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A New Coordinated Voltage Control Scheme for Offshore AC Grid of HVDC Connected Offshore Wind Power Plants

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SUMMARY

This paper proposes a coordinated voltage control scheme (CVCS) which enhances the voltage ride through (VRT) capability of an offshore AC grid comprised of a cluster of offshore wind power plants (WPP) connected through AC cables to the offshore voltage source converter based high voltage DC (VSC-HVDC) converter station. Due to limited short circuit power contribution from power electronic interfaced variable speed wind generators and with the onshore main grid decoupled by the HVDC link, the offshore AC grid becomes more vulnerable to dynamic voltage events. Therefore, a short circuit fault in the offshore AC Grid is likely to have significant implications on the voltage of the offshore AC grid, hence on the power flow to the onshore mainland grid. The proposed CVCS integrates individual local reactive power control of wind turbines and of the HVDC converter with the secondary voltage controller at offshore grid level. This secondary voltage controller controls the voltage at the pilot bus, the bus with the highest short circuit capacity in the offshore AC grid. By maintaining voltage at the pilot bus, reflecting the voltage variations of the entire offshore zone, the voltage profile of the offshore grid is indirectly maintained. During steady state operation, the secondary AC voltage controller generates reactive power references for individual wind turbines (WTs) based on their participation factors (PFs) and available reactive power margins, while during dynamic voltage events; the secondary voltage controller generates additional reactive power reference signals for WTs and the HVDC converter, to enhance VRT capability of the offshore AC network. The Participation Factor of each WT is calculated from their dV/dQ sensitivities w.r.t. the pilot bus. The WT and the HVDC converter control is modified to accommodate additional reactive power reference from the secondary controller, while maintaining their local VRT capability. A detailed model of 800 MW VSC-HVDC connected OWPP cluster developed in DigSILENT platform is considered in this study. VSC-HVDC transmission system operates at +/- 320 kV with active power balance (hence DC voltage) control assigned to the onshore converter, while frequency and AC voltage control at the offshore substation assigned to the offshore converter.

KEYWORDS

Coordinated Voltage Control - HVDC - LVRT - Offshore Wind Power Plant Control - Reactive Power

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1. INTRODUCTION

Several large-scale offshore wind power plants (OWPPs) have been developed in recent years and this trend is likely to continue in the near future [1]. VSC-HVDC transmission system is considered as a feasible and economical solution for long distance bulk power transmission from OWPPs to the onshore grid [2]. Traditionally, a major part of the power production has been delivered by conventional power plants with large synchronous machines driven by hydro or thermal prime movers. These generators provide ancillary services including short circuit power during a fault to ensure secure recovery of power system within the desired time frame. Today, WPPs are expected to deliver services similar to those of conventional power plants; therefore, Transmission System Operators (TSOs) are developing stricter grid code regulations to ensure power system stability and reliability [3]-[5]. Grid codes require wind power plants to be capable of active and reactive power control, voltage regulation, fault ride-through, and limitation of power quality impacts. The main focus of the research work presented in this paper is (1) Improved reactive power and voltage control of offshore grid, and (2) Enhancement of Low Voltage Ride Through (LVRT) capability requirements [6].

Offshore grid of VSC-HVDC connected offshore WPPs tend to have low short circuit capacity due to limited short circuit power contribution from power electronic interfaced wind generators and decoupling from the onshore grid through HVDC link. Therefore, the offshore AC grid becomes more vulnerable to dynamic voltage events [7]. However, due to inherent control flexibility provided by HVDC converters and modern WTs with VSCs, additional reactive power can be supplied during short circuit events to aid grid voltage to comply with grid code regulations [4]. The voltage/reactive power control and dispatch strategy of the WPP cluster, integrated in the offshore HVDC converter, is also important because several large-scale offshore HVDC connected WPPS are planned in the near future. A possible control strategy for a single WPP, discussed in the literature [8]-[9], is that the TSO generates (1) power factor, (2) reactive power, or (3) voltage amplitude as set points to the WPP controller. The measured/estimated values of these set points are compared with the actual values by a PI controller to generate set points for the individual wind turbines. However, application of such control strategies to a WPP cluster may not be adequate for large-scale offshore WPP cluster and therefore, is worth investigating.

In this context, the voltage control of an 800 MW offshore WPP cluster having four 200 MW WPPs located at different locations within close proximity connected to an offshore HVDC converter is investigated in this paper. A novel CVCS is proposed for the offshore AC Grid using the offshore HVDC converter and the WPP control capabilities to enhance the LVRT capability of the offshore AC grid and to optimally control its voltage profile during steady state operation thereby improving the power flow to the onshore grid. During steady state operation, the CVCS generates reactive power reference for WPP cluster by controlling the voltage at the pilot bus, the voltage reference at the pilot bus being supplied by an optimization program aimed at minimizing active power losses in the offshore Grid. The generated reactive power reference values from CVCS are then dispatched to each WPP based on their PFs and available reactive power margin. For a fault at an offshore bus, while individual local reactive power controller controllers injects reactive current based on the voltage dip observed at its terminal bus, the CVCS supplements by forcing additional reactive power injection from WTs (or HVDC converter) that observe relatively lower voltage dip due to their farther location from the faulted location, thereby improving overall LVRT capability of the offshore grid. The performance of the proposed control scheme is demonstrated by applying symmetrical fault in the collector cable of the WPP in the offshore AC Grid.

2. MODELING OF HVDC CONNECTED OFFSHORE WPP CLUSTER

WPP Layout:

An 800 MW offshore WPP cluster comprised of four 200 MW WPPs, marked as A1B1, A2B2, C1D1, and C2D2, and located at a distance of 7 km, 12, km, 17 km, 22 km respectively from the offshore HVDC converter station has been developed in the PowerFactory simulation environment as shown in Fig. 1. Each 200 MW WPP is composed of four parallel WT strings, each of 50 MW capacity composed of 8 numbers of series connected 6.25 MW WTs. The turbines are placed with an inter-machine distance of 1.2 km, approximately equal to seven times the rotor diameter.

Power Collector System:

The power collection system in each WPP consists of collector cables (feeders) and transformers. The 33 kV cables between WT5 and WT8 (i.e. the farthest from the collector bus) have current rating of 0.5 kA, while the 33 kV cables between WT5 and the collector bus are rated at 1 kA. Each WPP is connected to the collector bus through a 33/155 kV, 240 MVA step up transformer.

Aggregation of WPPs:

To study the impact of WPP on the power system, though it is preferable to consider the detailed WPP model instead of an aggregated WT model, the consideration of detailed model of WPP increases the computational burden. Therefore, most of the WPPs considered in this study are aggregated to simplify the WPP model without compromising the accuracy of the results. One of the WT strings (8 machines, 50 MW total capacity) in WPP-A1B1is modeled in detail. The remaining WTs in that WPP are represented by an aggregated model of 50 MW capacity for A1 (9-16) feeder. The rest of the strings in other WPPs are aggregated with each of 100 MW capacity. The WT aggregation method for WTs and export cables of a WPP has been adopted from [10], [11]; the overall WPP model is shown in Fig. 1.

WT Model:

A full converter based “type 4” WT model considered in this work is adopted from IEC 61400-27-1 – Part 1 [12], which is modeled for the short term power system stability studies.

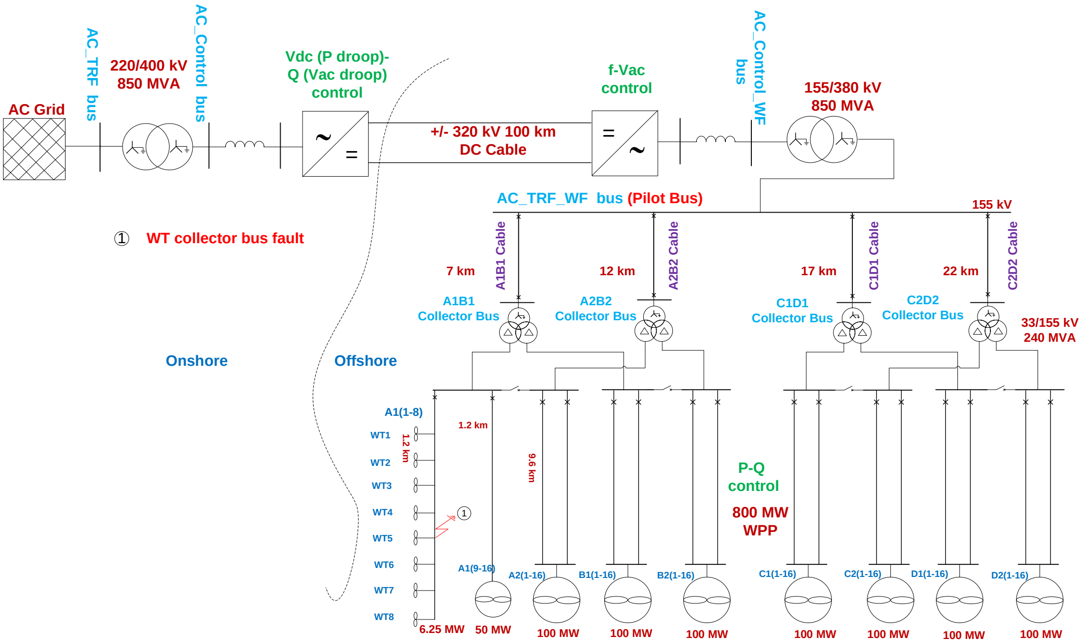

Fig. 1: Offshore HVDC Connected WPP Model

Onshore and offshore HVDC Converter Model:

The standard pulse width modulated (PWM) based converter model has been adopted for the offshore and onshore HVDC converters. The onshore HVDC converter is assigned with the power balance control of the HVDC link, by maintaining the DC voltage at the optimal value. It also controls the reactive power/AC Voltage at converter bus as per grid code regulations. The current references provided by the outer controllers are then handled by a standard inner current controller operating in the d-q reference frame [13]. The offshore HVDC converter is responsible for controlling the voltage magnitude at the offshore converter station (AC_Control_WF bus in Fig. 1), the frequency of the offshore AC network and allows the transfer of active power from the WPPs to the HVDC system. This is achieved by using a standard current control whose reference is provided by the outer converter controller [13].

3. PROPOSED COORDINATED VOLTAGE CONTROL SCHEME FOR VSC-HVDC BASED OFFSHORE WPP.

The principle of the proposed coordinated voltage control scheme at the WPP cluster and the HVDC converter for steady-state and dynamic operation to enhance the VRT capability of the offshore Grid is described in this section.

WPP Cluster Controller- Steady State operation:

The WPP cluster voltage controller is shown in Fig. 2. The reference voltage at the pilot bus, *V_pilot_Ref*, is provided by an optimization program, with minimum active power loss in the offshore grid as the objective function, for the available power output (*Pav*) from the WPP clusters. The available active power from all WPPs (*Pav)* is estimated from the forecasted wind speed, *Vw*. The optimal reference voltage at the pilot bus, *V_pilot_Ref*, is then fed to the WPP cluster voltage controller, which generates the required reactive power set point for the WPP cluster reactive power dispatcher, then these set points are dispatched to each individual WPP based on their PFs. The WPP dispatcher generates the reactive power references for each WT based on their available reactive power capacity and PFs. The mathematical model for the reactive power dispatch at the WPP level is given in (1).

$$
\begin{aligned}
&Q_{ref}^{WT_i} = \frac{PF_{WT_i}}{PF_{WPP}} * \frac{Q_{av}^{WT_i}}{Q_{av}^{WPP}} * Q_{ref}^{WPP} \\
&Q_{av}^{WPP} = \sum_{i=1}^{n} Q_{av}^{WT_i}\, with: Q_{av}^{WT_i} = \sqrt{(S_{Gen}^{WT_i})^2 - (P_{av}^{WT_i})^2} \qquad (1) \\
&PF_{WT_i} = \frac{dU_{pilotbus}}{dQ_i}, PF_{WPP} = \frac{\sum_{i=1}^{n} PF_{WT_i}}{n}
\end{aligned}
$$

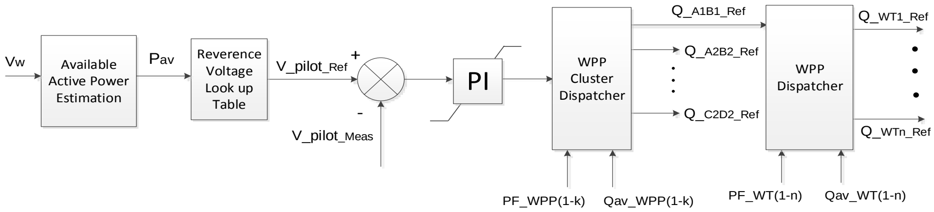

Fig. 2: WPP Cluster Voltage Controller

The reactive power reference for each WT, $Q_{ref}^{WT_i}$,is formulated as a proportional distribution of the WPP reactive power reference, Q_{ref}^{WPP}, based on the ratio of the participation factors and the available reactive power , where $P_{av}^{WT_i}$,$Q_{av}^{WT_i}$, and $S_{Gen}^{WT_i}$ are the available active and reactive powers and the MVA rating of the i^{th} wind turbine, Q_{av}^{WPP} is the total available reactive power of the WPP, PF_{WT_i} is the participation factor of the i^{th} wind turbine, and PF_{WPP} is the participation factor of the *WPP.*

Similarly, the mathematical model for the reactive power dispatch at WPP cluster level is given in (2).

$$
\begin{aligned}
&Q_{ref}^{WPP_i} = \frac{PF_{WPP_i}}{PF_{cluster}} * \frac{Q_{av}^{WPP_i}}{Q_{av}^{cluster}} * Q_{ref}^{cluster} \\
&Q_{av}^{cluster} = \sum_{i=1}^{k} Q_{av}^{WPP_i} \qquad (2) \\
&PF_{cluster} = \frac{\sum_{i=1}^{k} PF_{WPP_i}}{k}
\end{aligned}
$$

The reactive power reference for each WPP,$Q_{ref}^{WPP_i}$, is formulated as the proportional distribution of the WPP cluster reactive power reference, $Q_{ref}^{cluster}$, based on the ratio of participation factors and available reactive power , where $PF_{cluster}$ is the participation factor of the WPP cluster, and

$Q_{av}^{cluster}$ is the total available reactive power of the WPP cluster. Therefore, during steady state operation, for any unacceptable voltage deviation at the pilot bus, WTs and HVDC converter are commanded to generated/absorb additional reactive power based on the generated set points.

WPP Cluster Controller- Dynamic Operation:

A short circuit fault or any other dynamic event may result in low voltages in the offshore AC Grid. To improve the voltage recovery of the Offshore Grid as per Grid code requirements, WTs are expected to increase their reactive power contribution during and after the short circuit event for better voltage recovery of the Grid. The schematic of the WT reactive power controller adopted in this research work is shown in Fig. 3. The WT reactive power controller generates a base reactive current reference, *Iq_base,* during normal operation. If the voltage at the WT terminals deviate from the allowed dead band (normally +/- 0.1 pu), additional reactive current reference, *Iqv1*, generated from the WT low voltage ride through (LVRT) controller, based on the WT terminal voltage, *V_WT_meas,* is sent to the WT inner current controller. However, the WT LVRT controller gets only local WT voltage measurements. For certain faults/disturbances, e.g. WT collector cable faults within a WPP, the WTs in that WPP observe a low voltage dip depending on their distance from the fault location, and accordingly their local LVRT controllers demand additional reactive power. However, WTs of other neighboring WPPs may not observe the same voltage dip, hence, such WTs are unlikely to generate additional adequate reactive power required for fast and effective voltage control. This may lead to a low voltage profile within the WPP cluster and also at the WPP point of connection (PCC), i.e. at the pilot bus. The proposed cluster controller utilizes the reactive power margin of such wind turbines in order to improve dynamic voltage recovery more effectively following a short circuit fault. The additional reactive current produced by this controller, *Iqv2*, based on the pilot bus voltage, *V_pilot_Meas*, is added to the *Iq_base.* The priority current limiter then sets the active/reactive current priority depending on the TSO requirement and limits the total current reference to the WT as per the rating of the WT.

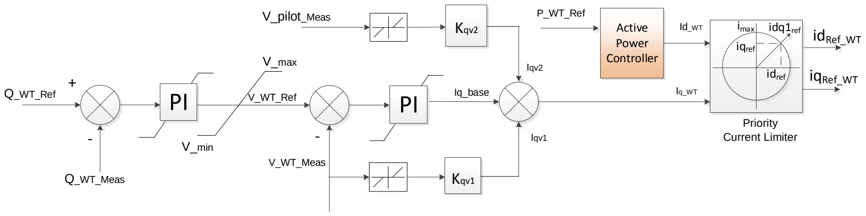

Fig. 3: WT Reactive Power Controller

HVDC Converter Control- Dynamic Operation:

Similar to the WTs, the LVRT controller is employed at the offshore HVDC converter, as shown in Fig. 4, which generates additional reactive current reference, *Iqv_H,* following a dip in AC voltage at the pilot bus of the offshore AC Grid due to a fault.

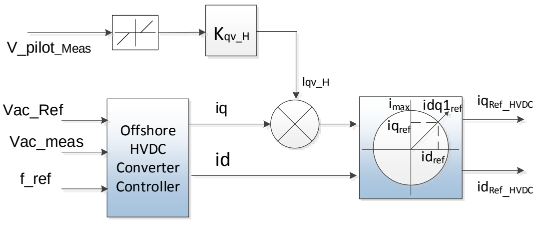

Fig. 4: Offshore HVDC Converter Control

4. SIMULATION AND ANALYSIS OF THE RESULTS

Steady State Operation:

The relation between the losses in the offshore Grid and the optimal pilot bus voltage for different active power output from WPP is shown in Fig. 5. It can be observed that there is a correlation between the optimal pilot bus voltage and the active power output from WPPs. With the proposed coordinated voltage control, the voltage at the pilot bus is maintained at its optimal value, depending on the power output from WPP, and thereby reducing the active power losses. To compare the active power losses with the proposed WPP cluster coordinated voltage control (CVC) scheme with the traditional WPP control, it is assumed that each WPP is in voltage control mode controlling the voltage at the low voltage side of the transformer on the WPP collector bus. The comparison of active power losses for both methods is shown in Fig.6, and it is evident that losses are relatively low with the proposed CVC scheme.

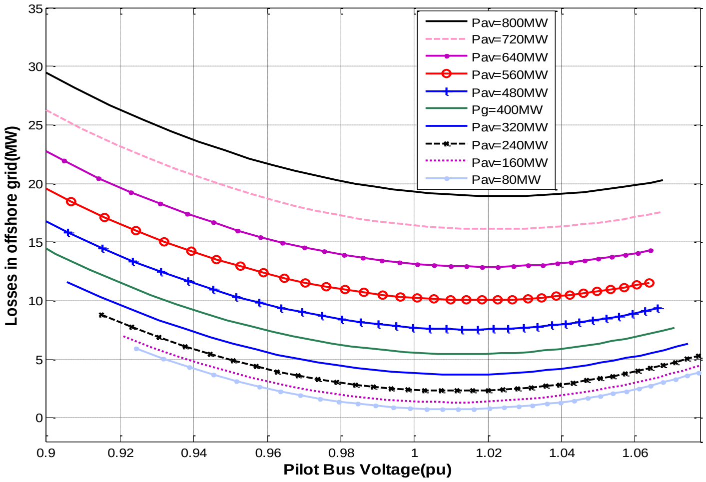

Fig. 5: Losses in the offshore grid Vs Pilot bus voltage

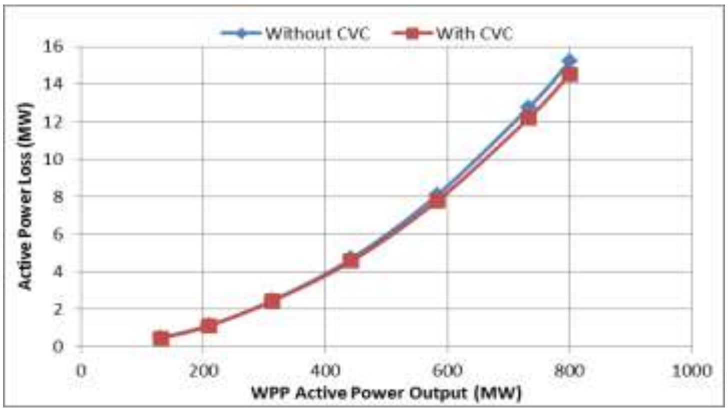

Fig. 6: Active Power Loss Vs Active Power output of WPPs

Dynamic Operation:

The effectiveness of the proposed CVC scheme is studied for a 3 phase to ground fault at the WTGA1 (5), i.e. WT collector bus fault as shown in Fig. 1. It is worth to observe the reactive power contribution from the WTs of the faulted WPP and the other non-faulted WPPs of the WPP cluster. The wind turbines, WTB1 under the WPP-A1B1 and WTA2 under the WPP- A2B2 have been considered for the study. The AC voltage at the terminal of WTA1 (5), WTB1, and WTA2 with and without considering the effect of coordinated voltage control (CVC) from WPPs along with reactive power contribution from corresponding wind turbines is shown in Fig. 7. As WTB1 observes larger voltage dip at its terminal, its (local) LVRT controls are activated to provide additional reactive power. However, the voltage dip observed at the WTA2 terminal is not sufficient enough to trigger its LVRT controller for a adequate time as the voltage dip is not sustained for longer duration. In general, the local LVRT control is activated when the voltage at WT terminal falls below 0.95 p.u. and vice versa. The LVRT controller, based on the pilot bus voltage from the CVC, triggers the WTA2 to inject additional reactive power during and after the fault which results in the improvement of the voltage profile at its terminals. Similarly, the CVC scheme can trigger the LVRT controllers of all WTs from other WPPs with an available reactive power margin to produce the required additional reactive power during a dynamic event to improve the voltage profile of the offshore AC Grid. It can also be observed that the voltage overshoot at the WTA2 terminals after the fault clearance is less with the CVC scheme and this could be an advantage to limit the temporary short term over voltages at WT terminals.

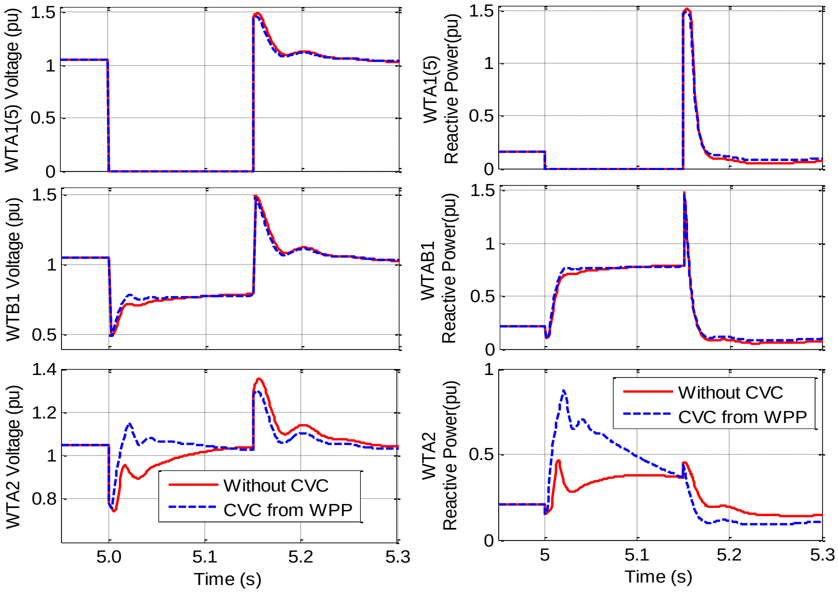

Fig. 7: Effect of CVC on the Terminal Voltage and reactive power output of WTs

The effectiveness of the proposed CVC scheme on the LVRT performance of the offshore AC grid, for a collector cable fault at WTGA1 (5), is shown in Fig.8. It can be observed that there is a considerable improvement in VRT capability using the CVC scheme. The active power flow at the offshore HVDC converter and DC voltage of the HVDC system is improved with the proposed CVC scheme as shown in Fig.8. It is also observed that during the fault clearance, the CVC from WPPs limits the peak of the temporary overvoltage at point of connection (PCC), i.e. at the pilot bus. This could be an advantage for the overvoltage protection under partial/full HVDC load rejection conditions as a result of the blocking of the converter (triggered by its internal protection system).

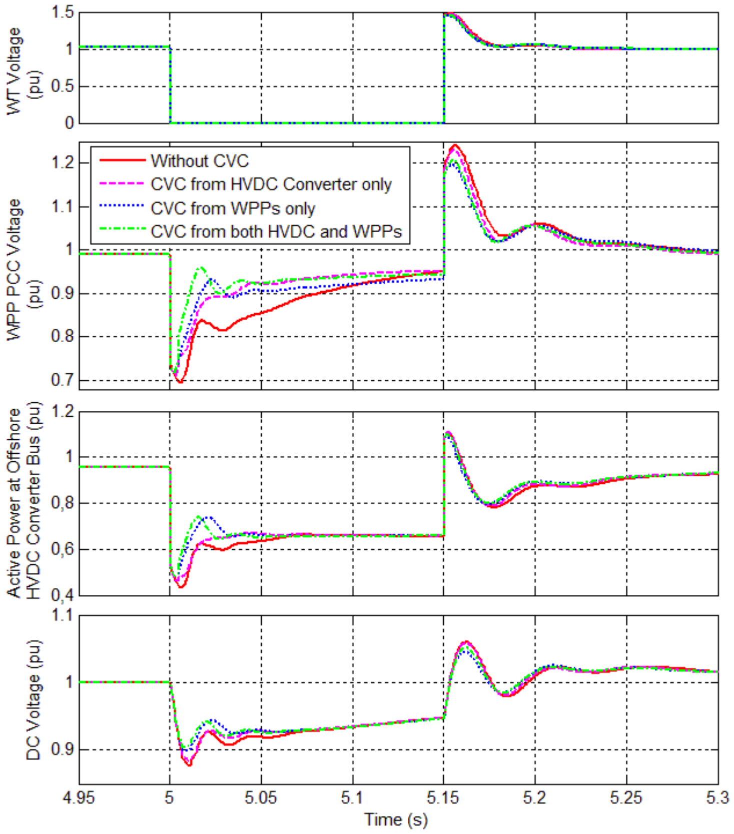

Fig. 8: Dynamics of Offshore HVDC Connecgted WPP for a collector cable fault at WTDA1 (5) with and without CVC (Coordinated Voltage Control)

5. CONCLUSIONS

A coordinated voltage control scheme for offshore HVDC connected WPP clusters, improving both the steady state and the voltage ride through performance of offshore AC Grid, is proposed in this paper. This control scheme integrates individual local voltage/reactive power control of wind turbines and the offshore HVDC converter, with the secondary voltage control at offshore grid level aimed to control voltage profile at the pilot bus. The proposed controller generates reactive power references which are distributed to the individual wind turbines and the HVDC offshore converter based on participation factors and the available reactive power margin of the WTs. The proposed coordinated voltage control scheme reduces the active power losses during steady state operation and improves low voltage ride through capability of the offshore AC Grid during faults. It is also observed that during fault clearance, CVC with WPPs limits the peak temporary overvoltage at the PCC, which will be beneficial for overvoltage protection under partial/full HVDC load rejections resulted by blocking of converter due to the action of protection system.. The proposed control scheme assumes fast communication channel within the WPP cluster. However, in case of communication failures, the individual WT operates in voltage/reactive control mode within their operational limits.

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