Fault Ride Through of VSC-HVDC Connected Offshore Wind Farms: A Simplified Model

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I. Introduction

Transmission System Operators (TSOs) impose technical requirements to the connection of offshore Wind Farms (WFs) to the grid. Among those requirements, Fault Ride-Through (FRT) capability demands that the WF must remain connected to the grid even for severe onshore grid faults [1]. In the case where a Voltage Source Converter (VSC) - High Voltage dc (HVdc) link is employed, the decoupling of the offshore from the onshore grid renders the WF unable to detect an onshore fault and respond to it by reducing its active power, which can lead to dc overvoltages above the protection limits in the HVdc line.

One way to deal with this is to use a dedicated communication system between the onshore grid and the WF and signal the need for active power reduction when a fault occurs. However, due to the rapid evolution of the phenomenon, a small delay or failure of the communication could lead to unacceptable overvoltages [2]. In order to avoid that, an artificial coupling of the onshore and offshore grid can be created. One technique proposed in literature is for the offshore VSC to induce an increase in the offshore frequency proportional to the dc overvoltage of the HVdc link [3]–[6]. The integrated frequency controller of the WF will trigger an active power reduction as a result, leading to a successful FRT.

To evaluate the performance of the aforementioned FRT solution without resorting to detailed simulations, a simplified model is proposed for the entire HVdc and WT system in order to assess the effect of various system parameters and controller settings on the expected FRT response. The simplified model can be used to provide a quick initial understanding of the expected results from a detailed simulation. Furthermore, the control parameters of a detailed model are traditionally selected through a trial and error procedure. A systematic way to choose them, based on design requirements, is described instead. The most fundamental design requirements for this FRT technique are the dc overvoltage in the HVdc link and the rate of change of frequency (ROCOF) in the offshore grid. Practical formulae are introduced to approximate both of them. These simple formulae also provide an intuitive explanation to the effect of the various physical and control parameters on a successful FRT. A comparison with detailed model simulations in DIgSILENT PowerFactory proves that the approximation captures the basic dynamics of the phenomenon. As a consequence, the simplified model can be used to even avoid extensive FRT simulations.

II. Approach

The system under study is depicted in Fig 1. The WF is comprised of Permanent Magnet Synchronous Generator (PMSG) based wind turbines (WTs) of total capacity 400MW. The HVdc link consists of the (onshore) Receiving End Converter (REC), the (offshore) Sending End Converter (SEC) and a 100km long ±150kV dc transmission line. The model of the system was developed in DIgSILENT PowerFactory.

Under normal conditions, the REC controller (Fig 1) regulates the dc voltage to its reference and hence it ensures that the dc power is injected into the grid. It also regulates the reactive power injected into the grid according to the TSO requirements. The SEC, on the other hand, is a grid-forming power converter that regulates the offshore voltage and frequency to their reference values.

In the case of a severe onshore voltage drop, the current magnitude limiter of the REC (Fig 1) will be activated, giving priority to the reactive current support of the grid, and the injected onshore active power will be abruptly decreased down to zero. The power imbalance will charge the dc capacitors and the dc voltage will begin to rise. The SEC controller will detect the increased dc voltage and cause an offshore frequency increase Δf^*_{off}.

Finally, the WF, which consists of WTs equipped with the frequency response block shown in Fig 2, upon detection of the increased frequency, will decrease its output power, leading to a successful FRT.

III. Main Body of Abstract

The simplified model of the plant is depicted in Fig 3. The shape of the active power curve p_G that the onshore grid absorbs depends mostly on the characteristics of the fault and an assumption regarding its form can be made (see Fig 3). The active power quickly drops to zero when the fault occurs and after some time it gradually returns to its initial value.

The dynamics of the HVdc link, especially during a fault, are dominated by the equivalent capacitance C_{dc} of the HVdc link. A power imbalance between the WF active power production p_{WF} and the onshore absorbed power p_G will cause an increase to the dc voltage V_{dc} according to the following equation:

$$p_{WF} - p_G = V_{dc} C_{dc} \frac{dV_{dc}}{dt} = \frac{1}{2} C_{dc} \frac{dV_{dc}^2}{dt}. \quad (1)$$

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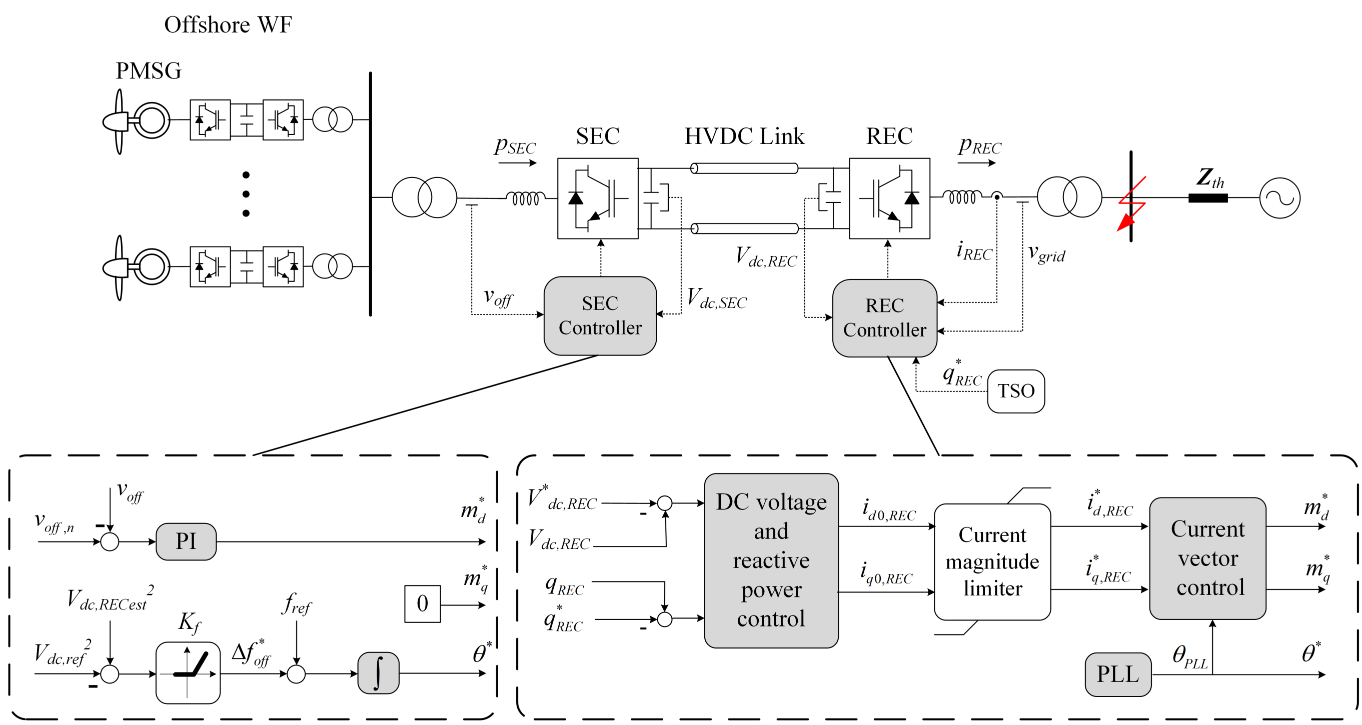


Fig. 1: The study case system modeled in DIgSILENT PowerFactory. The SEC and REC control systems feed the converters with the modulation parameters m_d^*, m_q^*, θ^* in the Park reference frame. The REC utilizes PI controllers for dc voltage and reactive power control and employs the standard current vector control technique [7].

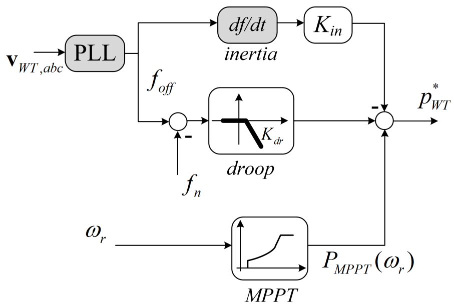


Fig. 2: Each WT frequency response block takes the frequency measurement from a PLL and reduces the available wind power P_{MPPT} by a droop and an inertia dependent factor to determine the WT output power p_{WT}^*.

The SEC will trigger an offshore frequency increase depending on the dc voltage deviation from its initial value $V_{dc,ref}$:

$$\Delta f = K_f (V_{dc}^2 - V_{dc,ref}^2) \tag{2}$$

where $\Delta f = f_{off} - f_{ref}$ is the deviation of the offshore frequency f_{off} from its reference value f_{ref} and K_f a SEC control parameter. The increased frequency will trigger a reduction in the WF active power through its frequency response block:

$$p_{WF} = P_{WF0} - K_{dr}\Delta f - K_{in}\frac{d\Delta f}{dt}, \tag{3}$$

where K_{dr} and K_{in} are the droop and inertial gains of the frequency response of the WF respectively and P_{WF0} the initial active power production.

By substituting:

$$\alpha = \frac{K_{dr}K_f}{\frac{1}{2}C_{dc} + K_{in}K_f} \tag{4}$$

and

$$\Delta P(t) = P_{WF0} - p_G(t) \tag{5}$$

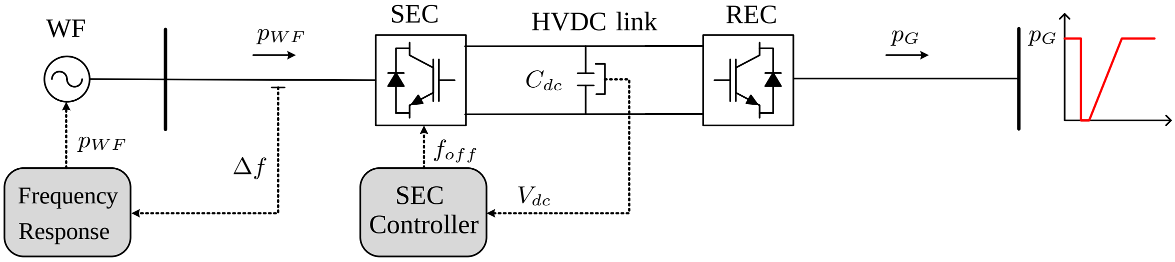


Fig. 3: Simplified System Model

and according to the model presented by (1), (2) and (3) the following differential equation is derived:

$$\frac{1}{\alpha}\frac{dV_{dc}^2(t)}{dt} + V_{dc}^2(t) = \frac{\Delta P(t)}{K_{dr}K_f} + V_{dc,ref}^2 \tag{6}$$

A. Time Domain

The solution of this differential equation has the form:

$$V_{dc}(t) = \sqrt{V_{dc,ref}^2 + \frac{1}{K_{dr}K_f}\int_0^t \alpha e^{\alpha(\tau - t)}\Delta P(\tau)d\tau} \tag{7}$$

We are mostly interested in the maximum dc voltage strain. It can be proven that the time t_0 at which this appears can be found by the numerical solution of the equation:

$$\int_0^{t_0} e^{\alpha\tau}\frac{d\Delta P(\tau)}{d\tau}d\tau = 0 \tag{8}$$

and depends only on α and the power curve p_G. For a given power curve p_G, the lower the value of α, the greater the value of t_0. Increased inertial gains K_{in} lead to higher values of α.

The maximum value of the dc voltage $V_{dc,max}$ can then be derived. At time t_0, the dc voltage reaches its peak value, therefore $\frac{dV_{dc}^2}{dt}|_{t=t_0} = 0$. From (6) we have for $t = t_0$:

$$V_{dc,max} = \sqrt{V_{dc,ref}^2 + \frac{1}{K_{dr}K_f}\Delta P(t_0)} \tag{9}$$

Therefore, the maximum dc overvoltage is roughly inversely proportional to the control constants K_f and K_{dr}. It also depends on $\Delta P(t_0)$. It can be shown that small values of α lead to a lower value of $\Delta P(t_0)$ and hence to lower dc overvoltages.

The second crucial parameter of the simulation is the ROCOF. Most WTs have limited df/dt withstand capability, so high ROCOFs could compromise the effectiveness of the FRT. An approximation of the ROCOF is given by

$$ROCOF \approx \frac{f_{max} - f_{ref}}{t_0} \overset{(2),(9)}{=} \frac{\Delta P(t_)}{t_0 K_f} \tag{10}$$

Therefore, the ROCOF is roughly inversely proportional to K_{dr} and depends on the constant α. It can be shown that a high value of α leads to higher ROCOF, both because t_0 is lower and because f_{max} is higher.

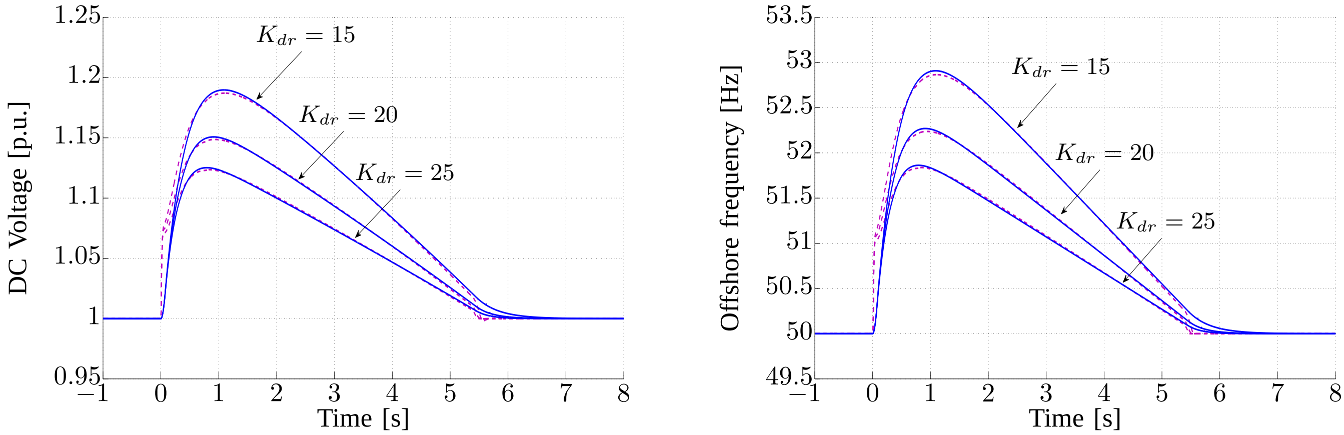
The practical usefulness of (9) and (10) is evident: Given different assumptions for fault power curves p_G, the parameters K_{dr}, K_{in} of the WT and K_f of the offshore converter can be chosen (one or more of them) so that both the maximum dc overvoltage and the ROCOF remain within acceptable limits.

B. Frequency Domain

From (6), a frequency response function can be formulated for $\Delta V_{dc}^2 = V_{dc}^2 - V_{dc,ref}^2$ with respect to the input ΔP. The form of the transfer function is:

$$\frac{\Delta V_{dc}^2(s)}{\Delta P(s)} = \frac{1/(K_{dr}K_f)}{1 + \frac{s}{a}}, . \tag{11}$$

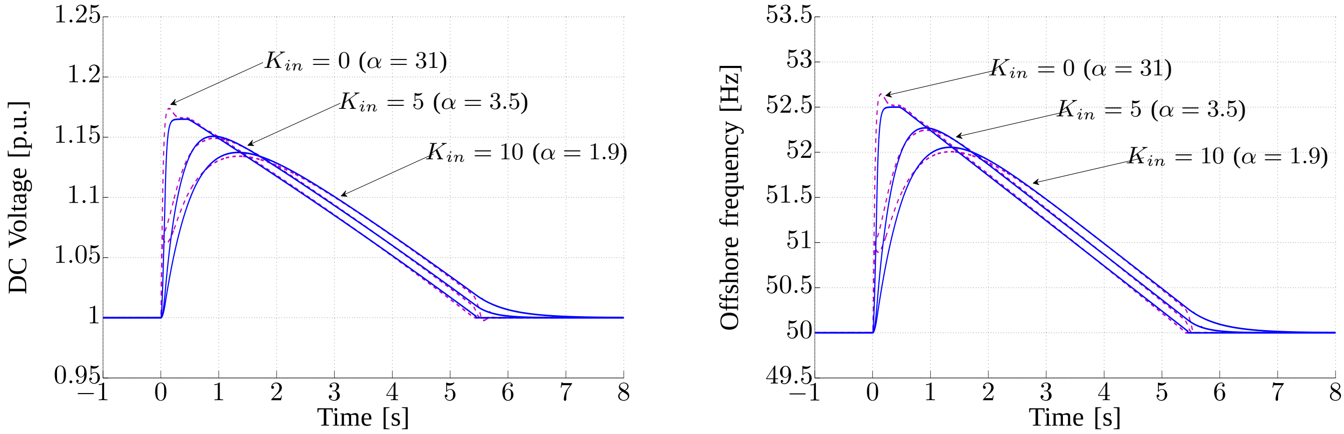
As the above transfer function indicates, the system behaves as a low pass filter (LPF) with time constant $1/\alpha$ and gain $1/(K_{dr}K_f)$. The output dc voltage is derived from a filtered version of the power imbalance ΔP. The same conclusions as in the time domain can be drawn. For example, low values of α lead to "smoother" output dc voltage for a given input power imbalance.



(a) DC Voltage deviation of the HVdc link during the FRT

(b) Frequency deviation in the offshore grid during the FRT

Fig. 4: Comparison between DIgSILENT PowerFactory simulation model (purple dashed line) and simplified model (blue solid line) for different values of K_{dr} ($K_f = 0.14$, $K_{in} = 5$).



(a) DC Voltage deviation of the HVdc link during the FRT

(b) Frequency deviation in the offshore grid during the FRT

Fig. 5: Comparison between DIgSILENT PowerFactory simulation model (purple dashed line) and simplified model (blue solid line) for different values of K_{in} ($K_f = 0.14$, $K_{dr} = 20$).

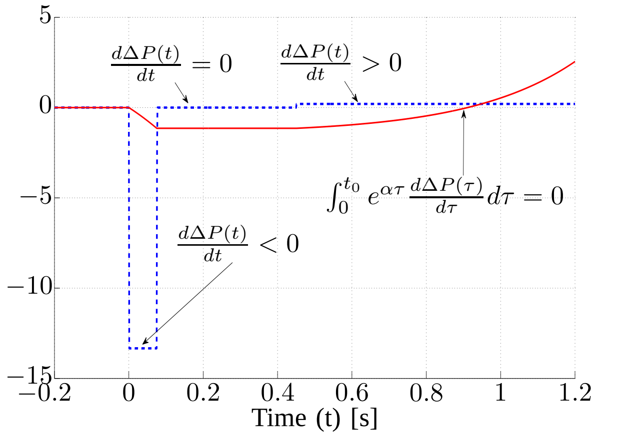
C. Simulations

The simulations in Figs 4 and 5 provide a comparison between the DIgSILENT PowerFactory model and the simplified model. Simulations for the different values of the control parameters are performed and the dc voltage ($V_{dc,REC}$ and V_{dc}) and offshore frequency (f_{off}) of the two models are plotted together. The simplified model is proved to be a good approximation of the detailed model. Furthermore, all the theoretical assumptions are verified. For example, in Fig 4, the increased values of the control parameter K_{dr} lead to a lower dc overvoltage, whereas in Fig 5 we can observe that lower values of α lead to a smoother output curve, as the frequency analysis suggested.

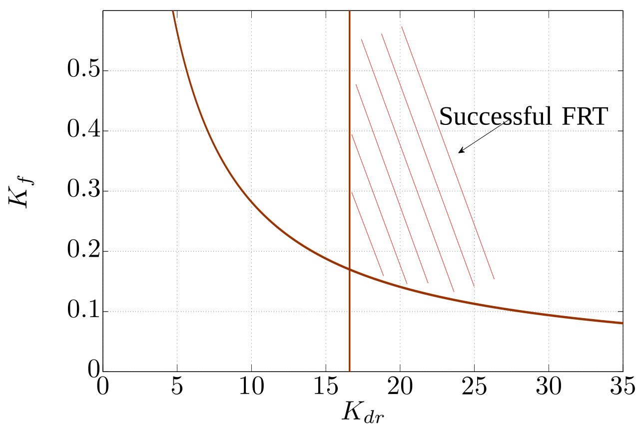
D. A simple design example

Suppose that the control objective is to choose the parameters K_f, K_{dr}, K_{in} in order to fulfill the following specifications: $V_{dc,max} \leq 1.15$ and ROCOF $\leq$ 3Hz/s= 0.06p.u./s. The following procedure can be adopted to design the system:

- Since the system of equations is underdetermined, we can start by choosing α to a modest value, say $\alpha = 3.5$.
- With the value of α known, we can solve (8) and find the dc voltage peak time. One graphical way to solve the equation is presented in Fig. 6a. The critical time of maximum voltage derived is $t_0 = 0.91s$. The critical time t_0 should be comparable to the expected fault clearing time. If we expect greater clearing times, a lower value for α should be chosen.
- We can now calculate $\Delta P(t_0 = 0.91) = 0.9080$. The design specification $V_{dc,max} \leq 1.15$ is translated from (9) into $K_{dr}K_f \geq 2.82$.



(a) Blue dashed line: the function $\frac{d\Delta P(t)}{dt}$. Red solid line: the function $\int_0^{t} e^{\alpha\tau} \frac{d\Delta P(\tau)}{d\tau} d\tau$. The integral becomes initially negative because of the negative $\frac{d\Delta P}{dt}$, but increases after that to reach 0 at time t_0.



(b) The shaded region of K_{dr} and K_f guarantees a FRT that satisfies the imposed design specifications according to the simplified model ($\alpha = 0.19$).

Fig. 6: Useful graphs for the design of the control system for a successful FRT based on the simplified model.

- From (10) and the design specification ROCOF ≤ 0.06, we get that that $K_{dr} \geq 16.6$.
- The region defined by the two previous inequalities is depicted in Fig. 6b. One choice of parameters in this region of the graph is $K_{dr} = 20$, $K_f = 0.14$.
- Finally, by substituting the values of K_{dr}, K_f and α to (4), we get $K_{in} = 5$. The simulation with the chosen parameters satisfies the requirements, as can be seen in Fig. 5.

IV. Conclusion

In this work, the dynamics of a FRT utilizing an offshore frequency increase for a VSC-HVdc connected WF were captured by a simple mathematical model. The model performed surprisingly well in comparison to a detailed DIgSILENT PowerFactory simulation. An analysis in the time and frequency domain was presented, which aided to quantitatively describe the effect of the various control parameters to the success of the FRT. Practical formulae that provide approximate values for the dc overvoltage and the ROCOF were presented. A systematic way to design the controllers was suggested, although many others may exist. The model in general seems to be an easy to use tool for the evaluation of a FRT.

V. Learning objectives

The most basic learning objectives that this work has to offer are the following:

- Understanding of the basic control of the HVdc link in a VSC-HVdc connected WF under normal operation and of the need for a FRT strategy due to the decoupling of the onshore and offshore grid.
- Understanding of the way by which the FRT strategy that utilizes offshore frequency increase can guarantee a successful FRT.
- Understanding of the basic dynamics of the aforementioned phenomenon through a simplified mathematical model.
- Ability to design based on that model the controller parameters that will guarantee a FRT that satisfies specific design criteria, such as a low maximum dc voltage strain and a low ROCOF.
- Possibility to use the simplified model instead of a detailed one in case the full simulation is not the scope of the project.

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