Comparison of Synchronous Condenser and STATCOM for Wind Farms in Weak Grids

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***Abstract*—When wind farms are integrated in weak grids, stability issues such as low-frequency oscillations arise. The grid industry used synchronous condensers instead of Static Synchronous Compensator (STATCOM) to improve stability. The goal of this paper is to compare performance of the two VAR devices on stability improvement for grid-interconnected wind farms. The topology structure and operation principle of the system with a wind farm, a synchronous condenser or a STATCOM are presented. The simulation is performed in the MATLAB/SimPowerSystems environment. Simulation results show that the synchronous condenser can effectively improve stability of the power system even without reactive power injection, while STATCOM only enhances system strength through reactive power compensation.**

***Index Terms*—reactive power compensation; synshronous condenser; STATCOM; wind; weak grid instability**

I. Introduction

When wind farms are integrated in weak grids, stability issues such as low-frequency oscillations arise. For example, Electric Reliability Council of Texas (ERCOT) observed oscillations at 4 Hz in a wind power plant under weak grid condition [1]. ERCOT installed two synchronous condensers (each $+175/-125$ MVA) at 345 kV level to offer reactive power support to Panhandle region and enhance the power system strength in April 2018. The estimated Panhandle export limit improvement is 250 MW [2]. The added synchronous condenser is one of contributions to increase the Panhandle Generic Transmission Constraint limit average to 3500 MW, a 13% increase of 3100 MW in 2017 [3].

Synchronous condenser is one type of VAR generators in power systems. Functionally, it can be seen as a synchronous machine without mechanic input. A synchronous condenser can either generate or absorb reactive power to/from the power grid and maintain the terminal voltage within limits. Similarly, STATCOM is also a type of VAR generators, though STATCOM relies on power electronic converter technology to generate reactive power only.

With both can provide reactive power support, it is understandable that both devices can help voltage stability. The goal of this paper, however, is to investigate which one can improve dynamic stability. Hence, we will investigate if the system shows stability improvement when a device is connected to the system while providing 0 reactive power.

The synchronous condenser is implemented with a Type-4 wind farm power system in this paper. Since the wind farm is interfaced to a grid through a grid-following converter, the systems may face high risk of instability when the grid is weak. Some studies about the stability issue of wind farm in weak grid have been reported in the literature [4], [5].

As comparison, a STATCOM is also installed. Fig. 1 presents the system topology. A STATCOM mainly consists of a solid-state voltage source and three-phase voltage source converts (VSCs). The reactive power regulation is realized by controlling the voltage at the point of interface.

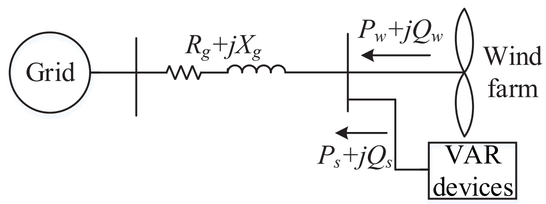


Fig. 1: Single-line diagram of the study system.

While a number of literature consider the synchronous condenser as a reactive power compensation to improve system performance [6]–[8], this paper is to demonstrate the synchronous condenser can enhance stability not only by reactive power injection but also by increasing the system strength. Comparison with STATCOM is also conducted. Simulation is performed in MATLAB/SimPowerSystems, and the results are presented and compared. The rest of this paper is organized as follows. The detailed Type-4 wind farm system model and its stability investigation are depicted in Section II. Section III introduces the structure and performance of STATCOM. Section IV presents the characteristics of a synchronous condenser without reactive power compensation and Section V concludes the paper.

II. Type-4 wind farm in weak grid

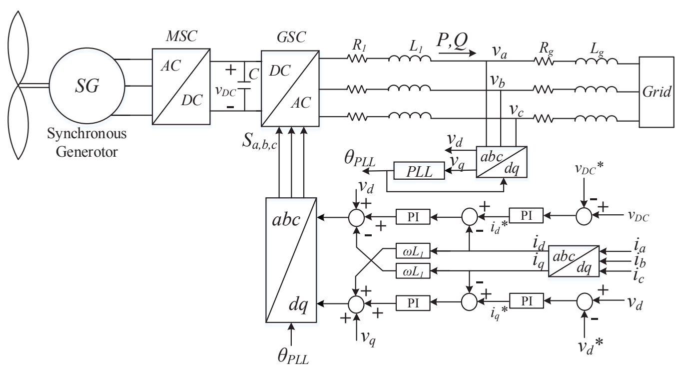
With the extensively investigating of Type-4 wind farm, the stability issues when connected with a weak grid are widely reported in the literature.

This section will illustrate the structure of a Type-4 wind farm system and its oscillation under a weak grid.

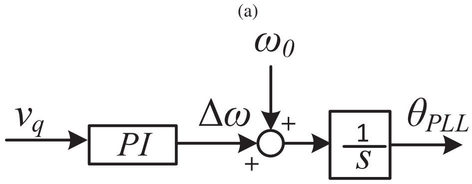
A. System model

A type-4 wind farm consists of a synchronous generator, wind turbine, DC-link capacitor, machine side converter (MSC) and grid side converter (GSC). The synchronous generator is connected to MSC, and a capacitor is placed between MSC and GSC. An inductor L_1 and capacitor C_1 are aggregated as a filter. After point of common coupling (PCC) bus, R_g and L_g represent the impedance and inductance of transmission line, respectively.

A vector control is used in GSC to regulate the DC-link voltage v_{dc} and PCC bus voltage v_{ac}. This control system includes two cascaded loops as an inner current loop and outer v_{dc}/v_{ac} loop. The inner-loop is decoupled into dq frame, where the d-axis current order is determined by outer-loop v_{dc} control and q-axis by v_{ac} control. Meanwhile, the outer-loop regulates v_{dc} and v_{ac} by comparing them with reference signals, which are represented by variables with asterisk (*). Both inner-loop and outer-loop use PI controller, the parameters are listed in TABLE I in Appendix. A diagram of type-4 wind farm with its control system is shown in Fig. 2.



(a)



(b)

Fig. 2: EMT testbed of a Type-4 wind farm in a weak grid. (a) Schematics of Type-4 wind farm and its control system. (b) Block diagram of PLL.

A phase-locked-loop (PLL) aligns the d axis with PCC voltage space vector and provides angle θ for abc to dq conversion. The PCC voltage is decoupled into v_d and v_q, and v_q is applied to the PLL. So the v_q is kept as zero and v_d has the same magnitude with $V_{\rm PCC}$. Then the wind farm power P and reactive power Q can be notated as $P = v_d i_d$ and $Q = -v_d i_q$. Since $-Q$ is proportional to i_q, and $V_{\rm PCC}$ and related to Q, the ac voltage control is a positive feedback control. Similarly, $v_{\rm dc}$ control can be referred to P control. In order to adjust $v_{\rm DC}$, we only need to change d-axis current i_d, and change i_q to adjust Q, separately. This is the principle of the vector control.

B. Simulation result

To investigate the dynamic performance of the wind farm, the X_g is given a step change from 0.2 pu at 5 second to emulates a parallel line tripping events. The PCC bus voltage $V_{\rm PCC}$ are displayed for different final values of X_g in Fig. 3. The dynamic responses are compared when X_g changes to 0.41 and 0.42. It can be observed that the system becomes unstable when X_g changes to 0.42 and keeps stable when X_g reaches to 0.41. So the marginal stable condition is $X_g = 0.41$ and oscillation frequency is about 9 Hz. Reference [9] demonstrates this kind of oscillation is caused by weak grid system.

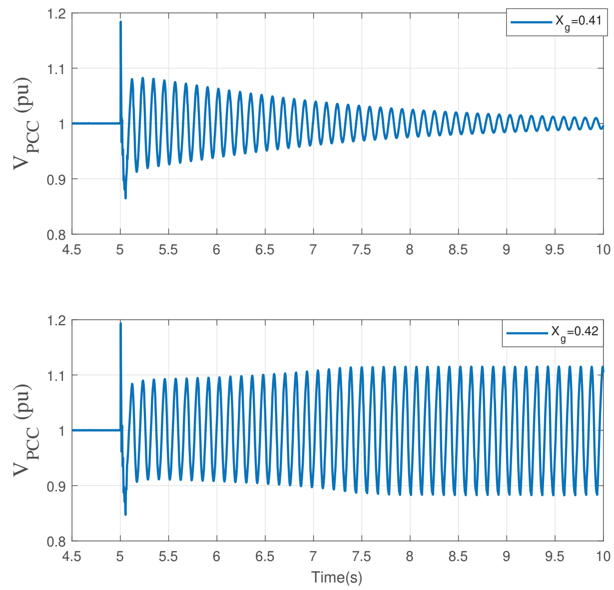


Fig. 3: PCC voltage of wind farm system.

III. STATCOM

STATCOMs have been widely used in modern power system to enhance the stability performance by providing reactive power compensation [10]. STATCOMs are also a hot topic in research area due to its advantages such as good characteristics at low voltage and fast response. A STATCOM consists of a three-phase GTO/IGBT voltage source converters (VSCs), step-down transformer with leakage reactance, DC capacitors and VSC controller. Fig. 4 shows a STATCOM connecting in PCC bus. The reactive power can be absorbed or generated at the its output terminal. Voltage difference across transformer leakage reactance determines the direction and amount of reactive power transferred between STATCOM and power system.

The transferred active power and reactive power transferred STATCOM can be derived as:

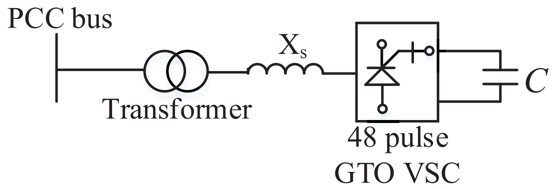


Fig. 4: STATCOM Model.

$$Q = \frac{|V_b|(|V_b| - |V_s|\cos\alpha)}{X_s} \quad (1)$$

$$P = |V_b||V_s|\frac{\sin\alpha}{X} \quad (2)$$

where V_b is PCC bus voltage, V_s is terminal voltage of STATCOM, X_s is the leakage reactance and α is voltage phase angle of V_b to V_s.

As (1) and (2) illustrate, it is necessary to ensure V_b and V_s be in-phase to realize reactive power control. And the STATCOM absorbs reactive power from system when its terminal voltage is lower than the system bus voltage. At this time, the STATCOM acts like a capacitor. In contrast, if the STATCOM voltage $|V_s|$ is higher than the system bus voltage, reactive power flows into the system, and the STATCOM acts like an inductor. There is no reactive power transfer if the two voltages are identical.

A. Operation structure

The VSC in the STATCOM is connected with transformers and injects or absorbs reactive power to the system through a line. The output voltage of VSCs are controlled by pulse width modulation (PWM). Since a simple VSC generates square voltage waveform, in order to minimize the distortion and harmonic to generate a nearly sinusoidal voltage in high power application, a 48-pulse VSC is used. The testbed of STATCOM model is developed based on the demo testbed in SimPowerSystems, which originates from [11].

The 48-pulse VSC is constructed by four three-level 12-pulse GTO-based converters and four zig-zag phase-shifting transformers. Four converters are connected in series to produce a 48-pulse voltage. The output voltages of converters are inputs of the the secondary windings of four transformers connected in Y or Δ. This kind of 48-pulse VSC is usually used in high-voltage application due to its low harmonics. Fig. 5 shows the schematics of 48-pulse VSC model.

The objectives of the VSC control are to regulate reative power and maintain a stable capacitor voltage. A controller is implemented as shown in Fig. 6. In this control, the outer ac three-phase voltage control provides the q-axis reference current, which is always in the same quadrature with the voltage to control reactive power. The feedback gain k in this loop is the current (or reactive power)/voltage droop gain. In this model, the rated power of STATCOM is 100 MVA and k is selected as 0.03 pu/MVA, then its terminal voltage varies from 0.97 pu to 1.03 pu when reactive power varies from 100 MVAr to -100 MVAr.

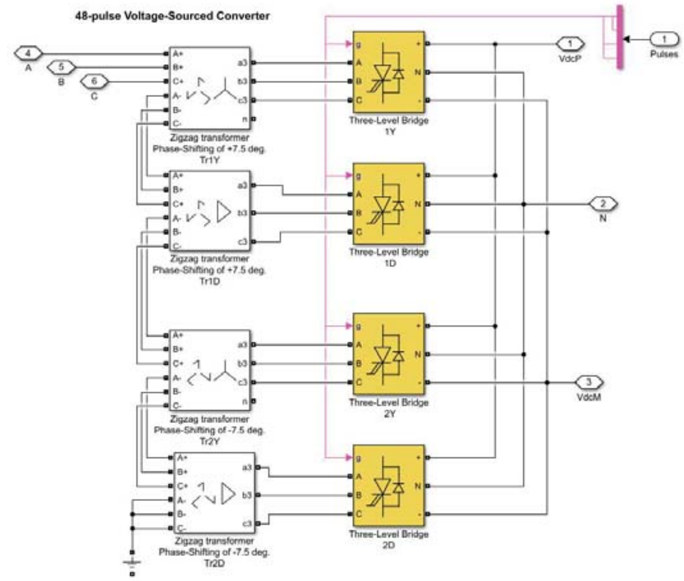


Fig. 5: Schematic diagram of 48-pulse VSC.

The outputs of the control loops are the phase shift angle α, pulse interval α_D and PLL output θ. The three variables are applied to a logic of pulse generation to regulate the VSC. This control algorithm is well explained in Ref [12]. The parameters of STATCOM and its control blocks are listed in TABLE II in Appendix.

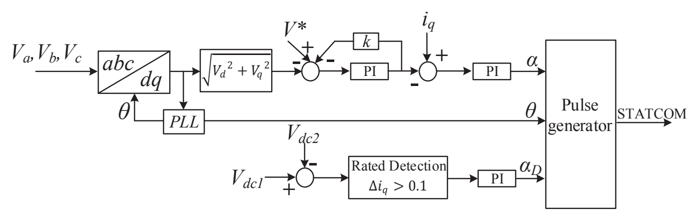


Fig. 6: Block diagram of STATCOM control.

B. Simulation results

Fig. 7-9 shows the dynamic responses of wind farm with a STATCOM. PCC voltage V_{PCC} and Q from STATCOM are presented for the disturbance X_g: 0.2 $\rightarrow$ 0.41 pu and 0.2 $\rightarrow$ 0.42 pu at 5 second. There is no reactive power generated or absorbed from STATCOM as Fig. 7 displayed. As the previous section presents, the wind farm marginal stable condition is $X_g = 0.41$. From Fig. 7 and 8, it is clear that the system collapses since STATCOM can't improve the stability of this system when X_g changes to 0.42 from 0.2 pu if there is no reactive power injection. It has the same performance with the system analyzed in Section II. Another case study is carried out when STATCOM compensates reactive power. Waveforms of Fig. 9 show the damped oscillation of V_{PCC} and Q around the steady-state point when X_g changes to 0.42 pu if STATCOM injects reactive power to the system for 0.75 pu. The results illustrate that the STATCOM enhances the performance of power system only through reactive power compensation.

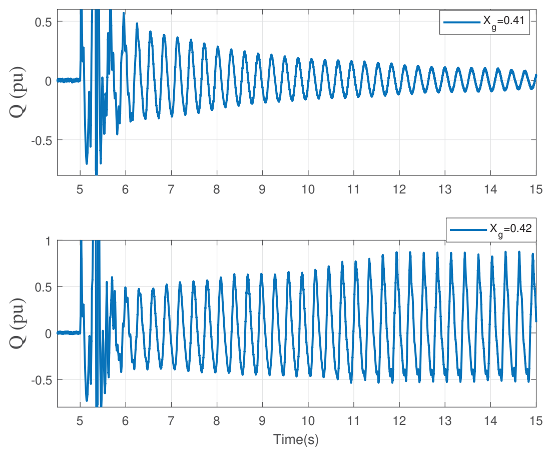


Fig. 7: Reactive power from STATCOM as X_g: 0.2→0.41 pu and 0.2→0.42 pu.

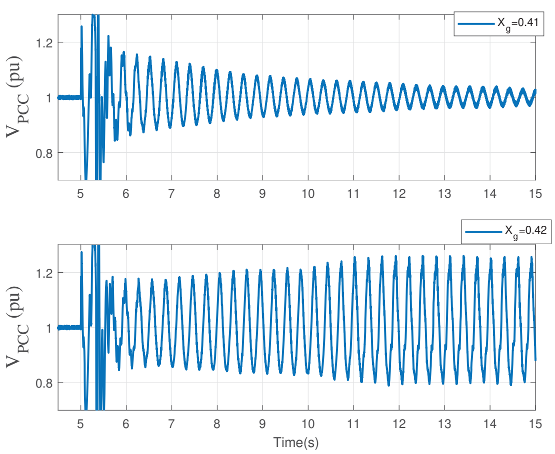


Fig. 8: PCC Voltage as X_g: 0.2→0.41 pu and 0.2→0.42 pu.

IV. Synchronous condenser

Over one hundred years ago, General Electric supplied the first synchronous condenser. Synchronous condensers play a more important role in modern grid. In this section, the structure, working principle, control system and simulation results are described.

A. Working principle

Synchronous condenser is a synchronous generator without mechanical input, so it provides reactive power support and additional short circuit power capacity. An excitation system is used to generates direct current for the synchronous motor field winding. It controls the field voltage and injects or absorbs reactive power to/from the system [13].

Excitation systems can be divided as DC and AC excitation system based on their power supply. The DC excitation is realized by a dc generator, and the dc current provided to the rotor of synchronous machine is through slip rings. AC type of excitation systems utilize a controlled or diode-based rectifier to convert an ac current to dc which is required by the generator field. IEEE has standardized the excitation system structures.

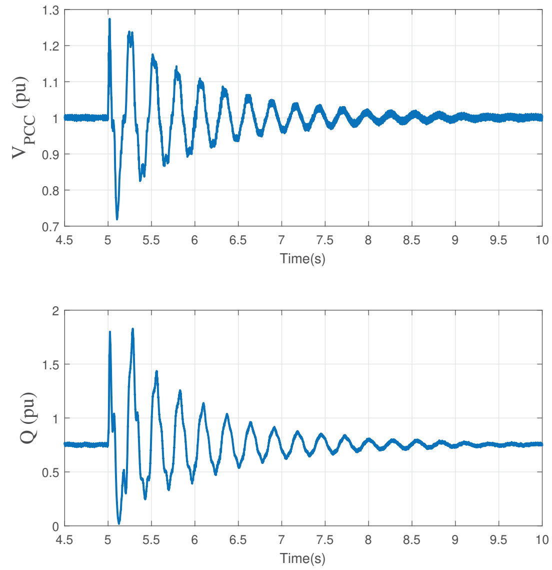


Fig. 9: PCC voltage and injected reactive power by STATCOM when X_g: 0.2→0.42 pu.

In this work, a DC excitation model is considered and shown in Fig. 10. The model is used to represent field controlled dc commutator exciters, where V_C is the motor terminal voltage, V_S is generated from power system stabilizer, V_{REF} is the reference signal and V_F is the feedback signal. At steady state, both V_S and V_F are zero, so only terminal voltage error is produced. Then the error is amplified by the main regulator. T_A and T_B represent the voltage regulator time constant.

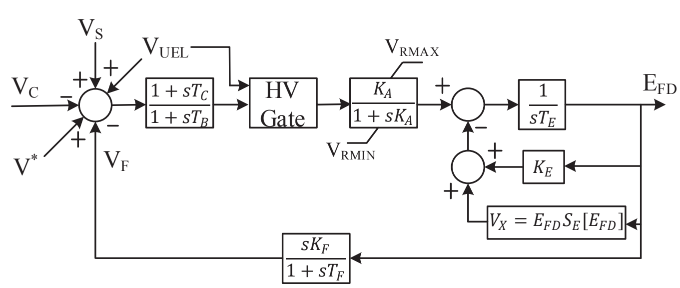


Fig. 10: Exciter model [14].

B. Simulation results

The synchronous condenser connected to the wind farm is shown in Fig. 1. The generated reactive power is controlled by an exciter. This synchronous condenser is connected to PCC bus via a 30 MVA Y-Δ connection transformer (22/220 kV).

The resulting PCC bus voltage and reactive power injections of synchronous condenser are displayed in Fig. 11. At 5 seconds, X_g is increased to 0.42 from 0.2 pu, the system shows a good damping even there is no reactive power injection. After a short-time oscillation, the system is back to the steady-state point. If the X_g continues to increase to 0.67 and 0.68 pu to emulate a weaker grid, we found that the marginal stable condition is $X_g = 0.67$ when reactive power keeps as 0, which clearly shows a better performance in this case of weak grid. Thus, the synchronous condenser can greatly improve the system even without reactive power compensation.

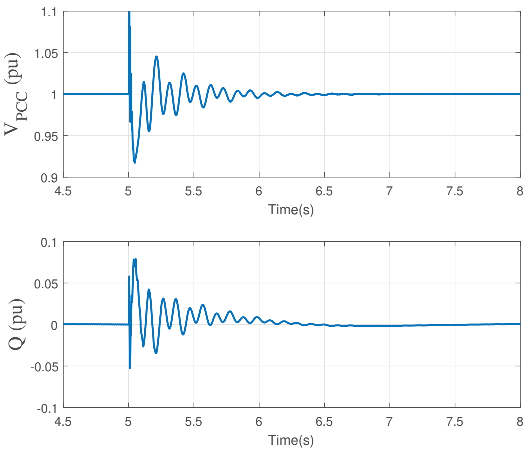


Fig. 11: PCC voltage and reactive power injected by synchronous condenser when X_g: 0.2→0.42 pu.

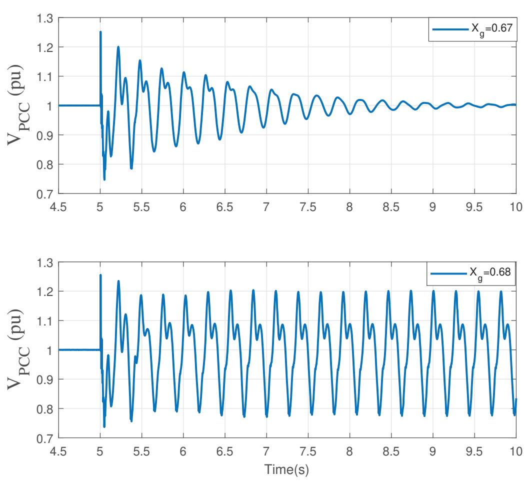


Fig. 12: PCC bus voltage when X_g: 0.2→0.67 pu and 0.2→0.68 pu.

V. Conclusions

In this paper, the dynamic response of Type-4 wind farm with STATCOM and synchronous condenser under a disturbance are presented. While the other literature mainly focus on the stability improvement by reactive power compensation, this paper shows that the synchronous condenser can enhance the performance of a weak grid even without any reactive power injection. As comparison, the STATCOM has cannot improve the system stability when no reactive reactive power transmitted.

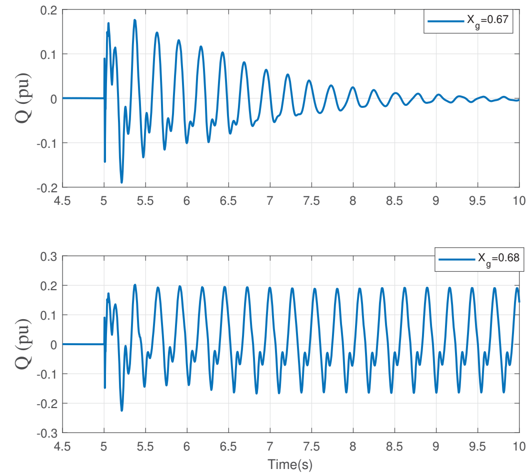


Fig. 13: Reactive power injected by synchronous condenser when X_g: 0.2→0.67 pu and 0.2→0.68 pu.

Appendix

TABLE I: Parameters of Type-4 wind farm

Parameters	Value (SI)
Rated Power	100 MW
Rated voltage	575 V
Nominal freq.	60 Hz
DC-link voltage	1100 V
L_1, R_1	0.06 mH, 0.45 $m\Omega$
C	90 mF
X_d, X'_d, X''_d	313 $m\Omega$, 71 $m\Omega$, 60.5 $m\Omega$
X_q, X''_q	114 $m\Omega$, 58.3 $m\Omega$
R_s, X_{ls}	1.44 $m\Omega$, 40.8 $m\Omega$
T'_{do}, T''_{do}	4.49 s, 0.0681 s
T''_q	0.0513 s
Inertia constant, pols	0.62, 2
Friction factors	0.01
Current PI controller	$0.4 + \frac{48}{s}$
DC voltage PI controller	$1 + \frac{100}{s}$
AC votlage PI controller	$0.25 + \frac{25}{s}$
PLL	$60 + \frac{4480}{s}$

TABLE II: Parameters of STATCOM

Parameters	Value (SI)
Rated Power	100 MW
Rated voltage	22 kV
Nominal freq.	60 Hz
DC capacitor	2000 μF
k	0.03
I_q PI controller	$5 + \frac{40}{s}$
voltage PI controller	$12 + \frac{30000}{s}$
DC voltage PI controller	$0.001 + \frac{0.01}{s}$
PLL	$60 + \frac{1400}{s}$

TABLE III: Parameters of synchronous condenser

Parameters	Value (SI)
Rated Power	20 MW
Rated voltage	22 kV
Nominal freq.	60 Hz
X_d, X_d', X_d''	654.4 $m\Omega$, 99 $m\Omega$, 79 $m\Omega$
X_q, X_q''	629.6 $m\Omega$, 79.2 $m\Omega$
R_s, X_{ls}	1.8 $m\Omega$, 55.4 $m\Omega$
T_{do}', T_{do}''	4.5 s, 0.04 s
T_q', T_q''	0.67 s, 0.09 s
Inertia constant, pols	0.6, 2
Friction factors	0.6
DC capacitor	2000 μF
T_C, T_B	1, 1
K_A	300
T_E, K_E	0.01, 2
K_F	0.01

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