A New 3-Phase 3-Wire 3-Level AC-DC Converter for Wind Energy Conversion Systems

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***Abstract*—This paper presents a new 3-phase 3-level 3-wire AC-DC converter structure for wind energy conversion systems (WECS). The multi-channel converter architecture with a phase shifting principle is proposed to solve the technical challenges of future MV PMSG WECS with 5 – 20 MW power rating. Also, the Discontinuous Conduction Mode (DCM) operation is used to achieve a low-cost solution and to reduce the control complexity. In case of 5 – 20 MW output power levels, the input and output ripple currents at the inductance and capacitance filters are studied using PSPICE simulation analysis. Simulation results demonstrate that the input and output ripple currents are reduced significantly, which lead to smaller inductance and capacitance values so that high-efficiency, high-reliability and light-weight WECS can be realized.**

Keywords— 3-phase 3-level 3-wire AC-DC converter, medium voltage PMSG, DCM operation, interleaving technique, power factor correction, wind energy conversion systems

I. INTRODUCTION

Today's wind energy conversion systems (WECS) are evolving toward medium voltage (MV) power converters with 10 MW - 20 MW Permanent Magnet Synchronous Generator (PMSG) power rating. The 10 MW wind turbines have been reported by the Sway Turbine AS. At the same time, the GE Energy is developing 15 MW turbines. The market trend shows that 10 - 20 MW turbines will be functioning in near future with rotor diameters more than 150 m [1] – [4]. The technical challenges of today's and future MV WECS are how to provide a low-cost solution, light-weight, high power density and highly efficient power processing system. In case of 10 MW - 20 MW PMSG power rating of wind turbine, high reliability and high fault tolerant MV power converter with high power factor correction, low-ripple input and output currents capability are also critical requirements for wind turbine life cycle [5], [6].

In recent years, a MV AC-DC converter system with diode bridge rectifier and 3-level boost converter architecture, as shown in Fig. 1, have been reported for WECS [7]. Indeed, diode bridge rectifier configuration is a cost-effective solution and a low complexity design, but according to the research that conducted by Chalmers University Of Technology [8], diode bridge structure can not provide maximum output power from MV PMSG. Unlike 2-level voltage source converter that can deliver maximum output power due to unity power factor correction, the pure diode bridge rectifier is only deliver 50% to the output stage [8]. From the engineering point of view, in case of 10-20 MW PMSG power rating, it is a questionable approach because the power availability of the MV PMSG is sacrificed. Besides, actually, the flow of current from the

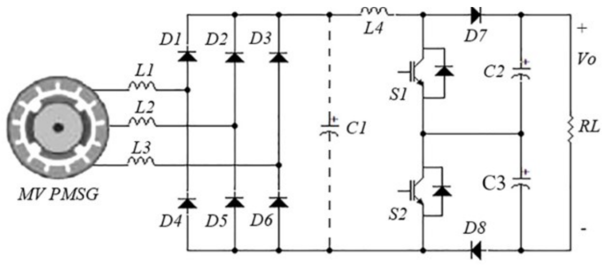


Fig. 1. Conventional MV AC-DC converter system with diode bridge rectifier and 3-level boost converter architecture

PMSG to the output stage is processed two times. When the switches S1 and S2 are turned off, the current flows not only through diode bridge rectifier, but also via diodes D7 and D8 in a series connection of Kirchoff Current Law. It means that higher conduction losses can not be avoided. Moreover, each diode of the diode bridge needs voltage rating equal to the output voltage *Vo*. In case of 3 MW 3500 V PMSG, diode D1 needs two diode modules 5SLD 0600J650100 in a series connection. Furthermore, a single channel MV converter structure suffers high input and output current ripple stresses. Consequently, bulky input and output capacitors with limited life cycle can reduce the reliability of the wind turbine system. For these reasons, a new 3-phase 3-level 3-wire MV AC-DC converter for WECS is proposed in this paper.

II. PROPOSED MV AC-DC CONVERTER

Fig 2 reveals the proposed 3-phase 3-level 3-wire MV AC-DC converter for WECS. This circuit is a single-stage AC-DC power processing system. Table I shows the parameters of the proposed converter. Fig. 3 illustrates the working principle of the proposed 3-phase 3-wire 3-level AC-DC converter when the switches S1 and S2 are turned-on and turned-off. Fig. 3(a) describes a steady state condition when the switches S1 and S2 are turned-on at the same time and the current flows from L1 to L2 and L3. Fig. 3(b) shows the flow of current after the switches S1 and S2 are turned-off.

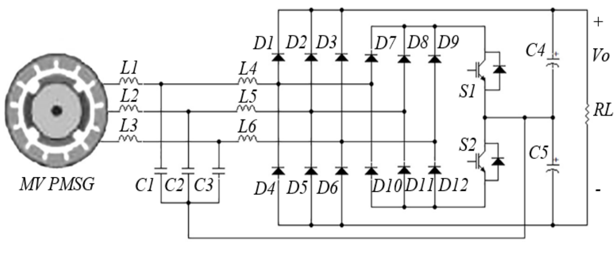
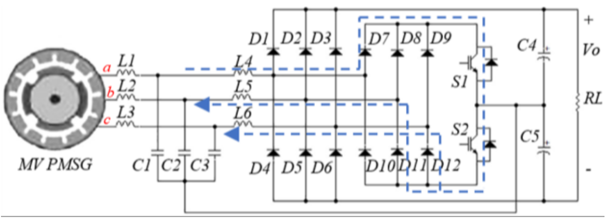


Fig. 2. Proposed 3-phase 3-level 3-wire MV AC-DC converter structure for wind energy conversion systems

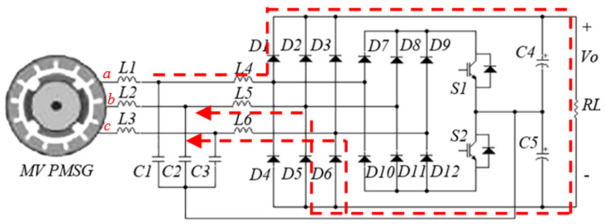
As can be seen in Fig. 3(b), when the switches S1 and S2 are turned-off, the current flows from the PMSG to the load only through two diodes (D1 and D5/D6) in a series connection. Consequently, this power processing mechanism reduces the conduction losses when the switches S1 and S2 are turned-off. Unlike the conventional MV AC-DC converter system with diode bridge rectifier and 3-level boost converter architecture in Fig. 1, when the switches S1 and S2 are turned-off, the current flows from the PMSG to the load through four diodes (D1, D7, D8, D5/D6).

TABLE I. PARAMETERS OF THE PROPOSED CONVERTER (FIG. 2)

Component:	***Parameter:***
MV PMSG	3 MW, 3000 V
Inductor L1, L2, L3	3600 uH
Inductor L4, L5, L6	700 uH
Capacitor C1, C2, C3	165 uF
Capacitor C4, C5	1850 uF
Switching frequency	1 kHz
Pulse witdh, duty cycle	190 us, 19 %
IGBT module S1, S2	5SNA 1200G450300, 4500 V, 1200 A
Diode module D1 – D12	5SLD 0600J650100, 6500 V, 2 x 600 A



(a)



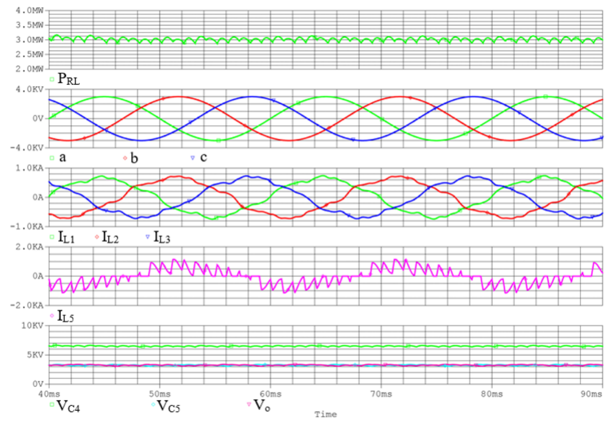
(b)

Fig. 3. The working principle of the proposed 3-phase 3-wire 3-level AC-DC converter structure for WECS (a). S1 and S2 ON states. (b). S1 and S2 OFF states

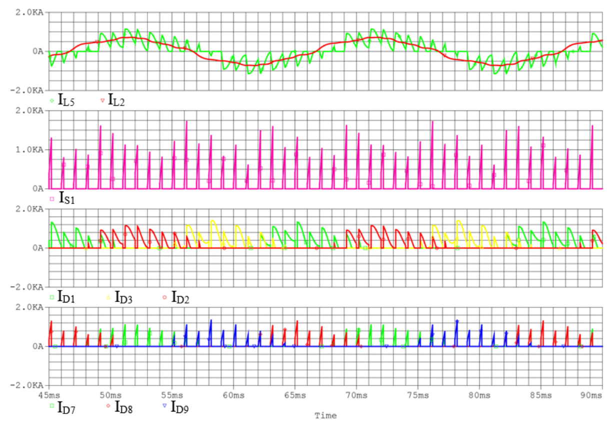
III. SIMULATION RESULTS

Fig. 4 demonstrates the simulation results of the proposed 3-phase 3-wire 3-level MV AC-DC converter for wind energy conversion systems. As shown in Fig. 4(a), the converter produces 3 MW output power (P_{RL}). The input currents I_{L1}, I_{L2} and I_{L3} shows that a better power factor correction can be achieved compared to diode bridge rectifier. The current at I_{L5} indicates that the MV AC-DC converter is designed to operate in discontinuous conduction mode (DCM) to reduce the control complexity. As a result, symmetrical dc-link voltages at V_{C4} and V_{C5} can be attained. Fig. 4(b) depicts the current stress at switch S1 (I_{S1}). The behavior of the currents I_{D1}, I_{D2}, I_{D3}, I_{D7}, I_{D8}, I_{D9} are also shown in this picture. Fig. 4(c) describes the ripple current stress at the input capacitors I_{C1}, I_{C2} and I_{C3} and at the output capacitors I_{C4} and I_{C5}. The voltage stress of the switches S1 and S2 (VCE_{S1}, VCE_{S2}) are about 3.5 kV or 50% of the output voltage *Vo*. The voltage stress of diodes D1 and D7 are the same as the output voltage. Actually, D1 – D12 suffer a voltage stress equal to the output voltage.

To increase the output power P_{RL} with lower ripple current stress at the input and output stages, the interleaving technique of 2-channel converters with a phase shift 180° is proposed, as illustrated in Fig. 5. The interleaving technique is not only provides low-ripple input and output currents, but also smaller input inductance and capacitance values can be obtained to increase the reliability and to provide a light-weight solution.



(a)



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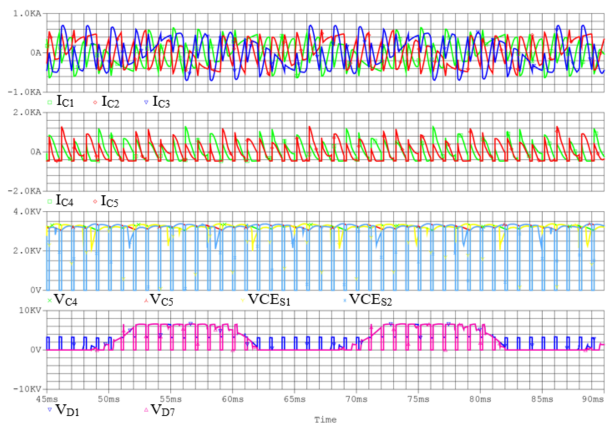


(c)

Fig. 4. Simulation results of the proposed 3-phase 3-wire 3-level MV AC-DC converter for wind energy conversion systems based on Fig. 3 and Table I.

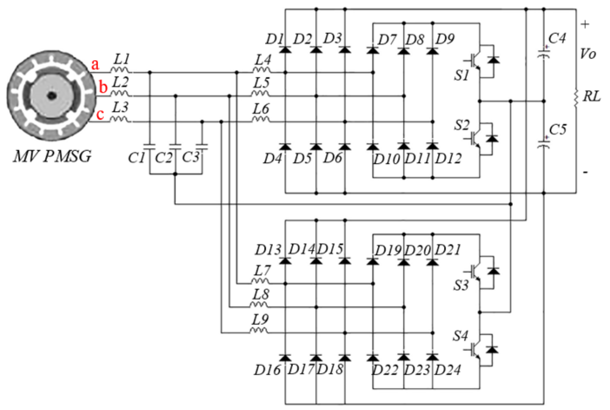


Fig. 5. 2-channel interleaving technique with a phase shift 180° of the MV AC-DC converter is proposed.

Table II specifies the parameters of the proposed two-channel interleaving with a phase shift 180° of the MV AC-DC converter. It can be compared with Table I that the inductor values of L1, L2 and L3 in Table II are only 1500 uH. On the other side, the capacitor values of C1, C2 and C3 are reduced to 60 uF. Fig. 6 demonstrates the simulation results of the proposed converter. It can be observed that the ripple current stresses at C1, C2 and C3 (I_{C1}, I_{C2}, I_{C3}) are lower compared to a single-channel solution. The output power P_{RL} is about 4.75 MW, as shown in Fig. 7. It is indicated by I_{L1}, I_{L2} and I_{L3} that the unity power factor correction can be accomplished.

TABLE II. PARAMETERS OF THE PROPOSED MV AC-DC CONVERTER FOR 5 MW WECS (FIG. 5)

Component:	***Parameter:***
MV PMSG	5 MW, 3000 V
Inductor L1, L2, L3	1500 uH
Inductor L4 – L9	780 uH
Capacitor C1, C2, C3	60 uF
Capacitor C4, C5	1250 uF
Switching frequency	1 kHz
Pulse witdh, duty cycle	220 us, 22 %
Interleaving technique	2-channel, 180° phase shifting
IGBT module S1, S2	5SNA 1200G450300, 4500 V, 1200 A
Diode module D1 – D12	5SLD 0600J650100, 6500 V, 2 x 600 A

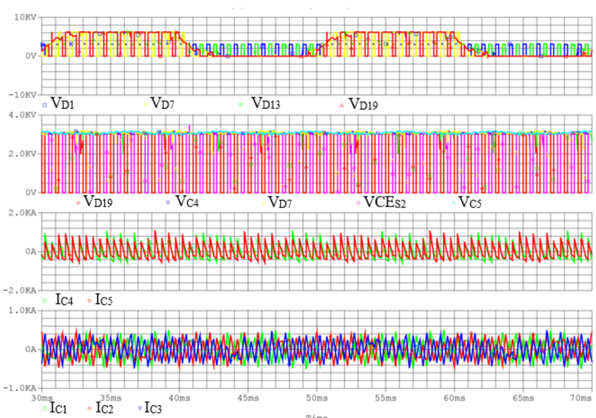


Fig. 6. Simulation results of the proposed 2-channel interleaving technique with a phase shift 180° of the MV AC-DC converter.

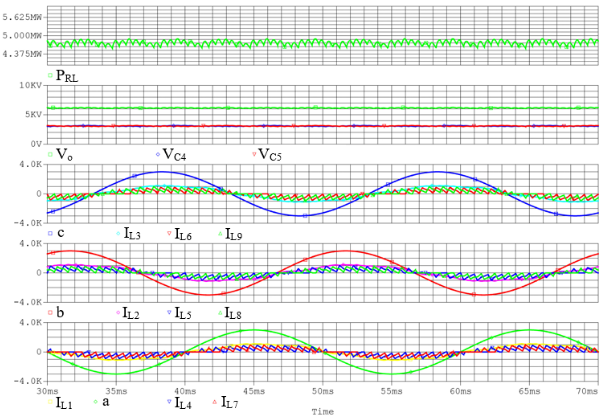


Fig. 7. The operation waveforms of the proposed MV AC-DC converter with 2-channel interleaving technique and a phase shift 180° for wind energy conversion systems.

Fig. 8 demonstrates 4-channel interleaving technique with a phase shift 90° of the proposed MV AC-DC converter for WECS to further reduce ripple current stress at the input and output capacitors. Table III describes the parameters of the proposed converter. With this 4-channel, the output power can reach 10 MW and the inductor values of L1, L2 and L3 are further reduced from 1500 uH to 250 uH. Fig. 9 shows the

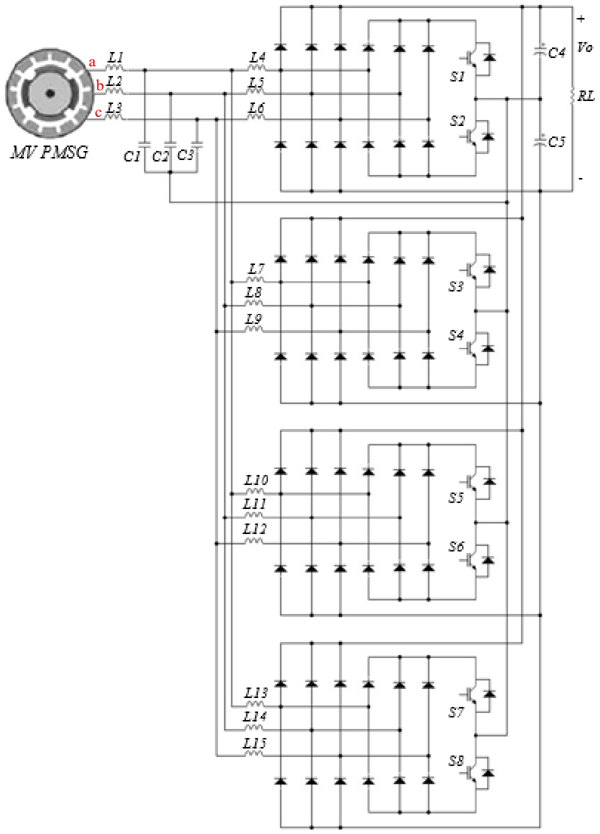
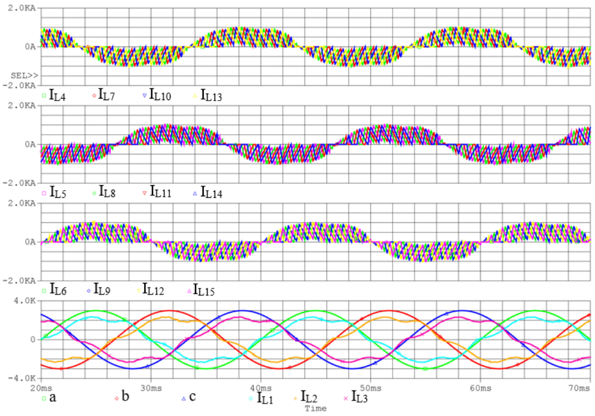
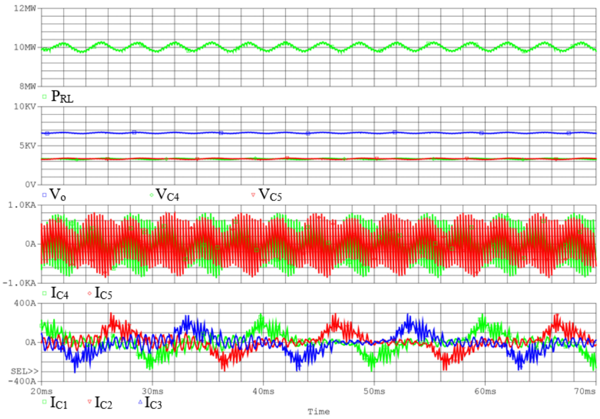


Fig. 8. 4-channel interleaving technique with a phase shift 90° of the MV AC-DC converter for WECS is proposed to further reduce ripple current stress at the input and output capacitors.

simulation results of the proposed 4-channel interleaving technique with a phase shift 90° of the MV AC-DC converter for 10 MW WECS. As can be seen in Fig. 9(b), the ripple current stress at both the input capacitors I_{C1}, I_{C2}, I_{C3} and the output capacitors I_{C4}, I_{C5} are reduced compared to 2-channel configuration in Fig. 6. Fig. 9(a) depicts that to obtain a DCM



(a)



(b)

Fig. 9. Simulation results of the proposed 4-channel interleaving technique with a phase shift 90° of the MV AC-DC converter for 10 MW wind energy conversion systems.

operation, smaller inductance values of L4 – L15 can be utilized so that a better power factor correction of I_{L1}, I_{L2} and I_{L3} can be obtained. However, there is a trade-off for this action which result in higher turned-off losses at the IGBT modules (S1 – S8). Therefore, 1 kHz switching frequency is considered for this converter design to maximize the converter efficiency. On the other hand, to further decrease the ripple current stress at the output capacitors I_{C4} and I_{C5}, higher capacitance values are required.

TABLE III. PARAMETERS OF THE PROPOSED MV AC-DC CONVERTER FOR 10 MW WECS (FIG. 8)

Component:	***Parameter:***
MV PMSG	10 MW, 3000 V
Inductor L1, L2, L3	250 uH
Inductor L4, L5, L6	720 uH
Capacitor C1, C2, C3	100 uF
Capacitor C4, C5	1950 uF
Switching frequency	1 kHz
Pulse witdh, duty cycle	250 us, 25 %
Interleaving technique	4-channel, 90° phase shifting
IGBT module S1, S2	5SNA 1200G450300, 4500 V, 1200 A
Diode module D1 – D12	5SLD 0600J650100, 6500 V, 2 x 600 A

Fig. 10 demonstrates the proposed 8-channel interleaving technique with a phase shift 45° of the MV AC-DC converter for future 20 MW WECS. The configuration of the input capacitors C1, C2 and C3 are different than previously. Table IV shows the parameters of the proposed 20 MW MV AC-DC

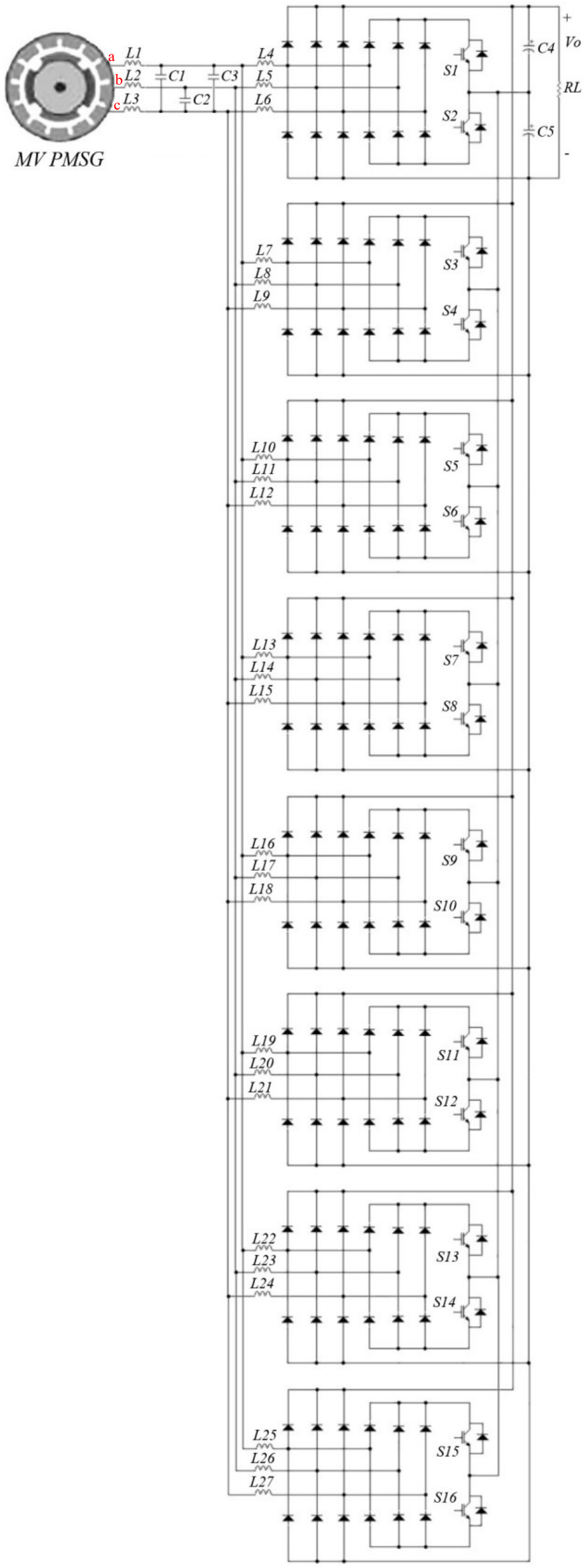


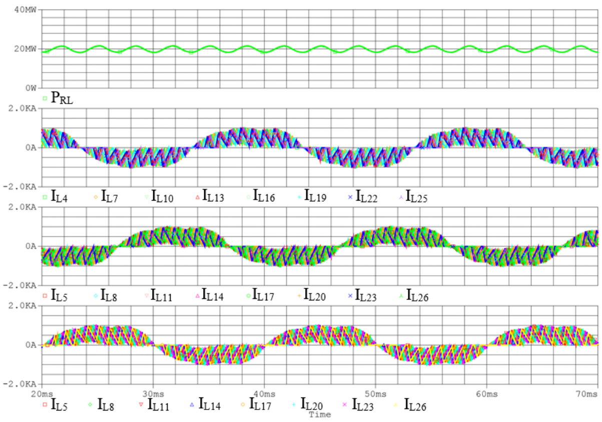
Fig.10. Proposed 8-channel interleaving technique with a phase shift 45° of the MV AC-DC converter for future 20 MW WECS.

converter. Because of the 8-channel MV AC-DC converter architecture with a phase shift 45°, the input inductance values of L1 – L3 are only 150 uH. Also, the input capacitance values of C1 – C3 are more reduced to 12 uF.

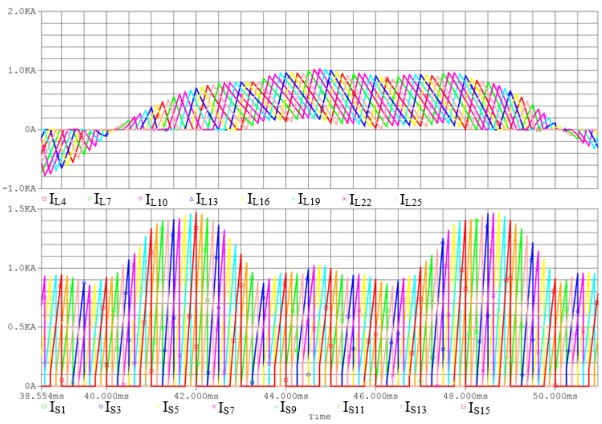
TABLE IV. PARAMETERS OF THE PROPOSED MV AC-DC CONVERTER FOR 20 MW WECS (FIG. 10)

Component:	***Parameter:***
MV PMSG	20 MW, 3000 V
Inductor L1, L2, L3	150 uH
Inductor L4 – L27	750 uH
Capacitor C1, C2, C3	12 uF
Capacitor C4, C5	1250 uF
Switching frequency	1 kHz
Pulse witdh, duty cycle	250 us, 25 %
Interleaving technique	8-channel, 45° phase shifting
IGBT module S1, S2	5SNA 1200G450300, 4500 V, 1200 A
Diode module D1 – D12	5SLD 0600J650100, 6500 V, 2 x 600 A

The advantages of higher channel number are not only reducing input and output current ripples, but also the output power of the converter is increased and for that reason the overall efficiency of the converter is also increased. Fig. 11



(a)



(b)

Fig. 11. The operation waveforms of the proposed 8-channel MV AC-DC converter architecture with a phase shift 45° for future 20 MW wind energy conversion systems.

and Fig. 13 demonstrate the simulation results of the proposed 8-channel MV AC-DC converter architecture for future 20 MW wind energy conversion systems. Fig. 12 shows the switching state of switches S1 – S16 with a phase shift of 45°. As can be seen in Fig. 13, the ripple current stress at the input capacitors I_{C1}, I_{C2} and I_{C3} are further reduced to below 50 A peak-to-peak. Therefore, higher reliability can be achieved.

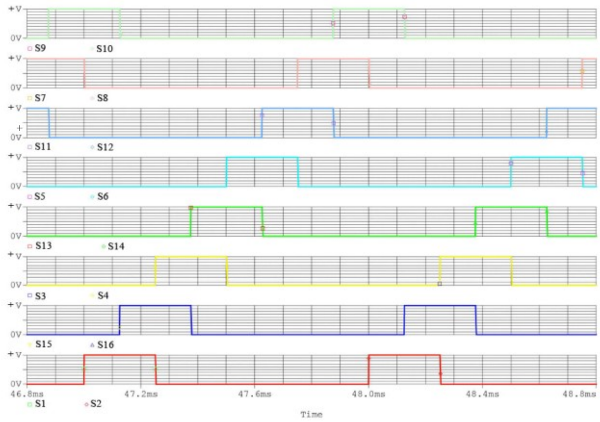


Fig. 12. The switching state of the proposed MV AC-DC converter architecture with 8-channel configuration and a phase shift 45°

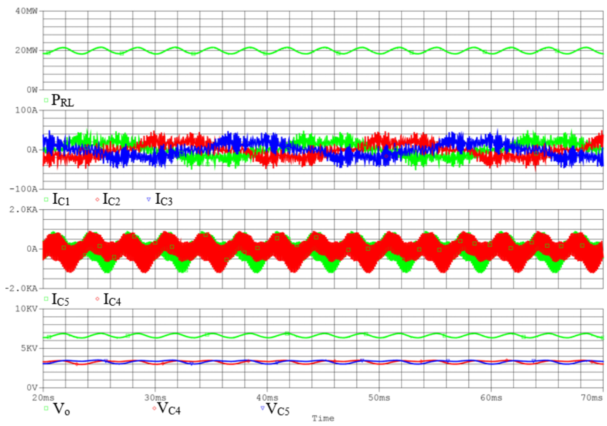


Fig. 13. Simulation results of the input and output currents with 8-channel configuration and a phase shift 45°.

IV. CONCLUSION

In this paper, a new 3-phase 3-level 3-wire MV AC-DC converter using 2-switch architecture was proposed for wind energy conversion systems. The 5 MW – 20 MW MV PMSG WECS power rating with 2-channel, 4-channel and 8-channel interleaving technique were discussed and analyzed in DCM operation to diminish the control complexity. The PSPICE simulation results confirm that the input and output ripple current stresses can be reduced significantly and the unity power factor correction typically can be obtained using the proposed multi-channel interleaving MV AC-DC converters. The proposed converter architecture with phase shifting principle is not only provide low-ripple input and output currents with highly-efficient power processing system, but also smaller inductance and capacitance values at the input and output filters can be achieved. Simulation results are also confirm that the voltage stress of the IGBT switches are only 50% of the output voltage. Therefore, lower switching losses can be accomplished. The main advantage of the proposed converter compared to the conventional diode bridge rectifier with 3-level boost converter configuration is that when the

IGBT switches are turned-off simultaneously, the conduction losses are reduced and higher efficiency can be realized.

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