CONTROL OF PMSG BASED WIND ENERGY CONVERSION SYSTEM WITH THREE-LEVEL BOOST AND NPC CONVERTERS

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Abstract-- **In this paper, a new medium voltage (MV) PMSG based variable speed wind Energy Conversion System (VSWECS) controlled by three level boost(TLB) and Five level Neutral point clamped(NPC) converter is presented to improve the performance. The dc-link control strategy for tracking the maximum power and maintaining constant Dc-link voltage will be performed by TLB. The simulation results for 3MW/3000V/50Hz non salient pole PMSG wind energy system are presented to validate the topology and control scheme.**

Keywords—Neutral-point clamped Converter(NPC), Maximum power point tracking (MPPT), Three-level Boost Converter(TLB), Permanent Magnet Synchronous Generator (PMSG),PI controller.

I.INTRODUCTION

The cost reduction of wind energy is required for the fast spread of the power generation with wind through more reliable, efficient, and economical wind energy conversion systems [1]. Wind energy has penetrated into the power sector considerably over few years which reflected on the need for grid integration of wind turbines [2]. Presently, most of the grid necessities address under voltage ride-through and grid support competencies of the wind turbines. The direct-drive PMSG based variable-speed WECSs are pretty popular for higher power ratings large wind turbines compared to other types of WECSs, because of their superiority owning to their advantages of higher power density, higher efficiency, lower maintenance costs, greater controllability, low losses, better fault-ride through and grid support capability from the recent research that has also been carried out on synchronous generators (SG) application in wind power generation [3].

Power electronic converters play an essential role in WECS, particularly within variable speed turbines generation. In addition to contribution to the adequacy of the system even with variable speed wind, converters allow control of reactive and active power if needed, as well as system operation at maximum power point [4]. As power electronic interface for grid connection a diode rectifier with a DC/DC boost converter and inverter has been used. In this arrangement, the DC-link voltage is controlled by means of the three phase inverter voltage amplitude and phase displacement angle. By means of state equations the DC-link voltage and linearized currents of the inverter can be attained [6]. For low power applications, the PMSG are commonly used and SG is used for current larger systems. By means of back-to-back PWM voltage source inverters the energy from SG in large systems are converted [16],[18]-[20].

The permanent magnet synchronous generators (PMSG) with adjustable speed wind turbine technology and full scale power converters is rapidly growing due to greater efficiency, reduction in maintenance and installation costs, lesser mechanical stress. Moreover, the lagging/leading grid reactive power control and voltage ride through operation can be attained without the requirement for further equipment. Various power converter topologies were being suggested for PMSG wind energy conversion systems (WECS) in a continuous effort to shrink price, raise reliability and expand wind energy conversion competence [6]-[9].

The price of the total system rises as the complexity of the power electronic converter rises. However, the overall system efficiency increases with higher order converter and control designs [17]. Reduction of the complexity of control of grid inverter at a little increase in price is possible with addition of a DC-boost stage. Similarly, controlled rectifier in place of the diode rectifier allows wider range of control of both the grid and generator reactive and real power transfer. To maximize the profits of the wind energy conversion system, a compromise must be obtained between efficiency and cost [3].

Keeping in mind the passive front-end converters marketable success, a new converter topology using diode rectifier, three-level boost (TLB) and NPC converter was proposed in [5] for MV PMSG WECS technology. This configuration is simple, low cost compared to back to back NPC converters. The dc-link MPPT control technique is proposed and applied to 3MW/3000V/50 Hz non-salient pole PMSG WECS to perform balancing of dc-link capacitors and MPPT [5]. With the proposed control scheme a simple modulation scheme can be used for NPC control. The simulation results in MATLAB confirm the suggested scheme.

This paper is organized as follows: Second part contains PMSG Modeling, Third part describes the Three-level boost converter topology and Fourth part describes necessity for MPPT, Control strategy of NPC Converter Techniques. Simulation results for the case study and analysis for grid connection.

II.MODELING OF PMSG

In direct-drive wind power generation systems for converting the mechanical power into electrical power

Permanent magnet synchronous machines (PMSMs) /generators (PMSGs) play important role [4]. PMSG modeling of the PMSG is explained with the help of following equations:

$$V_{ds} = R_s i_{ds} + L_d \frac{di_{ds}}{dt} - \omega_e L_q i_{qs} \quad (1)$$

$$V_{qs} = R_s i_{qs} + L_q \frac{di_{qs}}{dt} + \omega_e L_d i_{ds} + \omega_e \lambda_r \quad (2)$$

Where i_{ds} and i_{qs} are the stator instantaneous currents in the *dq*-axes reference frame, v_{ds} and v_{qs} are the stator instantaneous voltages in the *dq*-axes reference frame. Here, L_d and L_q are the *d*-axis and *q*-axis inductances, and ω_e is the electrical angular speed of the rotor, while, λ_r is the peak/maximum phase flux linkage due to the rotor-mounted Permanent Magnets.

In the abc reference frame electrical power input can be expressed as follows:

$$P_{abc} = V_{as} i_{as} + V_{bs} i_{bs} + V_{cs} i_{cs} \quad (3)$$

Or else in the dq-axes reference frame as:

$$P_{dq} = \frac{3}{2}\left(V_{ds} i_{ds} + V_{qs} i_{qs}\right) \quad (4)$$

In motoring mode, the active power is the power converted into mechanical power, expressed as:

$$P_{em} = \frac{3}{2}\left(e_d i_{ds} + e_q i_{qs}\right) \quad (5)$$

Where,

$$e_d = -\omega_e L_q i_{qs} = -\omega_e \lambda_q \quad (6)$$

And,

$$e_q = \omega_e L_d i_{ds} + \omega_e \lambda_r = \omega_e \lambda_d \quad (7)$$

Here, e_d and e_q are the back EMFs in the *dq*-axes reference frame, λ_d and λ_q are the *dq*-axes flux linkages. Substituting expressions (6) and (7) into (5), the active power can be re-expressed as follows:

$$P_{em} = \frac{3}{2}\left(\lambda_d i_{qs} - \lambda_q i_{ds}\right) \quad (8)$$

Hence, the electromagnetic torque developed by a PMSM is:

$$T_e = \frac{P_{em}}{\omega_e / \frac{P}{2}} = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_d i_{qs} - \lambda_q i_{ds}\right) \quad (9)$$

Or

$$T_e = \frac{3}{2}\left(\frac{P}{2}\right)\left(\lambda_r i_{qs} + \left(L_d - L_q\right) i_{qs} i_{ds}\right) \quad (10)$$

Where, P is the number of poles in the machine.

III. THREE-LEVEL BOOST CONVERTER .

In MV MW WECS, as the voltage ratings can simply go beyond the range that a single switching device can be able to handle. To avoid this problem, most superior choice is multi-level operation compared to the series or parallel connection of devices [5]. With multi-level operation, device voltage rating can be reduced to a fraction of output voltage so that power density of converter and efficiency increases, cost reduces. The switching frequency of TLB is double the conventional boost converter and thus offers lower input current ripple and output voltage ripple, faster dynamic response and better power handling capability [12]-[15]. The TLB circuit diagram is shown in Fig 1 and operation is explained thoroughly in [5].

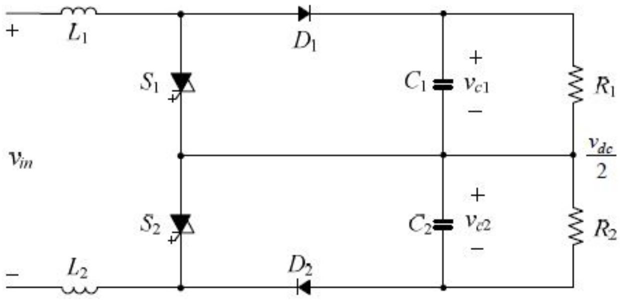

Fig 1. Configuration of three-level boost converter

IV. CONTROL SCHEME

The control scheme block diagram is shown in Fig 2. The Four variables: balancing of dc-link capacitors, the dc-link voltage, reactive power and active power are needed to be controlled tightly. The TLB achieves balancing of dc-link capacitors and MPPT, while the dc-link voltage and reactive power to the grid are controlled by NPC [5].

A. MPPT control:

MPPT is tracked with reference power which is obtained from power against wind speed curves by means of the expression:

$$P^* = \frac{1}{2}\rho A V_w^3 C_p \quad (11)$$

A PI controller is used in the current feedback control for adjusting the dc-link current i_{dc}. The active power is controlled to achieve MPPT which is only a product of dc link input current and voltage. In other words, the duty cycle D_1 controls the WECS active power. The boost nature of the TLB can be defined similar to the conventional boost converter as follows:

$$\frac{V_{dc}}{V_{in}} = \frac{1}{1 - D_1} \quad \text{For } \; 0 \le D_1 < 1 \qquad (12)$$

Where, the input dc-voltage V_{in} is uncontrollable and varies with respect to the generator speed (power). The second PI generates error duty cycle ΔD as follows:

$$\Delta D = \left(k_1 + k_2 / S \right)\left(V_{C1} - V_{C2} \right) \qquad (13)$$

Where $(k_1 + k_2 / S)$ is the transfer function of the PI controller. The duty cycle D_2 which, controls the neutral point balancing is

$$D_2 = D_1 + \Delta D \qquad (14)$$

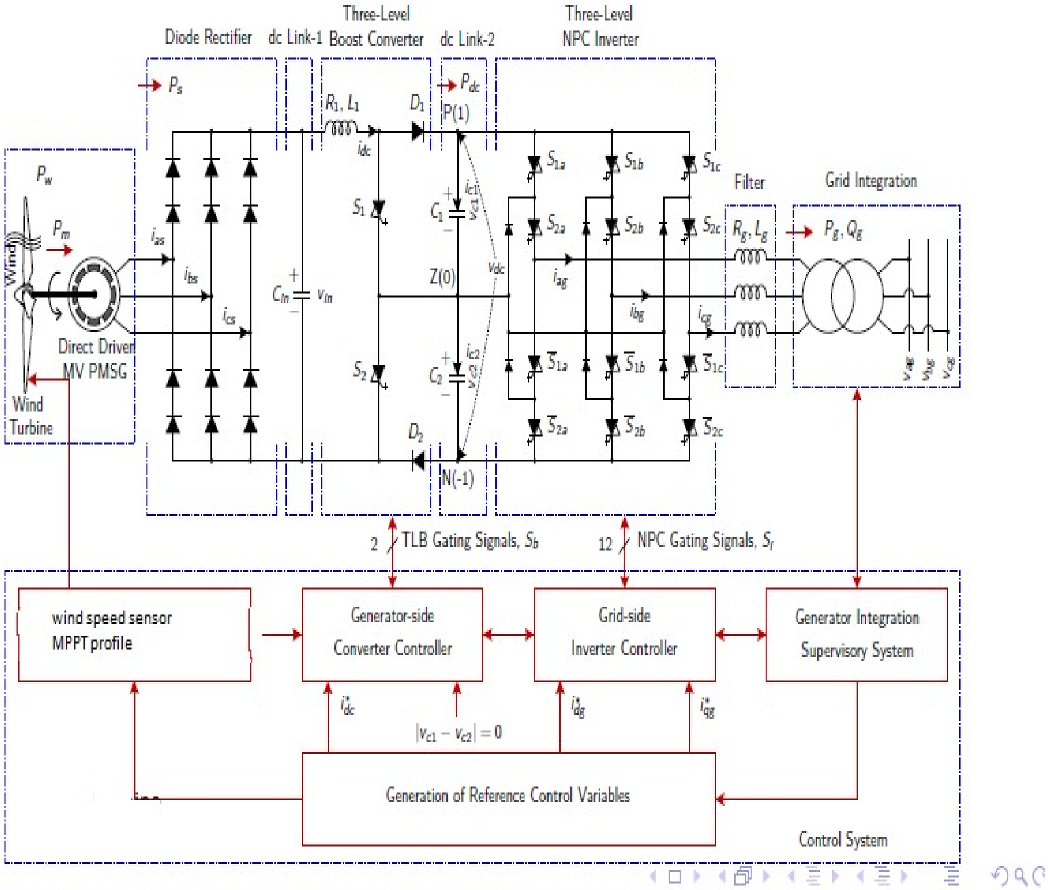

Fig 2. Dc-link MPPT control for PMSG Wind Energy Conversion System

B. Decoupled Voltage Oriented Control of NPC Converter

To control the dc-link voltage V_{dc} and reactive power Q_g to the grid independently the decoupled voltage oriented control (VOC) scheme is used. There are totally three feedback control loops in the VOC scheme: two inner current loops for the accurate control of the line currents i_{dg} and i_{qg}, and one outer dc voltage feedback loop for the control of dc voltage V_{dc}. With a suitable grid voltage placement, the phase line currents in the abc stationary frame, i_{ag}, i_{bg} and i_{cg}, are converted to the two-phase currents, i_{dg} and i_{qg} in the dq synchronous frame, which are the active and reactive components of the three-phase line current, respectively. The independent control of these two components provides an effective means for the independent control of system dc voltage and reactive power. The output of the decoupled controller can be expressed as

$$\begin{aligned} V_{di} &= -\left(k_1 + K_2 / S \right)\left(i^*_{dg} - i_{dg} \right) + \omega L i_{qg} + V_{dg} \\ V_{qi} &= -\left(k_1 + K_2 / S \right)\left(i^*_{qg} - i_{qg} \right) + \omega L i_{dg} + V_{qg} \end{aligned} \qquad (15)$$

As the NPC is controlled by TLB, a simple carrier based modulation scheme along with 3^{rd} harmonic injection is used.

C. Neutral Point Clamped Converters

The diode-clamped multilevel inverter uses cascaded DC capacitors and clamping diodes to generate multi-level AC voltage waveforms. The inverter can be generally configured as a three, four, or five-level topology, and the three-level inverter, often known as neutral point clamped (NPC) inverter, has found wide practical application, especially in medium-voltage (MV) variable-speed drives. Inverter is also a good candidate for MV (3 kV-6kV) wind energy systems. The main features of the NPC inverter include reduced THD, switch stress and *dv/dt* in its AC output voltages in comparison to the two-level inverter. More essentially, the inverter can be used in the MV wind energy systems without series connected switching devices [6]. For example, the NPC inverter using 6 kV IGBT or IGCT devices is suitable for the 4 kV WECS, for which there is no need to connect the switches in series. PMSG wind energy conversion system with three level NPC converter is shown in fig 2.

Simulation is carried out first with three level NPC and then with five level NPC to compare the results. The five-level diode clamped inverter per-phase circuit diagram is shown in Fig. 3, and the relationship between the switch status and v_{AN} for the five-level inverter is also given in Table 1[11].

Inverter individual three phases shares the dc bus, which has been subdivided by four capacitors into six levels. The voltage across each capacitor is V_{dc}, and the voltage stress across each switching device is limited to V_{dc} through the clamping diodes. State condition 1 means the switch is on, and 0 means the switch is off. Each phase has five complementary switch pairs such that turning on one of the switches of the pair require that the other complementary switch be turned off. The complementary switch pairs for phase leg a are (S1, S1'), (S2, S2'), (S3, S3') and (S4, S4')[12].

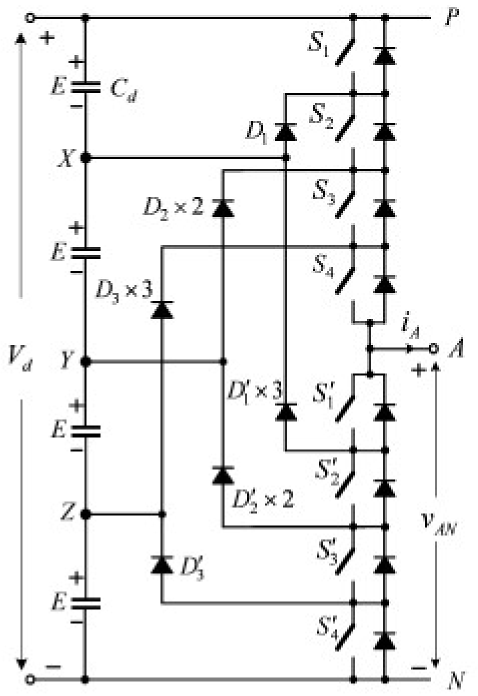

Fig.3 Per phase circuit of Five-level NPC Inverter

TABLE 1 Switching state of five-level NPC converter

v_{AN}	S4	S3	S2	S1	S4'	S3'	S2'	S1'
4E	1	1	1	1	0	0	0	0
3E	0	1	1	1	1	0	0	0
2E	0	0	1	1	1	1	0	0
E	0	0	0	1	1	1	1	0
0	0	0	0	0	1	1	1	1

V. Simulation Results

The MATLAB simulations are carried out on 3MW/ 3000V, 50 Hz PMSG based WECS with three level NPC and Five level NPC converters on the grid side with three level boost converters on the generator side.

A. With Three Level NPC:

The active power with three level NPC is shown in fig.4. The increase of P_g starts at t = 0.2 s and ramps nearer to its rated value (1pu) at t = 2.3 s, and is then maintained constant.

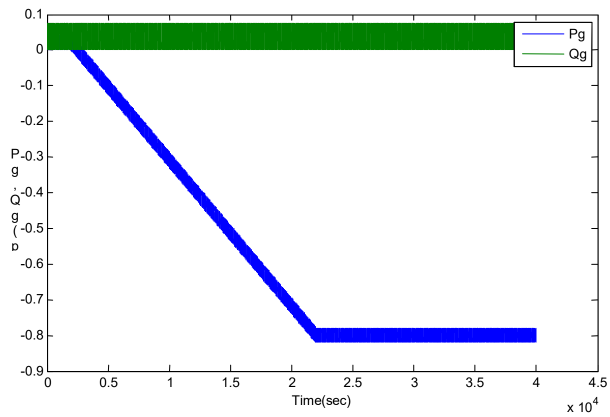

Fig.4 Grid active & reactive powers

The grid current amplitude i_{ag} (Fig. 5) is proportional to the active power as its reactive component is zero.The FFT analysis for I_{ag} is obtained as 1.96% and is shown in fig. 6.

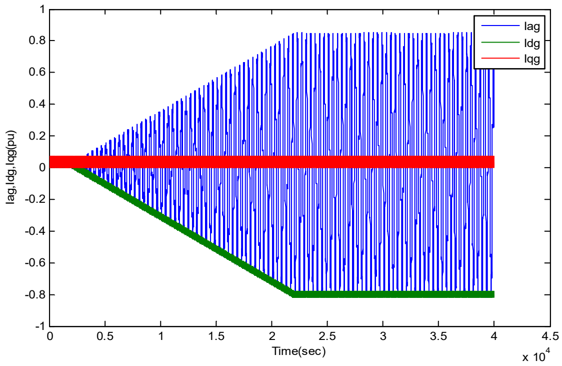

Fig.5 Grid phase-a currents & dq components

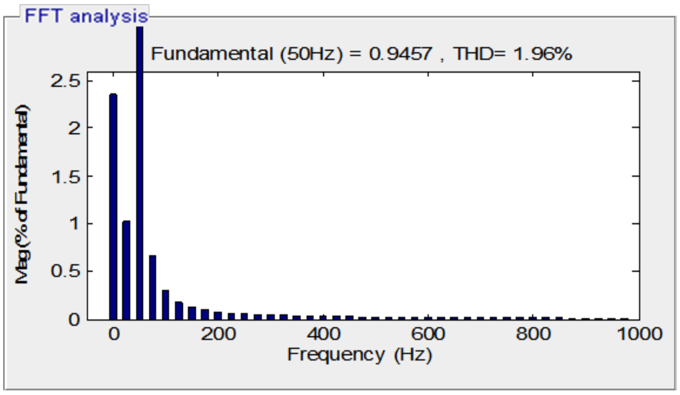

Fig.6 THD of Iag

B: With Five Level NPC:

The active power with five level NPC is shown in fig.7. The active power P_g starts to increase at t=0.2 sec and ramps up to its rated value at t= 2.2 sec and is then kept constant. (The minus indicates that the power is delivered from the inverter to the grid).

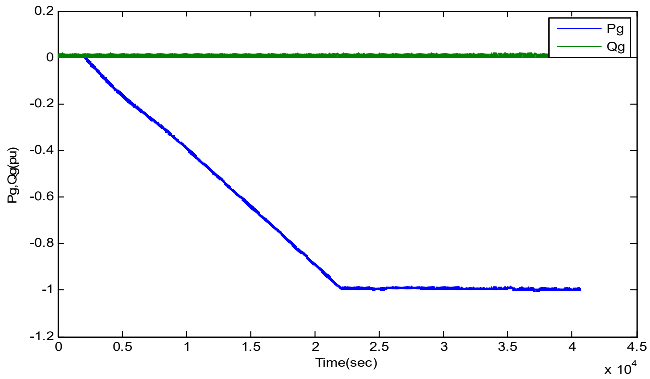

Fig.7. Grid active &reactive powers

The amplitude of the grid current iag (Fig. 8) is proportional to that of the active power since its reactive component is zero and its FFT analysis is shown in Fig.9 and it is found to be 0.63 %.

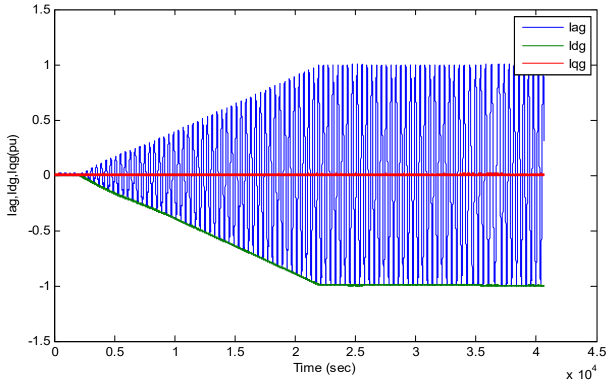

Fig.8 Grid phase-a currents & dq components

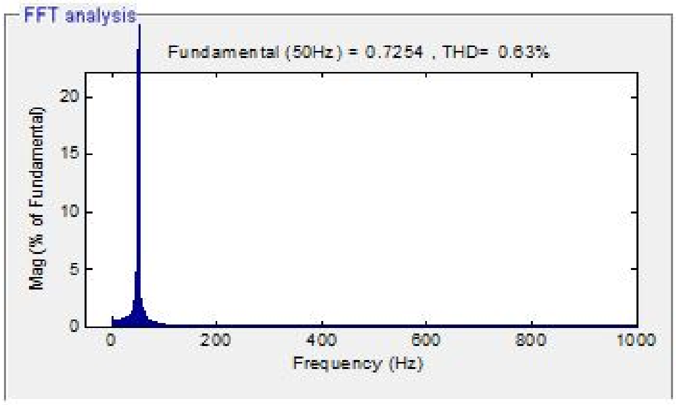

Fig 9. THD of Iag

The diode rectifier present in the system forces the PMSG power factor close to unity which is shown in fig. 10.

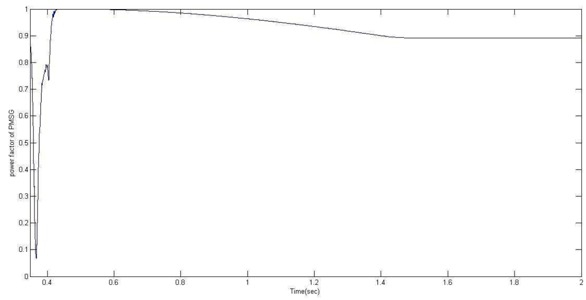

Fig 10. Power Factor of the Machine

VI. CONCLUSION

In this paper, a power converter topology using diode rectifier, three-level boost and NPC converters(three and five levels) have been proposed for MV PMSG WECS.. This configuration is promising WECS because of the following reasons:

1. The NPC converter no longer needs to control the balancing of capacitors and thus a simple modulation scheme can be used for the NPC control.
2. The equivalent switching frequency of TLB is twice the conventional boost converter and thus offers lower input current ripple and output voltage ripple, faster dynamic response and better power handling

capability and improves the active power& reactive power and reduces the total harmonic distortion.

3. It can be observed from the results that, the THD in current is improved with five level NPC when compared to three level NPC converters.
4. Wind speed transients are presented to demonstrate the significance of MPPT in WECS
5. Suggested scheme provides a less cost and better superior power conversion solution for PMSG based WECS

Appendix

TABLE II. 3.0MW/3000V/53.33Hz PMSG Parameters

Rated output power	3.0 MW
Rated mechanical shaft input power	3.02838 MW
Rated apparent power	3.6373 MVA
Rated line to line voltage	3000 V (RMS)
Rated phase voltage	1732.05 V (RMS)
Rated current of stator	700 A (RMS)
Rated frequency of stator	53.33 Hz
Rated power factor	0.8248
Rated speed of rotor	400 rpm
Number of pole pairs	8
Rated mechanical shaft input torque	72.2972 kN-m
Rated flux linkage of rotor	4.3034 Wb (RMS)
Resistance of stator winding	19.28 mΩ
d-axis synchronous inductance	4.1753 mH
q-axis synchronous inductance	4.1753 mH

TABLE II. Grid and Filter Parameters

Grid side converter(GSC) apparent power S_B	3.0 MVA
Grid phase voltage V_B	1732.05 V (RMS)
GSC rated current I_B	577.4 A (RMS)
GSC switching frequency	2000 Hz
Resistance of Filter	0.015 Ω
Inductance of Filter	1.6 mH

TABLE III. Three-Level Boost Converter Parameters

Input capacitor, C_{in}	3500 µF
Output capacitors, C_1 & C2	3500 µF
Inducrors, L_1 & L_2	8 mH
Switching frequency	2000 Hz

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