Optimizing offshore wind farm electrical system design and reactive power provision

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In this work the optimization framework developed in WP6, has been applied on an offshore transmission system defined by RWE Innogy UK.
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Abstract

In this paper, electrical system design for the offshore transmission system of a wind farm has been optimized such that the grid code compliance has been ensured and the total power losses are minimized (reduced levelized cost of energy).
As a case study, the optimization framework has been implemented on the preliminary design of an offshore transmission system, in which some aspects of the design are predetermined and the optimization problem has only a few degrees of freedom. In spite of this, the design has been optimized such that reactive power provision and grid voltage comply with the grid code requirements, while the total power loss in the system has been minimized. The optimization framework is applicable on any other design with any other degrees of freedom.

Optimizing the design of a combined wind farm collection grid and offshore transmission system can be conducted using the optimization framework discussed in this paper. Depending on the grid code requirements and the design stage, which affects the number of decision variables, the problem can be reformulated as a multi-objective or single objective optimization problem.

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Abstract

In this paper, electrical system design for the offshore transmission system of a wind farm has been optimized such that the grid code compliance has been ensured and the total power losses are minimized (reduced levelized cost of energy). As a case study, the optimization framework has been implemented on the preliminary design of an offshore transmission system, in which some aspects of the design are predetermined and the optimization problem has only a few degrees of freedom. In spite of this, the design has been optimized such that reactive power provision and grid voltage comply with the grid code requirements, while the total power loss in the system has been minimized. The optimization framework is applicable on any other design with any other degrees of freedom.

Optimizing the design of a combined wind farm collection grid and offshore transmission system can be conducted using the optimization framework discussed in this paper. Depending on the grid code requirements and the design stage, which affects the number of decision variables, the problem can be reformulated as a multi-objective or single objective optimization problem.

Keywords: Wind Farm, Steady-state analysis, Reactive power control, Optimization, Offshore transmission system, Grid compliance

1. Introduction

Development of offshore wind farms for electrical power production is rapidly increasing in size and number. Large grid connected wind power farms have significant impact on the electricity system and are therefore subject to most of the requirements that hold for conventional power plants. However, there are new challenges in wind farms as power plants that did not exist with the conventional ones. A typical challenge is caused by the rapid changes in wind speed, which affects the active power production (wind turbines can switch on and off) and that may cause considerable changes in reactive power demand Kanev et al. (2013). Reactive power provision methods for connecting (offshore) wind farms to grid depend on many items, including the type of the wind turbines generators, the length of ac transport cables, grid code characteristics, and specific control objectives. The reactive power controllers can be designed and used for power factor improvement, power loss reduction, increase in steady state transmitted power, also to limit transmission losses, to optimize transmission capacity, and to keep the grid voltage within the safe operational limits. Bayod et al. (2002); Chen (2005).

The reactive power control strategies state of the art has been divided by Fortmann et al. (2008) into two main categories: control at the Point of Common Coupling (PCC) and control at the wind turbine. The control strategies at the PCC can be designed to control the power factor, reactive power, or voltage. Power factor control can supply reactive power for the grid, in case of variations in the the active power supply. But, depending on the cause of the active power variations, the controller could have a poor performance. Controlling reactive power at the PCC is more common but, it also has some disadvantages in case of sudden changes in the output power. In order to prevent unwanted effect on the voltage, a fast control of reactive power set-point is required Fortmann et al. (2008). Also, voltage control at the PCC can be used to reduce the effect of the changes in active power supply of the wind farm on the voltage change. However, because of the communication delays, some changes in the voltage are inevitable Fortmann et al. (2008). The second category of reactive power control is the control at the wind turbine, which can have different structures. At the wind turbine, the reactive power set-point for each wind turbine and the measured voltage are inputs. Therefore, if a grid fault happens, the operation mode is switched from reactive power control to voltage control Fortmann et al. (2008).

In 2004-2005 Risø performed some initial research with the purpose of making wind farms operate more like a conventional power plant. In Sørensen et al. (2005); Hansen et al. (2006) the authors present a wind farm control concept with both centralized control and control for each individual wind turbine. In their approach, the controllers at turbine level ensure that active and reactive power reference commands provided by the centralized controller are followed.

In 2006, several reactive power control strategies were discussed by Amada and Moreno (2006), as well as the grid impact of a wind farm reactive power based on a statistical wind farm model. This work also investigates the effect of the wind farm output on the active power losses and reactive power balance in network elements. Around the same time at ECN EeFarm toolbox for Matlab was developed that was able to perform the steady-state analysis of electrical systems. The latest version of the toolbox, EeFarm II, was published in Pierik et al. (2009)

In the year 2007, the grid codes that were adapted for wind power integration up to then, were introduced in de Algeria I. M. et al. (2007), and the issues of connecting large wind power plants to the grid were addressed one more time. Moreover, some of the requirements for different wind turbine technologies such as DFIG and SCIG to help in reactive power compensation was discussed de Algeria I. M. et al. (2007). Modeling and control of wind farms with the purpose of following the grid code and connection to the grid (including reactive power and voltage control) was also discussed in an ECN' technical report Pierik et al. (2008).

Various other reactive power control methodologies have been developed by academia and industry to use the inherent reactive power production capabilities of wind turbines, to improve the steady-state and dynamic performance of Power systems Meegahapola et al. (2010); Kayikci and Milanovic (2007); Ullah and Thiringer (2007); Ullah et al. (2007). The inherent capability of DFIG turbines for reactive power production and transmission loss reduction has been further studied in Konopinski et al. (2009); De Oliveira-De Jesus et al. (2008). In another study on the reactive power generation by DFIG based wind farms, an overview of different options for reactive power supply by the wind farms in steady-state has been evaluated Erlich et al. (2007). Then, the reactive power supply during faults and fault ride through by the turbines has been discussed. It has been shown in this paper that using an optimization algorithm to control the reactive power in a wind farm and letting the wind turbines contribute in reactive power dispatch will help in cost saving considerably Erlich et al. (2007).

Some of the wind turbine types can be a controllable source of reactive power, such as DFIG turbines and full converter generator turbines. The reactive power limit of DFIG turbines and DFIG farms has been analyzed in Xu et al. (2009). Then, a reactive power controller has been explained and simulated for a DFIG turbine farm. It has been shown that the DFIG wind farm is able to contribute to the reactive power regulation of the grid, which helps to relief the design requirements of the offshore grid for reactive power provisionXu et al. (2009). In addition to wind turbines, there are other types of compensators for reactive power in wind power plants. For example, Shunt and Regulated Reactors, Static Var Compensator, Static Synchronous Compensator, etc., all introduced and explained in Camm et al. (2009).

During the past few years, many research efforts has been conducted on optimizing the capability of wind farms to compensate reactive power according to grid code. An example is the work done in El-Shimy (2012), which explains the modelling and improved analysis of the effective reactive power control by wind turbines in grid-connected wind farms. Another recent work addresses a multi-objective reactive power controller, which investigates the capability of DFIG turbines in a wind farm to deliver multiple reactive power objectives during variable wind conditions Meegahapola et al. (2013). Furthermore, Singh et al. (2013) proposed a new reactive power optimization for a DFIG turbine farm, based on genetic algorithm, to reduce the distribution losses. In this approach the control variable is the reactive power output of the wind farm that is used for minimizing losses and improving voltage profiles. Another example of utilizing genetic algorithms for reactive power control is the work in Li (2013) that considers wind farms connected to grid and addresses modeling and economic issues in reactive power and voltage optimization.

In this paper, reactive power provision by an offshore transmission system for a wind farm off the Netherlands coast, which is connected to shore via HVac, will be investigated and optimized. The objective is to satisfy the grid code requirements such that the power losses in the transmission system are minimized. The grid code requires either unity power factor at the onshore grid, or to provide required reactive power based on the P/Q grid code envelope.

For reactive power provision at the grid connection point most often different means of reactive power and voltage control will be used such as inductors, tap changers and STATCOMs , while solely using the inherent capabilities of the wind turbines may be insufficient to meet the grid requirements or may lead to relatively high losses. Therefore the reactive power set point at the Wind Power Plant level will be optimized, considering the WPP operating conditions, grid conditions and grid operator demands. This includes a trade-off between the grid operator demands and the type, rating and location of alternative means for voltage/reactive power control. The evaluation is performed by comparing energy losses and checking compliance to grid voltage / reactive power requirements for an HVac-connected offshore WPP.

The optimization algorithm in this work is designated as Covariance Matrix Adaptation Evolutionary Strategy (CMA-ES) which is a well-known, state-of-the-art optimization algorithm for single-objective real-valued problems, especially in black-box settings Hansen and Kern (2004); Hansen (2006).

The paper continues with introducing the case study wind farm and the transmission system in the next section. Afterward, the optimization problem is formulated and the optimization algorithm is introduced, and finally the simulation results are presented and discussed.

2. Wind farm and the Offshore transmission system

The case study in this paper is a 295 MW wind farm located about 90 km off the Dutch coast. The Dutch grid code requires the provision of a defined reactive power range at the onshore connection point. Moreover, the dutch grid code requires certain performance including voltage control or reactive power provision. In this regard some options have been studied to find the optimal electrical system design for the HVAC connected 295 MW offshore wind farm.

2.1. The case study wind farm

The wind farm consists of 59 full converter wind turbines (FCWT) of 5 MW, and the transmission system is AC 220 kV. The offshore transmission system's electrical elements are selected from a preliminary design made by RWE Innogy UK for this wind farm Soleimanzadeh et al. (2014). Therefore, the investment cost of components has not been optimized (by optimizing component selection). The wind farm layout and the routing of the array cables are depicted in Figure 1.

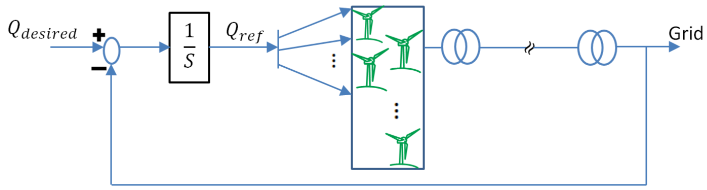


Figure 2: Reactive power control loop

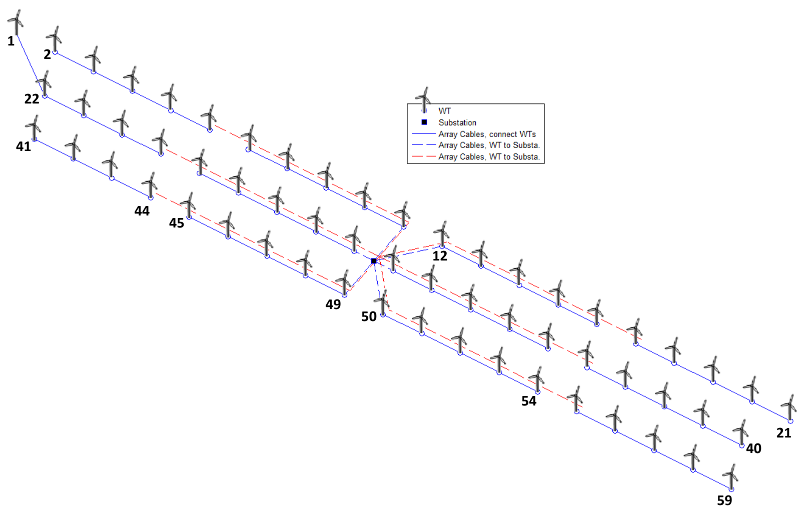


Figure 1: The case study wind farm with 59 wind turbines. Cable routing in the wind farm is illustrated by lines in blue and red.

In Figure 1, the blue solid lines represent the array cables connecting wind turbines strings, and the dotted lines (red and blue) show the array cables connecting each string to the sub-station (all the array cables are the same type). Some of the wind turbines are labeled with a number to be referenced later in the paper.

2.2. Offshore transmission system

In Soleimanzadeh et al. (2014) a few reactive power provision solutions are investigated for this case study wind farm. One of these solutions, which has the lowest investment cost in compare to others, has been represented in Figure 2.

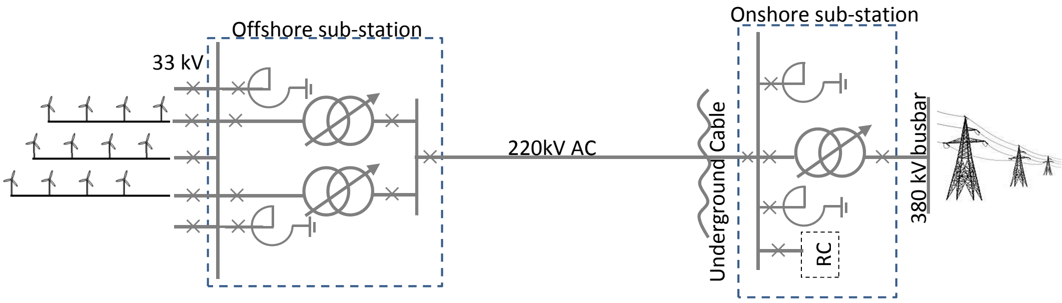


Figure 3: Single line diagram of the transmission system, with inductors on both onshore and offshore stations

In this quasi-steady reactive power provision approach, the inherent capability of the wind turbines has been used to provide a part of demanded reactive power. However, in order to reduce power losses, and to adjust the voltage and current level of electrical components within the allowable limits, the full capacity of the wind farm for reactive power provision may not be used. As a case in point, compensating a part of required reactive power by inductors or STATCOM installed at the onshore substation, can reduce the power loss along the transmission system. Furthermore, in order to control the voltage level within the required range, the tap changers of the transformers have been used. The single line diagram of the transmission system has been presented in Figure 3.

As it has been shown in this figure, inductors are used both on the onshore substation and the offshore substation for reactive power production. Using this configuration reduces the amount of power loss in the system, because the capacitive charging current needed along the cable is supplied from both sides, which reduces the maximum current passing through cable. However, installing inductors offshore, increases the platform weight and size and therefore the total costs. Thus, optimization can provide us with a more certain response about the best locations to install inductors. The inductor(s) could be installed either on one or two locations including offshore sub-station, and onshore sub-station.

The optimal size and location of the inductor(s) along the transmission line should be determined such that the power loss in the system is minimized. An optimization algorithm should be applied on this design, which determines the above mentioned electrical component sizes such that the power losses are minimized. Additionally, the optimization algorithm determines

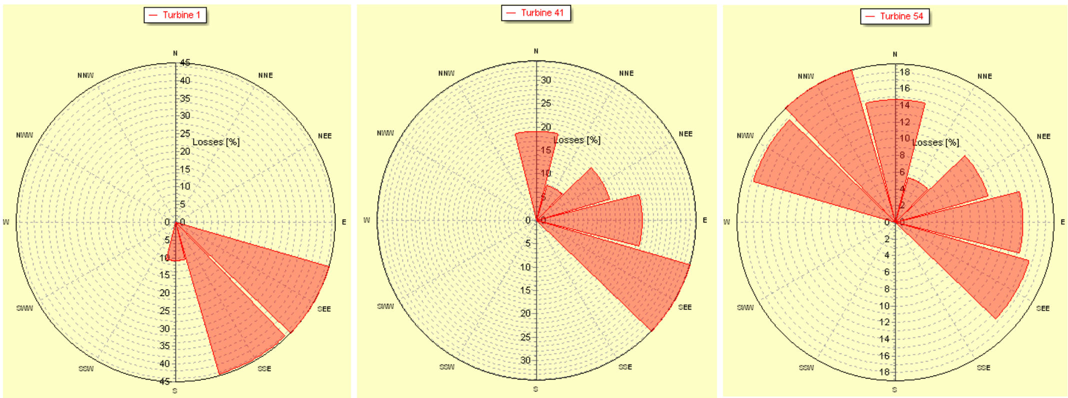


Figure 4: Wake losses, Wind turbines 1, 41, and 54

the optimal settings for the transformer's tap-changers to keep the voltage and current level of the electrical elements below the maximum threshold.

2.3. Modeling tools and implementation

As the first step, the determined layout of the wind farm has been analyzed and the annual power production along with the total power loss due to the wake effect have been computed. For this purpose ECN' FarmFlow tool Eecen and Bot (2010) has been used which computes the wind speed, direction and turbulence intensity all over the wind farm for the complete wind rose and each wind speed bin (for the complete operating range of the wind farm). From the output power for each wind speed bin and the wind speed distribution, the annual energy losses and the annually produced energy are determined.

The percentage of wake loss (power loss due to the wake effect in wind farm) in the complete wind farm operating range has been depicted in Figure 4 for a few random wind turbines in the farm. The wind turbines have been shown in Figure 1, by labels "1", "41" and "54". As Figure 1 illustrates, production losses in Turbine 1 due to wake effect happen when the wind direction is from south and south-east; but, Turbine 54 wake losses happen more often and with the wind direction from North-west, North, North-east, and east.

The results of this aerodynamic study, which are the produced power in wind farm by individual wind turbines, have been fed to the *electrical system model* as input. The electrical system model consists of wind farm model,

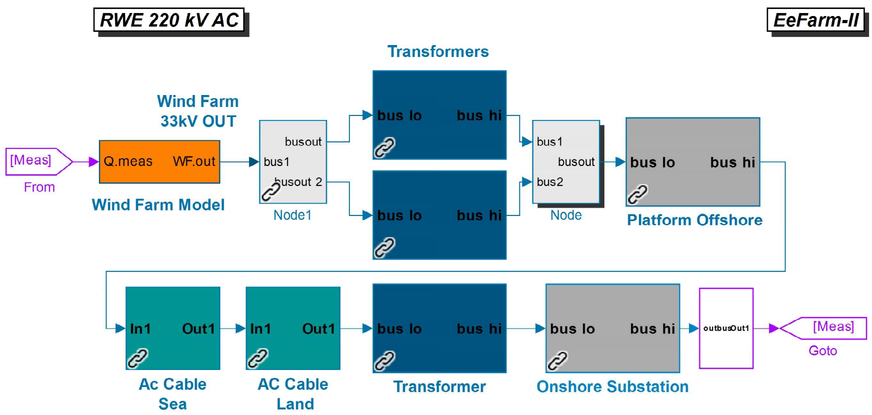


Figure 5: The Electrical system model in Simulink - the Electrical components are visible

which includes wind turbine models, array cables models with the actual lengths, and the transmission system model including onshore and offshore substations, inductors, transformers, and the transport cables.

The electrical system model has been made in MATLAB and Simulink using EeFarm-II, which is programmed as a Simulink Library Pierik et al. (2004).

The transmission system made by EeFarm-II is the one illustrated in Figure 3. The wind farm model and the connection of wind farm to grid can be built by EeFarm-II models by inserting the model blocks to a Simulink model and connecting them in the right order. The electrical blocks have one input and one output signal, which is a Simulink bus signal. The signal direction is from the individual wind turbine in the direction of the point of common coupling (PCC: the connection of the wind farm to the high voltage grid). The signal direction also shows the order in which the model blocks are evaluated, starting at the turbines and ending at the high voltage transformer at the PCC. The voltage at each wind turbine generator is set by the user and is assumed to be constant, but all other voltages are calculated by the model Pierik et al. (2009). The Simulink model made using EeFarm-II library has been illustrated in Figure 5. The model of the electrical components (such as array cables, transport cables, transformers, ...) are customized based on the RWE Innogy's preliminary design, and the wind turbine model has been made for 5-MW FCWT. The detailed model of each electrical element has been presented in Pierik et al. (2009).

In this system, there are two inductors in the two possible locations, one on the onshore sub-station and the other one on the offshore sub-station. To reduce total power losses, the optimization framework aims to find the optimal size and location for the inductors having the size boundary of $[0 \quad 300] MVA$. If an Inductor size was selected by the optimization algorithm to be approximately zero, it means that the location of the inductor is not selected for installing inductors. While optimizing reactive power compensation, the voltage level will be controlled using tap-changers of the transformers. The tradeoff between the number of taps in tap-changers and the amount of reactive current in the transmission system,is included in the optimization framework to achieve the optimized tap-changer settings. The assumptions and details of optimizing the design has been presented in the following Section.

3. Optimization framework

In this section, the optimization problem will be presented for above mentioned case study along with the optimization algorithm. The goal is to optimize the collection system design, including the electrical components sizes and settings for reactive power compensation and voltage control, such that the reactive power provision is based on the grid code requirements and the power losses in the system are minimized.

This case study starts with a preliminary design and aims to minimize power losses in the system by optimizing the design (or operation of the system). To make the preliminary design, economical aspects have been taken into account; therefore, it has been assumed that the design is cost effective and the investment cost has not been considered as an optimization criteria. This is equivalent to accepting most of the selected electrical components and the configurations, meaning that there is only a small margin left for optimization. However, the same methodology can be used for optimizing the design in earlier stages that brings the system closer to optimal.

The optimization framework focuses on different grid operating point and controls the reactive power/voltage optimally (by maximizing the production or minimizing power losses). Thus, at each grid operating point it would be possible to adjust the size of variable inductors, number of tap in tap changers, and the reactive power set-point of wind farm according to the optimized settings. Even though, variable inductors have been used in the transmission system, in case the quality of power is a concern, the variable

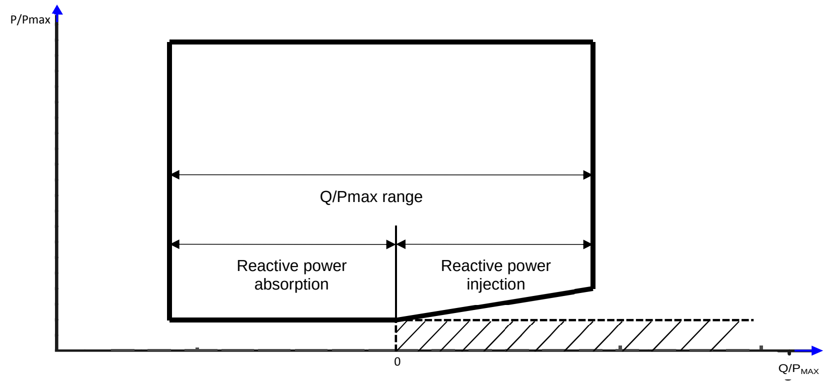


Figure 6: An approximation of reactive power capability requirement based on P_{max}

inductors can be replaced by STATCOM with the same inductor size (the maximum size) selected by the optimization framework.

3.1. Problem formulation

The primary goal of the design is to meet the grid code requirements to be able to connect the wind farms to the grid without jeopardizing the network security. The grid code determines the minimum requirements of the steady-state reactive power capability of a wind farm. The minimum requirements in the range of 0 to P_{max} is expressed by the Q/P_{max}. An *approximation* of this requirement is depicted in Figure 6. Furthermore, the steady-state reactive power capability dependencies to operating voltage has been also defined by the grid code. The reactive power requirements are lowered in certain ranges of the operational voltage at the connection point to grid. An *approximate* graph to represent reactive power capability dependency on operational voltage has been depicted in Figure 7.

The second optimization objective is to minimize power losses within the offshore transmission system. [1] Power losses in this system mainly depend on the size and location of the inductors and the reactive power set-points of the wind turbines.

As explained in Section 2, in this system, there are two inductors in the two possible locations, one on the onshore sub-station and the other one on

[1]The term *Power loss* in here means the copper losses in the electrical system. For other losses, we use other terms, for example *no-load loss*, *wake loss* (for wind turbine power loss due to wake interaction), and *Total Power loss* for summation of all the losses.

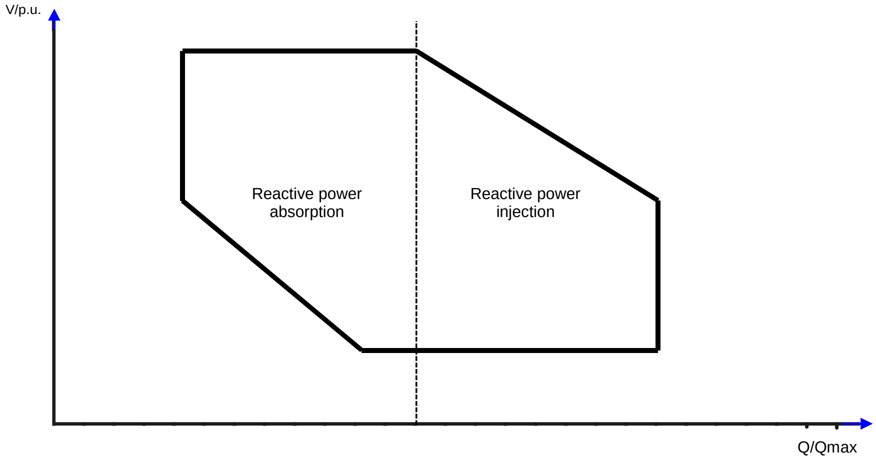


Figure 7: An approximation of reactive power capability requirement based on operational voltage

the offshore sub-station. The inductors are variable controlled and should be controlled at different grid operating points. The size of the inductors also depends on the reactive power generated by wind farm, which is determined by the reactive power set-points sent to the turbines. To reduce the total power losses, the optimization framework controls the reactive current flow in the system by optimizing reactive power set-points and the sizes of the inductors (settings in variable controlled inductors). The reactive power set-point of wind farm is determined by the optimization algorithm, then it is dispatched proportionally among wind turbines.

Furthermore, the maximum voltage level of the electrical components as well as the grid voltage will be controlled using tap-changers of the transformers, which their settings are optimized accordingly. Therefore, the tap changer settings, the inductor sizes as well as the reactive power set-point for the wind farm should be determined, such that the power losses are minimized.

Among the two objectives for this problem, the fulfillment of the reactive power based on the grid code requirements has been defined as a constraint in the problem formulation; and minimizing power losses has been defined as the objective function of this problem. Therefore, single objective optimization has been used, where the cost function is introduced as (1).

$$min \ \sum_{i}^{n} P_{loss,i}, \tag{1}$$

where, n is the total number of electrical components in the transmission system, and $P_{loss,i}$ is the total ohmic losses of component i excluding the failure time. The power loss due to failure of element i is calculated as (2) Pierik et al. (2009).

$$P_{fail,i} = f_{na,i}(P_{in,i} - \sum P_{fail,i}), \tag{2}$$

where, $f_{na,i}$ is the non-availability factor of component i; in other words, the fraction of time that component i is not in operation due to failure (received from the manufacturer or estimated). Moreover, $P_{in,i}$ is the input power to component i, and $\sum P_{fail,i}$ is the sum of average power reduction of components upstream of component i due to failure of components upstream of component i. Therefore, the total ohmic power loss for each component is obtained from (3).

$$P_{loss,i} = (1 - f_{na,i})P_{ohmic,i}, \tag{3}$$

in which $P_{ohmic,i}$ is the ohmic losses in component i that is not corrected for the failure of that component (in MW).

Power losses in this system mainly affected by the size and location of the inductors and the reactive power set-points of the wind turbines. Therefore, the optimization algorithm was set to find the size and location of each inductor as well as the reactive power set point for the wind farm, such that the power losses are minimized and required reactive power at the GEP is provided. Meanwhile, optimization algorithm should preserve the current and voltage levels of the electrical components including cables and transformers should be preserved below the maximum allowed limit. The maximum allowed values of voltage and current levels will be defined as constraints. To meet these requirements and satisfy these constraints Tap-changers within the transformers have been used. Since, a trade-off is required between voltage levels and reactive power control, the settings of the tap-changers are also variables to be determined by the optimization framework.

The allowable range of changes for tap changers are defined as boundaries of the problem (allowed range is -10 to +10 tap, with 1.5% Voltage change per tap). Moreover, the acceptable sizes for inductors are also boundaries of the optimization problem. The unknown variables that should be determined by the optimization algorithm, along with the optimization objective, constraints and boundaries are summarized in Table 1.

	Description	total number
Objective	Minimizing power losses, while	1
Parameters	Size and location of the inductors, tap number of transformer tap changers, Wind Farm Reactive power Set-point	5
Constraints	fulfilling reactive power requirements by the grid code, Voltage and Current level in (two) transformers, (two) AC Cables, (three) Inductors	15
Boundaries	Inductors size range, Tap Changes operating range, Wind Farm capability of Q production	5

Table 1: Recap- optimization objective, variables, constraints, and boundaries

In the following section the optimization method applied on this case study has been explained briefly.

3.2. Optimization Algorithm

The selected optimization method uses an Evolution Strategy with Covariance Matrix Adaptation (CMA-ES), which has application in different fields of engineering Hansen and Kern (2004). In Igel et al. (2007), CMA-ES is labeled as one of the most powerful evolutionary algorithms for optimization of non-linear and non-convex functions. It can be applied on both single-objective and multi-objective optimization problems. The algorithm uses a population to adapt its internal parameters. The population is a covariance matrix of a multivariate normal distribution, and each variate becomes a search variable Di Gaspero et al. (2013). Then, the search space is sampled using the normal distribution Hansen (2006).A high-level flowchart of CMA-ES algorithm is illustrated in Figure 8.

The optimization variables are introduced in Table 1, and they are real valued. A solution for this problem consists of 6 values, which the first two

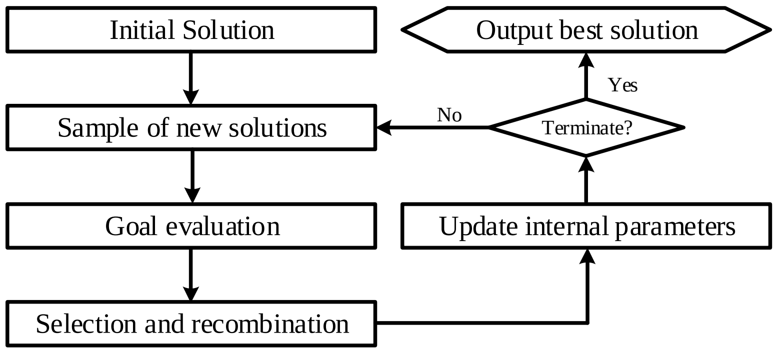


Figure 8: Flowchart of the CMA-ES algorithm Rodrigues et al. (2013)

are the sizes of the inductors, the next two are the tap numbers of the tap changers in each transformer; the 6th value is the cost function value (which is defined as power losses in the system), and the last value is an indicator to show if the solution is feasible. A solution candidate x is feasible only if all the constraints of the problem are satisfied; expressly, the inequality constrains $g_i(x) \leq 0$, $\forall i = 1, 2, .., p$ and equality constraints $h_i(x) = 0$, $\forall i = 1, 2, .., q$.

In order to meet the constraints, the search space is reduced to a smaller area identified as the feasible space. To ensure the convergence of the solution to this area of the search space, a penalty function has been implemented. The penalty value is determined by the degree of the constrains violation, such that a higher penalty allocated to a solution that violates severely the constraints of the problem Homaifar et al. (1994). The penalty function is defined as (4).

$$p(x) = \sum_{i=1}^{p+q} \lambda_i^{\beta}(x), \tag{4}$$

where β is a user-predefined value to adjust the scale of the penalty value; because, $|p(x)|$ should be of the same order of magnitude as the fitness function Coello (1999). Moreover, $\lambda_i(x)$ is defined as (5).

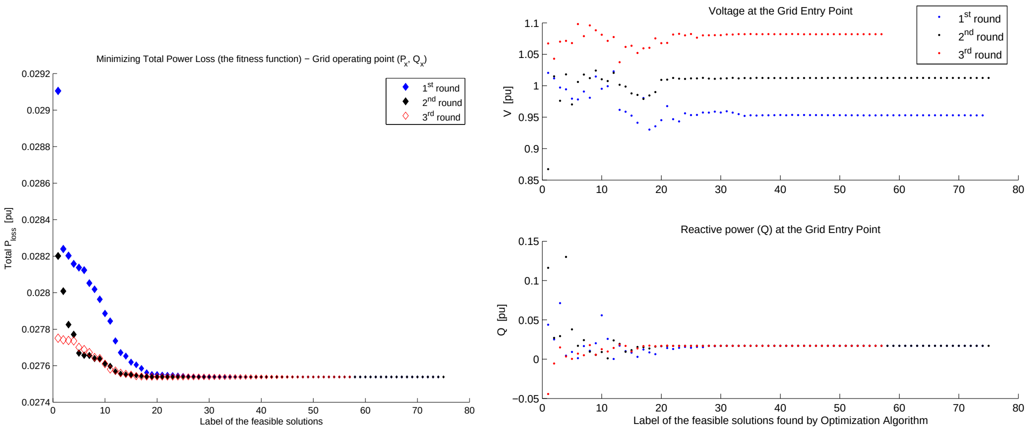
$$\lambda_i(x) = \begin{cases} 0 \text{ if } x \text{ is feasible} \\ |g_i(x)| \text{ if } x \text{ is infeasible } \wedge 1 \leq i \leq p \\ |h_i(x)| \text{ if } x \text{ is infeasible } \wedge 1 \leq i \leq q \end{cases} \tag{5}$$

The optimization algorithm was implemented on the offshore transmission system illustrated in Figure 3 with optimization objective, variables, constraints, and boundaries according to Table 1. The assumptions regarding problem formulations and implementation of the algorithm were explained in the first two paragraphs of Section 3.

4. Results and discussion

As explained in the previous section, the design optimization objectives are complying with the grid code and minimizing power losses within the offshore transmission system. The grid code requirements have been defined as constraints for the optimization problem and the total power loss in the system defined as the cost function (fitness value). The wind farm model was included in the CMA-ES algorithm loop and to find the best answer for the variables for each grid point operating mode, the loop has been run for 25 to 40 hours. Whereas, the fitness value is also checked, so a stop (good enough) criteria could be also defined. The complete process has been repeated for 3-4 times for each operating point with different population size, coordinate wise standard deviation, and run time.

As a case in point, the variation of the cost function and some of the constraints during optimization are presented for a few grid operating points. The operating points in which the full active power production (power production of $1pu$) and $0pu$ reactive power (unity power factor) are required, or in the same active power production level, $-0.4pu$ reactive power (Q) is required. Also, the operating point that 20% active power production (power production of $0.2pu$) and $0.35pu$ reactive power at the grid entry point are required, has been presented. The selected grid operating points, are according to the grid code requirements and are summarized as follows:
$P = 1\ pu, \quad Q = 0\ pu, \quad 0.9\ pu \leq V \leq 1.1\ pu$
$P = 1\ pu, \quad Q = -0.4\ pu, \quad 1\ pu \leq V \leq 1.1\ pu$
$P = 0.2\ pu, \quad Q = 0.35\ pu, \quad 0.9\ pu \leq V \leq 1\ pu$



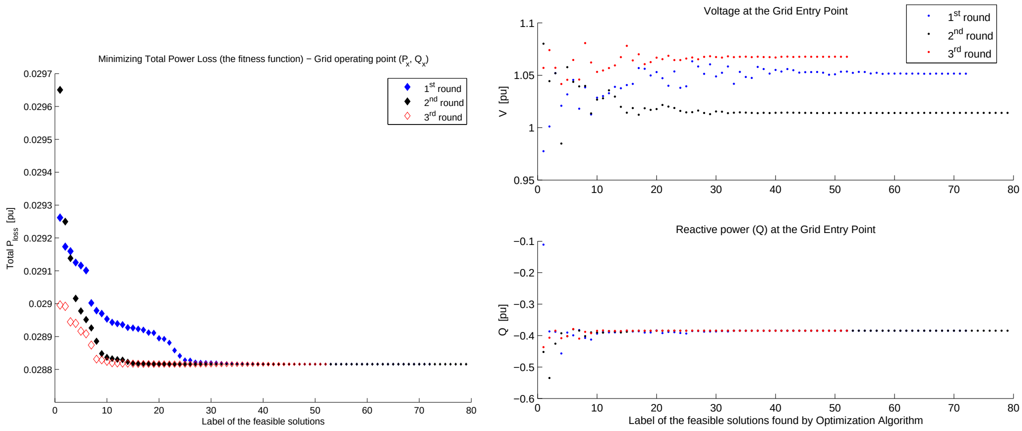
(a) convergence of the fitness function (total power loss) to a minimum level

(b) Obtained voltage and reactive power at the grid entry point (GEP)

Figure 9: Cost function convergence (total power loss) and satisfied V & Q constraints - Grid operating point $P = 1pu, Q = 0pu, 0.9pu \leq V \leq 1.1pu$

Figures 9 - 11 present the convergence of the fitness function (power loss) and resulted voltage and reactive power at the grid entry point (GEP) after 3 times running the optmization with different population size, step size and run time at each operating point. In both illustrated cases, the variables are determined by the optimization algorithm such that the presented minimized value for the fitness function (total power loss) is achieved, and the voltage and reactive power at GEP fit in the grid code requirement interval. To avoid unnecessary details, the obtained values for the variables have not been illustrated.

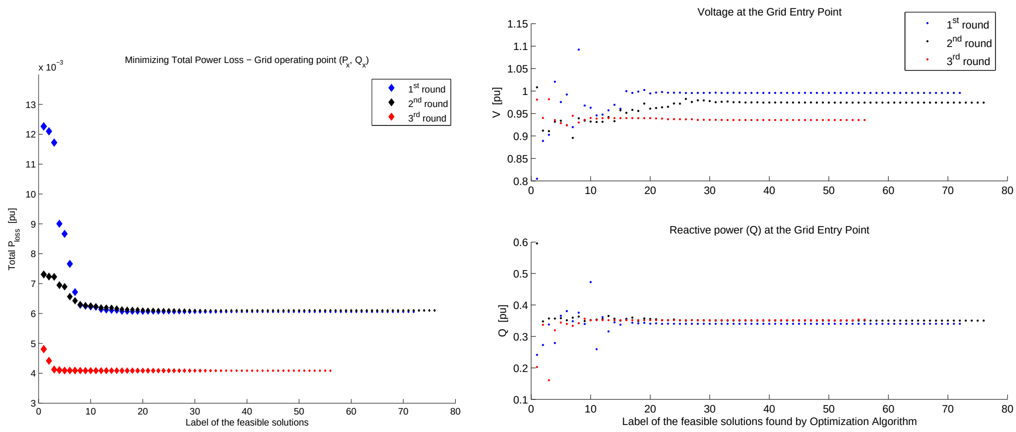
It can be seen in Figure 11 at this operating point, the fitness function has been converged to different minimum values. By assigning different initial conditions and running the optimization algorithm several times, the optimization algorithm converges to either one of these local minimum values. However, at the two other operating points with different initial conditions, population size, step size, and simulation time, the algorithm converges to (almost) the same local minimum. For each of these grid operating points all the constraints are satisfied and the optimization variables (e.g. inductor sizes & the tap number in the tap-changers) are obtained. By designing the transmission manually, also the inductor sizes and the tap number in the



(a) convergence of the fitness function (total power loss) to the minimum level

(b) voltage and reactive power at the grid entry point (GEP)

Figure 10: Cost function convergence (total power loss) and satisfied V & Q constraints-Grid operating point $P = 1pu, Q = -0.4pu, 1pu \leq V \leq 1.1pu$



(a) convergence of the fitness function value to the minimum level

(b) Calculated voltage and reactive power at the grid entry point (GEP)

Figure 11: Cost function convergence (total power loss) and satisfied V & Q constraints-Grid operating point $P = 0.2\ pu, \quad Q = 0.35\ pu, \quad 0.9\ pu \leq V \leq 1\ pu$.

tap-changers are determined such that all the constraints are satisfied. Table 2 presents a comparison between total power loss in the two systems, which one has been designed manually and the other one with the optimization algorithm. The comparison has been made among the three sample operating

Grid Code Requirements [pu]	P:1 & Q:0	P:1 & Q:-0.4	P:0.2 & Q:0.35
Total P_{loss}			
Manual design	0.029 [pu]	0.0297 [pu]	0.0123 [pu]
Design using Optimization	0.027 [pu]	0.0288 [pu]	0.004 [pu]

Table 2: Comparison

points.

For each of these grid operating points the optimization variables (e.g. inductor sizes & the tap number in the tap-changers) are obtained. Since the optimized variable are different for each grid operating point, in order to operate in the optimized state, the adjustments should vary by changing the grid requirements. Therefore, to be able to follow the requirements, variable inductors (thyristor controlled) should be used. In case of continuous and frequent changes in the grid operating points, having variable inductors may result in reduced quality of the produced power. This would require a trade-off between the power quality and the optimized performance (minimum power loss), which should be decided based on the region and based on the grid code. Another option is to use fixed inductors and a small STATCOM to help implementing the optimized adjustment. This option requires a trade-off between the optimized performance and the investment of the transmission system.

5. Conclusion

In this paper the design of an HVac offshore transmission system has been optimized such that the grid code compliance has been ensured and the power losses are minimized. An optimization algorithm has been selected along with the introduced aerodynamic tool and the electrical system models for steady-state analysis of the electrical system design; this has shaped the optimization framework.

The case study in this paper is the preliminary design of an offshore transmission system, to optimize the system design including the electrical components sizes and settings for reactive power compensation and voltage control, such that the reactive power provision is based on the grid code requirements and the power losses in the system are minimized. Since some of the electrical components of the case study transmission system where selected and fixed in an earlier design stage, the optimization has limited degrees of freedom. This reduces the significance of the benefit of using optimization in some of the grid operating points. Furthermore, in the earlier design stage, economical aspects (low investment cost of the electrical elements) have already been taken into account; therefore, in the optimization process the assumption is that the design is cost effective and the investment cost has not been considered as an optimization criteria. This is equivalent to accepting most of the selected electrical components and the configurations, meaning that there is only a small margin left for optimization. In spite of this, the design has been optimized such that reactive power provision and grid voltage comply with the grid code requirements, while the total power loss in the system has been minimized. All the analysis in this paper is in steady-state and the decision variables and design settings have been obtained separately for different grid code based operating points. For each of these grid operating points the optimization variables (e.g. inductor sizes & the tap number in the tap-changers & the wind farm reactive power set-point) are obtained.

The optimization applied on the case study in this paper can be generalized to any system as combined wind farm collection grid and offshore transmission system with the aim of grid compliance at lowest cost. Depending on the grid code requirements and the design stage, which affects the number of decision variables, the problem can be reformulated as a multi-objective or single objective optimization problem.

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