TotalControl

Advanced integrated supervisory and wind turbine control for optimal operation of large Wind Power Plants

Optimization of reactive power dispatch Deliverable – D2.4

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Definitions/Abbriviations

DFIG	Doubly-fed induction generator
OLTC	On-load tap changer

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EXECUTIVE SUMMARY

This deliverable focuses on optimization of the reactive power dispatch between the wind turbines in a wind farm so that the total electrical losses are minimized. Losses in the electrical infrastracture of large wind power plants are not negligible, represeting 2-3% of the total energy production. Since they depend on the square of the current flowing through the cable, electrical losses can be reduced by increasing the voltage in the collector system, either by controlling the reactive power injected/absorbed by the wind turbines, or through control of on-load tap changer transformer. The general principle of loss minimization lies in controlling the reactive power dispatch in wind farms in such a way to minimize the total losses in the wind farm collection system and the wind farm transformer.

A mathematical optimization to minimize the electrical losses in a wind power plant considering power flow constraints and converter capabilities is developed. This methodology is analysed through simulation of Lillgrund wind farm using real power measurements. Sensitivity studies are performed with respect to OLTC settings and sizing of the wind turbine converters to analyse their impact on loss reduction.

The developed optimization methodology can reduce the energy losses substantially around 6% of the total energy lost. Loss savings are proportional to the active power generation level. Sensitivity studies show that while increasing the converter size does not have any impact on reducing losses, increasing the OLTC voltage settings can double the energy saving.

INTRODUCTION

Increasing concern for climate change is driving the electrical power system all over the world towards fossil-free generations. European Commission has roadmap towards carbon neutral energy production by 2050 [1]. Renewable energy based power generation is essential in order to realise this goal. Wind power is one of the cheapest and most prevalent renewable energy source. By 2018, total installed capacity of wind power in Europe has been increased to 178.8 GW, which is second largest form of power generation in Europe [2].

The size of the wind power plants are continuously growing, resulting in ever-larger electrical infrastructure. The electrical losses in the infrastructure of these large wind power plants – mostly offshore - are not negligible, being around 2%-3% of the total energy production [3], [4]. Therefore, electrical losses have large economic impact. Modern wind turbines have power converters that can control their active and reactive power independently. This reactive power capability of wind turbines can be used to reduce the electrical losses. Electrical losses in the wind farm collection system is dependent on the square of the current flowing through the cables. For a given power flow, the current through the cables can be reduced by increasing the voltage of the wind turbines as well as at the wind farm level through control of on-load tap changer (OLTC) transformer connecting the wind farm to the external grid. Increase in voltage at the wind turbine level is achieved through reactive power control by the converter of the modern wind turbines. Doubly-fed induction generator (DFIG) based wind turbines have partially scaled converters to provide the reactive power support, while the fully-rated converter based wind turbines have full scale converters. It should be noted that the reactive power capability of these converters depend on active power setting as well as voltage of the converters. Furthermore, increasing the reactive power output might also increase the current in the cables. The general principle of loss minimization lies in controlling the reactive power dispatch in wind farms in such a way to minimize the total losses in the wind farm collection system and the wind farm transformer.

Recently, there has been some academic studies on loss minimization of wind farm. Zhang et. al. [5] developed reactive power dispatch strategy for loss minimization in a DFIG-Based Wind Farm. Simulations are performed for different values of wind speeds and reactive power references from system operator. Jung and Jang [6] developed a loss minimization methodology through reactive power assignment strategy for the wind turbines using linearized incremental loss calculation. Wang et. al. [7] developed a methodology for optimal reactive power dispatch for full-scale converter based wind farm to reduce power losses while supplying the reactive power reference as requested by the system operator. Li et. al. [8] performed a similar study also considering levelized production cost minimization. Not all these methodologies validate the results based on real data. Furthermore, these methodologies do not consider control of on-load tap changer (OLTC) transformer, which might have a large impact on the voltage level of the wind farm, thereby, reducing the losses.

This report develops a mathematical optimization to minimize the electrical losses in a wind power plant considering power flow constraints and converter capabilities. This methodology is analysed through simulation of Lillgrund wind farm using real power measurements. Sensitivity studies are performed with respect to OLTC settings and sizing of the wind turbine converters to analyse their impact on loss reduction.

1. Optimization Methodology

A mathematical optimization model is developed where the objective is the minimization of the total power loss in the wind power plant as shown below:

$$\min_{x} P_L(x)$$
$$P_L(x) = \sum_{(i,j)\in \mathcal{E}_{\mathcal{B}}} G_{ij}(V_i^2 + V_j^2 - 2V_iV_j\cos(\theta_i - \theta_j)) \quad (1)$$

Where

- x is the control (independent) variable
- i, j are the indices of the set of branch edges (lines) $\mathcal{E}_{\mathcal{B}}$ connecting the wind turbines
- P_L is the total power loss in the wind power plant
- G_{ij} the series conductance of the ij line
- V_i and V_j and θ_i and θ_i are the voltage magnitudes and phase angles at the sending end bus i and receiving end bus j of the line respectively.

Control variables: The vector of control variables x incorporates voltage set point of each wind turbine connected at bus i.

$$x = [V_i]^T \quad (2)$$

This optimization is performed under several constraints:

Equality Constraint:
Reactive power output at point of common coupling, Q_{PCC} is the amount of reactive power ordered by the system operator, Q_{TSO}.

$$Q_{PCC} - Q_{TSO} = 0 \quad (3)$$

Inequality Constraints:
Loading of the lines is equal or less than maximum permissible limit.

$$S_{l_i} \leq S_{l_i}^{max} \;\; \forall \;\; i \;\in \mathcal{E}_{\mathcal{B}} \quad (4)$$

Where $S_{l_i}$is the MVA flow through the cable i and $S_{l_i}^{max}$ is the rated MVA capacity of the cable.

Voltage limits of the wind turbine buses are within permissible limits.

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (5)$$

Typical values of $V_i^{min}$and V_i^{max} are 0.9 and 1.1 respectively.

Reactive power capability from the wind turbine is bounded by the converter size and parameters [9], resulting that

$$Q_{G_i}^{min} \leq Q_{G_i} \leq Q_{G_i}^{max} \quad (6)$$

It should be noted that reactive power capability, as shown in Figure 1, depends on active power generation level and on the wind turbine terminal voltage. This aspect makes the optimization function non-linear. The capability changes with the voltage level which is the control variable of the objective function. The capability curve is determined by the voltage and current limit of the wind turbine converter. This is explained in details and sensitivity studies are performed for different converter ratings later in the report.

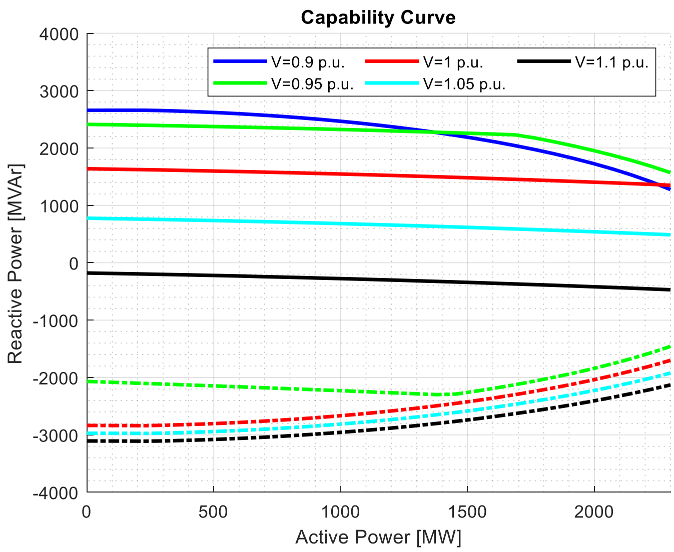

FIGURE 1 REACTIVE POWER CAPABILITY OF WIND TURBINE

The developed optimization methodology is tested using real data from Lillgrund offshore farm. The details of Lillgrund offshore windfarm are described in the next section.

2. ELECTRICAL MODEL OF LILLGRUND OFFSHORE WIND POWER PLANT

2.1. Layout

The layout of the Lillgrund offshore wind farm is shown in Figure 2. Lillgrund wind farm has 48 wind turbines each of 2.3 MW, thereby total installed capacity of the wind farm being 110 MW. The power ratings and thereby cable cross-section of cable segments between different wind turbines are estimated based on the number of wind turbines connected downstream to any particular cable segment. The electrical parameters – resistance, inductance and capacitance for the estimated cross-sections are shown in Table 1. These cable segments are denoted with different color coding in Figure 2.

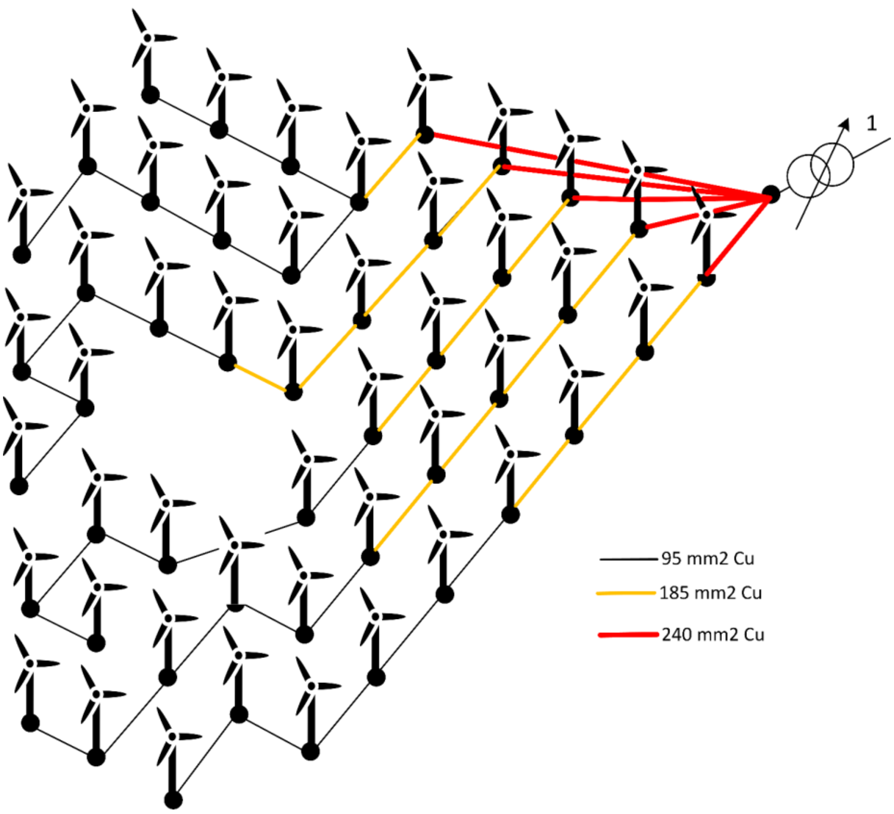

FIGURE 2 LAYOUT OF LILLGRUND WIND FARM

TABLE 1 ELECTRICAL PARAMETERS FOR DIFFERENT CABLE CROSS-SECTIONS

Cross Section (mm2)	Diameter (mm)	Capacitance (microF/km)	Inductance (mH/km)	Resistance (Ohm/km)
95	11.2	0.18	0.44	0.181053
185	15.8	0.22	0.39	0.092973
240	18.1	0.24	0.38	0.071667

The wind turbines of Lillgrund wind farm are fully rated converter based wind turbines aslo known as IEC 61400-27 Type 4 wind turbine as shown in Figure 3. In such a wind turbine, the generator is decoupled from the power grid through fully rated rectifier and inverter. This allows for much better speed control, power control as well as compliance with grid code requirements and provision of ancillary services. The converters are responsible of providing reactive power support and voltage control as described in the previous section to reduce the losses in the wind farm.

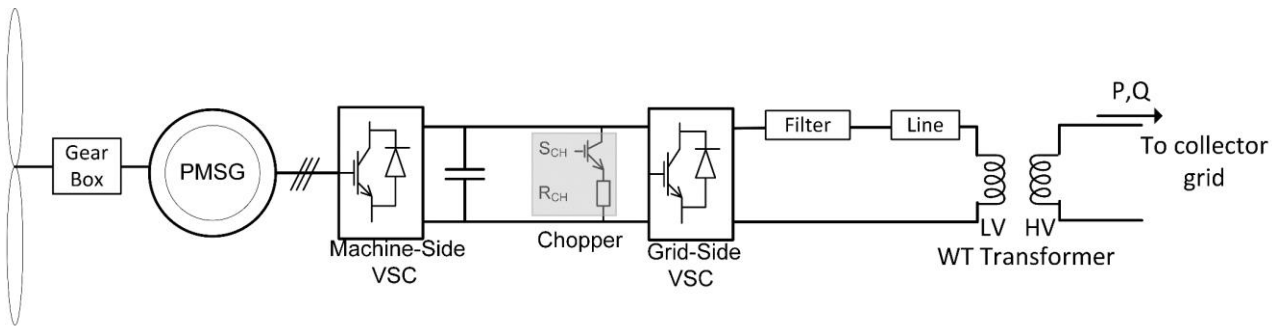

FIGURE 3 SCHEMATIC DIAGRAM OF FULLY RATED CONVERTER BASED WIND TURBINE

The wind turbines are further connected to the collection system through a transformer. The wind farm is connected to external power system through an on-load tap changing (OLTC) transformer. OLTC transformers are equipped with automatic controls which can regulate the tapping in the high voltage side of the transformer windings in changing grid conditions to either control the voltage at low voltage side or at high voltage side of the transformer. These transformers can either be owned by the grid operators or the wind farm owners. In case the grid operators controls the transformer, the voltage is generally controlled at a specific value in the low voltage side of the transformer (at the wind farm connection point) and the wind farm operators may not have the jurisdiction to control the OLTC. However, in case of wind farm owners controlling the OLTC, the voltage of the low voltage side of the transformer can be increased up to certain level without compromising the security/power quality of the power system. Increasing the voltage level definitely has positive impact in terms of minimizing losses in the wind farm collection system. Having higher voltage level implies lower current for a given active power flow, resulting in reduction of copper losses (I^2R). Sensitivity studies are performed for 2 different OLTC voltage levels and discussed in details later in the report.

The optimization problem is solved using Fmincon algorithm (interior point based solver for non-linear constrained problem)[10] , while the constraints are calculated using Newton-Raphson power flow implemented in Matpower [11].

3. Analysis of Results

The computation time required for performing optimization for a single operating point can vary from 2 minutes to 14 minutes with an average of 4.5 minutes. Since this work involves analysing the data from Lillgrund wind farm for atleast 1 year at time resolution of 5 minutes, optimization can't be practically run for the whole year (2011). In order to handle this challenge, 3 representative days are chosen as high wind day, medium wind day and low wind day respectively. Following which, the improvement in losses using the developed optimization methodology for these representative days are extrapolated for whole year. Histogram of the power production over 1 year of data can be seen in Figure 4. The annual energy production is 374 GWh and the calculated capacity factor is 38.8%.

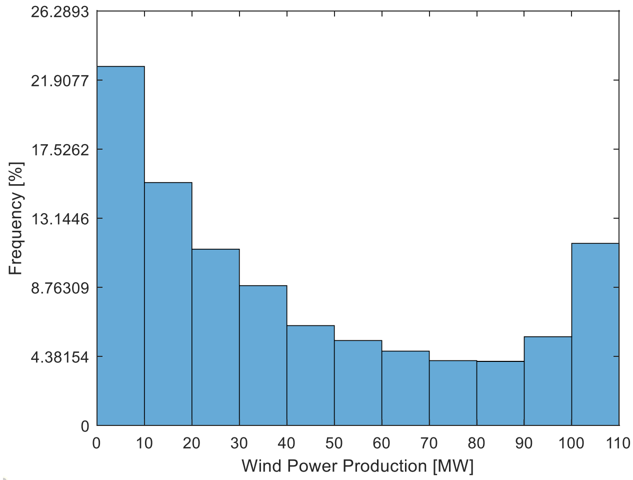

FIGURE 4 HISTOGRAM OF POWER PRODUCTION FROM LILLGRUND WIND FARM

3.1. Representative Days

3.1.1. High Wind DAY

Figure 5 shows the time series of wind power production in the representative day where the wind power fluctuates between 50 MW to 110 MW. Total energy produced in the whole day is 2.075 GWh.

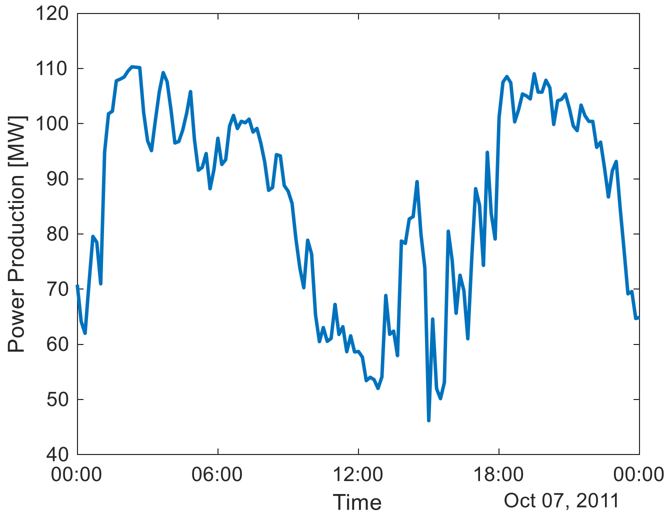

FIGURE 5 WIND POWER PRODUCTION IN REPRESENTATIVE HIGH WIND DAY

Power losses in the electrical system is shown in Figure 6. Total energy loss is 26.4 MWh which is around 1.3% of the total energy produced.

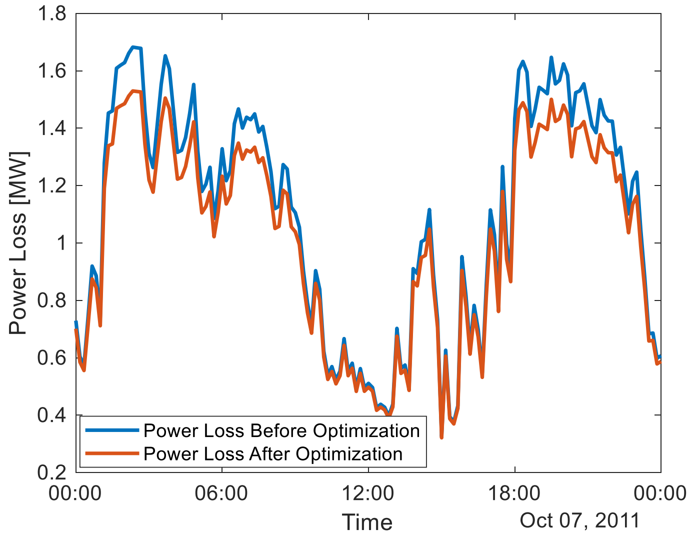

FIGURE 6 POWER LOSS BEFORE AND AFTER OPTIMIZATION FOR THE REPRESENTATIVE HIGH WIND DAY

Figure 6 also demonstrates the power loss after the optimization. Total energy loss after the optimization is 24.6 MWh. Therefore, 1.8 MWh of energy is saved through the optimization, i.e. 6.7% of the total energy lost in the whole day in average.

However, the improvement in losses is highly depending on the active power production by the wind turbines as evident from Figure 7. It can be observed that Figure 7 is highly correlated with active power production in Figure 5.

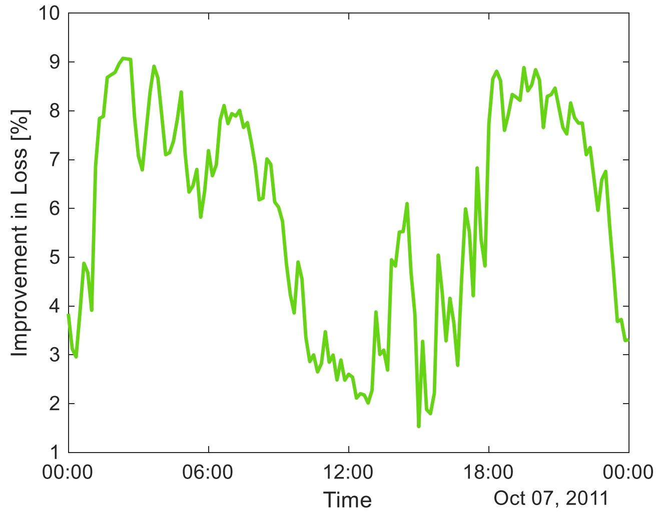

FIGURE 7 IMPROVEMENT IN LOSSES AFTER OPTIMIZATION FOR THE REPRESENTATIVE HIGH WIND DAY

In order to extrapolate the results for a whole year during high wind scenarios, power loss vs active power and improvement in loss vs active power are fitted as quadratic functions as shown in Figure 8 and Figure 9 respectively.

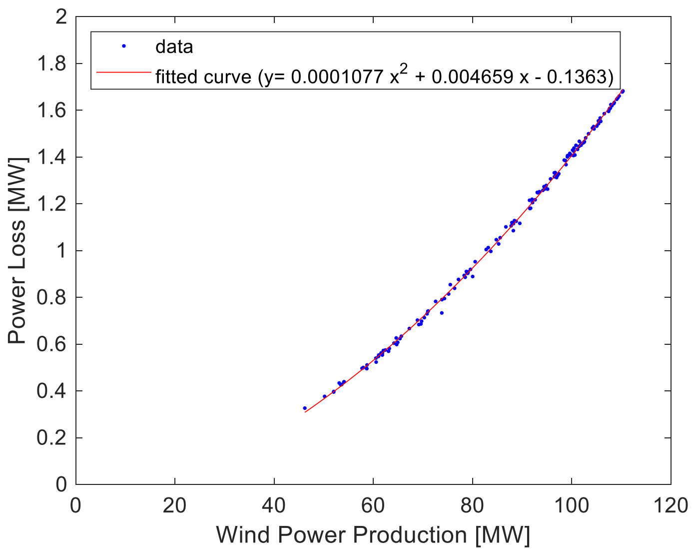

FIGURE 8 CURVE FITTING FOR ACTIVE POWER LOSS AGAINST ACTIVE POWER PRODUCTION DURING HIGH WIND SCENARIO

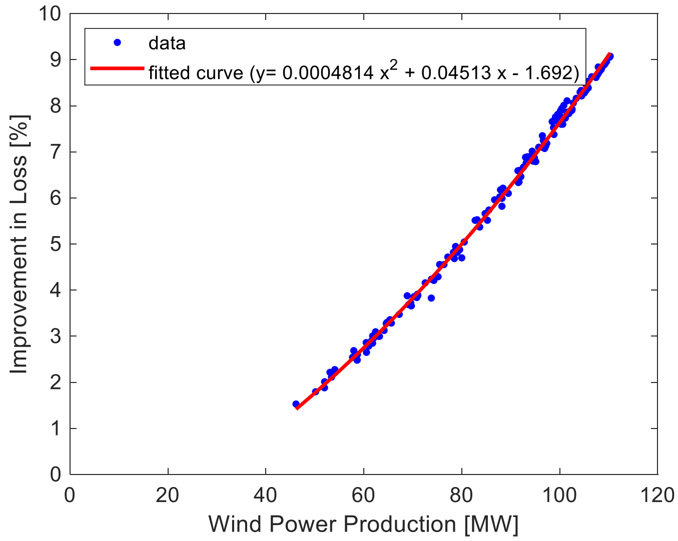

FIGURE 9 CURVE FITTING FOR IMPROVEMENT IN ACTIVE POWER LOSS AGAINST ACTIVE POWER PRODUCTION DURING HIGH WIND SCENARIO

It can be seen that the curves are very well fitted demonstrating the confidence to utilize the representative days results for whole year analysis.

3.1.2. Medium Wind Day

Similar to previous studies, optimizations are performed for a representative day where the wind power is varying up to 70 MW in the Lillgrund wind farm as shown in Figure 10. Total energy produced in whole day is 743.6 MWh.

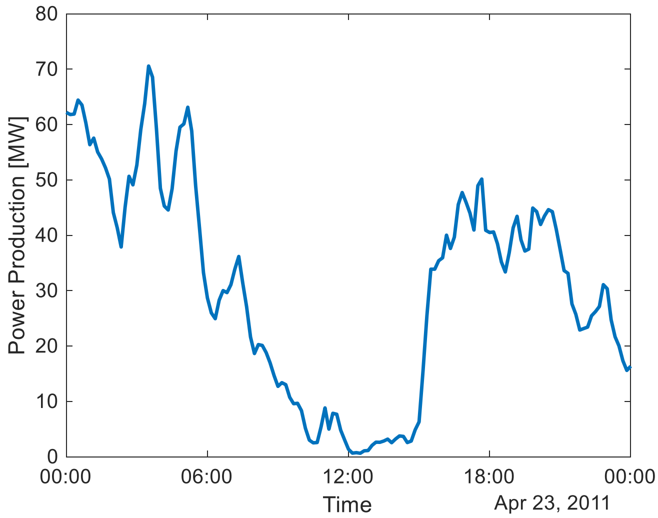

FIGURE 10 WIND POWER PRODUCTION IN REPRESENTATIVE MEDIUM WIND DAY

Power losses in the electrical system is shown in Figure 11. Total energy lost is 4.62 MWh which is around 0.62% of the total energy produced. It can be noted that the energy loss in percentage is much lower than that of high wind day. This is expected since power loss is function of square of current flow.

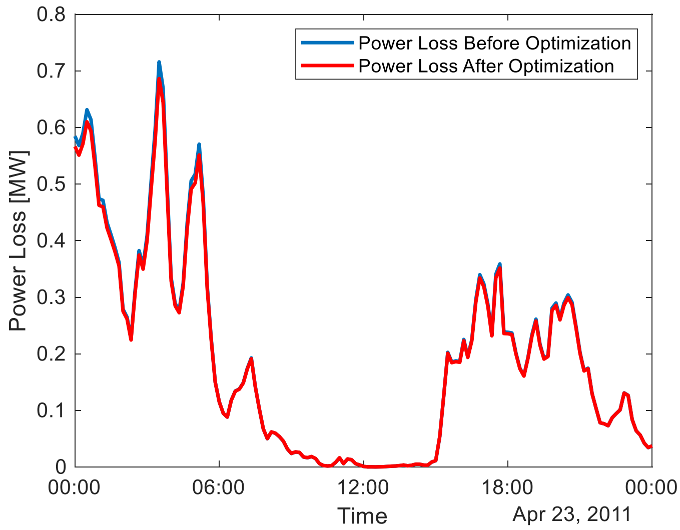

FIGURE 11 POWER LOSS BEFORE AND AFTER OPTIMIZATION FOR THE REPRESENTATIVE MEDIUM WIND DAY

Similarly to high wind day shown in Figure 9, improvement in losses depends on the active power production. Similar observations can be found in improvement in losses for medium wind scenario as shown in Figure 12.

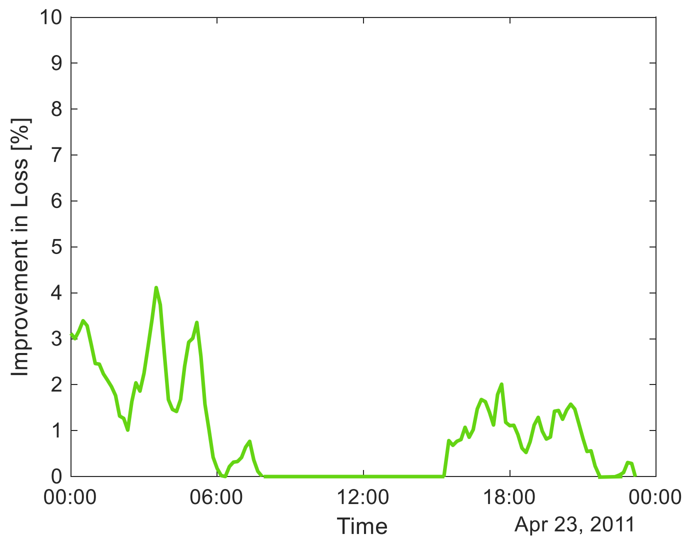

FIGURE 12 IMPROVEMENT IN LOSSES AFTER OPTIMIZATION FOR THE REPRESENTATIVE MEDIUM WIND DAY

In order to extrapolate the results for whole year during medium wind scenarios, power loss vs active power and improvement in loss vs active power are fitted as quadratic functions as shown in Figure 13 and Figure 14Figure 9 respectively.

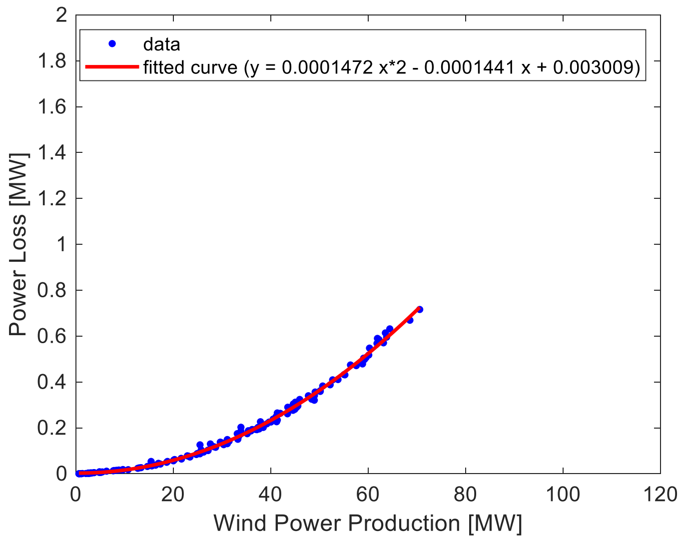

FIGURE 13 CURVE FITTING FOR ACTIVE POWER LOSS AGAINST ACTIVE POWER PRODUCTION DURING MEDIUM WIND SCENARIO

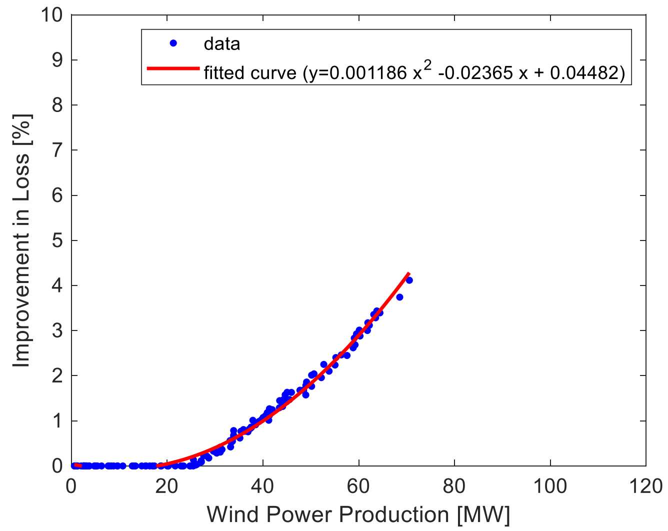

FIGURE 14 CURVE FITTING FOR IMPROVEMENT IN ACTIVE POWER LOSS AGAINST ACTIVE POWER PRODUCTION DURING MEDIUM WIND SCENARIO

3.1.3. Low Wind Day

Figure 5 shows the time series of wind power production in the representative day for low wind power generation. Total energy produced in the whole day is 260 MWh.

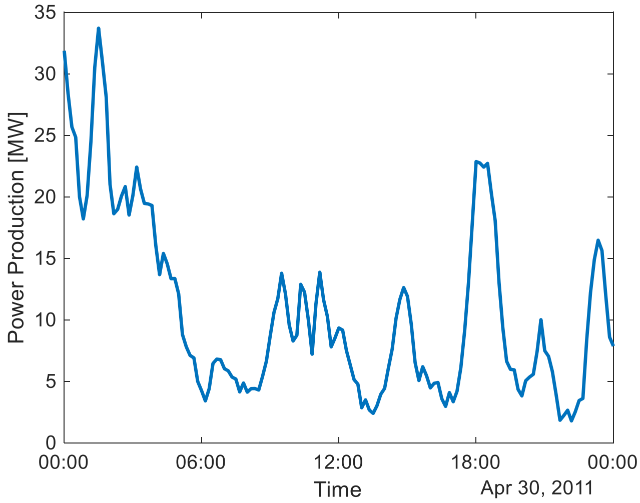

FIGURE 15 WIND POWER PRODUCTION IN REPRESENTATIVE LOW WIND DAY

Power losses in the electrical system is shown in Figure 16. Total energy lost is negligible value of 0.58 MWh, therefore the loss improvement is also negligible as shown in Figure 16 and Figure 17.

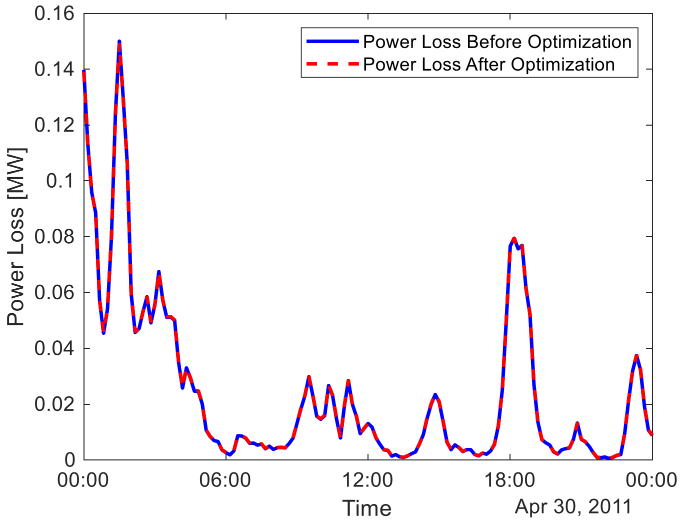

FIGURE 16 POWER LOSS BEFORE AND AFTER OPTIMIZATION FOR THE REPRESENTATIVE LOW WIND DAY

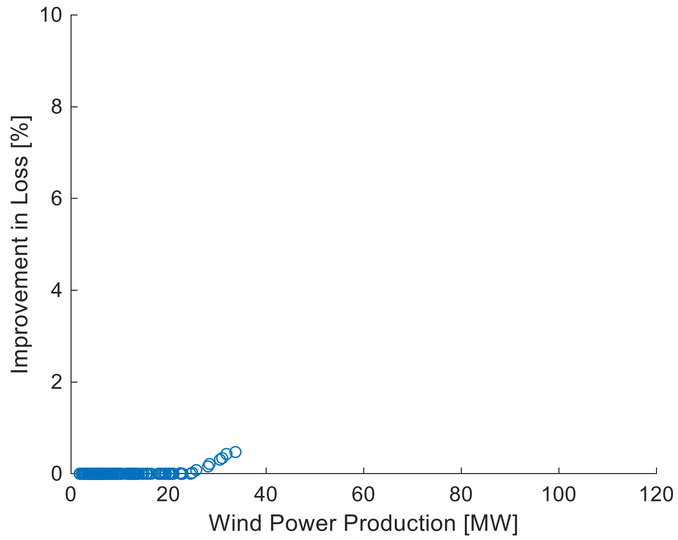

FIGURE 17 IMPROVEMENT IN LOSSES AFTER OPTIMIZATION FOR THE REPRESENTATIVE LOW WIND DAY

3.1.4. Extrapolation to annual data

The results from the representative days from previous section is extrapolated for whole year (histogram shown in Figure 4). The result of the extrapolation can be seen in Table 2.
For each of the bin of Figure 4, total energy production in the year is calculated, following which, energy loss and energy saving is calculated based on the curve fitted in Figure 8, Figure 9, Figure 13 and Figure 14.

TABLE 2 LOSS ANALYSIS FOR WHOLE YEAR

Wind Power Production Range [MW]	Total Annual Energy Production [GWh]	Total Annual Energy Loss [GWh]	Annual Energy Saving [GWh]
0-20 (Low)	30.86	0	0
20-60 (Medium)	103.46	0.61	0.01
60-110 (High)	239.93	3.18	0.23
Total	**374.26**	**3.80**	**0.24**

It can be observed that 3.80 GWh is lost which is around 1% of the total annual energy production. Out of this 3.80 GWh, 6.2% i.e. 240 MWh can be saved.

3.2. Sensitivity Analysis

3.2.1. Wind Turbine Converter Size

Wind turbine converter is designed based on voltage and current ratings, which limit the active and reactive power capability of the converter. As can be seen from [9], the reactive power limits of Equation (6), are determined as supremum of the following equation:

$$\mathrm{Q}_{lim} = \mathrm{Sup}\left(\sqrt{\left(\frac{V_{coll}V_{Cmax}}{\sqrt{R_{WT}^{\ 2} + X_{WT}^{\ 2}}}\right)^2 - \left(P + \frac{V_{coll}^{\ 2}R_{WT}}{R_{WT}^{\ 2} + X_{WT}^{\ 2}}\right)^2} - \frac{V_{coll}^{\ 2}X_{WT}}{R_{WT}^{\ 2} + X_{WT}^{\ 2}}, \sqrt{(V_{coll}I_{Cmax})^2 - P^2}\right) \quad (7)$$

where
P= active power output of the wind turbine
Q = reactive power output of the wind turbine
V_{coll}= voltage at the wind turbine connection point
R_{WT} = resistance of the wind turbine
X_{WT} = reactance of the wind turbine
V_{Cmax} = maximum converter voltage allowed based on converter design
I_{Cmax} = maximum converter current allowed based on converter design

It can be seen from Equation (7) that either converter voltage limit, V_{Cmax} or converter current limit, I_{Cmax} limits the reactive power capability. During loss minimization, Q_{max} is of relevance as opposed to Q_{min}. Figure 18 shows the reactive power capability, Q_{max} , for different values of V_{Cmax} and I_{Cmax} for V_{coll} = 1 p.u. It can be seen that towards low wind power generation, voltage limitation limits the reactive power capability; while at higher power production values, Q_{max} is limited by I_{Cmax}.

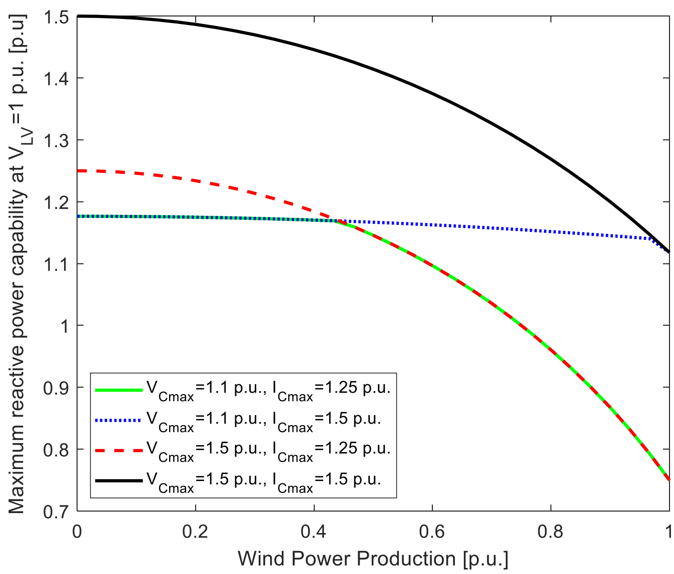

FIGURE 18 MAXIMUM REACTIVE POWER CAPABILITY OF THE WIND TURBINE FOR DIFFERENT CONVERTER SIZE

When optimization methodology are performed for these different V_{Cmax} and I_{Cmax} values, it is interesting to find out that converter sizes don't impact on the loss minimization. The reason being that the limits are not reached while optimization. Therefore, increasing the converter size does not add any additional value in terms of loss minimization.

3.2.2. Offshore Wind Farm transformer tap setting

As mentioned in the introduction, OLTC transformer plays major role in increasing the voltage level of the wind farm, thereby, resulting in reduction of losses. Sensitivity studies are performed in this section, where the OLTC transformer is controlled to control the low voltage side (PCC end) where wind farm is connected either at 1 p.u. or 1.05 p.u.

Figure 19 shows the active power loss with and without optimization for difeerent OLTC settings

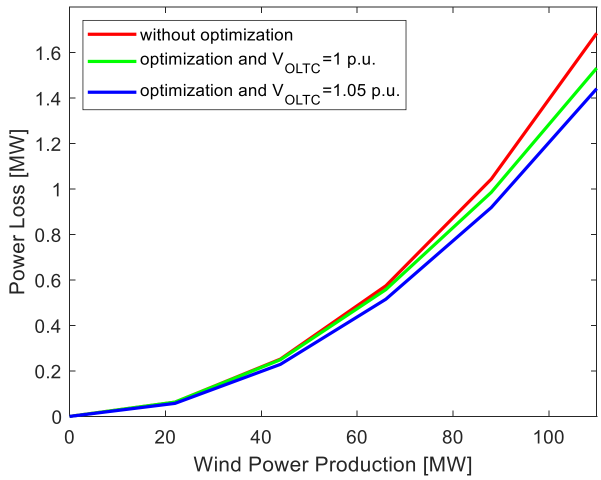

FIGURE 19 ACTIVE POWER LOSS WITHOUT OPTIMIZATION AND WITH OPTIMIZATION FOR DIFEERENT OLTC SETTINGS

With voltage at PCC to be 1 and 1.05 p.u. It can be observed that power loss reduction (a quadratic function of active power production) reduces more for $V_{OLTC} = 1.05$ p.u. as compared to $V_{OLTC} = 1$ p.u.

The improvement is losses by the proposed methodology for different OLTC voltages are shown in Figure 20. The improvement of losses is significant with OLTC settings of 1.05 p.u. varying from 8 to 14% as compared to 0-9% for $V_{OLTC} = 1$ p.u.

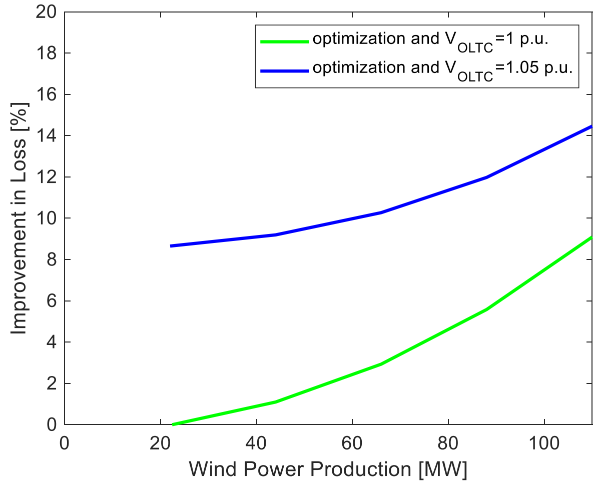

FIGURE 20 IMPROVEMENT OF LOSSES FOR DIFFERENT OLTC SETTINGS

When these findings are extrapolated for annual wind power production profile in same way as section 3.1.4, substantial energy savings can be observed. These findings are summarized in Table 3.

TABLE 3 COMPARISON OF ENERGY LOSS FOR DIFFERENT OLTC SETTINGS

	$V_{OLTC} = 1$ p.u.	$V_{OLTC} = 1.05$ p.u.
Annual Energy Saving [MWh]	240	470
Annual energy saving w.r.t annual energy lost [%]	6.2	12.37
Annual energy saving w.r.t AEP [%]	0.06	0.13

Table 3 shows that the energy saving is double when $V_{OLTC} = 1.05$ p.u. as compared to $V_{OLTC} = 1$ p.u.

4. Conclusions

Nonlinear, nonconvex optimization method is developed to dispatch reactive power set points among the wind turbines to minimize electrical losses for different active power production while satisfying the reactive power requirements from the grid. The studies are validated for Lillgrund wind farm using real measurements for 1 year. It has been observed that electrical losses can amount upto 1% of the annual energy production. The developed optimization methodology can reduce the energy losses substantially by around 6% of the total energy lost (success criterion of the DoA). Loss savings are more when the active power generation is high and vice versa.

Sensitivity studies are performed for different converter sizing and voltage settings of wind farm transformer. Although, increasing the converter size does not have any impact on reducing losses but it is observed that increasing the OLTC voltage settings from 1 p.u. to 1.05 p.u. can double the energy saving.

References

[1] European Commission, "The Commission calls for a climate neutral Europe by 2050*." [Online]. Available: https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6543. [Accessed: 24-Nov-2019].

[2] WindEurope, "Wind energy in Europe in 2018." [Online]. Available: https://windeurope.org/about-wind/statistics/european/wind-energy-in-europe-in-2018/. [Accessed: 24-Nov-2019].

[3] A. Colmenar-Santos, S. Campíez-Romero, L. Enríquez-Garcia, and C. Pérez-Molina, "Simplified Analysis of the Electric Power Losses for On-Shore Wind Farms Considering Weibull Distribution Parameters," *Energies*, vol. 7, no. 11, pp. 6856–6885, Oct. 2014.

[4] E. Díaz-Dorado, C. Carrillo, J. Cidrás, and E. Albo, "Estimation of energy losses in a wind park," in *2007 9th International Conference on Electrical Power Quality and Utilisation, EPQU*, 2007.

[5] B. Zhang, P. Hou, W. Hu, M. Soltani, C. Chen, and Z. Chen, "A Reactive Power Dispatch Strategy with Loss Minimization for a DFIG-Based Wind Farm," *IEEE Trans. Sustain. Energy*, vol. 7, no. 3, pp. 914–923, Jul. 2016.

[6] S. Jung and G. Jang, "A Loss Minimization Method on a Reactive Power Supply Process for Wind Farm," *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 3060–3068, Jul. 2017.

[7] N. Wang, J. Li, W. Hu, B. Zhang, Q. Huang, and Z. Chen, "Optimal reactive power dispatch of a full-scale converter based wind farm considering loss minimization," 2019.

[8] J. Li *et al.*, "Optimal reactive power dispatch of permanent magnet synchronous generator-based wind farm considering levelised production cost minimisation," *Renew. Energy*, vol. 145, pp. 1–12, Jan. 2020.

[9] M. Sarkar, M. Altin, P. E. Sørensen, and A. D. Hansen, "Reactive Power Capability Model of Wind Power Plant Using Aggregated Wind Power Collection System," *Energies*, vol. 12, no. 9, p. 1607, Apr. 2019.

[10] Mathworks, "fmincon: Find minimum of constrained nonlinear multivariable function - MATLAB fmincon - MathWorks Nordic." [Online]. Available: https://se.mathworks.com/help/optim/ug/fmincon.html. [Accessed: 12-Dec-2019].

[11] R. Zimmerman and D. Gan, "MATPOWER: A Matlab Power System Simulation Package."