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# Optimal fault ride through compliance of offshore wind power plants with VSC-HVDC connection by meta-heuristic based tuning

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ABSTRACT

This paper presents a novel iterative procedure augmented by electromagnetic transient type simulations and the state of the art mean variance mapping optimization algorithm. The aforementioned procedure enables the optimal tuning of coordinated fault ride through compliance strategies for offshore wind power plants with VSC-HVDC transmission. In particular, the formulated optimization task minimizes the electrical stresses experienced by the VSC-HVDC system and the offshore wind power plants during onshore faults. Moreover, it ensures that the onshore and offshore grid code profiles are not violated due to unwanted dynamics associated with the combined response of the VSC-HVDC system and the wind power plants. Two state of the art coordinated fault ride through strategies are optimized, namely the voltage drop and the frequency modulation technique. Simulation results demonstrate that the optimal tuning of coordinated fault ride through compliance strategies by the proposed iterative procedure enables improved dynamic response and reduced electrical stresses for the offshore wind power plant and the VSC-HVDC transmission.



## 1. Introduction

Currently, about 12 GW offshore wind power capacity is installed in North Europe [1]. In the majority of these projects, the offshore wind plants are connected to the mainland grid by voltage source converter based high voltage direct current (VSC-HVDC) transmission technology [2]. From the onshore power system control and stability perspective, the fault ride through (FRT) capability and the ability of VSC-HVDC system to support the AC grid voltage stability during AC faults has become important [3–6]. In that context, grid connection requirements have been released in a European level in order to set the boundary conditions for the design of national level grid codes [7].

From a technical perspective, two are the main challenges for the FRT compliance of the offshore wind power plants with VSC-HVDC transmission. The first one is the protection of the VSC-HVDC link from direct over-voltages [8]. The second one is the ability to effectively control the fault current injection of the VSC-HVDC station during the fault as well as during the post-fault period. The latter should be performed in a robust and effective manner respecting the over-current thermal limit of the power electronic components [9]. The typical FRT method used by manufacturers nowadays is the installation of the DC-Chopper controlled resistors at the HVDC link (onshore station) [10]. This strategy is robust and places the burden of the FRT mechanism only to the VSC-HVDC transmission link, leaving the offshore wind power plant units completely unaffected from the transients observed during faults at the onshore power system [3]. However, the main drawback is the increased capital investment cost. In that prospect, various coordinated FRT control strategies are proposed in the literature [8,11–13]. Two are the most common techniques, the controlled offshore voltage drop method, and the offshore frequency modulation technique.

The controlled offshore AC voltage drop strategy is studied in [8,11,14] and further improved in [15] for the case of wind power plants with double fed induction generator type wind turbines. Recently, the voltage drop method has been extended to the multi-terminal HVDC grid connection case of the offshore wind power plants in [16–18]. Although the previous references provide a detailed analysis, the compliance of the wind turbines with their own reactive current boosting requirements at the offshore AC island grid is neglected. Furthermore, the post-FRT active current dynamic behavior of the wind turbines which is affected by the choice of the active current ramping rate, is omitted. The latter influences the power restoration in the HVDC link during the post-fault period. Moreover, this power balance is affected by the active

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current ramping of the onshore VSC-HVDC converter station. A lack of coordination of these control modules would prolong the duration of the controlled AC voltage drop as a result of the extended direct over-voltage in the VSC-HVDC link. Furthermore, it might lead to the trip of the wind plants if the voltage profile at their terminals exceeds the offshore FRT envelopes given in the grid code.

With reference to the frequency modulation FRT strategy, a study is presented in [13,17]. In this coordinated control scheme, the offshore AC island grid frequency is adequately varied by the offshore VSC-HVDC converter station when direct over-voltages are measured in the offshore HVDC terminal. The latter triggers a dedicated controller at the offshore wind turbines to reduce the active power supporting the power balance in the HVDC link. Although the method provides satisfactory results, the boundary conditions of the frequency modulation shall be carefully assessed. In addition, the controllers should be adequately tuned in order to provide a fast enough response without triggering instabilities at the offshore AC island grid. Currently, the calculation of the FRT control parameters of HVDC link is carried out on a trial and error basis using detailed electromagnetic transient (EMT) type models which is a very time consuming process without always ensuring that the best values are selected. A methodology to effectively calculate the best control parameters for coordinated FRT strategies has not been yet presented in the literature.

This paper formalizes the tuning problem of coordinated FRT control strategies for offshore wind power plants with VSC-HVDC transmission as an optimization task. The latter accounts for robustness and minimum electrical stresses during the FRT compliance. The paper is an extension of the work presented in [18] focusing here only on the point-to-point VSC-HVDC connection while including the participation of the wind plants in the FRT process. The optimal tuning of the FRT control strategies is solved by means of an iterative procedure which uses EMT type simulation runs driven by a metaheuristic optimization algorithm. The iterative procedure treats the VSC-HVDC system and the connected offshore wind power plants as one power plant entity where specific requirements are imposed at the onshore and at the offshore point of common coupling (PCC). The objective functions of the optimization problem is mathematically formulated and solved for two state of the art FRT strategies, the controlled offshore voltage drop strategy and the frequency modulation technique. With regard to the voltage drop strategy, two sub-cases are addressed. In the first sub-case, the offshore wind turbines provide reactive current injection at the offshore island grid during the controlled AC voltage drop period. In the second sub-case, a new alternative technique is applied which uses a voltage dependent active current reduction controller at the offshore wind power plants. Due to the computationally complex nature of the problem (i.e. iterative evaluations of the fitness function involving EMT type simulations of the complete plant), an efficient stochastic optimization algorithm has been selected namely the mean variance mapping optimization algorithm. It ensures the achievement of a near-to-optimal solution within a reduced number of function evaluations (i.e. objective function and constraints). An extensive analysis of the numerical results provides insight into the value of the proposed iterative procedure with regard to the physical properties of emerging technologies of offshore grids.

## 2. EMT-enabled iterative procedure for optimal FRT compliance tuning

The optimal design of coordinated FRT control modules becomes challenging for two main reasons. Initially, the coordinated FRT strategy shall take into account the interactions among the offshore VSC-HVDC converter station and the wind turbine control modules.

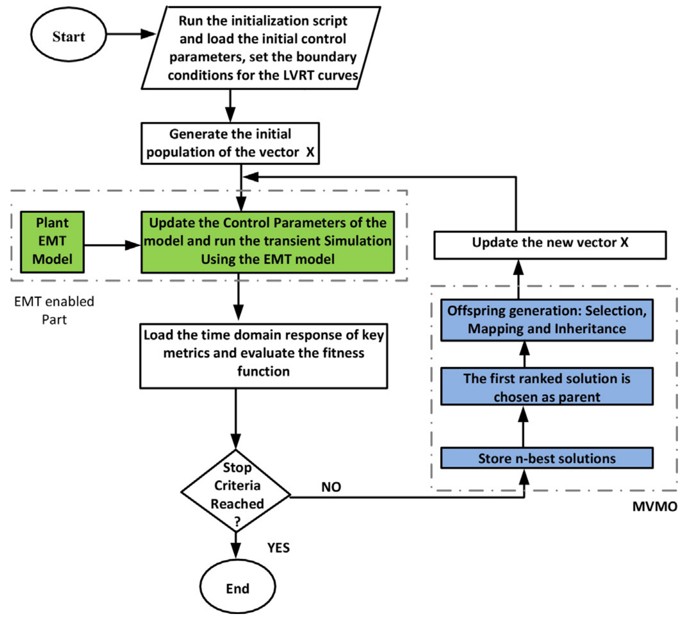


**Fig. 1.** Proposed iterative procedure for optimal FRT compliance tuning of the offshore wind plants with VSC-HVDC connection. (For interpretation of the references to color in the citation, the reader is referred to the web version of this article.)

Furthermore, the non-linear dynamic response of the associated current control limiters and state machines integrated in the control loops of the wind turbines and the VSC-HVDC system cannot be captured by linear models, making classical design methods non-applicable. In that frame, the concept of EMT-enabled tuning as introduced in [19] is adopted in this work.

### 2.1. Iterative procedure

The EMT-enabled iterative procedure is based on a sequence of time domain simulation runs, driven by an evolutionary optimization algorithm which iterates the vector of control parameters in order to define the best set which satisfies a defined objective function. The flow chart of the algorithm is presented in Fig. 1. The objective function is mathematically formulated with aim to reach the design goal (i.e. minimize the direct over-voltage, hence the stresses in the HVDC link in conjugation with the imposed AC voltage drop at the offshore island). The iterative procedure begins with a set of random FRT control parameters. An EMT type simulation is executed for a given fault. The time-domain response of key metrics (AC and DC terminal variables) are used in order to define the fitness function. As long as the problem has not yet converged, new control variables are generated by the optimization algorithm. The EMT model is updated with the new control variables and a new simulation run is executed. The iterations are terminated either when the upper boundary limit of iteration numbers is reached or the acceptable tolerance in the error of the fitness function is found.

### 2.2. Mean variance mapping optimization algorithm for the iterative procedure

The iterative procedure uses the mean variance mapping optimization (MVMO) algorithm [20]. Fig. 1 presents the algorithmic steps of the MVMO. The blue blocks highlights the steps involved in the evolutionary mechanism. The procedure starts with the generation of an initial population, which constitutes a vector comprising random samples of the optimization variables, each one drawn within the corresponding [min, max] bounds. The sampled values are normalized to the range [0, 1]. The optimization variables are