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Exploring Dynamic P-Q Capability and Abnormal Operations Associated with PMSG Wind Turbines

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Abstract: With the proliferation of large-scale grid-connected wind farms, subsynchronous oscillation (SSO) incidents associated with Type-4 wind turbines (WTs) with a permanent magnet synchronous generator (PMSG) have occurred frequently. These incidents have caused severe reliability risks to the power grid. Conventionally, P-Q capability charts are utilized to ensure the safety operating region of a synchronous generator. However, a PMSG WT exhibits completely different and dynamic P-Q capability characteristics due to the difference in energy conversion technique and several critical factors related to the WT power converters. This paper presents a comprehensive dynamic P-Q capability study of a PMSG WT with sufficient and accurate considerations of the WT control and operation in the dq reference frame, its power converter constraints, and grid dynamics. Models of a PMSG WT are first developed based on its control principle in the dq reference frame. Then, algorithms for obtaining the P-Q capability charts of the WT are developed with the considerations of complete WT constraints in different aspects. The study analyzes the root cause of many abnormal operations of grid-connected PMSG WTs, reported in the literature, from the dynamic P-Q capability perspectives. The proposed study is verified via an electromagnetic transient (EMT) model of a grid-connected Type-4 WT.



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Keywords: permanent magnet synchronous generator (PMSG); P-Q capability charts; subsynchronous oscillation (SSO); dq vector control

1. Introduction

Wind power has been becoming a primary renewable energy source in the electric power systems to replace power generated from conventional synchronous generators (SGs). Traditionally, for the safe operation of a SG, the control capability of the generator is defined by “Capability Charts” or “Operating Charts” [1,2]. In the same way, the power industry has specified P-Q capability charts for Type-4 WTs to ensure a stable and reliable operation of the WTs [3–7]. North America Electric Reliability Corporation (NERC) provided safety guidelines including two capability charts (Figure 1a): (i) a nearly complete semi-circle capability and (ii) a clipped reactive capability at 0.95 p.u. [6,7]. The Electric Reliability Council of Texas (ERCOT) described a rectangular capability chart in [8]. The Sandia reported reactive power injection rules in [9] for wind and PV power plants. They provided D-shape, rectangular, and triangular capability charts for a nominal grid voltage condition.

1.1. Problem Explanation and Past Works

A PMSG WT is totally different from a traditional SG. Instead of operating at a fixed speed and being connected to the grid directly, a PMSG WT operates in a wide speed range from 0 rpm to over the synchronous speed of the WT generator and is connected

to the grid via a full-scale back-to-back ac/dc/ac voltage-source converter (VSC) [10], all of which would affect the operating characteristics of the WT. Thus, the PQ capability charts of a PMSG WT would be highly dynamic and completely distinct from those of a traditional SG. So far, no attempt has been made to investigate the dynamic P-Q capability of a PMSG WT considering these factors. In [11], the reactive power capability of PMSG WTs is discussed in terms of the modulation technique and rated current boundary of power converters; however, the generator characteristics and PWM voltage saturation limit of power converters are not addressed. The authors proposed a distributed demand response control of PMSG-based WTs in [12], which incorporates the reactive power sharing capability based on fixed P-Q capability charts. Therefore, the proposed framework of [12] only operates well in a nominal voltage condition. To operate PMSG-based WTs robustly in different grid situations, several control strategies are described in [13,14], which consider MPPT capability along with generator speed variations but ignore the P-Q capability of power converters. In [15], the authors proposed an approach to improve the operation and performance of Type-4 wind power plants by adding a synchronous condenser. However, adding extra reactive power from an outside source can only mitigate certain burdens for the PMSG WTs. In the long run, this strategy will fail to maintain the WT operation within its safety boundary under uncertain and variable real-life grid conditions. A comparison of existing works related to the PMSG WT P-Q capability, and the proposed model is provided in Table 1.

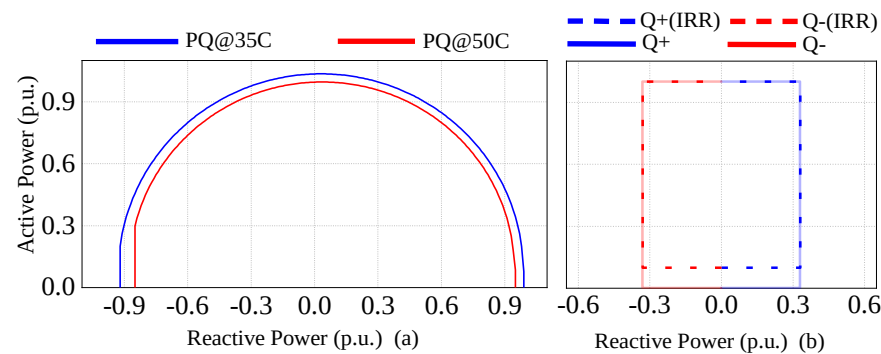


Figure 1. (a) P-Q capability charts provided by NERC [6] and (b) P-Q capability charts provided by ERCOT [8].

Table 1. Summary of existing works related to the PMSG WT P-Q capability found in the literature.

Refs.	Generator Characteristics	Controller Modulation Technique	MPPT Capability	Converter Rated Current Limit	Converter PWM Saturation Limit	Variable Grid Condition
[16]	X	✓	✓	✓	✓	X
[17]	X	X	X	✓	X	✓
[18]	X	X	X	✓	✓	X
[11]	X	✓	X	✓	X	X
[12]	X	X	✓	✓	X	✓
[19]	✓	X	X	✓	✓	X
[13,14]	✓	X	✓	X	X	✓
Proposed model	✓	✓	✓	✓	✓	✓

As a result, the electric utility grids have experienced numerous abnormal situations with the wind power plants [20–25]. From 2012 to 2014, the Guyuan wind farm in China recorded 58 times subsynchronous oscillation (SSO) phenomena that damaged the electric power facilities [20]. These oscillations started from the wind power plant and then extended to the power grid. In [21], ERCOT reported that thousands of WT generators

were tripped due to the severity of SSO events. In July 2015, frequent SSOs were captured through a wide-area measurement system (WAMS) of a direct-driven PMSG-based wind farm in Xinjiang, China [22], which tripped a large number of WT generators on the wind farm and caused unstable power system operation. Generator tripping in the wind farms has also occurred a significant number of times with regular capacitor switching by the electric utility company [23]. The existing research is still unable to properly explain the SSO phenomena and the unusual operations of PMSG WTs that have occurred in recent years.

1.2. Urgency and Importance of the Proposed Study

All the literature reviews and analyses shown in Section 1.1 indicate that it is important to conduct a detailed study on PMSG P-Q capability characteristics. Without such a study, one would be misled by many abnormal PMSG WT operation phenomena and unable to develop advanced PMSG control technology to overcome the challenges. A study on the P-Q capability characteristics of a Type-3 WT is conducted in [26]. However, a Type-4 WT has a structure that is completely different from that of a Type-3 WT. As a result, a detailed dynamic P-Q capability study of Type-4 PMSG WTs is presented in this paper by considering the MPPT capability of the WT generator, power converter constraints (such as PWM saturation limit and rated current boundary), and variable and uncertain operating conditions of the power grids. Overall, the results of this paper may guide the power community to identify the root cause of many abnormalities associated with the grid-connected PMSG WTs. The proposed study would also help legislators to improve the industry guidelines and introduce new control methods (e.g., a neural-network-based vector controller for a PMSG WT [27]) to get over the recent SSO incidents. The main contributions of this paper are as follows:

- In the model development, the paper emphasizes detailed characteristics of the combined PMSG WT generator and power converter in the dq reference frame.
- In the algorithm development, the paper emphasizes obtaining P-Q capability curves of a PMSG WT by considering different WT generator and power electronic converter constraints.
- It is found in this paper that a PMSG WT exhibits highly dynamic P-Q capability charts under variable WT speed and grid conditions.
- In the case studies, the paper reveals the root cause of abnormal operations associated with PMSG WTs and the significance of dynamic P-Q capability charts to understand irregular operations of Type-4 WTs and wind plants reported in the literature.

The remainder of this paper is organized in the following way. Section 2 explains briefly the key features of a PMSG WT and its MPPT control technique. The active and reactive power models of the PMSG WTs are developed in the dq reference frame in Section 3. Section 4 describes the algorithms to determine PMSG WT P-Q capability charts. Section 5 evaluates the PMSG dynamic P-Q capability characteristics. To verify the proposition, Section 6 builds a model for the EMT simulation of a PMSG WT. Section 7 shows several simulated case scenarios and discussions. Finally, Section 8 provides the concluding remarks and plans for the future study.

2. PMSG WT and Its Control

2.1. PMSG WT

A PMSG WT is made of three components: (i) a wind turbine, (ii) a PMSG, and (iii) two VSCs connected in a row (Figure 2). In the turbine, the blades extract wind power and transfer it to the PMSG. The PMSG converts wind energy (mechanical) into electrical energy. A frequency converter connects the PMSG stator windings to the power grid. The frequency converter is made of two VSCs: (i) machine side converter (MSC) and (ii) grid side converter (GSC). There is a dc voltage link between MSC and GSC.

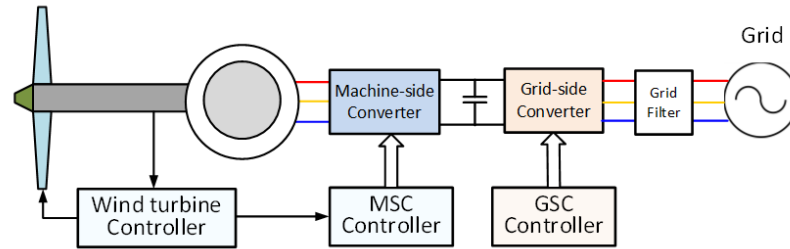


Figure 2. A PMSG wind turbine system.

2.2. MPPT Control

The mechanical power extracted by a WT from the wind is written by a popular cube law equation as in (1) [28]:

$$P_w = \frac{1}{2} \rho_{air} A_{blade} C_p(\beta, \lambda) v_w^3 \quad (1)$$

$$\lambda = R_{blade} \omega_m / v_w$$

where v_w , R_{blade} , ω_m , and A_{blade} represent the wind velocity in m/s, WT blades' radius in meters, WT blades' rotational speed in rad/s, and rotor blade swept area in m^2 , accordingly. ρ_{air} defines the air density in kg/m^3 . C_p is a constant to measure the performance efficiency of a WT. It is calculated from the tip-speed ratio (λ) and pitch angle (β) of rotor blades using aerodynamic laws and, therefore, may differ from one WT to another.

Figure 3 presents C_p vs. λ curves for different β values of a 2.5 MW PMSG WT [29]. For each β , there exists an optimal tip-speed ratio (λ_{opt}) for which C_p will obtain the largest value (i.e., extract maximum energy for that β). At a normal wind velocity, the rotor blades' angular speed is managed to an optimal magnitude ($\omega_{m,opt}$) via PMSG controls so that $\lambda_{opt} = R_{blade} \omega_{m,opt} / v_w$ while keeping β unchanged. At a high wind speed, the captured wind power exceeds the rated power of the machine. In that situation, a control signal is energized to limit the power generation beyond the rated value by regulating β .

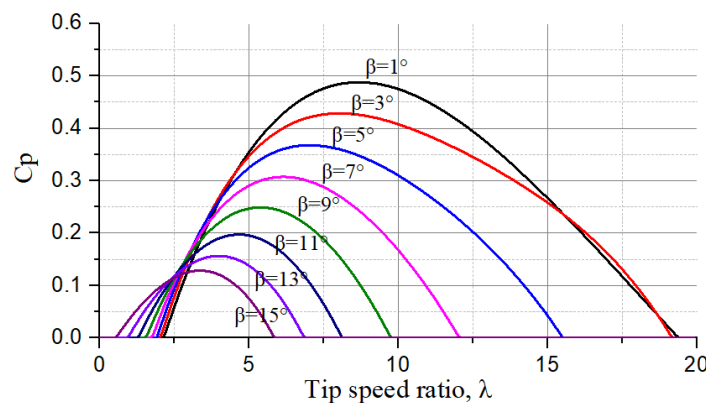


Figure 3. C_p vs. λ curves of a 2.5 MW WT.

2.3. PMSG WT Control

Typically, a PMSG WT has three control blocks: (i) a WT control block, (ii) a MSC control block, and (iii) a GSC control block (Figure 2). The WT control block generates a power/speed reference signal using the maximum power extraction principle. Following the speed/power reference, the MSC control block regulates the angular speed of PMSG and fulfills the maximum wind energy extraction goal. The GSC control block keeps the dc-link voltage constant and controls the reactive power generation/absorption of the PMSG. Typically, the rotor-flux orientation frame is used to design the MSC control block, and the PCC voltage orientation frame is used to design the GSC control block. Both

MSC and GSC control blocks can be considered to have two loops (Figure 4): (i) an inner current control loop and (ii) an outer active and/or reactive power control loop. Usually, the control loops are modeled in the dq reference frame. The power and current control loops generate d- and q-axis reference currents (i_d^* and i_q^*) and voltages ($v_{d_conv}^*$ and $v_{q_conv}^*$), respectively. According to the average model of a converter, the voltage (v_{dq_conv}) injected to the MSC/GSC ac side is expressed as in (2) [26]:

$$v_{dq_conv} = k_{PWM} \cdot v_{dq_conv}^* \quad (2)$$

where k_{PWM} is the ratio of the voltage at the MSC/GSC ac side to the PWM controlled voltage of the MSC/GSC.

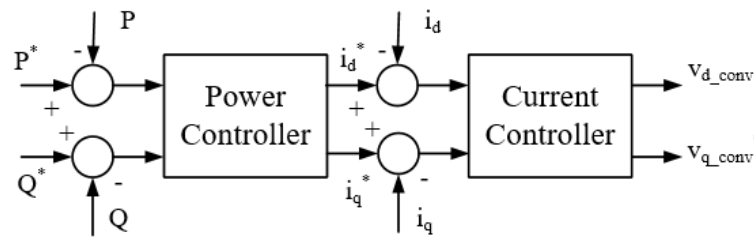


Figure 4. Design idea of MSC and GSC controllers of the PMSG WTs.

3. P-Q Model of a PMSG WT

To find a dynamic P-Q capability curve, the P-Q model of PMSG WTs must be developed, including the MSC and GSC control in the dq reference frame. In this paper, the P-Q capability analysis of the PMSG WTs includes the (i) MSC P-Q model, (ii) GSC P-Q model, and (iii) combined MSC and GSC P-Q model.

3.1. MSC P-Q Model

Using the generator sign, PMSG stator voltage, and flux linkage in the dq reference frame are obtained in the following way:

$$v_{s_dq} = -R_s i_{s_dq} - \frac{d}{dt} \psi_{s_dq} + j\omega_e \psi_{s_dq} \quad (3)$$

$$\psi_{s_dq} = (L_{ls} + L_m) i_{s_dq} + \psi_f \quad (4)$$

where R_s and L_{ls} are resistance and leakage inductance of the stator winding, L_m stands for the mutual inductance, ω_e is the electrical angular velocity of the PMSG, and ψ_f is the flux linkage generated by the permanent magnet (PM).

In (3), the stator dq voltage (v_{s_dq}) is defined as $v_{s_dq} = v_{sd} + jv_{sq}$, where v_{sd} and v_{sq} are d- and q-axis components. In the same way, the stator dq current (i_{s_dq}) and stator dq flux (ψ_{s_dq}) are defined.

For a steady-state condition, (5) is obtained from (3) and (4), in which I_{s_dq} and V_{s_dq} define the steady-state dq stator current and voltage, respectively:

$$V_{s_dq} = -R_s I_{s_dq} - j\omega_e (L_{ls} + L_m) I_{s_dq} + j\omega_e \psi_f \quad (5)$$

The active (P_s) and reactive (Q_s) power passing through the MSC to the dc-link can be written as in (6). Note that P_s is positive, i.e., generating power from the stator path to the MSC:

$$P_s + jQ_s = V_{s_dq} I_{s_dq}^* \quad (6)$$

3.2. GSC P-Q Model

Typically, the PMSG GSC is tied to the power grid through a LCL, LC, or L filter. The development of the GSC P-Q model having any of these three filtering configurations is

the same. In this study, we will focus on a GSC coupled to the grid through an L filter. In the L filtering scheme, L_f and R_f define the filter inductance and resistance, accordingly. Considering the generation sign principle, the voltage balance equation in the dq reference frame is expressed as in (7):

$$v_{GSC_dq} = R_f i_{dq} + L_f \frac{d}{dt} i_{dq} + j\omega_s L_f i_{dq} + v_{dq} \quad (7)$$

where ω_s is the grid voltage rotational frequency. v_{dq} and v_{GSC_dq} denote the d- and q-axis of the PCC voltage and GSC output voltage, accordingly. i_{dq} represents the d- and q-axis current components flowing through the GSC to the ac power grid.

For the steady-state condition, (7) can be written as (8), where I_{dq} , V_{dq} and V_{GSC_dq} define the steady-state dq components of the L -filter current, grid voltage, and GSC output voltage:

$$V_{GSC_dq} = R_f I_{dq} + j\omega_s L_f I_{dq} + V_{dq} \quad (8)$$

Following the PCC voltage orientation, the active and reactive powers coming from the GSC and injecting to the ac power grid are expressed as in (9):

$$P_{GSC} + jQ_{GSC} = V_{dq} I_{dq}^* = V_d I_d - jV_q I_q \quad (9)$$

3.3. Combined MSC and GSC P-Q Model

The active power transferred to the MSC will be eventually fed to the power grid via the GSC. However, the reactive power transferred to the grid includes just the GSC reactive power. Therefore, the aggregated P-Q model of MSC and GSC can be written as follows:

$$\begin{aligned} P_{PMSG} &= P_{GSC} = P_s \\ Q_{PMSG} &= Q_{GSC} \end{aligned} \quad (10)$$

4. Determine PMSG PQ Capability Charts

Primarily, a PMSG WT operation depends on the following limiting factors: (i) MSC current/power ratings, (ii) MSC PWM saturation constraint, (iii) GSC current/power ratings, and (iv) GSC PWM saturation boundary. To obtain PMSG P-Q capability charts, the above limiting factors should be kept in proper consideration. In the existing PMSG control design (Figure 4), the reference active and reactive power signals (P^* and Q^*) sent to the MSC or GSC control block should not cause the converters to operate over these limits.

4.1. Determine the MSC P-Q Capability Chart

Let us consider that S_{s_rated} is the rated apparent power of the PMSG stator. Therefore, the reference P_{MSC}^* and Q_{MSC}^* commands sent to the MSC control block should follow the below equation:

$$\sqrt{(P_{MSC}^*)^2 + (Q_{MSC}^*)^2} \leq S_{s_rated} \quad (11)$$

where P_{MSC}^* is positive (i.e., generating). Q_{MSC}^* would be either positive or negative.

However, (11) is not appropriate when the system does not operate under the nominal condition. For example, in a real-life situation, the dc-link voltage may drop significantly when the wind speed declines sharply. In that case, the MSC P-Q capability found by (11) would cause a higher current compared to the nominal current ratings. As MSC is very sensitive to current, it is important to use (12) instead of (11) for determining the MSC P-Q capability curves:

$$\begin{aligned} \sqrt{(I_{d_MSC}^*)^2 + (I_{q_MSC}^*)^2} &\leq I_{MSC_rated} \\ \sqrt{(I_{sd}^*)^2 + (I_{sq}^*)^2} &\leq I_{sdq_rated} \end{aligned} \quad (12)$$

Considering the PWM saturation boundary, the d- and q-axis control voltages of MSC fed to the PMSG stator circuit would follow the equation below:

$$\begin{aligned}\sqrt{(v_{d_MSC})^2 + (v_{q_MSC})^2} &\leq V_{dq_MSC_max} \\ \sqrt{(v_{sd}^*)^2 + (v_{sq}^*)^2} &\leq V_{sdq_max}\end{aligned}\quad (13)$$

where $V_{dq_MSC_max}$ is calculated by $V_{dc}/\sqrt{2}$ for the space vector PWM (SVPWM) method. For sinusoidal PWM (SPWM) technique, $V_{dq_MSC_max}$ can be expressed by $\sqrt{3}V_{dc}/2\sqrt{2}$.

Therefore, a flow chart to find the MSC P-Q capability together with the WT MPPT characteristics for wind power extraction is developed in Figure 5 based on both the rated current limit (12) and PWM saturation constraint (13). The flowchart has four major blocks. Block-1 computes the MSC P-Q capability based on the MSC current ratings only. For each condition, the stator voltage (V_{s_dq}) is kept in the record. Block-2 finds V_{s_dq} based on the PWM saturation boundary only. The WT MPPT power for pitch angle β of 1 degree is calculated in Block-3. In Block-4, V_{s_dq} recorded in Block-1 is reevaluated according to (13) to obtain the allowable stator voltage area. Then, the MSC P-Q capability chart is redetermined. The variable speed of the PMSG is defined by ω_e in the flowchart.

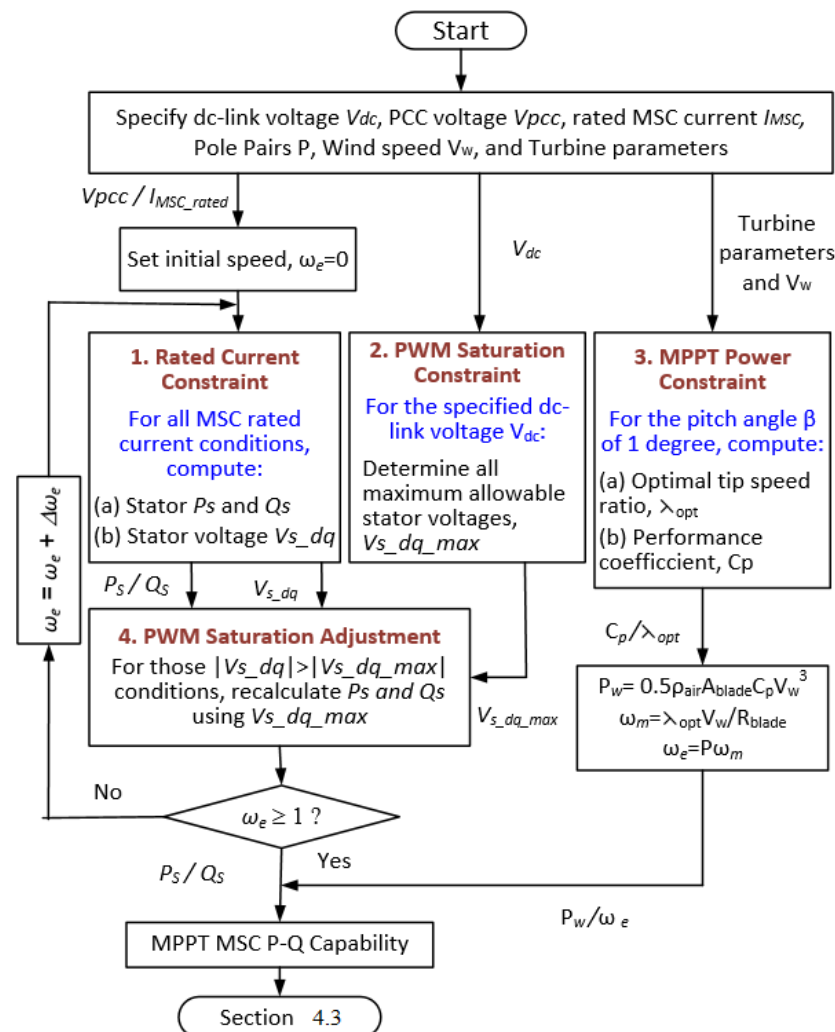


Figure 5. A flowchart for finding the PMSG P-Q capabilities based on the MSC PWM saturation and rated current limits.

4.2. Determine the GSC P-Q Capability Chart

Alike the MSC, PWM saturation and rated current limits should be considered to find the GSC P-Q capability charts. The reference current signals sent to the GSC control block have to meet the below equation:

$$\sqrt{(I_{d_GSC}^*)^2 + (I_{q_GSC}^*)^2} \leq I_{GSC_rated} \quad (14)$$

Following the PWM saturation boundary, the d- and q-axis control voltages of the GSC fed to the power grid should satisfy the below equation:

$$\sqrt{V_{d_GSC}^2 + V_{q_GSC}^2} \leq V_{dq_GSC_max} \quad (15)$$

where $V_{dq_GSC_max}$ is $V_{dc} / \sqrt{2}$ for SVPWM and $\sqrt{3}V_{dc} / (2\sqrt{2})$ for SPWM.

Considering both the PWM saturation and rated current constraints, a flow chart is developed in Figure 6 to find the GSC P-Q capability chart. The flowchart has three major blocks. The first two blocks (Block-1 and -2) compute the GSC P-Q capability based on the rated current and GSC PWM saturation limits separately. The computation could be simultaneous. Block-3 calculates the final GSC P-Q capability from the common areas of the previous two blocks.

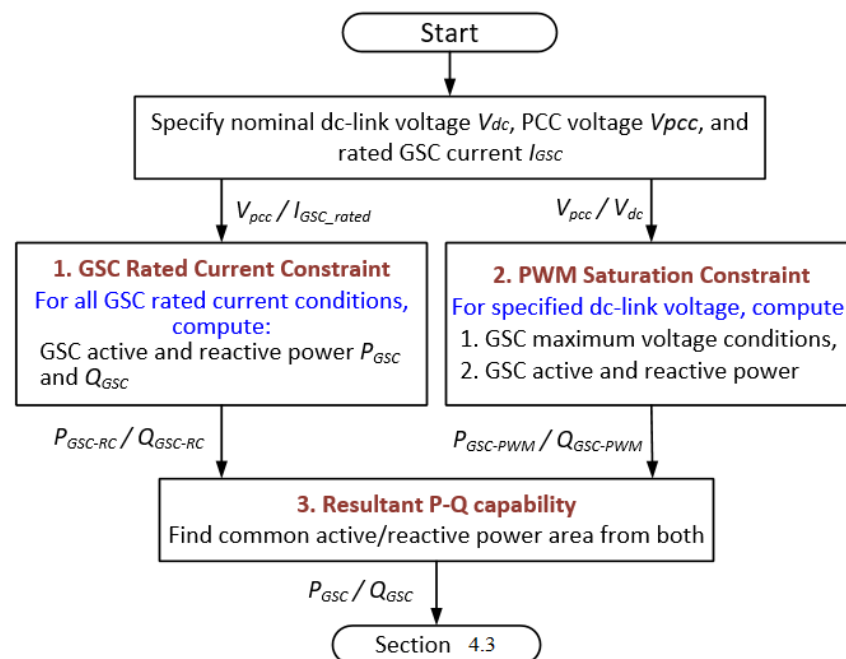


Figure 6. A flowchart for finding PMSG P-Q capabilities based on the GSC PWM saturation and rated current limits.

4.3. Determine PMSG WT P-Q Capability Chart

According to Figure 2, both the MSC and GSC P-Q capability must be considered for determining the overall PMSG P-Q capability chart. Neglecting the converter power loss, the active power transferred to the ac power grid via the GSC equals the active power transferred through the stator, i.e., $P_{PMSG} = P_{GSC} = P_s$. The reactive power transferred to the grid depends only on the reactive power generated/absorbed by the GSC that can be found from Figure 6, i.e., $Q_{PMSG} = Q_{GSC}$. Figure 7 shows a flowchart to obtain the overall PMSG WT P-Q capability curves.

In summary, MSC P-Q capability charts are determined first through Block-1 and Block-2 in Figure 5 with the MSC current constraint and PWM saturation limit, accordingly. Then, the MSC P-Q capability charts are reevaluated to see whether or not the obtained

results violate any limits (rated current/PWM saturation constraint) through Block-3 in Figure 5. If so, those results should not be included in the total P-Q capability chart. Next, the GSC P-Q capability charts are determined through Figure 6 with the GSC current and PWM saturation constraints. Finally, for the total P-Q capability chart of the PMSG WT, the active power is determined via the MSC/GSC active power and the reactive power is determined through the GSC reactive power (Figure 7).

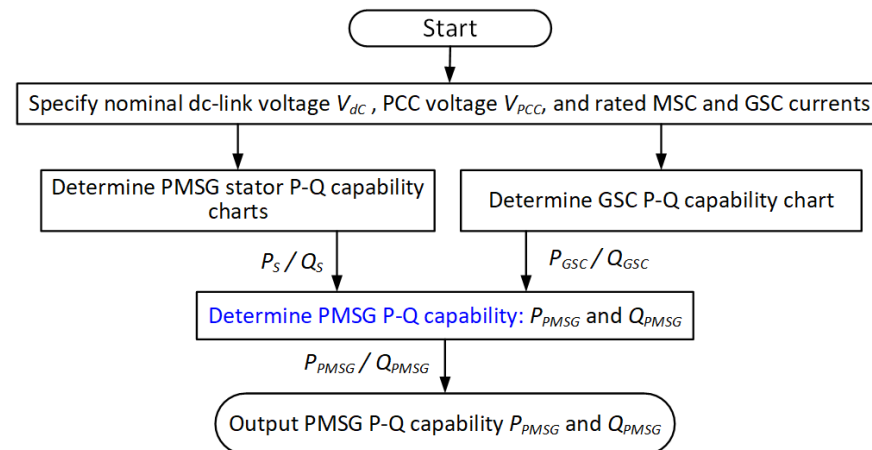


Figure 7. A flowchart for obtaining PMSG P-Q capability curves based on the MSC and GSC PWM saturation and rated current limits, where PMSG stator P-Q capability charts are determined based on Figure 5 and GSC P-Q capability chart is determined based on Figure 6.

5. Analyzing Dynamic P-Q Capability Charts

A PMSG WT is modeled considering the specifications given in Table 2 [30] to analyze the dynamic P-Q capability chart. In this study, all P-Q capability charts are shown per unit. PCC line voltage and nominal PMSG power are considered the base voltage and base power in the per unit calculation.

Table 2. Simulation parameters of a PMSG WT.

Parameter	Value
Nominal power	2.0 MVA
DC-link voltage	1400 V
PCC line voltage	690 V (rms)
Stator winding resistance	0.0039 p.u.
d-axis synchronous inductance	0.4538 p.u.
q-axis synchronous inductance	0.4538 p.u.
Rated rotor flux linkage	0.896 p.u.
Rated rotor speed	22.5 rpm
Number of pole pairs	26
Filter inductance	0.2 mH
Filter resistance	0.003 Ω

5.1. Analyzing P-Q Capability for the Nominal Case

The PCC voltage is 1 p.u. for the nominal case. Considering 1400 V as the voltage at dc-link and SPWM as the converters' modulation technique, the maximum stator voltage ($V_{s_dq_max}$) would be $\sqrt{3}V_{dc} / (2\sqrt{2}V_{base}) = 1.2425$ p.u. According to the flowcharts described in Section 4, the P-Q capability charts of the MSC, GSC, and PMSG WT MPPT are calculated and presented in Figure 8. To observe the speed variation effect in the PMSG operation, all P-Q capability charts are plotted in three-dimensional planes. From Figure 8, the below remarks are obtained.

- The MPPT curves are within the MSC rated current P-Q capability area (Figure 8a). This indicates that the power extracted by the WT can be transferred fully through the MSC from the rated current perspective.
- At zero speed, the P-Q capability region of MSC is shown by the smallest circle. Gradually, the capability area increases as the WT rotating speed increases (Figure 8a).
- The P-Q capability region of GSC (yellow) is encompassed by the area of the GSC capability considering both PWM saturation and rated current constraints (Figure 8b).
- For a higher wind speed, a high stator voltage is required to convert wind energy until crossing the PWM saturation boundary (Figure 8c).
- At a high wind speed, active power transfer through the MSC is limited for the PWM saturation boundary. For example, the P-Q demand ($P = 0.85$ p.u., $Q = -2.78$ p.u.) at $\omega_e = 2$ p.u. in Figure 8d is allowable to pass through MSC for rated current constraint but limited for the PWM saturation boundary.

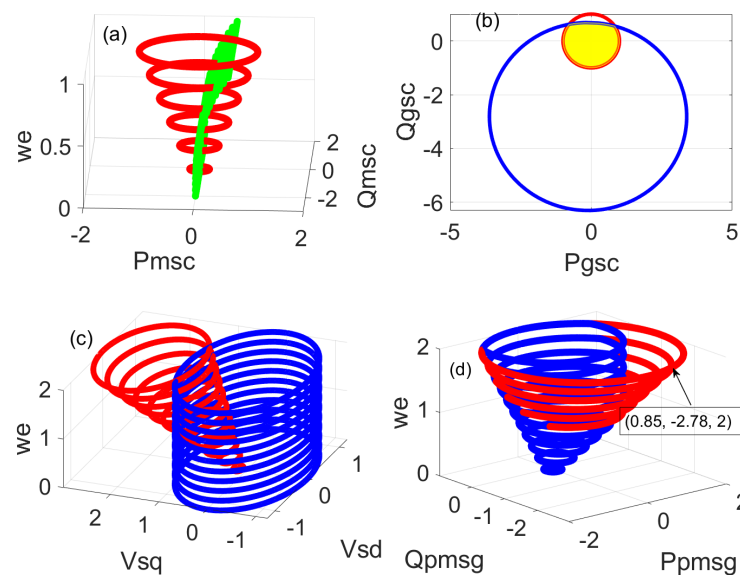


Figure 8. PMSG P-Q capability curves at the nominal operating case: (a) MPPT curves (green) and MSC P-Q capability (red) for the MSC rated current constraint only, (b) GSC P-Q capability for the GSC PWM saturation (blue) and rated current (red) limits, (c) stator voltage for the MSC rated current (red) and PWM saturation (blue) limits, (d) MSC P-Q capability for the PWM saturation (blue) and rated current (red) limits.

5.2. Analyzing P-Q Capability for Different PM Materials

A PMSG usually uses rare-earth permanent magnets for the low speed and high torque requirement of WT applications. However, rare-earth PMs have insecurities and cost risks. Therefore, rare-earth-free ferrite PMs are gaining popularity in PMSG WT applications. To understand how different PM materials impact the PMSG P-Q capability charts, an analysis is conducted with ferrite PMs ($\phi_f = 0.298$ p.u.) (Figure 9) and compared with the results of the rare-earth PMs shown in Figure 8. From the figures, the following remarks are obtained:

- Low flux linkage of the ferrite PMSG shrinks the MSC rated current P-Q capability charts, while high flux linkage of rare-earth PMSG enlarges the circles (Figures 8a and 9a).
- The active power extracted from the ferrite PMSG WT cannot be transferred fully through the MSC due to the smaller MSC P-Q capability region (Figure 9a).
- For the MSC, a larger speed range is allowable for the ferrite PMSG energy conversion until the MSC PWM saturation boundary is satisfied (Figures 8c and 9b).

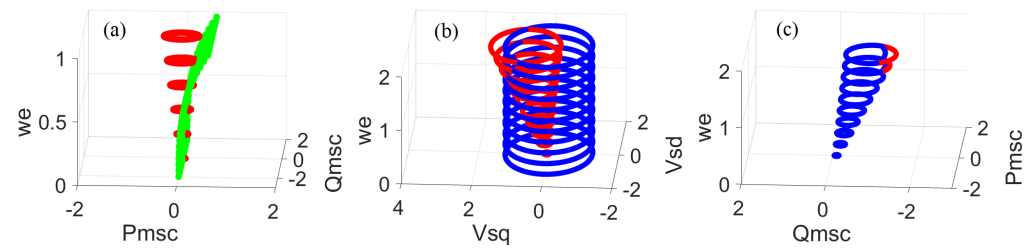


Figure 9. PMSG P-Q capability curves for the ferrite PMs (SPWM). (a) MPPT curves (green) and MSC P-Q capability (red) for the MSC rated current constraint only, (b) stator voltage for the MSC rated current (red) and PWM saturation (blue) limits, (c) MSC P-Q capability for the PWM saturation (blue) and rated current (red) limits.

5.3. Analyzing P-Q Capability for Different Pole Pairs of PMSG

There are several advantages to having a large number of poles in a PMSG WT, e.g., no need for a gearbox in wind power MPPT. To understand the impact of pole pairs on the PMSG P-Q capability charts, a study is performed using a PMSG with 12 and 48 pole pairs, while the rest of the parameters are the same as those shown in Table 2. The resultant charts are shown in Figure 10. From the figure, the following remarks are obtained:

- High pole machines produce more flux compared to low pole machines that enlarge the MSC P-Q capability charts and allow to transfer more extracted energy through the MSC (Figure 10a,d).
- For the MSC, a smaller speed range is allowable for the high pole PMSG energy conversion until crossing the MSC PWM saturation boundary (Figure 10b,e).
- The active power extracted from the high pole PMSG WT cannot be transferred fully through the MSC due to the PWM saturation constraint (Figure 10c,f). For example, the P-Q demand ($P = 1.13$ p.u., $Q = -4.8$ p.u.) at $\omega_e = 1.8$ p.u. in Figure 10f is allowable to pass through MSC for the rated current constraint but limited for the PWM saturation boundary.

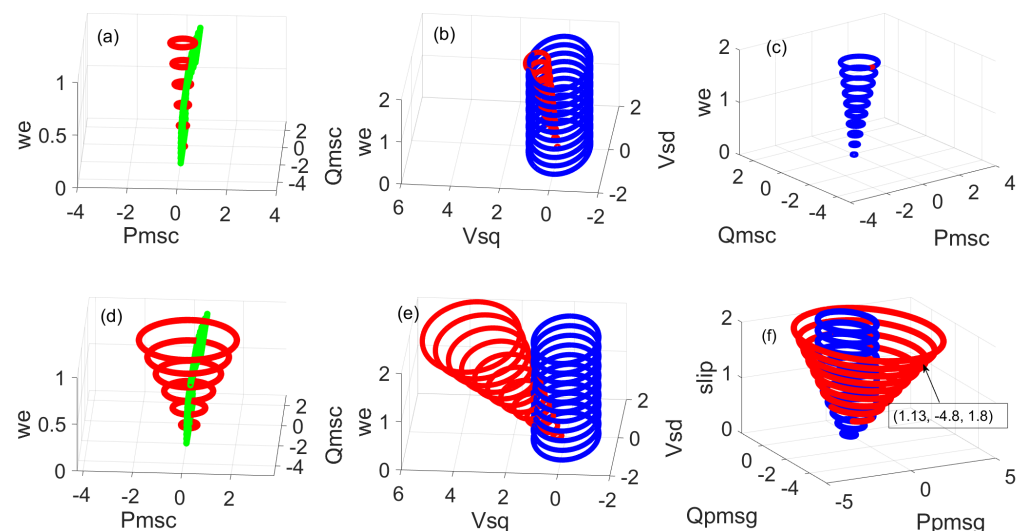


Figure 10. PMSG P-Q capability area for different pole pairs (SPWM): (a–c)— $P = 12$; (d–f)— $P = 48$.

5.4. Analyzing P-Q Capability for Different PWM Techniques of Power Electronic Converters

To understand the impact of different PWM techniques on the PMSG P-Q capability charts, a study is conducted using SVPWM-controlled MSC and GSC. The resultant charts are shown in Figure 11 and compared with Figure 8. From the figures, the following remarks are obtained:

- For the MSC, the SVPWM technique allows increasing the PWM saturation boundary more than SPWM (Figures 8a and 11a). Therefore, this will benefit the wind power MPPT to operate over a wider speed range until the MSC PWM saturation constraint is violated.
- For the same speed, more energy can be transferred through the MSC due to the larger PWM saturation boundary of the SVPWM technique (Figures 8d and 11b).
- Under the PWM saturation limit, the P-Q capability region of GSC is larger in the SVPWM technique compared to SPWM (Figures 8b and 11c). Therefore, the resultant GSC P-Q capability curve is bigger in the SVPWM case, which allows transferring more active and reactive powers to the ac grid via the GSC.

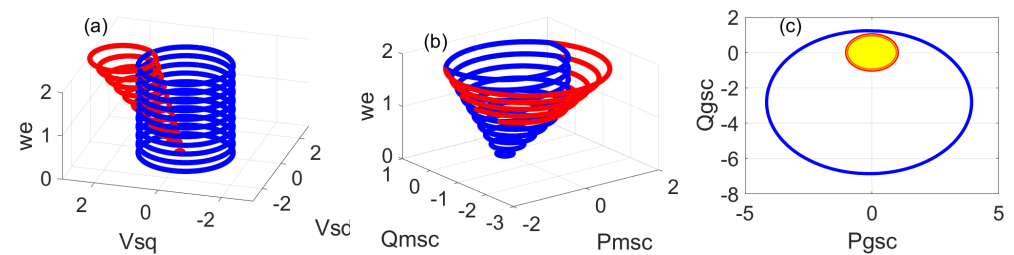


Figure 11. PMSG P-Q capability areas under SVPWM technique of power electronic converters, (a) stator voltage for the MSC rated current (red) and PWM saturation (blue) limits, (b) MSC P-Q capability for the PWM saturation (blue) and rated current (red) limits, (c) GSC P-Q capability for the GSC PWM saturation (blue) and rated current (red) limits.

5.5. Analyzing P-Q Capability for Variable Voltages at dc-Link

A study is performed considering two different dc-link voltages: (i) 850 V and (ii) 2250 V. Figure 12 shows the simulated results. From Figure 12, the following remarks are obtained:

- For the MSC, the higher the dc-link voltage, the larger the speed range that would be allowable to convert wind energy until crossing the MSC PWM saturation boundary (Figure 12a,d).
- For the same speed, the higher the dc-link voltage, the more energy that can be transferred through the MSC (Figure 12b,e).
- For the GSC, a low voltage at the dc-link shrinks the P-Q capability region, whereas a higher dc-link voltage expands the area (Figure 12c,f). For example, the P-Q demand ($P = 1.1$ p.u., $Q = -0.25$ p.u.) at $V_{dc} = 850$ V in Figure 12c is allowable to pass through GSC for the rated current constraint but limited for the PWM saturation boundary.

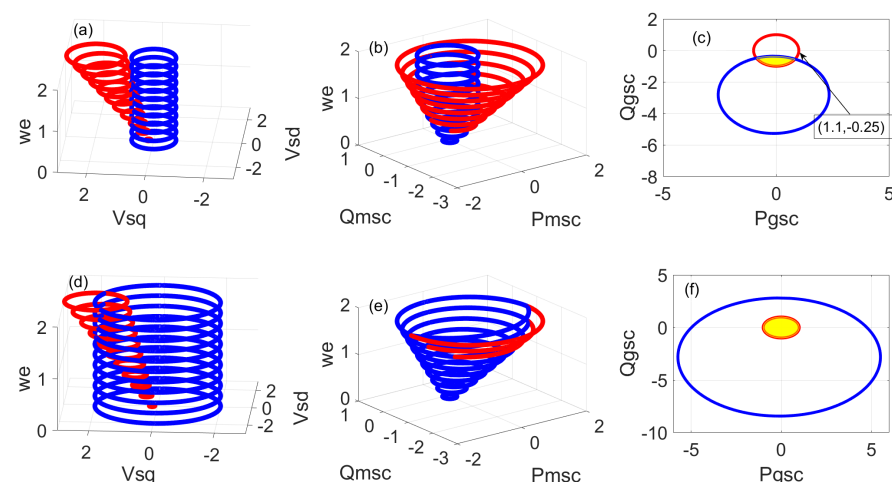


Figure 12. PMSG P-Q capability curves for variable voltages at dc-link (SPWM): (a–c)— $V_{dc} = 850$ V; (d–f)— $V_{dc} = 2250$ V.

5.6. Analyzing P-Q Capability for Variable Voltages at the PCC

The PCC voltage cannot remain the same in real-life situations. It may increase/decrease due to a number of reasons, such as load variation, and fault occurrence in the ac power grid. When a PMSG injects active and reactive powers into the grid, the PCC voltage may change too. To analyze the effect of the PCC voltage on the PMSG P-Q capability chart, a study is performed with two PCC voltages: (i) 0.5 p.u., and (ii) 1.5 p.u. The results are shown in Figure 13. From the figure, the following remarks are obtained:

- Change in the PCC voltage cannot affect the MSC P-Q capability charts (Figure 13a,b,d,e).
- For the GSC, a low PCC voltage shrinks P-Q capability curves under both PWM saturation and rated current constraints. On the other hand, a higher PCC voltage expands the curves. However, the curves move apart from one another (Figure 13c,f). Therefore, the resultant GSC P-Q capability area decreases.

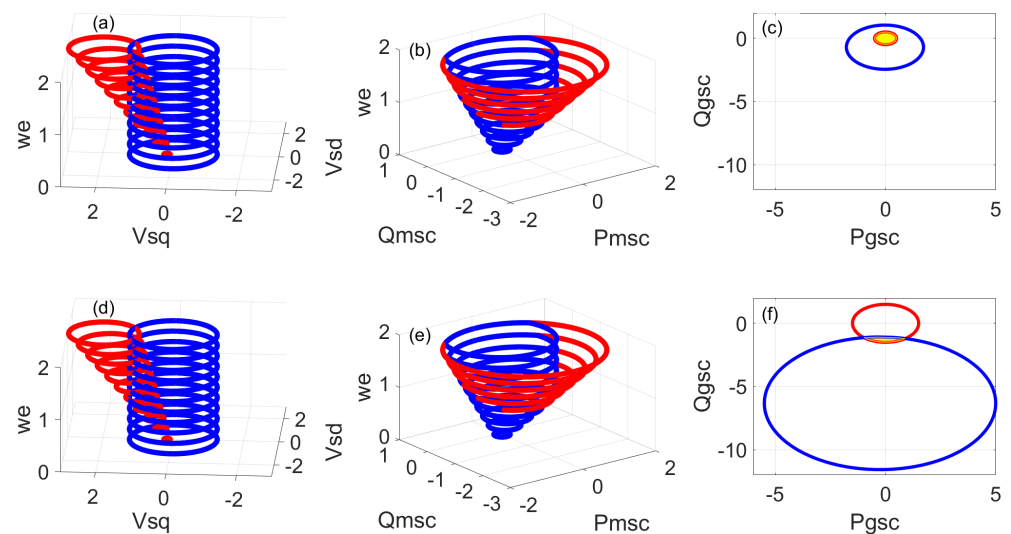


Figure 13. PMSG P-Q capability curves for variable voltages at the PCC (SPWM): (a–c)— $V_{PCC} = 0.5$ p.u.; (d–f)— $V_{PCC} = 1.5$ p.u.

6. EMT Simulation Model for Analyzing Operation of PMSG WTs

To understand the significance of dynamic P-Q capability for secure and reliable power system operation, an EMT model with control of a grid-connected wind power plant containing Type-4 PMSG WTs is built using MATLAB/Simulink (Figure 14). In the model, Table 2 parameters are used for the PMSG WT and the plant model is an aggregated plant model with N Type-4 WTs. If $N = 1$, the model reduces to a grid-connected Type-4 WT EMT model.

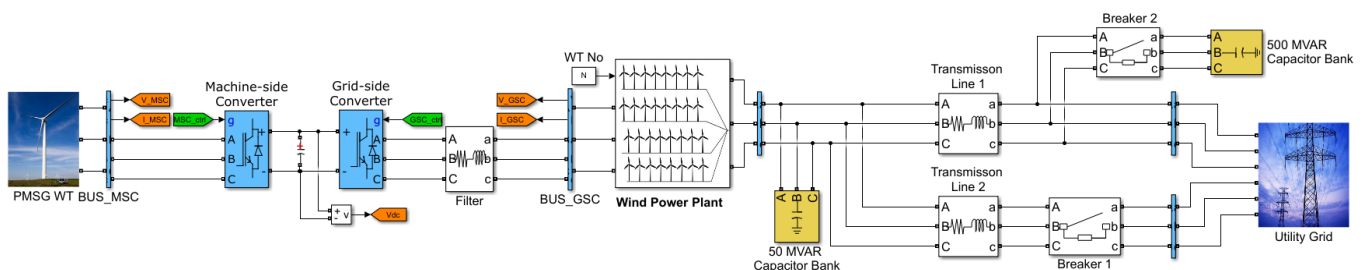


Figure 14. EMT model and control of a PMSG WT built in MATLAB/Simulink software.

6.1. GSC Controller of a PMSG WT

Figure 15 presents the existing GSC control method used in the PMSG industry. The standard vector control approach is used to control the GSC. The GSC controller has a nested-loop configuration. It consists of an inner current control loop and an outer control

loop. The reference signal of the reactive power in the outer loop is limited by the nominal P-Q capability chart. For this purpose, a reactive power limitation block is modeled. The block calculates the allowable reactive power generation/absorption limit (Q_{max} and Q_{min}) from the active power reference signal P_{PCC}^* shown in Figure 16 and the P-Q capability area specified by the ERCOT or NERC.

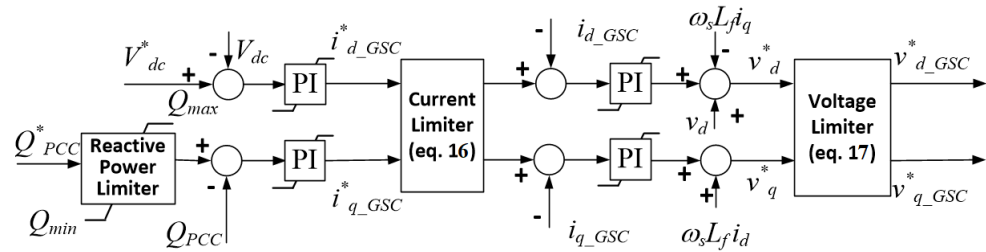


Figure 15. Standard vector control diagram modeled in the GSC.

Another block is modeled to limit the d- and q-axis reference currents coming from the outer control loop. GSC can generate both active and reactive powers separately until the apparent power of the converter is within the limit. Once the apparent power reaches its limit or the condition $\sqrt{I_{d_GSC}^{*2} + I_{q_GSC}^{*2}} \geq I_{dq_GSC_rated}$ satisfies, GSC will emphasize active power generation and limit reference currents presented to the inner current controller following the active power priority control mode as shown by

$$\begin{aligned} i_{d_GSC}^* &\leftarrow i_{d_GSC}^* \\ i_{q_GSC}^* &\leftarrow \text{sign}(i_{q_GSC}^*) \sqrt{(I_{dq_GSC_rated})^2 - (i_{d_GSC}^*)^2} \end{aligned} \quad (16)$$

To operate the GSC within the PWM saturation boundary, a block is modeled to adjust the voltages coming from the inner control loop as follows:

$$\begin{aligned} v_{d_GSC}^* &\leftarrow V_{dq_GSC_max} \cdot \cos(\angle v_{dq_GSC}^*) \\ v_{q_GSC}^* &\leftarrow V_{dq_GSC_max} \cdot \sin(\angle v_{dq_GSC}^*) \end{aligned} \quad (17)$$

6.2. MSC Controller of the PMSG WT

Figure 16 presents the traditional MSC control method used in the PMSG industry. The standard vector control technique in the rotor-flux orientation plane is built into the MSC controller. Like GSC, it also has a faster inner current control loop and a slower outer power/speed control loop. A $P - \omega$ lookup table is modeled to extract maximum energy from the wind. The table generates a speed reference for the outer-loop speed controller. Based on the reference signal, the speed controller controls the generator angular speed and extracts maximum wind energy.

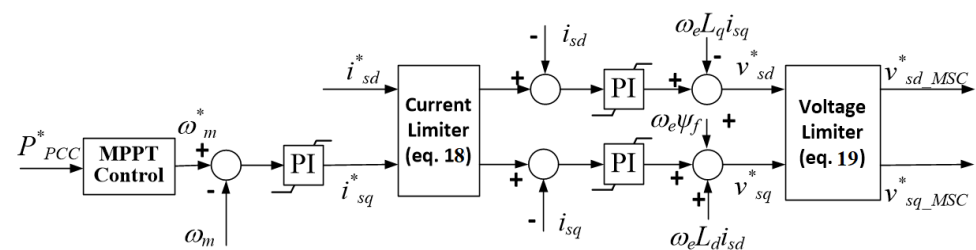


Figure 16. Standard vector control diagram modeled in the MSC.

A block is modeled to limit the d- and q-axis reference currents generated by the outer control loop based on the active power priority mode control, which is implemented in the current limitation block as follows:

$$\begin{aligned} i_{sd}^* &\leftarrow \text{sign}(i_{sd}^*) \sqrt{(I_{sdq_rated})^2 - (i_{sq}^*)^2} \\ i_{sq}^* &\leftarrow i_{sq}^* \end{aligned} \quad (18)$$

To operate the MSC within the PWM voltage saturation boundary, another block is modeled to control the voltages produced by the current control loop as follows:

$$\begin{aligned} v_{sd}^* &\leftarrow V_{sdq_max} \cdot \cos(\angle v_{sdq}^*) \\ v_{sq}^* &\leftarrow V_{sdq_max} \cdot \sin(\angle v_{sdq}^*) \end{aligned} \quad (19)$$

The parameters of the controller are tuned based on a well-known frequency response technique that has been widely used in the literature [31,32]. We used the frequency response technique, dynamic models of the MSC and GSC systems, and the PI control block provided in the MATLAB/Simulink software to tune the parameters of the MSC and GSC controllers.

7. Analyzing Abnormal Operation of PMSG WTs

In this section, case studies, including two industry cases reported in the literature, are conducted to evaluate the abnormal operations of PMSG WTs from dynamic P-Q capability perspectives.

7.1. Case Study 1: An Abnormal Operation Due to the MSC

To understand the significance of pole pairs of PMSG machines and their impact on the P-Q capability charts, two separate simulations are performed on a grid-tied PMSG WT with two different pole numbers. In this case, the number of WTs connected to the grid is set as 1, i.e., $N = 1$. A variable wind speed as shown in Figure 17a is applied to the WT. Figure 17 compares the control performance of the PMSG WT with two different pole numbers: (a) $P = 26$ and (b) $P = 48$. The other WT parameters are kept the same as Table 2. Figure 17c shows the MPPT power during the simulation time frame. For the GSC, the reactive power reference is kept at 0 MVar. Therefore, the active and reactive powers generated by the WT follow both the ERCOT and NREC regulations. For the PMSG with 26 pole pairs, MSC can control the rotating speed of the WT and extract the maximum power from the wind (Figure 17c) and GSC also maintains the dc-link voltage and grid current stability as shown in Figure 17b,d1. However, the active power, dc-link voltage, and grid current fail to maintain stability at high wind speed for the PMSG WT with a higher number of pole pairs ($P = 48$), and an abnormal phenomenon is observed (Figure 17b,c,d2), which may cause severe damage to the WT. This happens due to the conventional control of PE converters, which does not consider the variability of the P-Q capability chart and uses a fixed one in the controller design. The results are consistent with the study shown in Section 5.3. The case study reveals that the existing PMSG P-Q capability chart and control methods cannot address variable nature of PMSG WT P-Q capability and ensure safe and reliable power system operation.

7.2. Case Study 2: An Abnormal Operation Due to the GSC

In this case, we investigate a situation in which the actual dynamic P-Q capability of the GSC is not similar to the ERCOT or NERC P-Q capability curve. To simulate the situation, the NERC P-Q capability chart is modeled in the GSC control block. The wind speed is the same as that of Figure 17a. The reactive power reference is kept fixed at 0 MVar between 0 and 3 s, 0.40 MVar between 3 and 6 s, 0.80 MVar between 6 and 9 s, 1.1 MVar between 9 and 12 s, and 0.70 MVar after 12 s (Figure 18b). The references are set in such a way that the active and reactive powers stay within the NREC P-Q capability

area. However, during the simulation, an abnormal phenomenon is observed for a higher reactive power demand (9–12 s) as shown in Figure 18, which may damage the WT severely. The reason behind this occurrence is the actual GSC P-Q capability chart instead of a dynamic which encompasses the common area between the PWM saturation and rated current constraint circles (yellow area in Figure 8b), while the NERC P-Q capability chart considers the rated current boundary only (red circle in Figure 8b). The abnormal operation occurs when the active and reactive powers generated by the PMSG WT are outside the yellow area in Figure 8b but within the NERC red circle in Figure 1a. The PCC voltage increases when the WT starts to generate power and inject into the grid. This increase in the PCC voltage causes the GSC P-Q capability chart to shrink (Figure 13c,f).

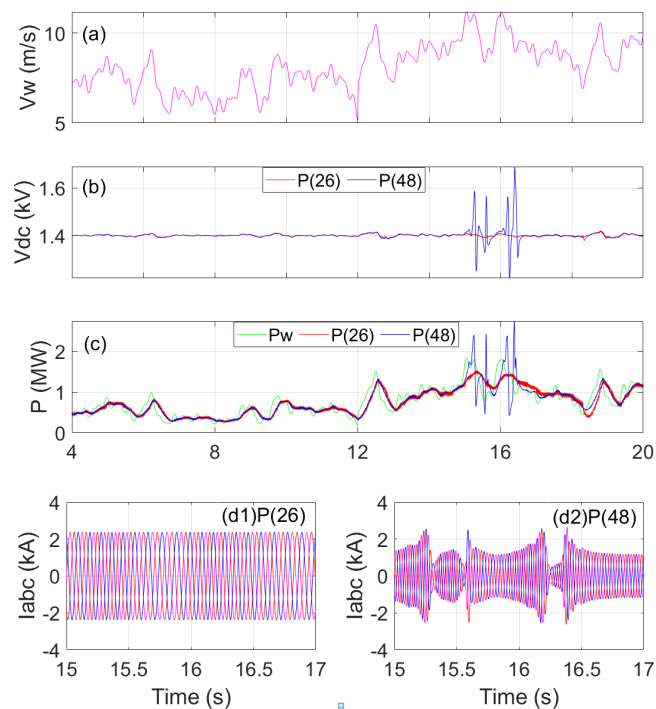


Figure 17. An abnormal operation of the PMSG WT due to the MSC. (a) Wind speed variation, (b) voltage at the dc-link, (c) active power injected to the PCC, and (d) three-phase currents at the PCC.

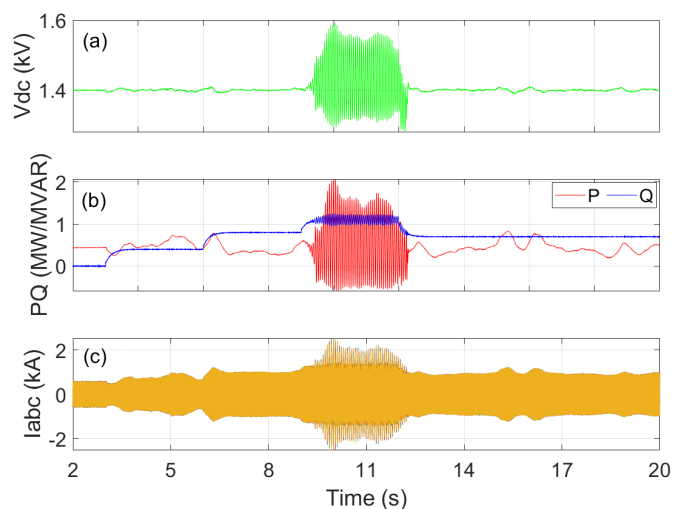


Figure 18. An abnormal operation of the PMSG WT due to the GSC and its impact on (a) voltage at the dc-link, (b) active and reactive power injected to the PCC, and (c) three-phase currents at the PCC.

7.3. Case Study 3: An Abnormal Operation Due to the Capacitor Bank Switching

This is a real industry case regarding an irregular operation of HydroOne's Type-4 wind farm that was caused by the common switching on and off of utility capacitor banks [23]. It is pointed out in [23] that the abnormal operation of the wind farms and a lack of a clear industry guideline have confused all involved parties. The wind speed is the same as that of Figure 17a, and the number of WTs connected online in the wind farm is set as 250, i.e., $N = 250$. Similar to [23], a capacitor bank of 50 MVar is added at the connection point of the wind farm with the grid (as shown in Figure 14) to meet the reactive power compensation requirement, and another utility capacitor bank of 500 MVar is connected at the substation bus and may switch on and off routinely. Figure 19 shows the result of this case study. When the substation capacitor banks were switched on at $t = 15$ s, a sharp voltage boost (approximately 1.75 p.u.) appeared at the WT PCC (Figure 19c), which caused the WT PQ capability region to shrink sharply as illustrated in Figure 13. This made the GSC of the WTs shift into an overmodulation operation mode after $t = 15$ s and triggered an abnormal operation event (oscillations in dc-link voltage, active/reactive power, and grid current as shown in Figure 19a,b,d), which would trip the WTs and result in the power generation loss of the wind farm. The result of this case study is consistent with the real-case result reported in [23] and explains the root cause of the abnormal operation of the Type-4 wind farm.

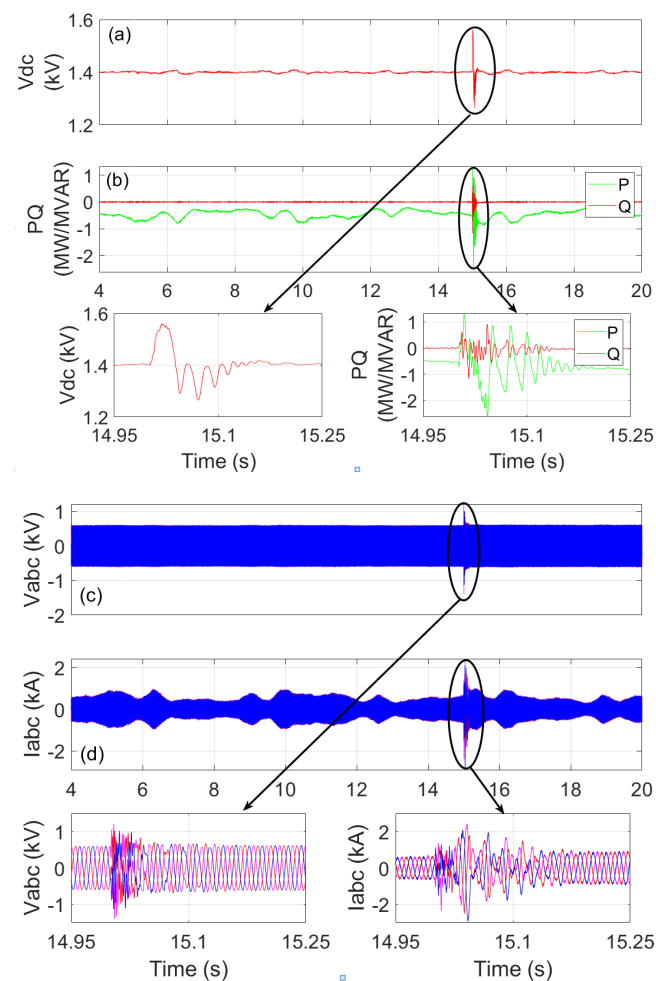


Figure 19. An abnormal operation of the PMSG WT due to the capacitor bank switching. (a) voltage at the dc-link, (b) active and reactive powers injected to the PCC, (c) three-phase voltages at the PCC, and (d) three-phase currents at the PCC.

7.4. Case Study 4: An Abnormal Operation Due to the Fault and Low Grid Strength

This is another real industry case about an irregular operation of an ERCOT Type-4 wind farm that was caused by a three-phase to ground fault [33]. For this case study, 250 WTs are connected online in the wind power plant (WPP). Then, the WPP is connected to the grid through two 120 kV transmission lines as shown in Figure 14. The substation capacitor bank is turned off. The grid strength is approximately 3.8 in normal operation conditions with both transmission lines connected online. If one of the 120 kV lines is out of service due to a fault in the grid, the grid strength will be reduced to 1.9, and the power grid will be considered a weak grid. This is equivalent to a real case reported in [33]. A variable wind speed as shown in Figure 20a is applied to the WTs. Figure 20b–e show the result of this case study. At $t = 15$ s, a three-phase to ground fault occurs, causing one transmission line to be tripped. An undamped oscillation in the dc-link voltage, active/reactive power, PCC voltage, and grid current appear (Figure 20b–e) because of the increasing wind speed and the WPP power is transmitted to the grid through a higher line impedance, which shrinks the P-Q capability area of GSC, as illustrated in Figure 13d, and pushes the GSC into over-modulation operation. As a result, an abnormal operation event occurs (Figure 20d), which will cause the WTs to be tripped and result in the WPP power generation loss. The result of this case study is consistent with the real-case result reported in [33].

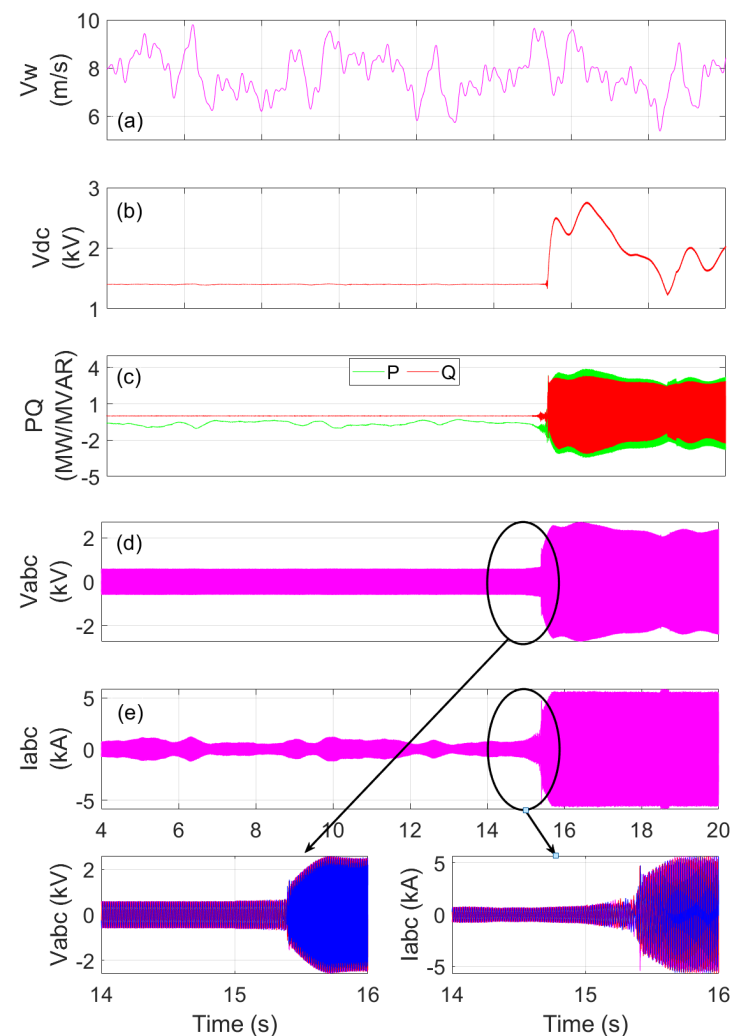


Figure 20. An abnormal operation of the PMSG WT due to the fault and low grid strength. (a) Wind speed variation, (b) voltage at the dc-link, (c) active and reactive powers injected to the PCC, (d) three-phase voltages at the PCC, and (e) three-phase currents at the PCC.

7.5. Lessons from the Case Studies

The case studies shown above reveal several important attributes associated with Type-4 wind turbines. First, unlike the conventional synchronous generators, the P-Q capability characteristics of a Type-4 WT are influenced by many factors, including WT generator design, WT power converter design, grid condition, etc., and are highly dynamic and difficult to estimate. Second, due to the dynamic P-Q capability nature, it would be difficult to ensure the safety operation of Type-4 WTs when a constant and predetermined P-Q capability curve is used for the WT. On the other hand, the safe operation of the WTs based on the dynamic P-Q capability chart of the WT is also challenging, as it can be affected by many unknown factors and is thus difficult or impossible to determine. Third, the case studies show that many SSO and MC events and weak grid instability issues, reported in the literature, are actually caused by the P-Q capability variability of the WTs, particularly the impact of the WT power converter PWM saturation constraint under uncertain conditions. Fourth, the case studies demonstrate that existing PMSG WT control technologies, even with the PWM saturation and rated current limitation functions of (16) to (19), are unable to prevent WT power converters from getting into an abnormal operation mode, such as SSO, MC, and weak grid instability. As a result, developing a new control method to overcome the challenge is urgently needed for a PMSG WT.

8. Conclusions

The P-Q capability chart is one of the crucial factors for the design and control of a grid-connected PMSG WT. Proper chart selection ensures the stability and reliability of the overall grid operation. In this paper, we performed an extensive dynamic P-Q capability analysis of a PMSG WT considering the control topology, constraints, and variable grid conditions. The study reveals that the PMSG P-Q capability is dynamic and distinct from the standards specified by the power industry. PMSG design parameters, such as the PM materials used, and pole pairs are important to specify PMSG P-Q capability charts. The study also finds that changes in dc-link voltage and PCC voltage in real-life situations have a big impact on the P-Q capability chart. The PMSG P-Q capability region may shrink due to the PWM modulation technique used and the constraints of both power converters. Four abnormal operations of PMSG WTs, including two real industry cases, are studied and illustrated through EMT simulations. The results show several SSO phenomena that occur for using a fixed P-Q capability instead of a dynamic one. These SSO events are very harmful to the PMSG WTs and the electric power grid as well. To prevent this loss, a new standard and control technology should be developed to ensure the reliable and efficient operation of grid-connected PMSG WTs under any conditions.

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Nomenclature

The following abbreviations are used in this manuscript:

SSOs	Subsynchronous oscillations
WTs	Wind turbines
PMSG	Permanent magnet synchronous generator
EMT	Electromagnetic transient
SG	Synchronous generator
NERC	North America Electric Reliability Corporation
ERCOT	Electric Reliability Council of Texas
VSC	Voltage-source converter
MPPT	Maximum power point tracker
WAMS	Wide-area measurement system
MSC	Machine-side converter
GSC	Grid-side converter
PM	Permanent magnet
PCC	Point of common coupling
SPWM	Sinusoidal pulse-width modulation
SVPWM	Space vector pulse-width modulation
WPP	Wind power plant

References

1. Nilsson, N.E.; Mercuri, J. Synchronous generator capability curve testing and evaluation. *IEEE Trans. Power Deliv.* **1994**, *9*, 414–424. [\[CrossRef\]](#)
2. Adibi, M.M.; Milanicz, D.P. Reactive capability limitation of synchronous machines. *IEEE Trans. Power Syst.* **1994**, *9*, 29–40. [\[CrossRef\]](#)
3. *IEEE Std. 2800*; Standard for Interconnection and Interoperability of Inverter-Based Resources Interconnecting with Associated Transmission Electric Power Systems. IEEE: Manhattan, NY, USA, 22 April 2022.
4. *IEEE Std. 1547*; Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces. IEEE: Piscataway, NJ, USA, 2018; pp. 1–138.
5. Public Service Enterprise Group (PSEG), Long Island. Performance Requirements for Transmission-Connected Non-Synchronous Resources. Available online: <https://www.psegliny.com/aboutpseglongisland/-/media/787F7080CA8843B482B8F40F69A8C8FD.ashx> (accessed on 1 April 2021).
6. North American Electric Reliability Corporation (NERC). Reliability Guideline BPS-Connected Inverter-Based Resource Performance. Available online: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Inverter-Based_Resource_Performance_Guideline.pdf (accessed on 1 September 2018).
7. North American Electric Reliability Corporation (NERC). Reliability Guideline Improvements to Interconnection Requirements for BPS-Connected Inverter-Based Resources. Available online: https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline_IBR_Interconnection_Requirements_Improvements.pdf (accessed on 1 September 2019).
8. Electric Reliability Council of Texas (ERCOT). Inverter-Based Resource (IBR) Workshop. Available online: https://www.ercot.com/files/docs/2022/04/11/ERCOT_SMA_IBR_PQ_Curve_Examples.pdf (accessed on 1 April 2021).
9. *Reactive Power Interconnection Requirements for PV and Wind Plants*; SANDIA REPORT—SAND2012-1098; Sandia National Laboratories: Albuquerque, NM, USA, February 2012.
10. Soderlund, L.; Eriksson, J.T. A permanent-magnet generator for wind power applications. *IEEE Trans. Magn.* **1996**, *32*, 2389–2392. [\[CrossRef\]](#)
11. Hojabri, H.; Mokhtari, H.; Chang, L. Reactive Power Control of Permanent-Magnet Synchronous Wind Generator With Matrix Converter. *IEEE Trans. Power Deliv.* **2013**, *28*, 575–584. [\[CrossRef\]](#)
12. Khazaei, J.; Nguyen, D.H.; Asrari, A. Consensus-Based Demand Response of PMSG Wind Turbines With Distributed Energy Storage Considering Capability Curves. *IEEE Trans. Sustain. Energy* **2020**, *11*, 2315–2325. [\[CrossRef\]](#)
13. Geng, H.; Yang, G.; Xu, D.; Wu, B. Unified Power Control for PMSG-Based WECS Operating Under Different Grid Conditions. *IEEE Trans. Energy Convers.* **2011**, *26*, 822–823. [\[CrossRef\]](#)
14. Dehkordi, M.J.; Zadeh, S.V.; Mohammadi, J. Development of a Combined Control System to Improve the Performance of a PMSG-Based Wind Energy Conversion System Under Normal and Grid Fault Conditions. *IEEE Trans. Energy Convers.* **2019**, *34*, 1287–1295. [\[CrossRef\]](#)
15. Ramakrishna, R.H.; Miao, Z.; Fan, L. Dynamic Performance of Type-4 Wind with Synchronous Condenser during Weak Grids and Faults. In Proceedings of the 2021 IEEE Power & Energy Society General Meeting (PESGM), Washington, DC, USA, 26–29 July 2021; pp. 1–5.
16. Fernandez, L.M.; Garcia, C.A.; Jurad, F. Operating capability as a PQ/PV node of a direct-drive wind turbine based on a permanent magnet synchronous generator. *Renew. Energy* **2010**, *35*, 1308–1318. [\[CrossRef\]](#)

17. Xie, Q.; Zheng, Z.; Huang, C.; Dai, T. Coordinated Fault Ride Through Method for PMSG-Based Wind Turbine Using SFCL and Modified Control Strategy. *IEEE Trans. Appl. Supercond.* **2021**, *31*, 5402805. [\[CrossRef\]](#)
18. Sarkar, M.; Altin, M.; Sørensen, P.E.; Hansen, A.D. Reactive Power Capability Model of Wind Power Plant Using Aggregated Wind Power Collection System. *Energies* **2019**, *12*, 1607. [\[CrossRef\]](#)
19. Rezaei, F.; Esmaili, S. Decentralized reactive power control of distributed PV and wind power generation units using an optimized fuzzy-based method. *Int. J. Electr. Power Energy Syst.* **2017**, *87*, 27–42. [\[CrossRef\]](#)
20. Dong, X.; Xu, T.; Zhang, Y. Dynamic Practical SSR Incidence and Influencing Factor Analysis of DFIG-based Series-compensated Transmission System in Guyuan Farms. *High Volt. Eng.* **2017**, *43*, 321–328.
21. Shair, J.; Xie, X.; Wang, L. Overview of emerging SSO in practical wind power systems. *Renew. Sustain. Energy Rev.* **2017**, *99*, 159–168. [\[CrossRef\]](#)
22. Liu, H.; Xie, X.; He, J. Subsynchronous Interaction between Direct-Drive PMSG Based Wind Farms and Weak AC Networks. *IEEE Trans. Power Syst.* **2017**, *32*, 4708–4720. [\[CrossRef\]](#)
23. Li, C. On Capacitor Switching Transient Immunity of Inverter-Based Renewable Generations. *IEEE Trans. Power Deliv.* **2015**, *30*, 2339–2345. [\[CrossRef\]](#)
24. North American Electric Reliability Corporation (NERC). Odessa Disturbance Texas Events: 9 May 2021 and 26 June 2021 Joint NERC and Texas RE Staff Report. Available online: https://www.nerc.com/pa/rrm/ea/Documents/Odessa_Disturbance_Report.pdf (accessed on 1 September 2021).
25. Shi, T.; Nayanisiri, D.; Li, Y. Sub-synchronous oscillations in wind farms—an overview study of mechanisms and damping methods. *IET Renew. Power Gener.* **2021**, *10*, 4854–4864. [\[CrossRef\]](#)
26. Lu, B.; Li, S.; Das, H. S.; Gao, Y.; Wang, J.; Baggu, M. Dynamic P-Q Capability and Abnormal Operation Analysis of a Wind Turbine with Doubly-Fed Induction Generator. *IEEE J. Emerg. Sel. Top. Power Electron.* **2021**, *10*, 4854–4864. [\[CrossRef\]](#)
27. Fu, X.; Li, S. Systems, Methods and Devices for Vector Control of Induction Machines Using Artificial Neural Networks. U.S. Patent 10,990,066, 27 April 2021.
28. Li, S.; Haskew, T.A.; Muljadi, E.; Serrentino, C. Characteristic Study of Vector-controlled Direct-driven Permanent Magnet Synchronous Generator in Wind Power Generation. *Electr. Power Components Syst.* **2009**, *37*, 1–17. [\[CrossRef\]](#)
29. Miller, N.W.; Sanchez-Gasca, J.J.; Price, W.W.; Delmerico, R.W. Dynamic modeling of GE 1.5 and 3.6 MW wind turbine-generators for stability simulations. *IEEE Power Energy Soc. Gen. Meet.* **2003**, *3*, 1977–1983.
30. Wu, B.; Lang, Y.; Zargari, N.; Kouro, S. *Power Conversion and Control of Wind Energy Systems*; John Wiley & Sons: Hoboken, NJ, USA, 2011.
31. Frequency-Response Based Tuning—MATLAB & Simulink. Available online: <https://www.mathworks.com/help/slcontrol/ug/frequency-response-based-tuning-basics.html> (accessed on 1 April 2021).
32. Garrido, J.; Ruz, M.L.; Morilla, F.; Vázquez, F. Interactive Tool for Frequency Domain Tuning of PID Controllers. *Processes* **2018**, *6*, 197. [\[CrossRef\]](#)
33. Huang, S.; Schmall, J.; Conto, J.; Adams, J.; Zhang, Y.; Carter, C. Voltage Control Challenges on Weak Grids with High Penetration of Wind Generation: ERCOT Experience. In Proceedings of the 2012 IEEE Power and Energy Society General Meeting, San Diego, CA, USA, 22–26 July 2012; pp. 1–7.

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