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Towards reactive power dispatch within a wind farm using hybrid PSO

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ABSTRACT

With the increasing penetration of wind power generation, the stringent grid codes are imposed by the system operators insisting the wind turbines to behave similar to that of synchronous generators. As a part of fulfilling the grid code in terms of steady state reactive power injection at point of common coupling, in this research work, the problem of optimal reactive power dispatch within a wind farm is formulated and a hybrid particle swarm optimization algorithm is proposed to get the optimal solution. The effectiveness of the proposed method is tested by simulations of the power collection grid of practical off-shore wind farm. The test results are compared with interior-point method based non-linear constrained optimization tool, *fmincon*, in Matlab. The analysis is carried out considering with and without wake effects on the wind farm at various grid bus voltage conditions. The test results demonstrate the effectiveness of the proposed method in achieving optimal solution for various operating conditions.

Introduction

Due to increasing penetration of wind power generation several System Operators (SOs) have imposed mandatory grid code requirements on the wind farms, to provide more control capabilities, regarding active and reactive power outputs similar to that of conventional power plants. There exist several control strategies, by which a single wind turbine alone can control its active and reactive power outputs [1,2]. However, each independent unit in a wind farm is to be operated in unison, such that grid code requirement pertaining to the steady state reactive power support at the Point of Common Coupling (PCC) is always met [3]. This requires an overall wind farm level dispatch centre controlling the net reactive power generation within a wind farm.

The Optimal Reactive Power Dispatch (ORPD) problem has a significant influence on the economic and secure operation of power system. Several conventional methods such as linear programming, quadratic programming, Newton based methods have been used for solving the OPF problem. However, one of the drawback of these conventional methods is that the discrete variables are treated as continuous variables and rounded off to their nearest value after optimization. This introduces numerical approximations and causes increase in the objective function value and/or violations of the inequality constraints causing convergence problem and limits the scope of practical application. Mingbo et al. [4] proposed primal–dual interior-point algorithm to handle the discreteness of the switchable shunt capacitors/reactors and On-Load Tap Changing Transformers (OLTCs) by incorporating a positive curvature quadratic penalty function during iterations. Soler et al. [5] proposed a penalty based non-linear solver for optimal reactive power dispatch problem. However, these methods give rise to difficulty in triangular factorization, and thus, increase the computational time. To mitigate this problem, heuristic based methods have successfully applied to large-scale power system optimization problems [6]. These heuristic methods [7–9] became more popular as they can handles both continuous and discrete variable at a time. Abido [7] proposed PSO for optimal power flow problem where the inequality constraints are handled as penalty functions augmented with fitness function. In [8], AlRashidi et al. proposed a hybrid PSO in which basic PSO acts like global optimizer to find the best combinations of the mixed type control variables and Newton–Raphson based load flow serves as a minimizer to reduce the non-linear power flow mismatches.

However, the ORPD problem with in a wind farm is different to that of conventional power system and it puts forth many challenges which need to be addressed.

- As wind power generation is intermittent, it requires frequent settings of reactive power devices along with Wind Turbines (WTs).
- Optimization method has to deal with large number of control variables, both discrete and continuous, in a wind farm having large number of wind turbines.
- Unlike in conventional power system, the OLTC switching has overall effect on all the bus voltages of the wind farm, causing difficulty in constraints handling.

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- The optimization method should have optimal solution for all operating conditions of the wind farm with different voltages at PCC.

The objective of this research work is to develop a fast ORPD tool for frequent reactive power settings in a wind farm, capable enough to handle large number of control variables and manage discrete variables due to OLTC transformers and switched capacitors. Finally, it should have an optimal solution under varied operating conditions of wind farm and PCC voltages, and meeting the grid code requirements. Not much literature is found on ORPD within a wind farm. de Almeida et al. [10] has proposed an optimized dispatch control strategy based on primal–dual predictor corrector interior point method for active and reactive powers delivered by a Doubly Fed Induction Generator (DFIG) in a wind park. Pappala et al. [11] proposed an adaptive PSO for reactive power management within an offshore wind farm where, for simplicity reasons, the reactive power of all wind turbines is kept equal. It simplifies the problem from *n*-dimension (number of WTs in the wind farm) to 1-dimensional problem. In [12], the same authors tried to extend the optimization problem over a time period by considering the wind power forecast inputs. However, whole wind farm is replaced by a single large machine of rating equal to the sum of all wind turbines. Reactive power dispatch within a wind farm using PSO is carried out in [13]. However, no collector grid simulation is carried, as a result, the total active and reactive power outputs of the wind farm equal the sum of the active and reactive powers, respectively, generated by each DFIG in a wind farm. In [14], authors have analysed the ability of wind turbines to provide reactive power support, the control of various elements of the wind farm and it is found that collector grid saturation limits the reactive power output of individual generators. In [15], Marcela Martinez-Rojas et al. proposed a PSO for optimal reactive power dispatch within a wind farm considering the reactive power requirement at the PCC.

In this paper, optimal reactive power dispatch problem within a large wind farm is formulated and a Hybrid Particle Swarm Optimization (HPSO) method is used to optimally set the reactive power outputs of all the generators and other compensating devices along with the OLTC transformer tap, such that the active power loss in the collector grid is minimized and simultaneously, meeting the grid code in terms steady state reactive power requirements at PCC and maintaining bus voltages with in the limits. For better convergence, the voltage constraint violations are penalized in proportion to number of violations. The analysis is carried out for various operating conditions considering with and without wake effects. The test results are compared with interior-point method (IPM) based non-linear constrained optimization tool *fmincon* in Matlab. The effectiveness of the proposed HPSO method, in achieving optimal solution along with the better convergence characteristics, is demonstrated on a practical offshore wind farm of Denmark.

System description

Wind farm layout

For optimal allocation of reactive power settings of wind turbines and other compensating devices, HornsRev1 wind farm is considered [16,17]. The typical layout of a wind farm is shown in Fig. 1. HornsRev1 wind farm is of 160 MW capacity with 80×2.0 MW (10 rows each with 8 turbines). Collector system operating voltage is 33 kV, and is connected to a 36/150 kV, 160 MVA step-up transformer at offshore substation. The length of collector grid cables, collector grid to off-shore substation and transmission cables, taken in this study, are shown in Fig. 1. For analysing the grid code compliance in term of reactive power, it is assumed that two 40 MVAr fixed shunt reactors are connected at buses 83 and 84 and also a 25 MVAr SVC is connected at bus 84. The offshore substation transformer is assumed to have OLTC facility on HV side with tap setting from 0.96 to 1.04 with 0.01 step-size. The collector cable system parameters and current loadings used for analysis are given in Table 1 [18,19]. In determining the dielectric loss in XLPE cables, the dielectric loss angle $tan\delta = 0.0004$ is taken.

Reactive power capabilities of wind turbine

The reactive power generation of a DFIG wind turbine can be controlled by the rotor current, which depends on converter rating. In general, the total reactive power generation is limited by rotor voltage at low speed and by rotor current at high speed, however, the maximum reactive power limit is imposed by stator current [20,21]. The reactive power limit under low voltage can be avoided by moderate increase in the converter size. This brings the wind turbine a capability of generating/absorption of reactive power even for zero active power output but with the expense of high converter cost. In [21], it has been suggested that reactive power can be enhanced by star-delta switching of stator voltage. In the present optimization problem, at any given wind speed and wind power generation, the corresponding min–max limits on reactive power output of each turbine are calculated from the P–Q chart. The Vestas V80 2.0 MW wind turbines are used in HornsRev1 wind farm and its P–Q capability chart is shown in Fig. 2 [22].

Grid code requirement

Increase in wind power penetration has led to imposition of grid code by many countries for the connection of new wind farms and this grid code has been a driver for the development of wind turbine technology. Grid code stipulates that wind farms should participate in voltage and frequency control of power system, and emphasizes wind farm behaviour under disturbance (voltage dip due to grid fault). Comprehensive reviews of grid code technical requirement for large wind farms are available in [23,24]. In case of reactive power control, grid code prescribes either power factor or reactive power injection at the point of common coupling with respect to PCC voltage deviation or net active power injection, respectively. In this work, the steady state reactive power requirement in terms of power factor vs. PCC voltage variations for Energinet.dk European electricity market [25,26], shown in Fig. 3 is considered for analysis.

Optimal reactive power dispatch problem formulation for wind farm

At any given operating condition, the on/off states of wind turbines and their active power outputs along with the PCC bus voltage are taken as inputs, and in return, the optimal reactive power settings of wind turbines along with the compensating devices are estimated through this algorithm. In spite of using generator bus voltages, the generator reactive power outputs are taken as control variables. The advantage of this is explained in Section 'Control variable selection'. The bold facet lower case letters are used for vectors and bold facet upper case letters are used for matrices.

Let $\mathcal{N}$ represents the set of all buses, $\tilde{\mathcal{N}}$ the set of all buses except slack bus, $\mathcal{G}$ the set of generator buses, $\mathcal{L}$ the set of load buses, $\mathcal{Q}$ the set of buses with shunt reactors/capacitors, $\mathcal{T}$ the set of OLTC transformers in the system, $\mathcal{B}$ the set of cable segments and $|\mathcal{N}|$ the size of $\mathcal{N}$. The bus voltages are represented in rectangular form as