



Optimal operation of hybrid high voltage direct current and alternating current networks based on OPF combined with droop voltage control

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ARTICLE INFO

Keywords:

HVDC-HVAC
OPF
Distributed control
Droop control

ABSTRACT

This study focuses on the operation and control of HVDC multi-terminal systems that transmit the power being generated in offshore wind farms to the terrestrial AC grids. The aim of the paper is to propose and validate an algorithm to ensure optimal operation of HVDC-HVAC systems. This algorithm is implemented in a central controller that, knowing the electrical characteristics of the DC and AC systems, the power generation from the wind farms and the power demand, executes periodically an AC/DC Optimal Power Flow (OPF) and sends the appropriate voltage references to the grid side converter's control. The voltage control of the DC grid is distributed and based on droop law, implemented in grid side converters. The droop offset is modified periodically so as to adapt to the actual operating conditions and ensure optimal operation according to a specified objective function. Dynamic simulations show the system optimal operation in terms of loss minimization under wind speed changes, loss of communications and demand variation. These results are validated experimentally after implementing the control scheme in an HVDC scaled experimental platform. Dynamic simulations are also performed to show that the system can still be operated based on the proposed strategy even during contingencies implying the disconnection of a power system element (converter and DC cable).

1. Introduction

The wind power statistics corroborate the increase of wind installations during the last years. According to the European Wind Energy Association (EWEA), 12800 MW of wind power capacity was installed and grid-connected in the EU during 2015 [1]. From the new installations, 9766 MW were installed onshore and 3034 MW offshore. The wind power installed in 2015 was larger than any other form of power generation the same year (it accounted for 44.2% of total 2015 power capacity installations). All these data point to an encouraging future for the wind industry, but, onshore locations with the best wind profiles are finite and most of them occupied by finished projects or under development. To face this problem, there are basically two solutions allowing to continue increasing the wind power contribution in the energy mix despite the saturation of the best terrestrial sites. One promotes the reuse of wind turbines that occupy the best locations replacing them by other wind turbines of larger power and with more advanced technologies. The old wind turbines can be then allocated in other sites, facilitating and expanding the use of renewable energy. The other solution is based on continuing exploiting the offshore sites.

Focusing on the latter, the installation of wind farms in offshore sites, does not only represent an alternative to terrestrial locations, but also offers more favourable wind profiles (more constant and less turbulent). It has often lower social opposition due to its lower visual impact and allows the installation of larger wind turbines (and, thus, with larger rated power). Depending on the distance that separates the offshore wind farm from the terrestrial grid, it may be more interesting for technical and economical reasons, to use High Voltage Direct Current (HVDC) instead of High Voltage Alternating Current (HVAC) transmission [2]. Taking this into account, the transmission system is likely to merge interconnections with both HVDC and HVAC. The resulting transmission system can include a number of different AC and DC systems and each subsystem can include multiple terminals.

One of the challenges in HVDC multi-terminal systems is the distribution of the power flows in the HVDC grid, ensured through DC voltage control. A classification and comparison of the voltage control methods for HVDC grids is investigated in [3]. A special focus has been given to distributed control of the DC voltage from different converters [4] and, in particular, to DC voltage droop control [5,6]. The power flows in HVDC grids connected to HVAC systems have been analysed in

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literature and several methodologies have been proposed to ensure optimal operation of the whole system, ranging from centralized strategies to distributed. Many studies have been focusing on optimal power flows either in AC grids or in DC grids [7–9] addressing existing challenges in terms of mathematical modelling, convergence, computation time or global solution guarantees. All these aspects are specially significant in AC power flows, showing, in general, more complexity due to its non linear, non convex and large scale nature [10]. However, some studies do analyse the operation of AC and DC grids coupled. For instance, the impact of DC links on the convergence of AC/DC power flows is addressed in [11]. On the other hand, a method which derives the voltage droop settings to minimize the adverse effect of a disturbance on the DC side is proposed in [12] considering AC system stability.

The optimal operation of hybrid AC-DC systems is addressed in [13,14] covering several optimization goals and with different levels of accuracy when modelling the power system elements and their losses. Optimal (economic) operation of hybrid HVDC-HVAC systems taking into account contingencies has been proposed through a Security Constrained Optimal Power Flow approach in [15–17]. In all the cases [13–17], the analysis are performed from a steady-state point of view. Therefore, the before cited studies address OPF in AC-DC systems, but do not study its integration with distributed controls and its dynamic performance. On the other hand, the existing studies addressing the dynamic performance of HVDC multi-terminal systems based on OPF (for instance [6]), do not include their connection and power interaction with the AC system on their formulation and do neither show the impact of eventual contingencies.

Taking into account the previous gap, the present work addresses the OPF for hybrid systems considering its integration with distributed controls and the effect of communications. For this purpose, the OPF formulation for HVAC-HVDC systems detailed in [14] (only analysed in steady state) is expanded, proposing an OPF to be executed periodically as a centralized high hierarchy control that sends the appropriate references to a distributed lower level control. The developed control scheme enables to optimally operate HVDC-HVAC systems under normal operation and under contingencies implying the loss of one of the system elements.

In order to ensure optimal operation, the central controller knows the electrical characteristics of the whole system (and therefore, its admittance matrix) and receives periodically the wind power farm generation and the power demand. So, one of the advantages of using a centralized controller is that it can collect the information of different devices of the system to operate it optimally. The drawback is that it requires a communication system. Therefore, the proposal is to operate the system based on a centralized control sending signals to local controls or distributed controls. These distributed controls are responsible for achieving the references received to optimally operate the system. In this system, the distributed controls correspond to the converters and generating units controls. In grid side converters, voltage droop ensures the voltage control of the HVDC system and reactive power control allows to exchange the required reactive power with the AC grids, providing reactive power support if needed. The active and reactive power controls of the generating units perform primary and secondary control functions of the AC system to keep voltage and frequency within limits. The distributed controls do also ensure stable operation when communications are lost. Additionally, it is shown that the proposed control scheme can also deal with contingencies.

To the best knowledge of the authors, the combination of a centralized OPF with distributed controls for operating HVDC-HVAC systems taking into account the effect of communications and eventual contingencies has not been analysed in literature. The main contributions of the study are listed next. First, a novel methodology which combines centralized and distributed controls is proposed for operating HVDC-HVAC systems and it is implemented for minimizing losses, including transmission and converter losses. Dynamic simulations show

how the methodology leads to stable operation and loss minimization in different scenarios, like wind power variation and demand changes. Second, the operation strategy proposed is shown to be able to deal with contingencies including the loss of a power system element or the loss of the communication system. Third, the methodology proposed is validated experimentally. The results obtained through dynamic simulations and experimentally for wind power variation, loss of communications and demand variation coincide, verifying the operation in real time of a hybrid DC-AC system in a scaled laboratory platform. Dynamic simulations are also presented to show that the proposed control scheme does not compromise the system operation if a contingency occurs, like the disconnection of a converter or DC cable. Last, but not least, the effect of wind power measurements uncertainty on the control scheme performance is analysed.

2. Optimization problem

The optimization problem solved periodically by the central controller involves DC and AC power systems and can be thus, considered as a non-linear constrained optimization type. Mainly two strategies can be used to solve DC and AC power flows: sequential and unified. The sequential approach [18] separates the problem in two parts corresponding each one to DC and AC power flow equations, respectively. Unified approach, [19] solves all the equations together.

The optimal power flow tool here presented is based on a unified strategy. Several objective functions can be defined in this optimization tool. An interesting one is the overall losses in the HVDC-HVAC network, including transmission and converter losses. This objective function is the one used to show the system performance in Section 4.1. The general layout of an HVDC-HVAC transmission system to which the tool is applied is shown in Fig. 1.

The converter topology is Voltage Source Converter (VSC), so active and reactive power can be controlled independently. The VSCs connected to the wind farms (wind farm rectifiers) inject the wind power to the HVDC grid. In normal operation, the wind farm rectifiers absorb all the power produced from wind farms and inject it into the DC grid. They also provide the needed reactive power to maintain the AC wind farm voltage. The power in the DC network is delivered to the AC grid through grid connected VSC, that are in charge of HVDC grid voltage control and which deliver reactive power support to the AC grid when needed. The AC grid is constituted by AC links that enable the electrical power transmission to the consumption nodes. The active and reactive power demands in the AC nodes and the wind farm's generation are an input for the tool. The electrical characteristics of the DC and AC grids and the converter loss parameters are also known data. The tool determines the active and reactive power produced from generators and converters and the power flowing through branches that minimize the specified objective function while accomplishing the electrical system constraints.

It is worth mentioning that the OPF AC/DC leading to the following formulation was previously validated [14,20]. It was first implemented through MATLAB® Optimization toolbox and it was benchmarked with the OPF tool from [21], implemented in MATPOWER®. Both tools led to the same results for the system analysed (5 AC 3 DC) when minimising losses and when minimising the deviation from a preset voltage profile [20]. On the other hand, the OPF AC/DC tool was also implemented in GAMS® [14], leading to the same results that MATLAB® Optimization toolbox for small and large power systems. However, as GAMS® was proved to be far more efficient than MATLAB® from a computational point of view, it has been chosen for implementing the expanded OPF executed by the central controller.

2.1. Notation

All the variables and parameters required for the mathematical formulation of the problem are detailed below.

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