Dynamic Performance of Type-4 Wind with Synchronous Condenser during Weak Grids and Faults

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***Abstract*—This paper presents the dynamic behavior of Type-4 wind during weak grid and faults when integrated with a synchronous condenser. The main objective of this work is to demonstrate the possible performance improvements in the type-4 wind plant operations by connecting a synchronous condenser in parallel. The synchronous condenser effectively damps low-frequency oscillations during weak grids, enhances the power transmission capability, improves the steady-state and transient stability of the grid, and augments the low voltage ride through (LVRT) performance capability of the type-4 wind. We have illustrated these benefits by integrating a 75 MVA synchronous condenser to a 200 MW type-4 wind plant. We have demonstrated the advantages of this integration through several test cases conducted in the PSCAD/EMTDC software environment.**

***Index Terms*—Type-4 Wind, Weak Grid, Synchronous Condenser, Fault analysis, Low Voltage Ride Through (LVRT),**

I. Introduction

The operating wind capacity is around 110 GW as of 2020. Since the wind generators contribute 7.2% of the nation's electricity, we have to ensure stability under all scenarios. Specifically, wind and solar plants are vulnerable when operated during low grid strength and inertia, as reported in [1]. Short-Circuit Ratio (SCR) is the metric used to distinguish between a weak and strong grid. ERCOT reported sustained low-frequency oscillations in 2018 when they operated their system in low-system strength conditions [2]. Apart from the system conditions, the fast-acting current controller and phase-locked loop (PLL) bandwidth also impact the system's dynamic response [3]. ERCOT's summer dynamic assessment report shows that with synchronous condenser installed, the 4-5Hz oscillations are damped out [4]. They have further advocated wide-area PSCAD studies to capture the dynamics during transient events.

In the past, grid codes permitted islanding of wind turbines during voltage sags and swells and frequency deviation. High penetration of wind power plants has made grid operators change or rethink about these existing standards. The wind generating units are currently required to connect to the grid during a transmission line fault or a voltage dip. And they are also responsible for supporting the grid voltage during a fault . [5]. NERC also has recommended an investigation on reactive power injection to the grid during the low voltages, in [6]. The current limit of the power electronic devices does not encourage operators to inject any reactive power following a disturbance [7]. Synchronous condenser can supply reactive power close to twice its rating during a fault [8]; thus by integrating a synchronous condenser into the wind farm, we can ride through the grid faults while adhering to the norms.

In this paper, we concentrate on presenting the advantages of connecting a synchronous condenser to a wind farm. This paper describes the damping of low-frequency oscillation by a synchronous condenser. Also, we illustrate the LVRT capability of the type-4 wind in the presence of the synchronous condenser. Besides, the findings will also shed light on the type-4 wind system response to faults.

The rest of the paper is organized as follows. Section II provides the system description and the simulation results for weak grid and faults. Section III concludes the paper.

II. Performance evaluation in PSCAD/EMTDC

We demonstrate type-4 wind dynamic performance with a synchronous condenser in a weak grid and during faults by simulating a detailed model in the PSCAD/EMTDC environment. We will be using the system shown in Fig. 1 for our analysis. To illustrate the dynamics, we have considered the type-4 wind model in [9]. The grid-side controller regulates the dc bus voltage. It also includes the cascaded AC voltage and reactive controller, which varies the q-axis reference current based on the voltage dip/swell. We have modified the transmission network to simulate for weak grid and faults and the parameters are present in Table I. The 75 MVA synchronous generator model comes from the VSC-HVDC example in PSCAD/EMTDC [10].

A. Weak grid and Synchronous Condenser connected.

1) Case 1: Type-4 wind performance with a Synchronous Condenser delivering 0.3 p.u. reactive power:

Herein, we demonstrate the effectiveness of synchronous condenser in mitigating the 4 Hz undamped oscillations. A large disturbance is simulated by tripping one 220 kV transmission line for a period of 2 seconds without the synchronous

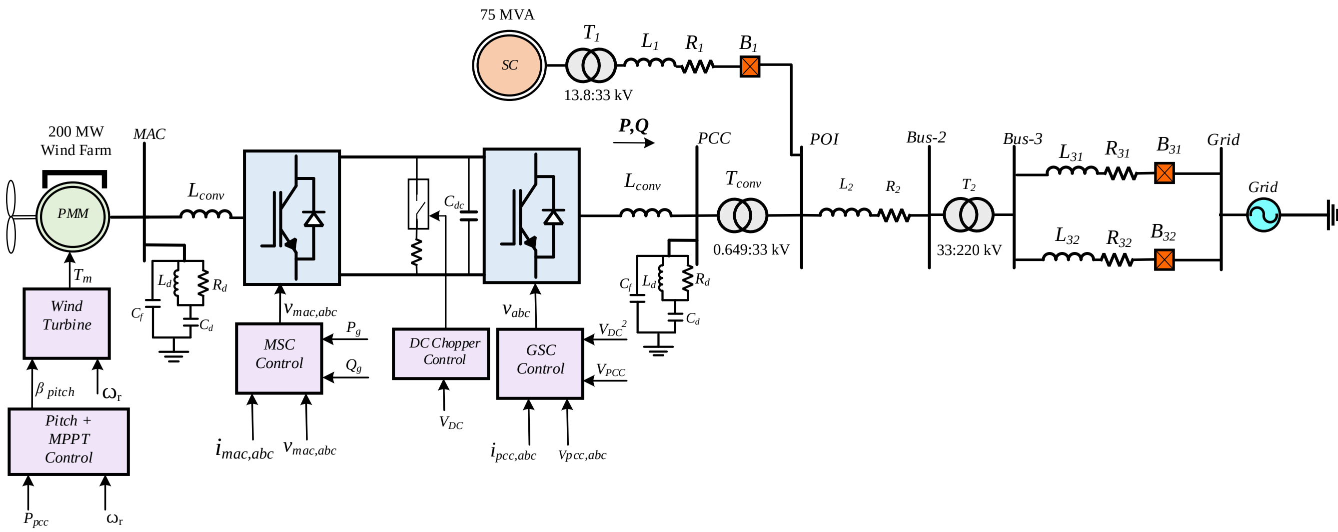

Fig. 1. PSCAD testbed: 200 MW Type-4 wind farm is connected to the grid, with 75 MVA Synchronous condenser interfaced at the 33 kV bus.

condenser connected. At t = 6 s, we close the breaker B_1 and present the type-4 wind's response with the synchronous condenser connected.

For t < 2 s: The system is stable since the $SCR = 3.85$. The wind speed is 10m/s, and the grid side inverter is injecting maximum available active power of 200 MW to the grid and maintain the reactive power at zero as shown in Fig. 3(a) and (b) . In Fig. 2 the PCC voltage is also 1 p.u. Since we have disconnected the synchronous condenser during this interval, it dispatches zero real and reactive power.

At t = 3 s, a disturbance is created by tripping one of the 220 kV lines. It will lead to a decrease in the grid strength and the $SCR = 1.4031$. At t = 3 s, breaker B_{32} is open and B_{31} is closed. Due to the tripping, poorly undamped oscillations of 4 Hz are observed in the system for 2 seconds, as shown in Fig. 3.

At t = 6 s, the synchronous condenser is added to the system and the oscillations slowly damp out. The synchronous condenser has an overdamped response, and it delivers 0.3 pu reactive power from t = 8 s, as demonstrated in Fig. 3(d). Also, the synchronous condenser dispatches zero real power during the event, as depicted in Fig. 3(e).

Fig. 2 presents the type-4 wind performance with and without synchronous condenser during a weak grid condition. Incidentally, oscillations were damped, despite the synchronous condenser contributing zero reactive power (not shown,limited space) [11]. This study demonstrates that 4 Hz oscillation during a weak grid can be damped when a synchronous condenser is connected in parallel.

2) Case 2: Dynamic response of Type-4 to increase in wind speed with the synchronous condenser connected.:

Fig. 4 presents the response of type-4 wind with the synchronous condenser when the wind speed increases. In case-2, we illustrate the advantage of connecting synchronous condenser in parallel with type-4 wind during a weak grid

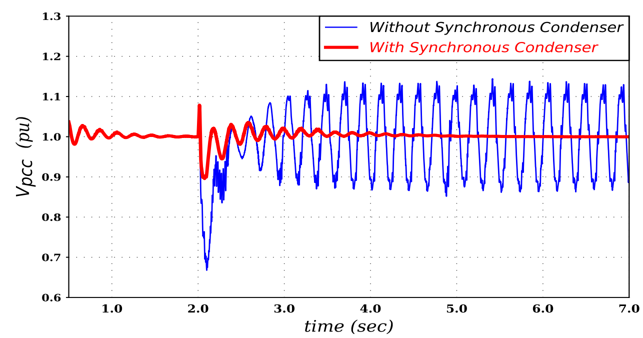

Fig. 2. Type-4 wind system performance with and without Synchronous Condenser in a weak grid scenario

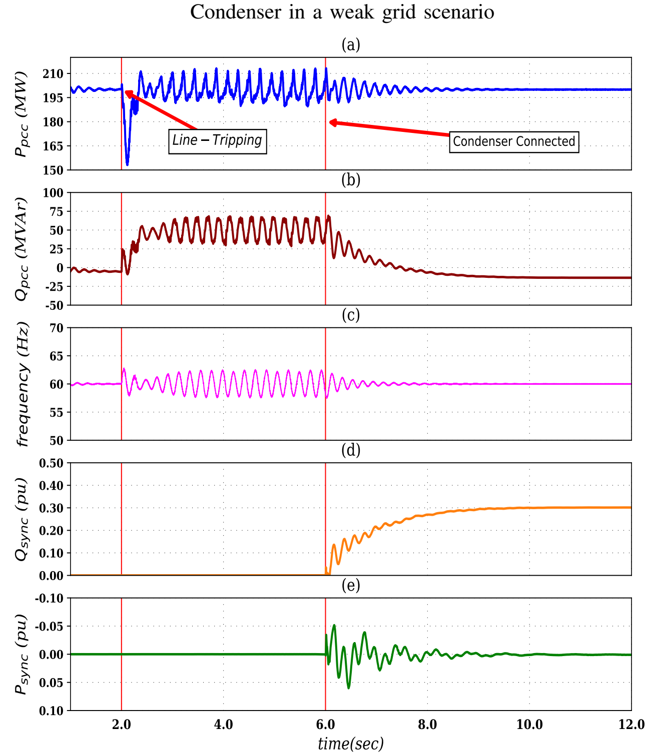

Fig. 3. Transient responses of the system when a fault occurs at $t = 2$ s and at $t = 6$ s the synchronous condenser is connected.

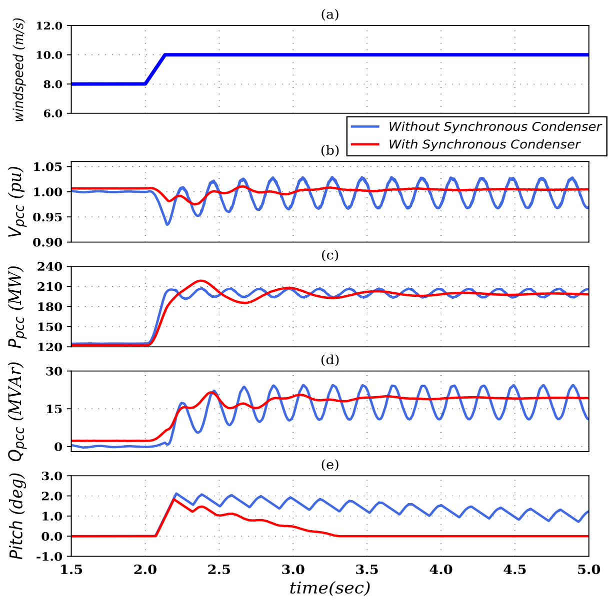

Fig. 4. Response of type-4 to increase in wind speed (8 to 10 m/s) in a weak grid scenario and when the Synchronous condenser is connected in parallel.

(SCR = 1.96). For wind speed of 8 m/s, the type-4 wind system will inject 120 (MW) real power to the grid as presented in Fig. 4(c). The pitch angle is equal to zero degrees.

At t = 2 s: The wind speed increases from 8 to 10 m/s. As shown in Figs. 4(b) –(e) without the synchronous condenser, 4 Hz oscillation are initiated in the system as the wind speed rises. However, with the synchronous condenser, these oscillations are damped, and the type-4 wind is injecting a 200 MW to the grid. In Fig. 4(e), with the synchronous condenser, the pitch angle increases to 2 deg initially and reduces to zero degrees at 3.2 seconds. Also, the type-4 wind plant will inject 20 MVAr to the grid, as illustrated in Fig. 4(d).

From Fig. 4, we can conclude that synchronous condenser enhances the power transmission capability during weak grids.

3) Case-3: LVRT performance of the system during Asymmetrical fault.:

Herein, we demonstrate the type-4 wind system LVRT performance during asymmetrical faults. We have connected the synchronous condenser to evaluate the reactive power injected during the fault. The reactive power limit on the grid side of the type-4 is varied based on the voltage dip. We have simulated a temporary single phase to ground fault at t = 2 s for a fault duration of four cycles.

For the fault at Bus-3, the positive sequence voltage reduces to 0.7 p.u. Fig. 5(b), and the negative and zero sequence voltage component increases to 0.3 p.u. Figs. 5(c) and (d). From Fig. 6, it is evident that the current is limited and balanced since the sequence components are negligible. Further, the sum of the sequence currents I^+, I^-, and I^0 is less than 1.05 p.u. as in Fig. 6(a).

The maximum wind generation loss (50 MW) during the fault is similar with or without the synchronous condenser. While riding through the fault, the type-4 wind can dispatch 40 MVAr, but with the synchronous condenser in parallel, the system can deliver 100 MVAr to the grid Fig.5(f). Hence, increasing the transient stability of the grid. Although not shown, the system's response to an LL-G fault is similar, given the same initial conditions.

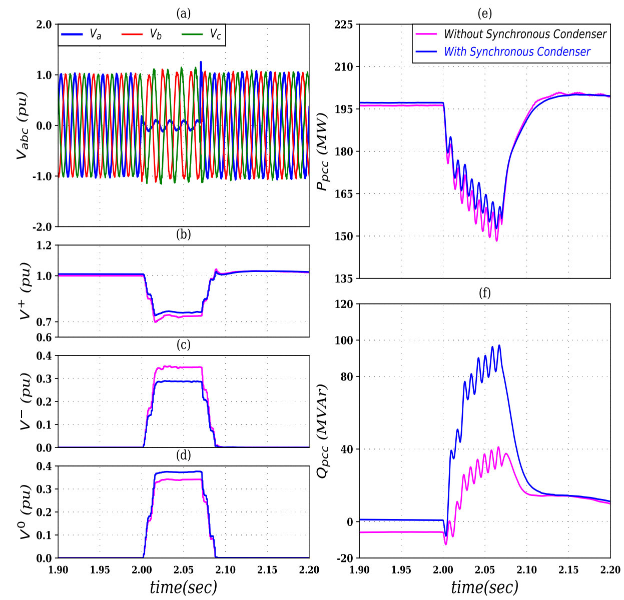

Fig. 5. Response to a single-phase-to-ground fault with and without the synchronous condenser.

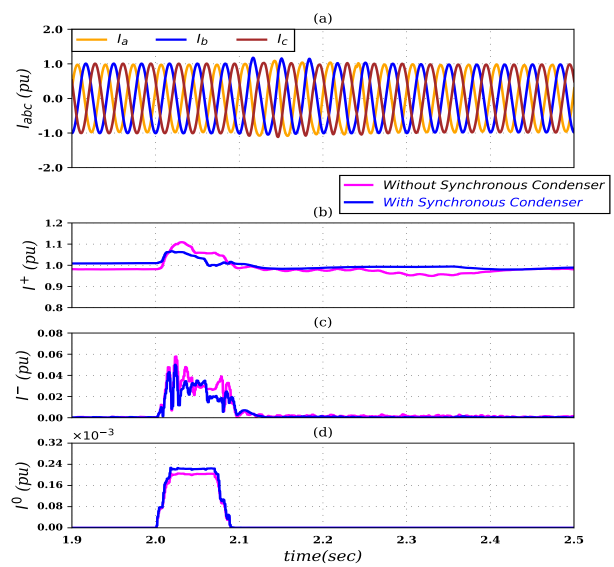

Fig. 6. Current injected by the type-4 wind during a single-phase-to-ground fault

4) Case 4: LVRT performance of the system during three-phase to ground fault.:

Here, in this case, we demonstrate the type-4 wind system response to a three-phase-to-ground fault. We simulate the

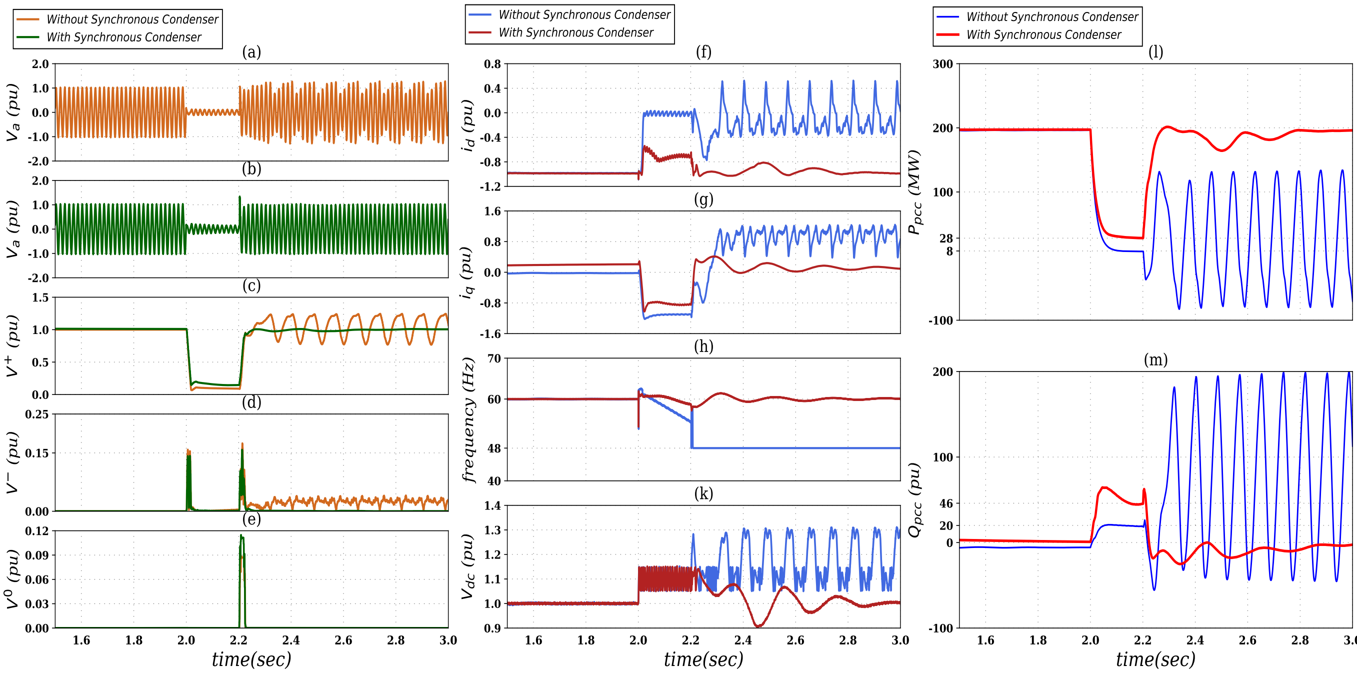

Fig. 7. Response of the system to three-phase-to-ground fault. (Fault duration = 0.2 sec)

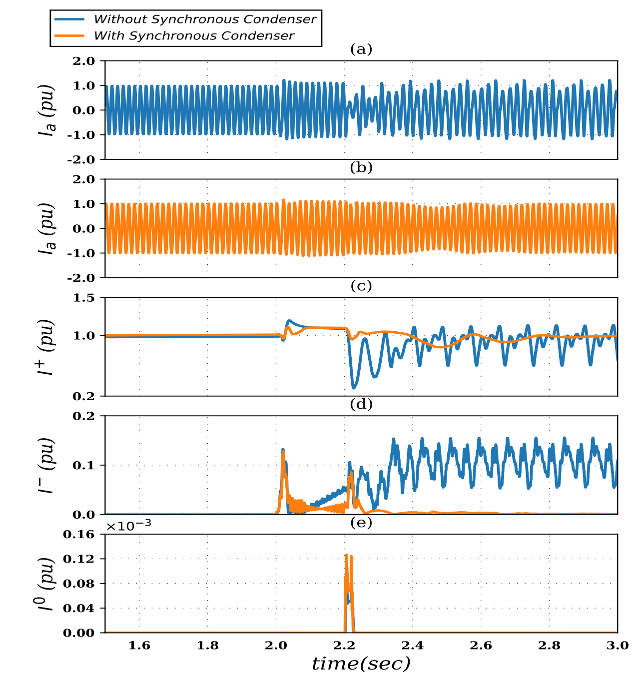

Fig. 8. Current injected by the type-4 wind during a three-phase-to-ground fault

three-phase fault with and without the synchronous condenser. At the time of the fault, we assume a constant wind speed of 10 m/s. We incept a three-phase fault at the Bus-3 for 0.2 seconds. Following the fault, the standalone type-4 wind system becomes unstable, as shown in Fig. 7. Post fault (t = 2.2 s), the system oscillates at a frequency of 12 Hz. However, with the synchronous condenser connected to the system, the type-4 wind can effectively ride through the three-phase-to-ground fault Fig. 7.

During the three-phase fault, the system is balanced since negative and zero sequence components of voltage and current are negligible. After the inception of the fault, the frequency drops down sharply, and post fault, the frequency settles down to 48 Hz, as shown in Fig. 7 (h). Further, the type-4 wind dispatches 8 MW and 20 MVAr active and reactive power, respectively, while riding through the fault. But, with the synchronous condenser connected, the frequency change is minimum. Also, through the fault, the system delivers 28 MW and 46 MVAr, which is twice the power provided by the standalone type-4 wind. Fig. 7 (l) and (m). The current injected by the type-4 wind rises at the time of fault but is limited and balanced Fig. 8 (b) and (c). From Figs.7 and 8, we can conclude that the synchronous condenser improves the LVRT performance of the type-4 wind .

Further, we have evaluated the LVRT performance for the worst-case scenarios with the synchronous condenser in parallel. We study the system's dynamic performance by varying the time duration of the fault, as shown in Fig. 9. After the inception of a three-phase-to-ground fault at t = 2 s, the voltage drops to 0.15 p.u. Throughout the fault duration, the system injects 47 MVAr reactive power to the grid, as presented in Fig. 9(b). The settling time of the voltage and the fault duration have a positive correlation, as seen in Fig. 9(a). However, from Fig. 9, it is also evident that the system becomes unstable for fault duration greater than or equal to 4.25 s.

Fig. 10 presents the relative LVRT capability of the two systems. From Figs. 7, 9 and 10, we have shown that synchronous condenser improves the LVRT performance and increases the LVRT capability of the type-4 wind system.

TABLE I
TRANSMISSION LINE PARAMETERS

Parameter	Value
Grid Voltage ,Frequency	220 kV, 60 Hz
L_2, R_2	0.86123 mH, 0.1623 Ω
L_{31}, R_{31}	387.1 mH,14.5 Ω
L_{32}, R_{32}	192.76 mH, 7.2639 Ω
Transformer reactance (T_{conv}), X_{tconv}	0.0025 pu
Transformer reactance (T_2), X_{t2}	0.0025 pu
Transformer reactance (T_1), X_{t1}	0.1 pu
L_1, R_1	2.6 mH, 0.4870 Ω

III. CONCLUSION

This paper presents the type-4 wind plant's dynamic performance with the synchronous condenser during weak grid and faults. The synchronous condenser is integrated into the type-4 wind at the POI bus. We have demonstrated the integration benefits through a set of time-domain simulation case studies in the PSCAD/EMTDC software environment. The following are the conclusion of the case studies:

- When connected to the system, the synchronous condenser ensures the stable operation of type-4 wind plants by damping the 4 Hz oscillations.
- The type-4 wind system becomes unstable during a weak grid (SCR =1.96) while dispatching real power close to its rating. However, when operated with the synchronous condenser, the type-4 wind delivers rated power in a stable manner.
- The synchronous condenser injected reactive power close to its full capacity during unbalanced faults. Hence, it enhances the transient stability of the grid during faults.
- The cascaded reactive and ac voltage control of Type-4 supports LVRT operation for a maximum duration of 0.15 seconds. The synchronous condenser further extends the LVRT capability up to 4 seconds.

From these case studies, we have shown that the synchronous condenser enhances the steady-state and transient stability of the grid, damps low-frequency oscillation during weak grid and faults, increases power transmission capability during weak grid, and improves the LVRT performance and capability of Type-4.

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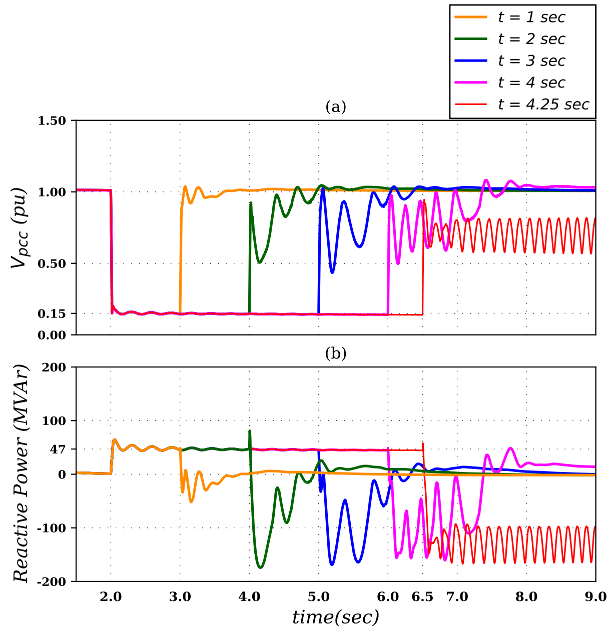

Fig. 9. LVRT capability of Type-4 with Synchronous condenser connected.

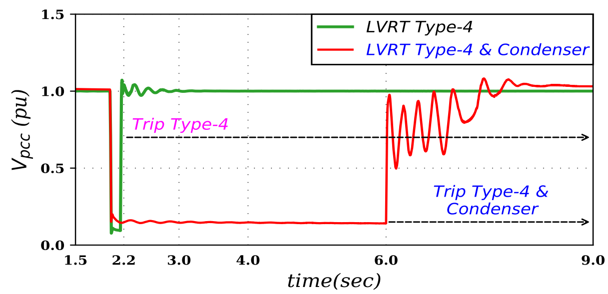

Fig. 10. LVRT capability of the system.

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