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# Rectifier Systems for Variable Speed Wind Generation – A Review

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*Abstract*-**The drive towards high efficiency wind energy conversion systems has resulted in almost all the modern wind turbines to operate in the variable speed mode which inevitably requires back-to-back power electronic converters to decouple generator dynamics from the grid. The aim of this paper is to present an analysis on suitable topologies for the generator-side converter (rectifier) of the back-to-back converter arrangement. Performance of the two most popular rectifier systems, namely, the passive diode bridge rectifier and the active six-switch two-level rectifier are taken as two extremes to evaluate other topologies presented in this paper. The other rectifier systems considered in this study include combinations of a diode bridge rectifier and electronic reactance(s), a combination of a rectifier and a dc-dc converter and a half controlled rectifier. Diode-clamped and capacitor-clamped three-level active rectifier topologies and their possible switch reductions are also discussed in relation to the requirements of modern high power wind energy conversion systems (WECSs). Simulation results are presented to support conclusion derived from this analysis.**

## I. INTRODUCTION

The back-to-back converter arrangement consists of a generator-side converter, an intermediate dc-link and a grid-side inverter. The generator side converter can be a passive rectifier, a hybrid rectifier or an active rectifier. The simplest and most popular passive generator-side converter is the diode-bridge rectifier. However, phase current harmonics and unregulated dc-link voltage with high ripple content are the major drawbacks of this topology. Multi-pulse rectifiers fed from phase shifted transformers are proposed to reduce ripples in the dc-link voltage [1]-[3]. However, the need of bulky transformers and increased component count make this solution not attractive for WECSs. Alternatively, electronic smoothening inductors can be used to reduce dc-link voltage ripples [4]. As a result of this voltage ripple cancellation, phase current harmonics also get reduced slightly. Moreover, the generator side, or in other words the ac-side, is found to be more suitable compared to the dc-side to have these electronic smoothening inductors connected since they help to compensate voltage drop across synchronous reactance of large permanent magnet synchronous generators (PMSG) [5][6]. However, all these topologies do not support dc-link voltage regulation.

Therefore, in order to regulate the dc-link voltage a dc-dc converter should be placed after the diode bridge rectifier [7] [8]. But, in terms of phase current harmonic distortion, the performance of this arrangement is still similar to that of electronic smoothening inductor based topologies [4]. The half controlled boost rectifier can be considered as the topology next in line capable of regulating the dc-link voltage. However, the absence of the sinusoidal shape in phase currents in alternative 60 degree intervals of a cycle, which is due to the lack of bridge symmetry, makes this topology is also an incomplete solution [9].

The full controlled six-switch two-level active rectifier can be considered as the ultimate solution capable of achieving both sinusoidal phase current impression and dc-link voltage regulation. But, it does not meet voltage, and consequently power, requirements of modern multi-megawatt (multi-MW) WECSs. In this context, diode-clamped and capacitor-clamped three-level converters have gained more attention [10]. These two topologies and possible switch reductions are also discussed in the latter part of the paper.

## II. CLASSIFICATION OF GENERATOR-SIDE CONVERTER SYSTEMS

The basic function of the generator-side converter is to convert alternating voltages and currents of the generator into dc quantities for the use of the subsequent grid-side inverter. And essentially, this is a unidirectional conversion since the wind turbine is only supposed to supply power to the grid, not the other way around. Therefore, the full spectrum of ac-dc converter topologies, shown in Fig. 1, is available for the generator-side converter design. Theoretically, all of these converter topologies can be used in WECSs. However, the selection of a suitable topology depends on number of factors such as power rating, power density, reliability/robustness, complexity, cost, dc-link voltage requirements, harmonic distortion, power losses etc. Therefore, the rest of this paper is aimed to give an analysis on each converter category, at least taking one topology from each category. Selected topologies are highlighted with bolded text in Fig. 1.

## III. PASSIVE RECTIFIER SYSTEMS

### *A. Diode-bridge rectifier*

The most simple generator-side converter is the diode-bridge rectifier shown in Fig. 2. Furthermore, the natural commutation of diode-bridge rectifiers eliminates the need for sensors, complicated controllers and gate drivers and thus the cost, power losses and failure rate are extremely low compared to any other rectifier arrangement. Moreover, the diode-bridge rectifier is a well matured product and thus high-power off-the-shelf modules are readily available in the market for direct deployment in wind generation systems. But, as mentioned before it has several drawbacks such as phase current harmonics, unregulated dc-link voltage and ripples in the dc-link voltage [9].

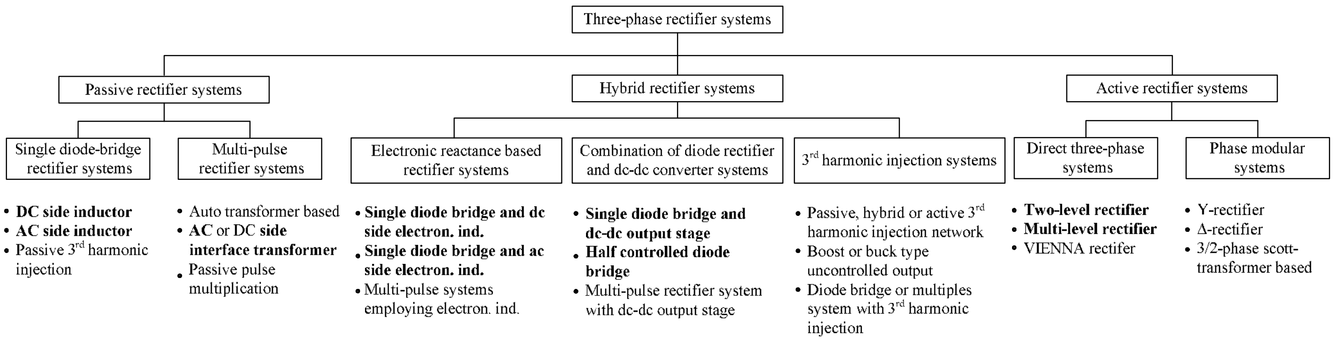



Fig. 1. Classification of three-phase rectifier systems [9].

Ripples in the dc-link voltage can be reduced with the use of a large dc-link capacitor as shown in Fig. 3(a) by the trace marked as $V_{dc}$. However, it increases the peak current stress on diodes as well. The corresponding current variation is also shown in the same figure by the trace marked as $i_a$. An enlarged view of this current waveform for $C$=2.5mF is shown in Fig. 3(b) and it reveals that the converter enters in to the discontinuous conduction mode (DCM) at high values of the dc-link capacitance [4], [9]. Consequently, harmonic distortion of phase currents gets increased as shown in Fig. 3(c). Therefore, dc-link capacitor alone cannot improve the performance of the diode-bridge rectifier and thus current smoothening inductor(s), either placed in the ac-side or dc-side as shown in Fig. 4(a) and Fig. 4(b) respectively is(are) compulsory [11].

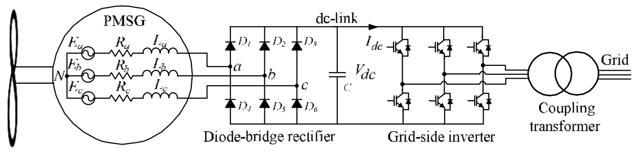



Fig. 2. PMSG based variable speed WECS with a diode-bridge rectifier as the generator-side converter.

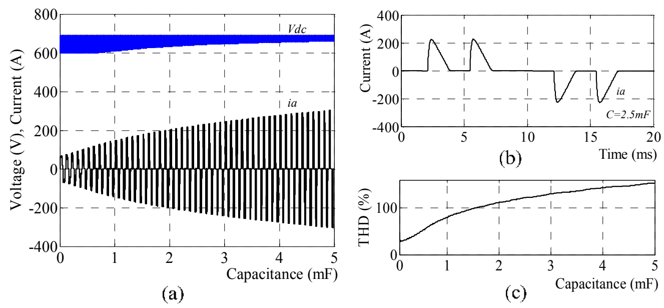



Fig. 3. Performance of diode-bridge rectifier (a) decrease in dc-link voltage ripples and increase in phase current spikes with the increase of dc-link capacitance, (b) shape of the phase current waveform at $C$=2.5mF, (c) increase of total harmonic distortion (THD) with the increase of dc-link capacitance.

Phase current waveforms of both systems at five discrete values of smoothening inductance are given in Fig. 4(c and d). According to Fig. 4(c) phase current becomes smooth and square in shape with the increase of the dc-side smoothening inductance. Consequently, THD gets reduced with the increase of the inductance as shown in Fig. 4(e). However, this improvement is far below compared to that of the ac-side smoothening inductance, shown in Fig. 4(d and f). Therefore, in terms of harmonic distortion, ac-side is preferred for the connection of smoothening inductor(s). However, smoothening inductors attached to the ac-side introduce voltage drops and thus the output voltage inevitably gets lowered with the increase of the inductance as shown in Fig. 4(h). On the other hand, the inductor attached to the dc-side does not introduce such drops and thus the output voltage is independent of the inductance as evident from Fig. 4(g). Therefore, in general, dc-side seems to be the better choice to have a smoothening inductor connected provided that the generator and the turbine are designed to withstand phase current harmonics with THD ≈ 28% and associated torque ripples.

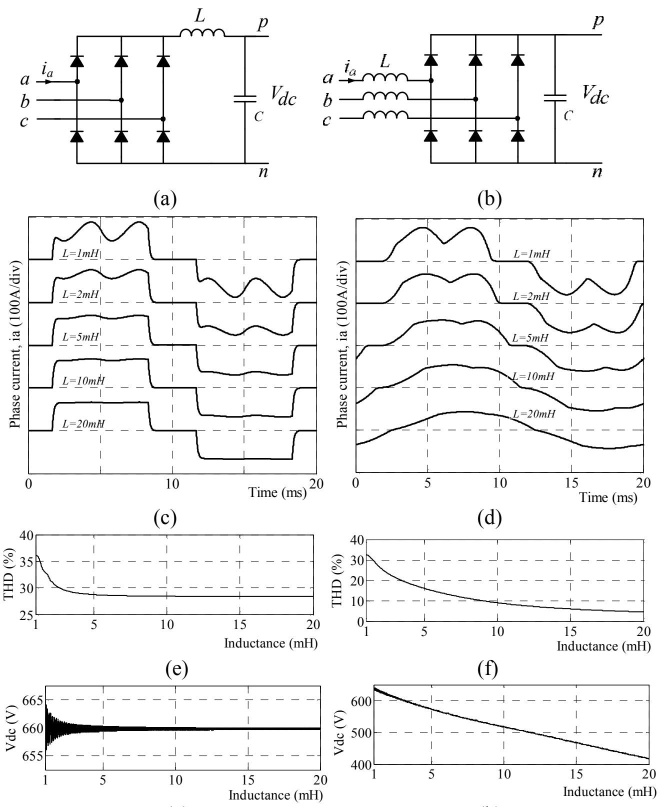



Fig. 4. Performance of diode-bridge rectifier (a) with a dc-side smoothing inductor, (b) with ac-side smoothing inductors, (c) (d) phase current, $i_a$, at five different inductor values, (e) (f) variation of THD with inductance, $L$, (g) (h) variation of the dc-link voltage with inductance, $L$.

The absence of voltage boosting is another disadvantage of the diode-bridge rectifier since the dc-link voltage varies with the speed of the generator as shown in Fig. 5(a) [12]. The corresponding power and current variations are also shown in the same diagram. The variations of inverter output voltage and power angle required to transfer the captured wind power into to an infinite bus at unity displacement power factor are shown in Fig. 5(c) and Fig. 5(d) respectively. A simple comparison between the two voltage variations shown in Fig. 5(a) and Fig. 5(c) reveals that the required inverter output voltage variation is extremely lower compared to that of the rectifier output voltage. In numerical terms, the voltage at the rectifier terminal doubles for a wind speed change from 0.5 p.u. to 1.0 p.u., whereas the required increase of the inverter output voltage is less than 10%. The grid-side inverter satisfies both of these voltage changes by varying the modulation index as shown in Fig. 5(b) [13].

The modulation index is set to 1.0 for the minimum dc-link voltage at the rectifier terminal which corresponds to the cut-in wind speed of the wind turbine generator. The modulation index is then reduced with the dc-link voltage. Consequently, a rather low modulation index (about 0.3) has to be used for the rated wind speed. This high power delivery at low modulation indices results in poor switch utilization in the grid-side inverter [13].

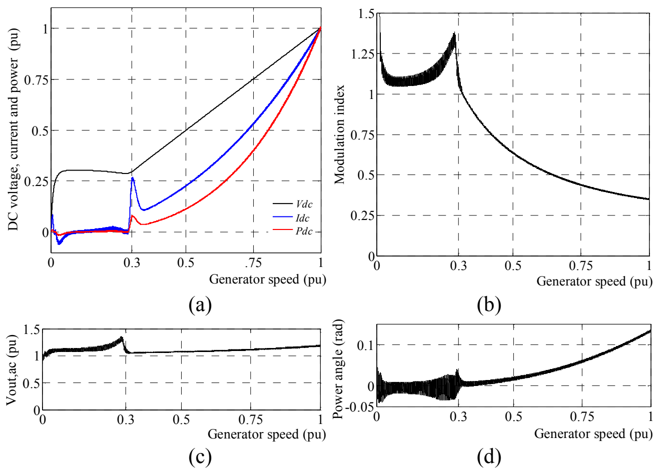



Fig. 5. (a) Variation of the output voltage, current and power of a diode-bridge rectifier, (b) modulation index of the grid-side inverter, (c) output voltage of the grid-side inverter, (d) power angle.

## B. *Multi-pulse rectifier*

An improvement suggested to overcome some of the aforementioned drawbacks is the use of multi-pulse rectifiers [1][2] [14][15]. This is basically series or parallel connection of standard diode-bridge rectifiers through phase shifting transformers as shown in Fig. 6(a) and Fig. 6(b) respectively [15]. With the introduction of these transformers dc-link voltage ripples of the two rectifiers get phase shifted by $30^0$ as shown in Fig. 6(c and d). As a result, part of dc-link voltage ripples get cancelled out and the end result will be a more smoothened voltage. Phase current harmonics also get reduced as shown in Fig. 6(e and f).

With the results shown in Fig. 6(c to f) it is clear that 12-pulse rectifier shows significant improvements in the reduction of dc-link voltage ripples and phase current harmonics. The same analysis can be extended for higher order systems, such as 18-pulse rectifiers, 24-pulse rectifiers etc., and can be shown that it is possible to reduce the dc-link voltage ripple down to 5% and THD in phase currents down to 1% with the increase in the number of diode-rectifier modules [14] [15].

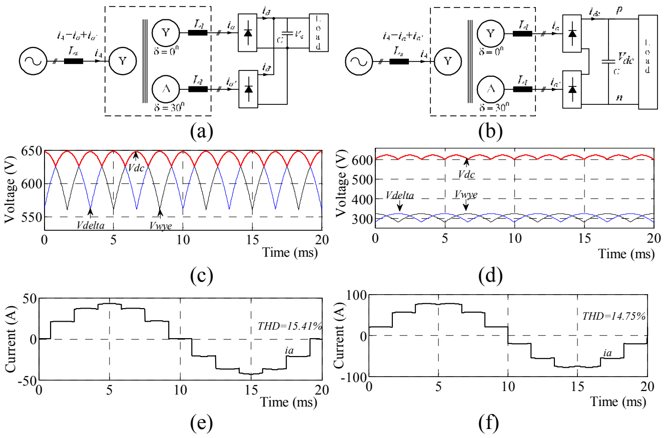



Fig. 6. (a) Parallel connected 12-pulse rectifier, (b) series connected 12-pulse rectifier, (c) (d) individual rectifier voltages and the total dc-link voltage, (e) (f) phase current, $i_a$.

# IV. HYBRID RECTIFIER SYSTEMS

As seen in the previous section, multi-pulse rectifier systems show significant improvements in terms of dc-link voltage ripple reduction and phase current harmonic mitigation. But the increase in the diode count and, specially, the need of additional phase shifting transformers make multi-pulse rectifiers less attractive in wind generation systems. Therefore, alternative technologies have been developed to address the issues of dc-link voltage ripples and phase current harmonics of conventional 6-pulse rectifiers.

## A. *Electronic reactance based hybrid rectifier systems*

As discussed at the beginning of Section III, the major drawbacks of the 6-pulse rectifier are dc-link voltage ripples, phase current harmonics, torque ripples on the generator and current stresses on the dc-link capacitor. The same section has emphasized that the solution is based on adding smoothening inductors to the ac-side or dc-side. However, large smoothening inductors increase the cost, weight and volume of the converter. Moreover, they degrade the dynamic response.

Therefore, instead of passive smoothening inductor a small power electronic unit, known as electronic smoothening inductor (ESI), can be used to obtain similar performance [4]. The schematic diagram of the dc-side ESI implementation is shown in Fig. 7(a). The ESI is only supposed to absorb voltage ripples and thus its switches can be rated only for the ripple voltage and not for the total dc-link voltage. Therefore, power rating of the ESI can be reduced down to 12% of the rated power of the rectifier.

A simulation was carried out with and without the ESI to show its efficacy and the corresponding results are shown in Fig. 7(b to d). In the first half of the simulation the ESI was disabled and thus usual current and voltage waveforms of a diode-bridge rectifier appear as shown in the first half of Fig. 7(c and d). The ESI was turned on at 20ms and therefore voltage and current waveforms get smoother proving the efficacy of the ESI. Similar analysis can be carried out for the ac-side implementation of the electronic inductance and show that it behaves in the same way and reduces dc-link voltage ripples and current harmonics.

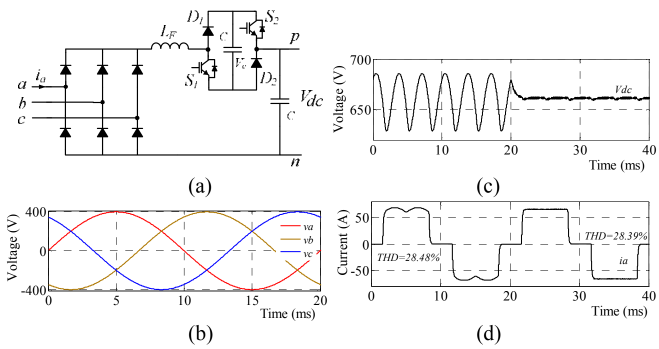



Fig. 7. (a) Schematic diagram of the dc-side ESI implementation, (b) supply voltage, (c) dc-link voltage without and with ESI, (d) phase current without and with ESI.

Voltage drop across synchronous reactance is significant in large PMSGs [5]. However, the above topology with an electronic inductance attached to the dc-side does not help to solve this problem. Therefore, instead of the dc-side three ESI units can be connected in series with the generator outputs as shown in Fig. 8(a) and operate them as electronic capacitors. This arrangement is known as magnetic energy recovery (MER) [4][5][16][17]. Single line diagram of this arrangement and corresponding vector representations are shown in Fig. 8(b) and Fig. 8(c and d) respectively. The vector diagram shown in Fig. 8(c) corresponds to a general rectifier without magnetic energy recovery switches (MERSs). It can clearly be seen from this diagram that the output voltage $U$ is obviously lower than the induced voltage $E$ of the generator. Moreover, power factor is also less than the unity. MERSs compensate the voltage drop across the inductor by acting as series connected capacitors. The corresponding vector diagram is shown in Fig. 8(d)

In order to evaluate performance of MERSs, simulations were carried out for three systems. The first system contained only a conventional diode-bridge rectifier. The second system was equipped with MERSs. In the third system MERSs were replaced with capacitors so that it gives a clear comparison between MERS and series compensation with capacitors. The corresponding output voltages for different loading conditions are shown in Fig. 9(a) which proves the efficacy of MERSs in compensating the voltage drop across synchronous reactance of the PMSG. Furthermore, it shows that series connected capacitors are not as effective as MERSs.

Due to the voltage drop across synchronous reactance the amount of power that can be taken out from the generator also drops. In that context, MERSs help to increase the output power as well. The corresponding power variations against different loading conditions are shown in Fig. 9(b). Generator voltage and current waveforms of the $a$-phase are shown in Fig. 9(c). An enlarged view of this diagram is given in Fig. 9(d) to illustrate the power factor correction feature of MERSs. Based on these results it can be concluded that MERSs significantly improve the power factor as well.

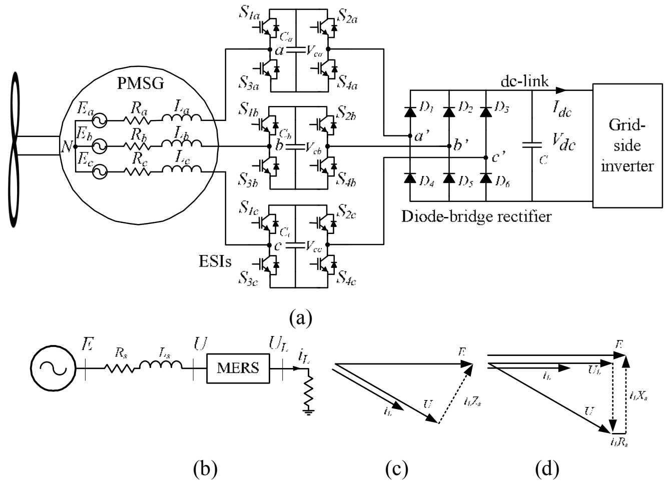



Fig. 8. (a) Schematic diagram of the ac-side ESI implementation, (b) single-line diagram, (c) vector diagram showing voltage and current vectors without MERS, (d) vector diagram showing voltage and current vectors with MERS.

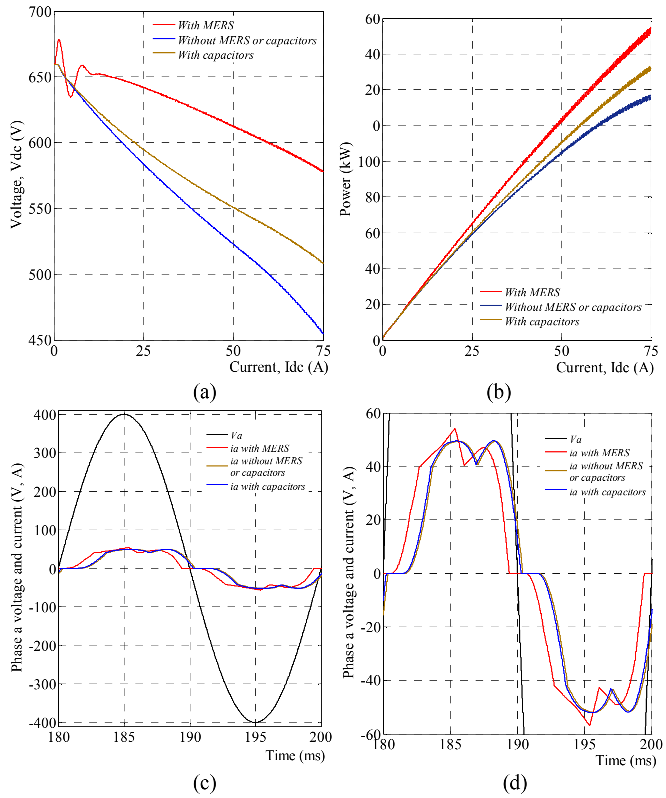



Fig. 9. Efficacy of MERSs (a) dc-link voltage, (b) output power, (c) supply voltage and current of the a-phase, (d) enlarged view of the supply voltage and current of the a-phase.

### *B. Combination of a diode-bridge rectifier and a dc-dc converter*

Even though aforementioned ESI based rectifiers are capable of performing MER, reducing voltage ripples and current harmonics, the problem of unregulated dc-link voltage is still present. As a result, grid-side inverter operates at low modulation indices at high power conditions resulting in poor switch utilization. Therefore, all these topologies require an intermediate dc-dc converter stage for dc-link voltage regulation and thus meet requirements of modern WECSs.

The intermediate dc-dc converter can be a buck converter, boost converter or buck-boost converter. However, out of these three configurations boost converter is the most popular and therefore, the following analysis is based on the single switch boost converter (also known as boost chopper) topology. Schematic diagram of this particular topology is shown in Fig. 10(a). In some cases the winding inductance of the PMSG itself can effectively be used as the boosting inductor and therefore only an additional diode and a switch would suffice to implement the boost chopper as shown in Fig. 10(b). The voltage waveforms shown in Fig. 10(c) demonstrate the voltage regulation capability of the boost rectifier with dc-side inductor. Furthermore, it produces the same output voltage even at increased values of the boosting inductance. In contrast, the boost rectifier with ac-side inductors, shown in Fig. 10(b), looses voltage regulation after certain values of the boosting inductance. The corresponding simulation results are shown in Fig. 10(d) where the output voltage is regulated at 600V for inductor values up to 2.5mH. Further increase of the inductance decreases the output voltage and the power factor.

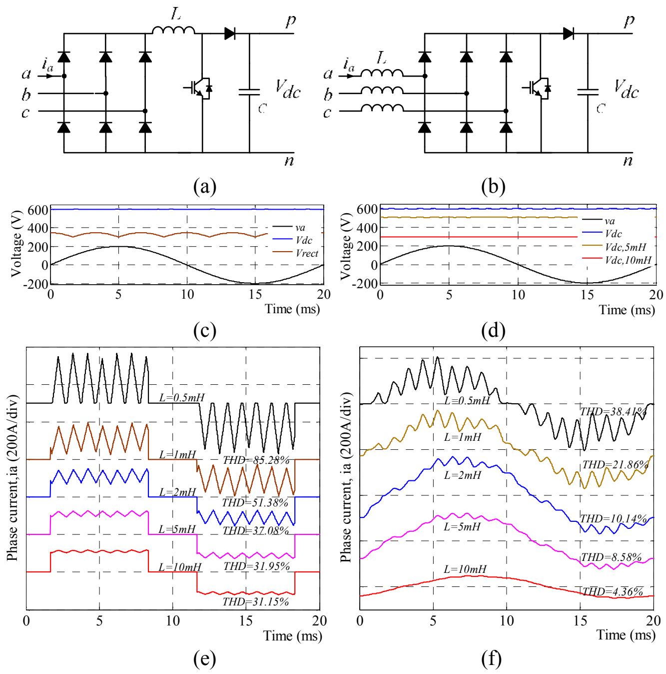



Fig. 10. (a) Boost rectifier with a dc-side boost inductor, (b) boost rectifier with ac-side boost inductors, (c) (d) supply voltage and output voltage, (e) (f) phase current, $i_a$, at different inductor values.

A close look on current waveforms shown in Fig. 10(e) would reveal that the optimum shape of phase current that can be obtained from the boost rectifier with dc-side inductor is more or less similar to that of electronic smoothening inductance based implementations. The only difference is voltage regulation. In contrast, the boost rectifier with ac-side inductors significantly improves the THD as shown in Fig. 10(f). Therefore, this arrangement would be more suitable for PMSG based WECSs with large synchronous reactance that can effectively be used as boosting inductors [18].

Both arrangements of the boost rectifier, shown in Fig. 10(a and b), results in high THD at low inductor values and low loading conditions. Moreover, high peak current loading on semiconductor devices and the large EMI filter effort make these two boost topologies not suitable for modern multi-MW WECSs [9][19]. A solution has been proposed in [2] with the phase-shifted operation of three interleaved converter units as shown in Fig. 11. Each converter unit of this arrangement equally contributes for the output power and thus the stresses on power devices drop to 1/3 compared to the arrangements shown in Fig. 10(a and b). Furthermore, the phase shifted operation reduces the current ripple and as a result THD becomes very low.

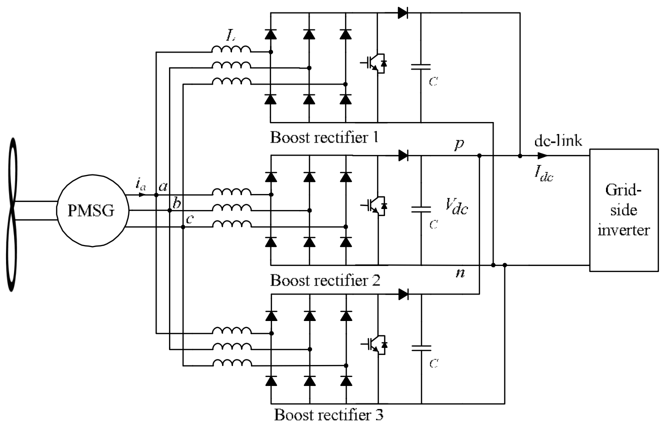



Fig. 11. Interleaved three-unit boost rectifier.

Two simulations were carried out to compare performance of the conventional operation and phase shifted operation of the above rectifier in terms of THD in phase currents at low loading conditions. In the conventional operation, the same carrier waveform is used to perform pulse width modulation (PWM) of each converter switch. As a result, all the converters conduct at the same time resulting increased ripples in individual phase currents and the total phase current as shown in Fig. 12(a) and Fig. 12(c) respectively. In contrast to this, the phase shifted operation uses three carriers which are phase shifted by $120^0$ and as a result each converter unit conducts at different intervals as shown in Fig. 12(b). This helps to reduce ripple in the total phase current as shown in Fig. 12(d).

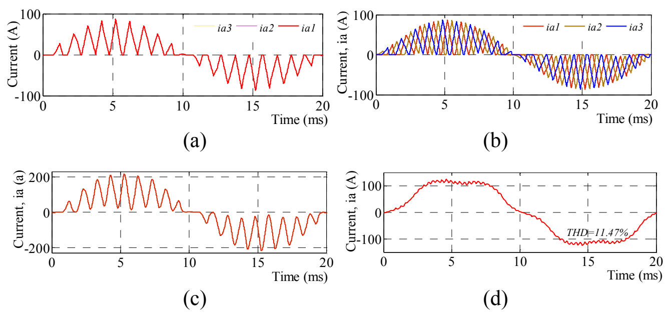



Fig. 12. (a) (b) Phase current, $i_a$, of individual converter units, (c) (d) total current in the $a$-phase.

## C. Half controlled diode-bridge rectifier

Even though the interleaved three-unit boost rectifier, shown in Fig. 11, is capable of reducing harmonic distortion in phase currents it requires additional boosting inductors, diodes and switches and thus would not be feasible for WECSs. In this context, the half controlled diode-bridge rectifier shown in Fig. 13(a) can be considered as the alternative solution with reduced component count [20]-[23].

The half controlled rectifier can be controlled in two ways. In the first and most simple method all three switches are controlled using a common PWM signal [9][18][20][21]. In other words, they are turned on and off simultaneously. This unified operation reduces the complexity of the controller. In this operation, the upper three diodes, $D_1$-$D_3$ act as boosting diodes. The equivalent circuit for an instance where the phase-$a$ voltage, $E_a$, is most positive and the phase-$c$ voltage, $E_c$, is most negative is shown in Fig. 13(b). When both phase-$a$ and phase-$b$ are positive and the switches are turned-on the current is built up in all three phases. During the off time, the stored energy in inductors is released to the load at a boosted output voltage. The magnitude of the dc-link voltage can be controlled through the duty cycle of the switches. At this particular instance, the diodes $D_1$ and $D_2$ act as boosting diodes. The diodes $D_3$ is in the reverse biased condition. The generator winding inductances act as boosting inductors. The boosting switches $S_1$ and $S_2$ complete the structure of the boost converter. When the phase-$b$ voltage is negative it conducts until the inductor $L_b$ gets discharged.

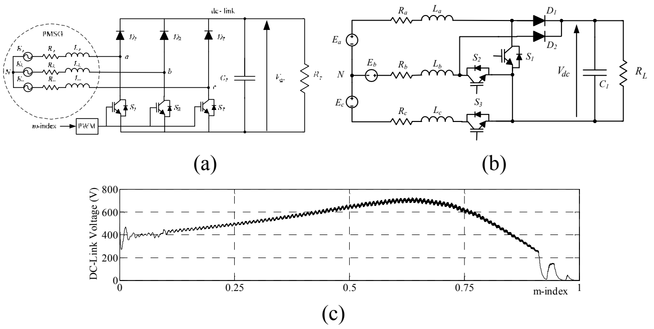



Fig. 13. (a) Half controlled diode-bridge rectifier, (b) equivalent boost converter, (c) variation of the dc-link voltage with the modulation index..

Similar diagrams can be drawn for other instances as well to analyze the boosting operation. For low modulation indices the output dc-link voltage shows a linear relationship with a peak at 0.65 as shown in Fig. 13(c). Further increase of the modulation index will reduce the output voltage and it collapses near unity index due to the short circuit of phase windings. At very low modulation indices, near zero, this rectifier behaves exactly like an uncontrolled rectifier.

Simulation results for this unified operation are shown in Fig. 14(a and b). The $a$-phase input voltage and output voltage are shown in Fig. 14(a). The corresponding phase current waveforms at different inductor values are shown in Fig. 14(b). These current waveforms prove the superiority of the half bridge rectifier in reducing THD compared to aforementioned single-switch boost rectifier for a given boosting inductance.

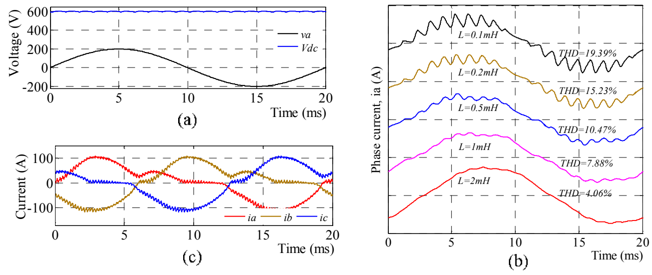



Fig. 14. (a) Supply voltage and output voltage of a half controlled rectifier, (b) phase current, $i_a$, at different inductor values with control method 1, (c) phase current, $i_a$, with the control method 2

Even though the aforementioned control method is simple it does not provide power factor correction. In contrast, the second control technique enables power factor correction. In this method the input voltages are measured and then phase angle is derived using a phase locked loop. Phase currents are also measured, converted into the synchronous reference frame and controlled to bring the power factor to unity. Subsequently, conventional space vector or carrier based PWM can be used to control switches. This brings the power factor closer to unity as shown in Fig. 14(c). However, due to the lack of bridge symmetry the half controlled rectifier can impress sinusoidal phase currents only when two phase voltages are positive. Therefore, harmonic distortions in phase currents appear in alternative $60^0$ intervals.

# V. ACTIVE RECTIFIER SYSTEMS

## A. Full controlled two-level active rectifier

With the above analysis it can be concluded that the bridge symmetry is indispensable if the rectifier is supposed to achieve both voltage regulation and sinusoidal current impression [9]. The most common and well matured converter topology that produces the bridge symmetry is the standard six-switch two-level active rectifier shown in Fig. 15(a). The variation of the $a$-phase current of the generator-side converter is shown in Fig. 15(b). According to this figure THD of phase current is reduced to 1.38%. This is a significant improvement compared to all the aforementioned rectifier systems. DC-link voltage regulation capability of this topology is well known and hence will not be discussed here exclusively [24].

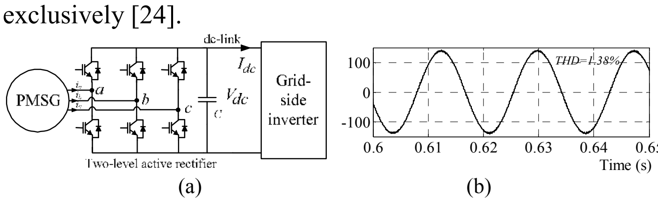
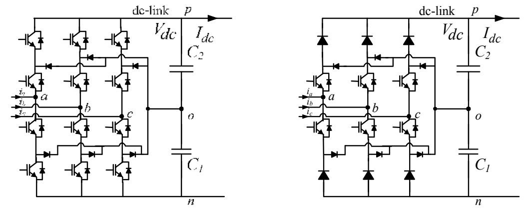



Fig. 15. WECS with a full controlled two-level active rectifier and inverter.

## B. Full controlled diode-clamped three-level active rectifier

Traditional six-switch two-level rectifiers do not meet voltage and power requirements of modern multi-MW WECSs [10][25][26][38]-[40]. As a result, diode-clamped and capacitor-clamped three-level rectifiers have become popular [25]-[30]. Schematic diagram of the standard diode-clamped three-level active rectifier is shown in Fig. 16(a). Compared to the two-level converter, this topology can either double the dc-link voltage from a given ac-supply or reduce voltage stress on switching devices to a half if the same dc-link voltage is used [29][31]. The three-level diode-clamped converter shown in Fig.16(a) possesses the bi-directional power flow capability which is not essential in WECSs. Therefore, it is possible to remove some of the switches as shown in Fig. 16(b) [32][33].

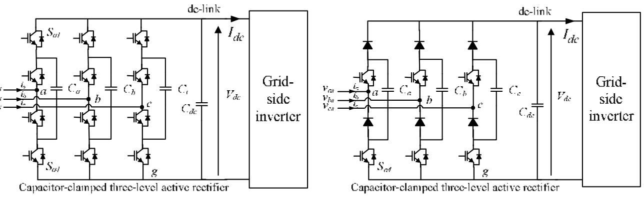



(a) (b)

Fig. 16. (a) Diode-clamped three-level active rectifier, (b) possible switch reductions.

### C. Full controlled capacitor-clamped three-level active rectifier

Schematic diagram of the standard capacitor-clamped three-level active rectifier is shown in Fig. 17(a). This converter produces three voltage levels under balanced conditions and four voltage levels under unbalanced conditions [34] [35]. Switch reduction is possible for this converter topology as well and the corresponding reduced generator-side converter is shown in Fig. 17(b) [33].




(a) (b)

Fig. 17. (a) Capacitor-clamped three-level active rectifier, (b) switch reductions.

In comparison to the diode-clamped three-level inverter component count is low in the capacitor-clamped converter. However, drawbacks of clamping capacitors, such as bulkiness and less reliability make this converter not very attractive in WECSs. However, these drawbacks can be overcome by replacing conventional clamping capacitors with compact and highly reliable supercapacitors and making the converter to absorb short term wind power fluctuation [35].

## VI. WECSs WITH MULTIPOLE SPLIT-WINDING PMSGs

Multipole PMSGs with full-power back-to-back converters appear to be the configuration adopted by most of the large wind-turbine manufactures in the near future [10]. The major problem in interfacing such machines to the grid is the limitation imposed by the ratings of currently available switching devices in the converter [36]. The current approach to realize the back-to-back converter with existing devices is the use of several converter modules in parallel and supply them up through split windings of the generator [10] [37]. Furthermore, parallel modules provide redundancy and harmonic reduction through interleaved modulation. The two most common arrangements of converter modules are shown in Fig. 18. The converter module shown in Fig. 18(a) can be a fully controlled two-level back-to-back system or a boost rectifier followed by a two-level inverter. A transformer is also required for the grid integration. On the other hand, the configuration shown in Fig. 18(b) does not require such transformer and thus more attractive for nacelle installation. The power electronic building blocks in this arrangement consist of a rectifier (diode-bridge or a boost) at the generator side and a H-bridge on the grid-side as shown in Fig. 18(c).

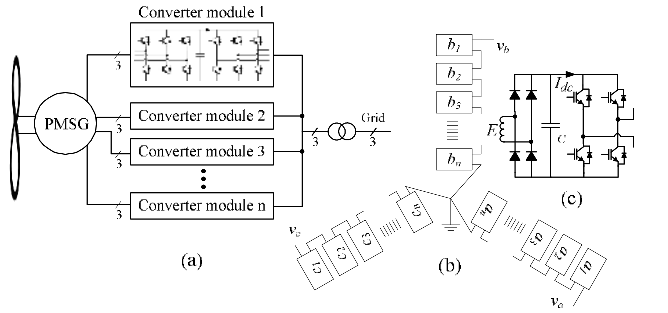



Fig. 18. (a) Power converter topology with modules connected in parallel, (b) transformer less grid interface with series connected modules, (c) internal arrangement of power electronic building blocks.

## VII. CONCLUSIONS

This paper presents an analysis of generator-side converter topologies that are suitable for PMSG based WECSs. The diode-bridge rectifier is the simplest generator-side converter. However, phase current harmonics and unregulated dc-link voltage with high ripple content are the major drawbacks. Even though, multi-pulse rectifiers are capable of reducing dc-link voltage ripples the need of bulky transformers and increased component count make this solution not attractive for WECSs. Alternatively, electronic smoothening inductors can be used to reduce dc-link voltage ripples. Generator-side is found to be more suitable to have electronic smoothening inductors connected owing to the possibility of compensating voltage drop across synchronous reactance of large PMSGs.

In order to regulate the dc-link voltage, an intermediate dc-dc converter can be placed after the diode-bridge rectifier. However, in terms of phase current harmonic distortion performance of this arrangement is still similar to that of electronic smoothening inductor based topologies. Even though, the half controlled boost rectifier regulates the dc-link voltage it can produce sinusoidal phase currents only at alternative 60 degree intervals due to the lack of bridge symmetry.

The full controlled six-switch two-level rectifier is the ultimate solution which can produce both sinusoidal phase currents and dc-link voltage regulation. However, it does not meet voltage and power requirements of modern multi-MW WECSs. In this context, diode-clamped and capacitor-clamped three-level converters gained more attention. Furthermore, owing to the unidirectional power flow of wind generators, it would be possible to implement these topologies with reduced number switches. The trend towards multipole split-winding PMSGs in modern WECSs and suitable multi-module converter topologies are also discussed.

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