International Journal of Research and Review
DOI: https://doi.org/10.52403/ijrr.20210819
Vol.8; Issue: 8; August 2021
Website: www.ijrrjournal.com
E-ISSN: 2349-9788; P-ISSN: 2454-2237

Review Paper

Analysis on the Topology and Control of Power Electronics Converters for Wind Energy Conversion Systems

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ABSTRACT

Power Electronics converters become nowadays the most important part in Wind Energy Conversion Systems (WECS). They are an intermediate between the generator and grid to achieve low cost, high power density and reliability. This paper deals with the analysis on the topology and control of the most power Electronics Converters for generators using in WECS. Design, (dis)advantages, and market penetration are analyzed and discussed. The control includes maximum power point tracking, dc bus voltage control, balancing of the dc capacitor voltages, and reactive power generation are also analyzed. Simulations have been carried out using MATLAB/SIMULINK on the control strategies for the case of back to back converter with Pulse Width Modulation (PWM) demonstrating its good potential to meet the grid connection requirements.

Keywords: Wind Energy Conversion Systems (WECS), power electronics converters, back to back converter, maximum power point tracking, Pulse Width Modulation (PWM).

INTRODUCTION

The penetration of wind energy in the electricity production becomes more and more important with 591 GW global cumulative wind energy capacity in the worldwide reached at the end of 2018 [1]. As power level increases, the controlling of the wind turbine becomes very important. The WECS is composed of a wind turbine, an electric generator, a power electronic converter and the corresponding control system. Power electronics converters are used for matching the characteristics of wind energy generator to grid connection requirements, such as frequency, voltage, control of active and reactive power and harmonics, etc. In recent years, many power converter techniques have been developed for integrating with the electrical grid. They have greatly affected the grid due to their low power factor to enhance power extraction [2]. Many control strategies for wind generators have already been developed so as to efficiently utilize the wind power, which is variable in nature [4, 5].

This paper aims to analyze the topology and control of the most power Electronics Converters for generators using in WECS. The basic market developments are discussed with a focus on cost, size, and power density and finally the performances of a back to back PWM converter are evaluated through simulations for power tracking and load frequency required.

POWER ELECTRONICS FOR GENERATORS AVAILABLE IN THE MARKET

Power electronics for squirrel cage induction generator (SCIG)

Thyristor soft-starter with transformer was first introduced by Danish wind Turbine Company (Vestas, Siemens) to connect the SCIG to the grid [6, 7]. It operated as a fixed speed WECS. The scheme is presented in Fig. 1:

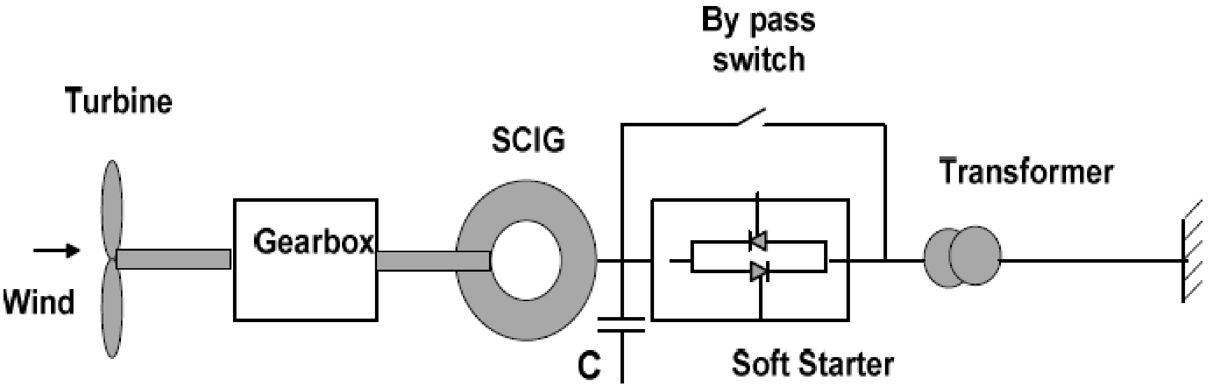


Fig. 1: Scheme of the thyristor soft-starter with the transformer [7]

It can be founded this system is simple and cheap construction, in addition no synchronization device is required [8]. The high starting currents of induction generators are usually limited by a thyristor soft-starter. The current limiter or soft-starter, based on thyristor technology, typically limits the rms value of the inrush current to a level below two times of the generator rated current. The soft-starter has a limited thermal capacity and it is short circuited by a contactor, which carries the full load current, when the connection to the grid has been completed. Then to avoid capacitor bank for SCIG and working at variable speed WECS, SCIG with back to back converters was introduced [9]. The most common configuration of power converters for WECS based on variable-speed wind turbine and SCIG is that composed of back-to-back voltage source converters with a large capacitor on the dc-link. The power flowing of the grid side converter is controlled in order to keep the dc-link voltage constant, while the control of the generator side is set to satisfy the SCIG magnetization demand and control the speed or torque [10]. BaiShan Mei et al. study a kind of topology of back-to-back PWM full power converter with a SCIG [11]. The proposed system configuration is shown in Fig.2.

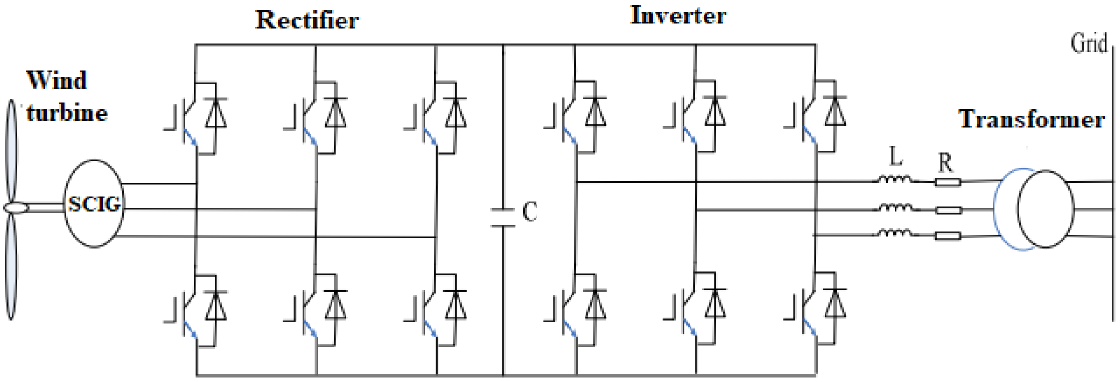


Fig. 2: Topology of back to back converter with SCIG [11]

It requires the generator to run at a wide speed range and has fast rotation velocity response to operate in MPPT mode. The main objective of this converter is to maintain constant voltage and frequency required. Standard vector control techniques have been done in [12].

The matrix inverter was also introduced to provide direct AC-AC conversion and is considered an emerging alternative to the conventional two-stage AC-DC-AC converter topology [13, 14]. A matrix converter provides a large number of control levers that allows for independent control on the output voltage magnitude, frequency and phase angle, as well as the input power factor. A WECS with SCIG based on matrix converter has been done in [10, 15]. The Schematic diagram is showed in Fig. 3.

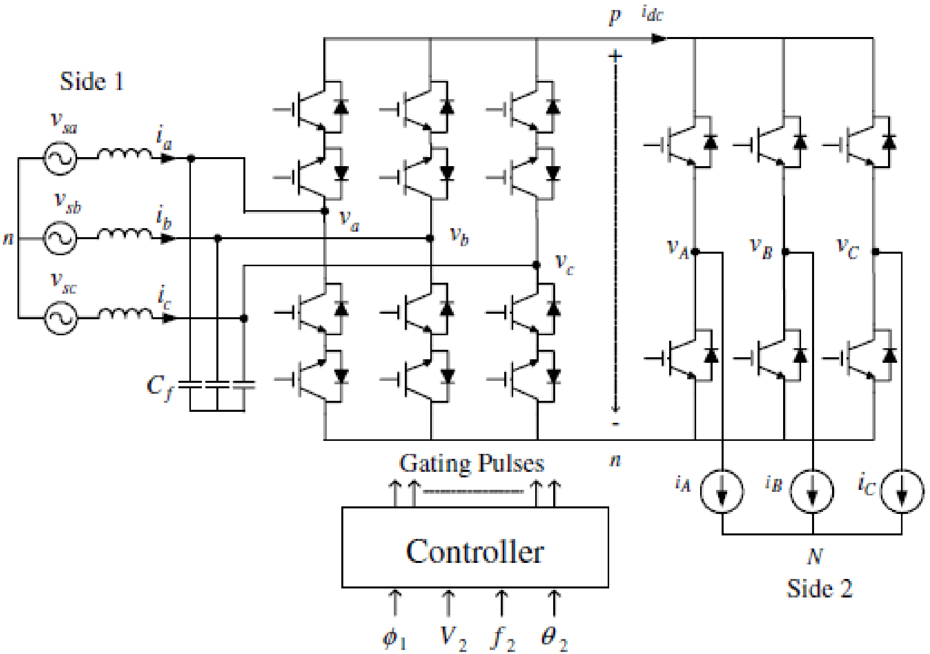


Fig. 3: Schematic diagram studied matrix converter topology [15]

The matrix converter interfaces the SCIG with the grid and implements shaft speed control to achieve maximum power point tracking at varying wind velocities. Perturbation and observation method has been done in [10] to track the maximum power point.

Power converters for Doubly Fed Inductor Generator (DFIG)

The DFIG generally uses a back-to-back converter, which consists of two bidirectional converters using a common dc link, one connected to the rotor and the other one to the grid. In Variable-speed WECSs, the power electronic converters control both the active and reactive power delivered to the grid. This gives potential for optimizing the grid integration with respect to steady-state operation conditions, power quality, voltage, and angular stability. The topology is showed in Fig. 4.

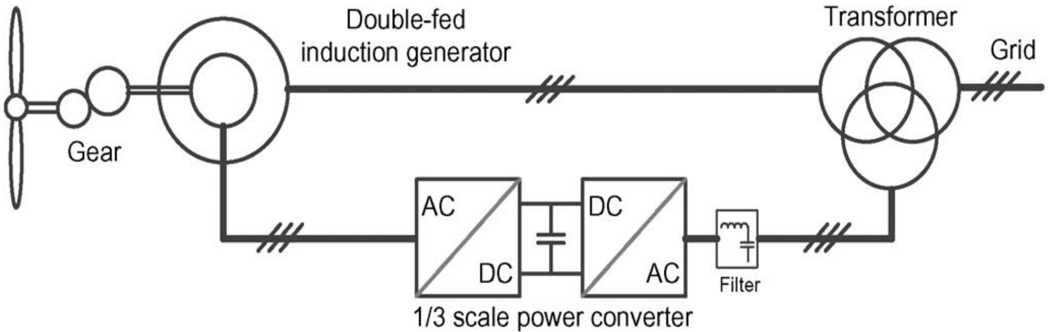


Fig. 4: Back to back converter for DFIG [10]

Self-commutated converter systems, such as IGBT-based switching converters, are normally used for this type of system. This speed-adjustable design is typically deployed in the power range between 1.5 MW and 6 MW. In a DFIG converter, only up to one-third of the power flows through the power semiconductors in both directions. The reactive power to the grid from the generation unit can be controlled as zero or to a value required by the system operator within the converter rating limit. In general, the harmonics generated by the converter are in the range of some kilohertz. Thus, filters are necessary to reduce the harmonics. Moreover, this converter performs reactive power compensation and a smooth grid interconnection. The smaller frequency converter makes this concept attractive from an economical point of view. In this case, the power electronics is enabling the wind turbine to act as a dynamic power source to the grid. However, its main drawbacks are the use of slip rings and the protection schemes/controllability in the case of grid faults [16, 17]. Others advantages, because of inverter rating are almost 30% of the total system power, it reduces inverter cost. Without the use of capacitor bank, Power-factor control can be implemented at a lower cost. The control based on the feedback technique in order to reduce the oscillation of the generator is done in [18]. This control is based on the power flow from DFIG to switching the back to back converter. Another control technique, Fuzzy controller is used in [19]. This control allows to generate the voltage command signal for both rotor side and grid side of the back to back converter in order to control the capacitor DC voltage and the reactive power or the voltage at the grid terminals. A protection device, namely, “Crowbar,” is used to save the rotor circuit and power electronic converter from high rotor transient current. Dao Zhou et al. used lifetime models and Monte Carlo based variation analysis, to predict the time-to-failure distribution of the key power semiconductors of the back to back converter [20]. A case of 2 MW wind power converter was studied. It can be seen that the lifetime of the grid-side converter and the rotor-side converter deviates a lot by considering the electrical stresses, while they become more balanced by using an optimized reliable design. A PI current control loop at both rectifier side and inverter side can be done to predict the dq references axis currents to switching back to back converter [21].

Power converters for Permanent Magnet Synchronous Generator (PMSG)

Different converters topologies have been emerged for the PMSG.

Thyristorised Grid Side Inverter

The AC output of PMSG is converted into DC using the diode rectifier and then again converted back to AC using thyristorised inverter coupled to the grid. The topology is depicted in Fig. 5.

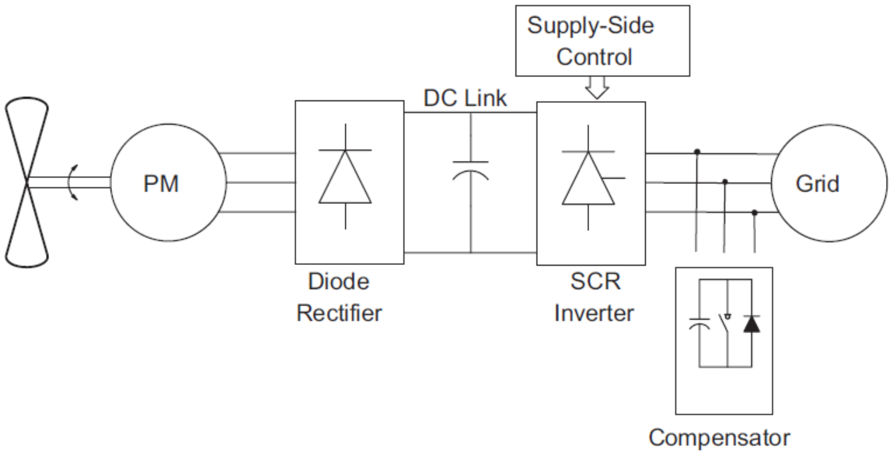


Fig. 5: Topology of Thyristorised Grid Side Inverter with PMSG [22]

The output of PMSG is rectified with the help of an uncontrolled rectifier to form a DC link [22]. A line commutated thyristorised inverter converts the DC power into AC and coupled with the grid. It allows continuous control of the inverter firing angle, regulating turbine speed through the DC-link voltage; hence, obtaining optimum energy capture [22]. The advantages of this topology as compared to the hard-switched inverters are reduced cost and higher available power rating. The main disadvantage of this scheme is that it requires an active compensator for meeting reactive power demand and reduction in total harmonic distortion.

Back-to-back PWM converter

The back to back PWM converter is the most popular converter topology for PMSG based WECS. Advantage of this is that it provides active and reactive power control and because of Pulse Width Modulation techniques it also increases power factor. The topology is showed in Fig. 6.

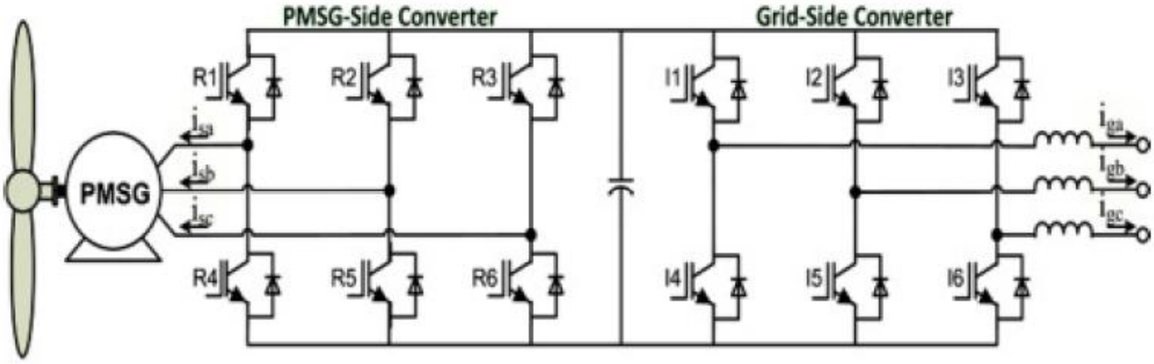


Fig. 6: Topology of back to back PWM converter with PMSG [23]

The generator side rectifier is controlled through a PI controller such that the q-axis current is held to zero to obtain maximum electrical torque with minimum current. A MPPT is used in determining the optimum rotor speed for each wind speed to obtain maximum rotor power. The grid-side control sets the inverter current through a PI controller and the DC-voltage error. The current error is used to drive the inverter switching signals. A PLL is used on each side to ensure unity power factor is maintained throughout the entire system [23]. An intermediate chopper circuit can be used for stable operation under line fault condition and output power smoothening is achieved via coordinated action of DC link voltage and pitch angle control of wind turbine [24].

PMSG WECS using three-level boost and NPC converter

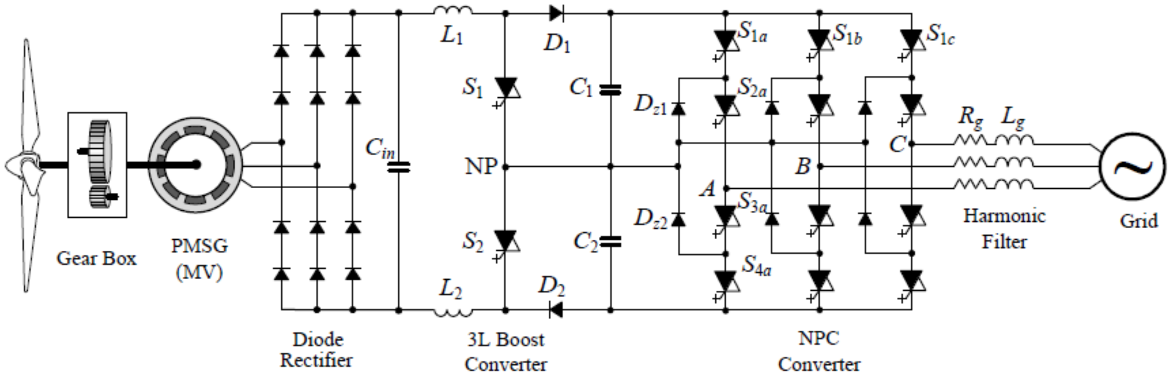


Fig. 7: PMSG WECS using three-level boost and NPC converter [26]

The output of the generator is rectified by an uncontrolled rectifier and Maximum Power Point Tracking (MPPT) is achieved through a boost converter [25]. Considering the commercial success of passive front-end converters, a new converter configuration using diode rectifier, three-level boost (TLB) and NPC converter for Medium Voltage PMSG WECS technology is proposed in [26]. This configuration simple, less costly and less in weight compared to back to back converter NPC converters. The topology is presented in Fig. 7.

It operates in two regions depending on whether the input voltage is lower or higher than half of the output voltage. A predictive control scheme is proposed in [27] for the low voltage ride-through enhancement of direct-driven PMSG based megawatt-level wind turbines. The advantage of the technique used is that no wind speed measurement is required and the controller adapts to the parameter variations of the turbine or generator. By controlling the dc-link current through a current feedback control using PI controller, the active power (MPPT) can be controlled as it is simply a product of dc link input voltage and current.

Matrix Converter interfaced PMSG WECS

This topology has the advantage that generated voltage of PMSG is converted into desired AC output voltage without the need of any intermediate AC to DC conversion stage. Removing the dc link capacitor becomes the main attraction for matrix converter that has very high merit over back-to-back converter like free from commutation problems, improved voltage gain with simplified control, and extremely fast transient response [28]. Also, it provides the flexibility of more control levers for independent control on frequency, voltage magnitude, phase angle and input power factor. It depicted in Fig. 8.

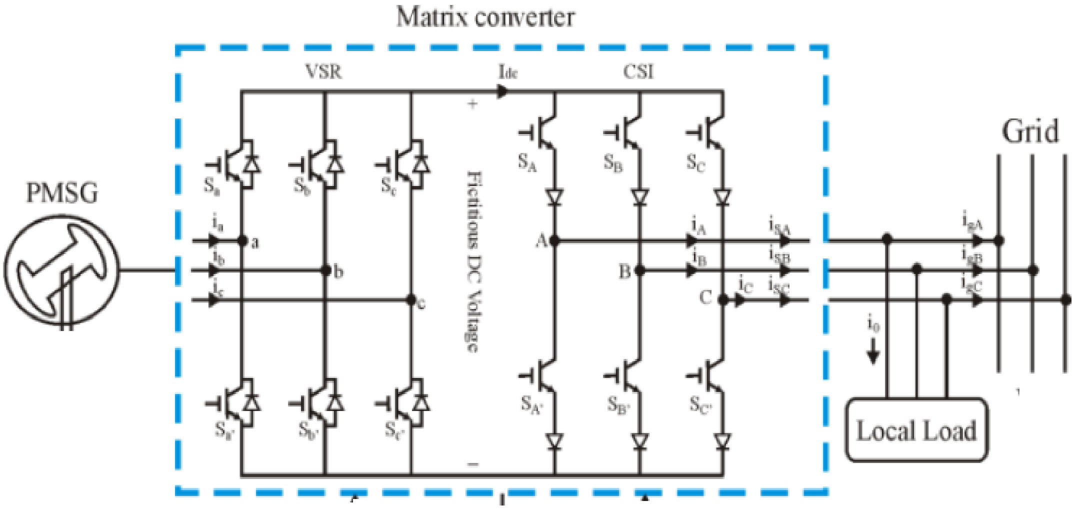


Fig. 8: Matrix Converter interfaced PMSG Wecs [28]

In [29] the output of PMSG is converted by a Reduced Matrix Converter (RMC), placed in the nacelle of each turbine, into a high frequency single phase AC voltage. The space vector pulse width modulation together with adaptive fuzzy logic control is used to enhance the performance of system under various abnormal conditions like abrupt change in wind speed, disconnection from grid, misfire in the converter, sudden out of one phase, change in load [30]. The control is based on the monitoring of the angular frequency which is compared with current reference value and then error is sent to the Adaptive Fuzzy Control System (AFCS), which generates the Space Vector PWM phase angle.

Comparison and discussion between all WECS converters

Taking into account MPPT control, Back-to-back PWM converter, Matrix Converter, three-level boost and NPC converter are the most promising solution converter topology for WECS. For power rating of 2MW or higher, the medium voltage (MV) back-to-back (BTB) neutral-point clamped (NPC) converters are most preferable choice for wind turbine manufacturers as they reduce cost, size and complexity of the system compared to the BTB two-level converters. The disadvantages of this topology are: pre-charging of the capacitors to the same voltage level is required, large number of capacitors makes the system bulky and expensive, balancing control of flying capacitor voltages is required. With the abilities of more output voltage levels, higher voltage amplitude and larger output power, multilevel converter topologies are becoming interesting and popular candidates in the wind turbines application [31, 32]. All of these solutions are already used by manufacturers Gamesa and Siemens. Back-to-back PWM converter is the most frequently used three-phase power converter topology so far in wind turbines systems [33, 34]. A technical advantage of the BTB PWM solution is the relatively simple structure and few components, which contributes to a well-proven robust and reliable performance. This kind of topology becomes our focal point in this work and the topology adopted is the same like the one presented in Fig. 6. The dc-link regulation is done by PI loop control as showed in Fig. 9.

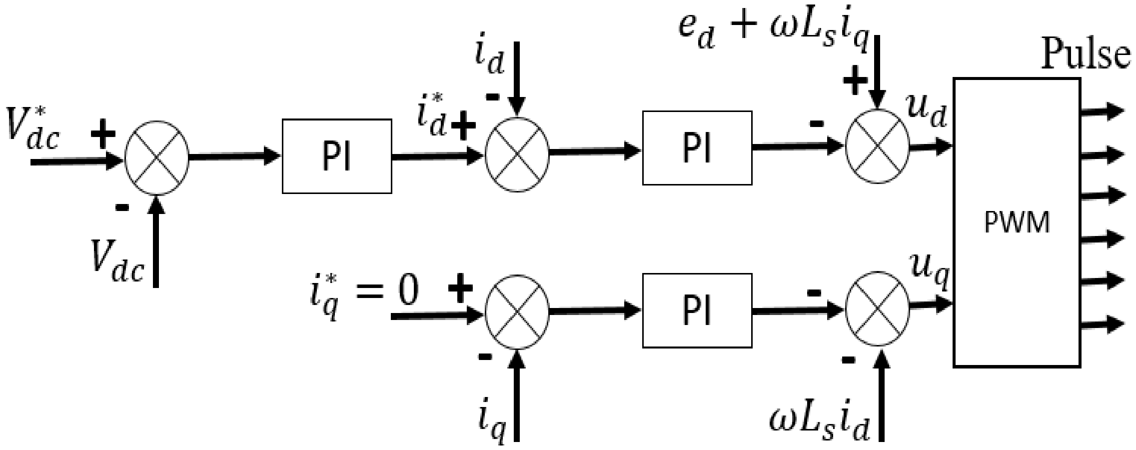
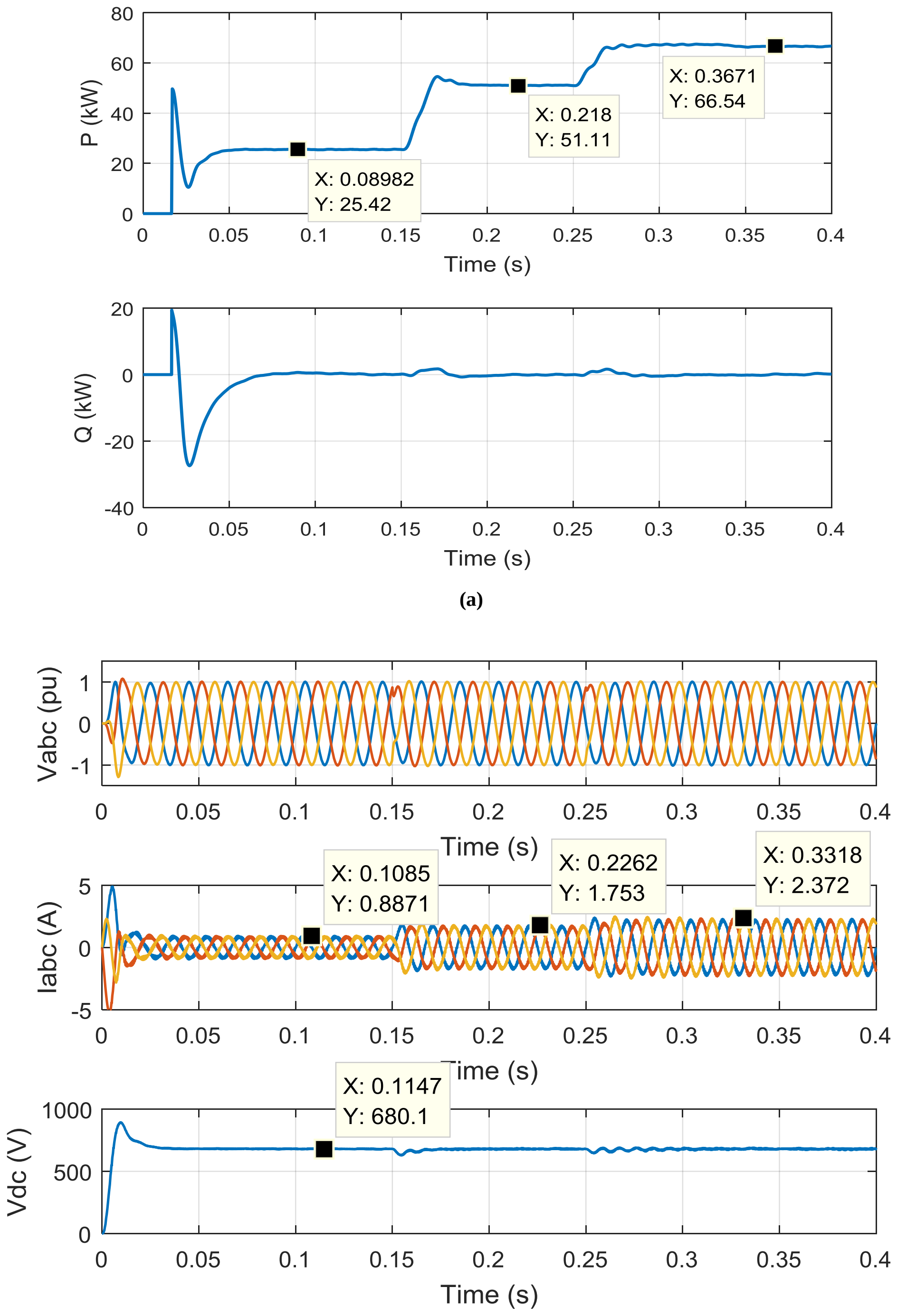


Fig. 9: Control loop for dc-link voltage regulation

V_{dc}^*, is reference value of V_{dc}, i_d and i_q are generator currents in d-q axis, with i_d^* and i_q^*, references values i_q^* is set to zero to get the unity power factor.

RESULT

Simulations were carried out using MATLAB/Simulink for 10 MVA, 25kV, 60 Hz WECS turbine to supply three loads on grid respectively 25 kW, 380 V, 50 Hz; 25 kW, 380 V, 50 Hz; 15 kW, 380 V, 50 Hz. The DC-link capacitor is 1800 µF and the DC-bus voltage is regulated to 680V. The size of the DC link capacitor of a VSC converter is determined by the Wc/Pnom ratio where Wc = energy stored in the capacitor bank at nominal DC link voltage (Joules) and Pnom = nominal power of the converter. The first load is connected at t=0s, the second one at t=0.15s and the last one at t=0.25s and the switching frequencies for converter is 2 kHz. The whole simulation is done from 0 to 0.4 s. The rests of the parameters of the system are presented in the appendix.



(a)

(b)

Fig. 10: Simulations result for the three phase back-to-back PWM converter: (a) active and reactive powers (b) grid voltage, loads currents and dc-link voltage regulation

DISCUSSION

In Fig. 10(a), the active power tracking for the three loads (connected at each time) and reactive power demand are showed while grid voltage and current and dc-link voltage are presented in Fig. 10(b). After t=0.025 s, the active power starts to increase to reach the rated value (25 kW) at t=0.005 s and is then kept constant till the next connection of the second load. The amplitude of the grid current (Fig. (b)) is proportional to that of the active power since its reactive component is zero. The same phenomenon is observed till the connection of the last load. It can be noted that the waveforms of three phase output currents are essentially sinusoidal. This result, in turn, demonstrates that there are no low order harmonics in the output voltage. As the load increase, the grid current increase and maximum power tracking is reached. This result is caused by choice of the parameters of input filter and PWM. It can be seen from the Fig. (b), besides, active power was transmitted to grid stably, DC-link voltage was restored to original value and remained stable after short-term regulation.

CONCLUSION

In this paper, an analysis based topology and control of WECS powers converters has been done. Several converters for marketed WECS generators have been discussed in term of cost and reliability and market penetration. PWM Back to back converter is one of the solution propose because of its simple structure and cost less and ability to track the maximum power. Finally, simulations have done to validate the potential of PWM Back to back converter with fast response.

Acknowledgement: None

Conflict of Interest: None

Source of Funding: None

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How to cite this article: Aguemon DP, Agbokpanzo RG, Dubas F et.al. Analysis on the topology and control of power electronics converters for wind energy conversion systems. *International Journal of Research and Review*. 2021; 8(8): 127-137. DOI: *https://doi.org/10.52403/ijrr.20210819*

APPENDIX

Parameters of the transformer between the WECS turbine and the converter:
Pn = 50 kVA, fn = 60 Hz
Winding 1: Vn = 25 kV, R = 50 Ω, L = 0.66315 H
Winding 2: Vn = 380 V, R = 0.034656 Ω, L = 0.00045964 H
PI parameters for rectifier side
Kp = 7, Ki = 800
PI parameters for inverter side
Kp = 0.3, Ki = 300

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