefit is obtained when the transmission line capacity is about 110 MW.

Effect of Transmission Line Cost

The effect of transmission line investment cost on optimum line sizing was studied by varying the transmission line costs within a certain range. The range of variation was estimated from the data obtained from the web site of PJM interconnection [4]. The transmission line investment cost for 50 MW capacity was varied in the range of 33 to 110 Million Rupees (MM₹) /km and the respective costs of different line sizes were calculated assuming linear interpolation. A sensitivity analysis was performed for five different line sizes taken in increments of 20% of the rated wind farm capacity. The wind farm is rated at 250 MW and the five different line capacities of 50,100,150,200 and 250 MW were used in the study. Figure 2.3 shows the variation in the net benefit with respect to varying transmission line costs

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at the different transmission line capacities.

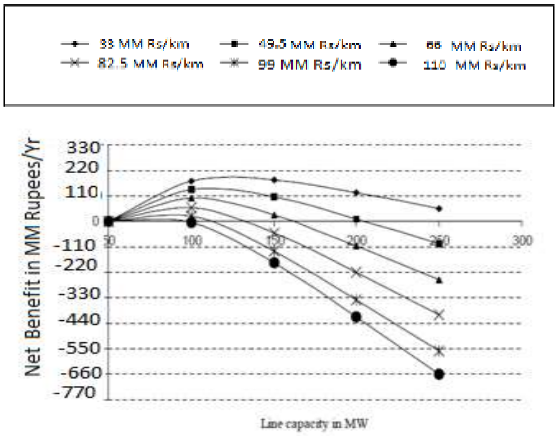

Figure 2.3: Variation of net benefit with transmission line cost

It is noticed from Figure 2.3 that the net marginal benefit associated with transmission line capacity expansion decreases with increase in transmission line cost. The curves shift downwards indicating less benefit as the line costs increase. The top curve is for the line cost of 33 MM₹/km. At this value the net benefit is more than zero even when the transmission line capacity is equal to the total installed wind capacity. The net benefit becomes negative with increasing transmission line cost. The net benefits are positive when the transmission line capacity is somewhere between 50 and 100 MW in the entire range of investment costs. It can be estimated from Figure 2.3 that the line capacity for the maximum net benefits decrease from about 125 MW to about 80 MW as the line investment cost increases from 33 to 110 MM₹/km. The negative benefits in Figure 2.3 indicate wind utilization that is not cost justified. Wind energy usage can be maximum and still cost effective as long as the investment costs are balanced by the benefits.

Figure 2.3 shows that the optimum line sizing is reduced from about 120 MW to about 80 MW as the line investment cost is increased from 33 to 110 MM₹/km. This analysis is useful in studying the effect of investment in deciding appropriate line sizing for wind farm integration to power systems.

Effect of Customer Interruption Cost

Earlier Studies show that wind power contributes to the overall system reliability. An increase in system reliability due to wind power application results in a decrease in the customer interruption cost. The effect on customer interruption costs due to wind application depends on the system IEAR and on the wind power delivered to the system load. The wind power delivery is however constrained by the transmission line capacity and unavailability. The effect of customer interruption cost in determining optimum transmission system can be evaluated by varying the system IEAR. The sensitivity analysis was performed by choosing a wide range of system IEAR. The system IEAR of more than 825 ₹/kWh has been noted in existing electric system in India.

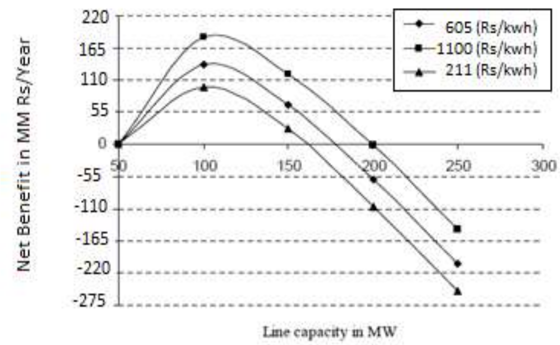

Figure 2.4: Variation of net benefit with system IEAR

Figure 2.4 shows the net marginal benefits in expanding the wind transmission capacity above 50 MW. Each curve represents a different system IEAR. The net benefits, therefore, increase with increasing IEAR, and the curves in Figure 2.4 shift upwards. It can be seen from Figure 2.4 that net benefit reaches to zero at approximately 180 MW line size for IEAR of 605 ₹/kWh. The optimum line size for wind utilization is at about 110 MW capacity for all values of system IEAR.

Effect of Line Length

The benefits from integrating a remotely located wind farm to a power grid greatly depend on the distance of wind farm from the main grid system. The length of the transmission line is equal to the distance between the wind farm location and the grid access point. The investment cost attached to a transmission line normally varies linearly with the length. This section presents the results from studies done to evaluate the impact on the system reliability of the length of the transmission line connecting a wind farm to a power grid. Studies were done considering the 250 MW wind farm at five different distances i.e. 10, 50, 100, 150 and 200 km from the RTS access point. This analysis can be useful in selecting the proper transmission line capacity to

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connect wind farms at various distances from the main grid.

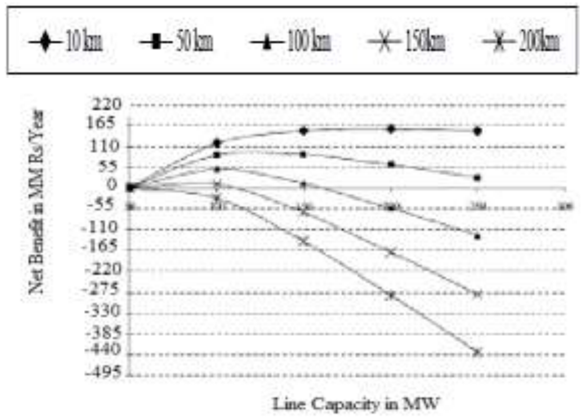

Figure 2.5: Variation of net benefit with transmission line length

Figure 2.5 shows the net marginal benefits with the variation in transmission line capacity at the five different line lengths. It can be seen from the figure that the net benefit decreases with the increase in the line length. The curves, therefore shift downwards with increase in the line length. The maximum net benefits is reduced to about one fourth the amount as the wind site distance is increased from 100 km to 150 km from the grid connection point. For a given line capacity, the net benefits increase significantly as the distance between the wind farm and the grid connection point is decreased. It can be seen that there is no marginal net benefit in connecting a wind farm that is 200 km away. It can also be seen from the figure that the net benefit decreases more rapidly with increase in the line length for 250 MW line capacity than for a 100 MW line capacity. This rapid decrease in net benefit is observed because the wind farm seldom produces rated capacity output and hence the benefits obtained from wind energy is very small compared to the increase in investment cost of 250 MW line capacity.

A wind farm situated near a power system grid can be connected more economically than one that is located farther away. The net benefit becomes negative as the capacity of a 150 km line is increased above 110 MW. The line capacity for optimum benefits varies with the line length. The optimum line capacity is about 110 MW to connect wind farm located at a distance of 100 km from a power grid. The optimum line capacity is increased to about 200 MW to connect a wind farm that is 10 times closer to the grid. The results show that more benefits from wind energy is obtained by connecting a wind farm located closer to the main grid with a larger line capacity than connecting a wind farm that is located farther away.

Effect of Wind Regime

It is known that the wind regime at the wind farm site has significant effect on the reliability of the wind integrated system. The evaluation of benefits associated with power delivery from wind farms at installed locations with different wind variation pattern can be useful in deciding appropriate transmission line capacity for a particular wind site. Figure 2.6 compares the net marginal benefits from wind sources located at geographical sites with wind data from three Vankusawade Wind Park locations, Zone 1, Zone 2 and Zone 3. The mean wind speeds at the three locations are given in Table 1.

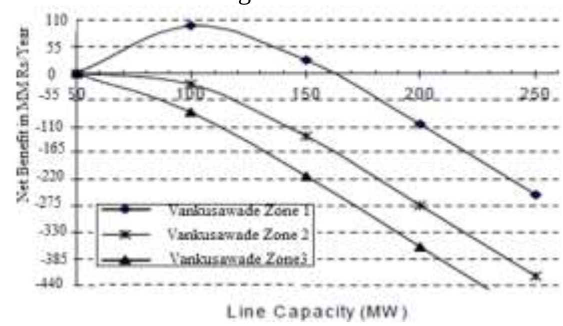

Figure 2.6: Variation of net benefit with wind regime

It can be seen from the Figure 2.6 that relatively high benefits are obtained from the Zone 1 when compared to the other two sites for any transmission line capacity. Zone 1 has a better wind resource than the other two sites, and is the only site among the three that provides a monetary benefit in expanding the line capacity above 50 MW. Studies similar to these can be done for a wind farm location of interest to determine the actual benefit from wind sources in a power system.

Effect of Wind Penetration

Previous studies [2] have shown that when wind penetration increases and reaches to a certain level then the benefits from wind power application in electric power systems decrease and eventually become negligible. This section shows the results from the study performed to check the effect of wind penetration on the actual benefits from the wind. The results are then analyzed to evaluate the appropriate transmission line size for wind power delivery. Reliability cost/benefit analysis was carried out at three different levels of wind penetration.

In this assessment a 8% wind penetration by integrating a 250 MW rated wind farm to the RTS is

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considered. This study considers three different wind penetration levels at 8%, 15% and 20% (i.e. connecting 250 MW, 427 MW and 570 MW wind farms respectively) to the RTS. Each wind penetration case is studied separately considering various tie line capacities. Five different line sizes at 20%, 40%, 60%, 80% and 100% of the rated wind farm capacity were used in the study.
Table 2 shows the cost-effective line size for various wind power penetration levels. The wind farm in each case is assumed to be at a distance of 100 km from the main power grid. Columns 3 and 4 of the table show the cost-effective line size in MW and in percentage of wind farm rated capacity respectively. It can be seen that optimum line capacity varies with varying wind power penetration. It can be noticed from Column 4 that the cost-effective line capacity, expressed in percent of the rated wind farm capacity, reduces with the increase in wind power penetration. This reduction in the optimum line size is a result of the relative decrease in the wind benefits compared to the investment cost of the transmission line.

Table 2: Cost-Effective Line Sizing at Different Wind Power Penetration levels

Wind Farm		Transmission Line	
Penetration in Percentage	*Installed Capacity in MW*	*Capacity in MW*	*% of Wind Farm Rated Capacity*
8%	250	110	44%
15%	427	170	40%
20%	570	210	37%

The results shown in Table 2 were obtained considering IEAR of 210.65 ₹/kWh. The effect of IEAR for various wind penetration levels were studied using three various IEAR values. The results are shown in Figure 2.7.

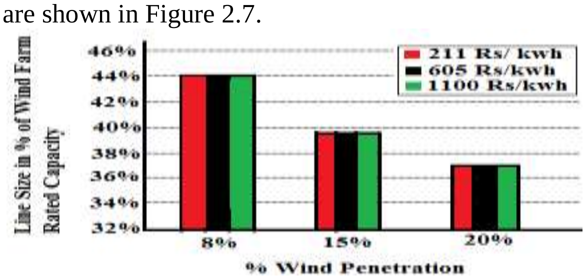

Figure 2.7: Cost-effective line sizing with varying IEAR

It can be seen from the Figure 2.7 that the cost effective line size is the same for all the values of IEAR for each level of wind penetration. It can be noticed from the figure that cost-effective line size decreases with increase in wind penetration for each IEAR value.

The results shown in Table 2 and Figure 2.7 were obtained considering the wind farm to be located 100 km away from the grid access point. The effect of transmission line length was studied for various wind power penetration level. Five different line lengths were used for the study. The variation in cost effective line size for various transmission line length on different wind power penetration levels are shown in Figure 2.7. The line sizes are expressed in percentage of the rated wind farm capacity.

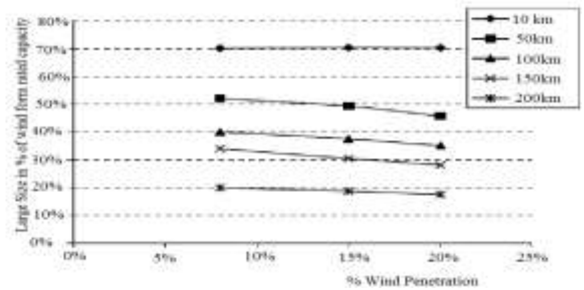

Figure 2.8: Cost-effective line size for varying line length

It can be seen from Figure 2.8 that the cost-effective line size varies with wind penetration for the different line lengths. The benefits from wind energy increases as the distance of the wind farm from the grid is decreased. The curves in Figure 2.8 shift upwards to indicate that the optimum line capacity to connect a wind farm increases as the line length decreases. The result is also shown in Figure 2.5. The top curve in Figure 2.8 shows that the optimum line sizing to connect a wind farm 10 km away, increases with increasing wind penetration. On the other hand, the optimum line capacity decreases with increasing wind penetration for wind farms located at large distance from the grid. It can be noticed that the optimum line size decreases with increase in the wind power penetration for the line length of 100, 150 and 200 km.

Conclusions

The principal objective of power system planner is to design reliable and economical system facilities. This objective becomes great challenging when considering transmission system facility to deliver wind power. An analytical approach for reliability/cost analysis is presented in this paper for determining cost-effective transmission line size for wind power delivery.

The benefits associated with wind power integration to a conventional system were analyzed for various case studies. The benefits are significantly limited by the power transmission capacity. The benefits

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associated with wind power delivery were compared with the investment cost of the respective line expansion. The marginal net benefit, which is the total benefit less the investment cost in line expansion above 50 MW rating, varies with different system parameters.

The results show that the net benefits normally increase when line capacity is increased from a relatively small capacity rating, and reach an optimum level. Further increase in line capacity results in a decrease of the net benefit. Studies with different transmission line investment cost show that the optimum transmission line size reduces with increase in line cost. The length of the transmission system increases with the increase in distance between the wind farm and the grid access point. The optimum line capacity for wind farm integration decreases with an increase in the line length. In other words, a wind farm situated near a power system grid can be connected more economically than one that is located farther away.

Wind regime at the wind farm location has great influence in the benefits that can be obtained from wind power generation and therefore greatly influences the economic line sizing for transporting the wind power to a grid system. Studies were conducted on different wind farm locations in the Indian province of Vankusawade Wind Park, Maharashtra. The results show that the optimum line size is relatively large for a wind site with good wind resources. The effect of wind power penetration on the optimum line sizing was also analyzed in the studies. The cost-effective transmission line size reduces with increase in wind penetration. The effect of line length and system IEAR were also studied for each level of wind penetration. The relatively benefits from wind transmission system expansion are evaluated from the resulting reduction in the customer interruption costs. An increase in system IEAR results in a higher reduction in the customer interruption costs and therefore the net benefits from increasing line size increases with system IEAR. The optimum line capacity, however, does not vary with the system IEAR.

Reliability cost/benefit analysis presented in this paper was carried out on a base system with various sensitivity studies. The method illustrated in this paper can be used for any wind site located at any distance from a grid system, and for any level of wind power penetration in a power system. Reliability/cost analysis as presented in this paper can be useful for evaluation of wind integrated power system for optimizing benefits available from wind. The analysis described in this work can provide important guidelines to the system planner to determine optimum transmission system for wind power.

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