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Design of Simplified Active NPC (ANPC) Inverters for Fault Tolerant Operation Using WECS

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Abstract:-*Simplified Active NPC (ANPC) Inverters Enable A Substantially Increased Output Power And An Improved Performance At Zero Speed For High-Power Electrical Drives. This Paper Analyzes The Operation Of Simplified ANPC Inverters Under Device Failure Conditions, And Proposes The Fault-Tolerant Strategies To Enable Continuous Operating Of The Inverters And Drive Systems Under Single Device Open- And Short-Failure Conditions. Therefore, The Reliability And Robustness Of The Electrical Drives Are Greatly Improved. Moreover, the Proposed Solution Adds No Additional Components To standard ANPC Inverters; Thus, The Cost For Robust Operation Of Drives Is Lower. Simulation Results Are Provided For Verification. Furthermore, A Comprehensive Comparison For The Reliability Function Of ANPC And NPC Inverters Is Presented. The Results Show That ANPC Inverters Have Higher Reliability Than NPC Inverters. Two Inverters Have Similar Reliability For Device Open Failure, While ANPC Inverters Have Higher Reliability Than NPC Inverters For Device Short Failure. Therefore The Input Voltage Is Renewable Energy And Is Rectified To DC Using Rectifier Circuit And Stored In The Battery.*

Index Terms:*Active Npc (Anpc), Electrical Drives, Fault Tolerant, High Power, Multilevel Inverter, Reliability.*

I INTRODUCTION

Wind turbine usage as sources of energy has increased significantly in the world. With growing application of wind energy conversion systems (WECSs), various technologies are developed for them. With numerous advantages, permanent-magnet synchronous generator (PMSG) generation system represents an important trend in development of wind power applications. Extracting maximum power from wind and feeding the grid with high-quality electricity are two main objectives or WECSs. To realize these objectives, the inverter is one of the best topology for WECS.Multilevel inverters have found successful applications in medium-voltage high-power electrical drives, such as mining, pumps, fans, and tractions. Since multilevel inverters have a large number of power devices, any device failure may cause the abnormal operation of the electrical drives, and require shutdown of the inverter and the whole system to avoid further serious damage. However, in some critical industrial processes with high standstill cost and safety-aspect concern, a high reliability and survivability of the drive system is very important. Therefore, fault-tolerant operation of multilevel inverters has drawn lots of interest in recent years, and several researchers have addressed the fault-tolerant issues for the popular multilevel topologies, such as neutral-point-clamped (NPC) inverters, flying capacitor inverters, cascaded H-bridge inverters, and generalized inverters. In most fault-tolerant solutions, additional components (such as power devices, fuses, or even phase legs) are required to be added to standard multilevel inverters for fault-tolerant operation. This will increase the cost and may even reduce the reliability of the inverters and drive systems due to employing more components. Moreover, both device open and short failure may occur in the inverters, depending on the characteristics and failure mechanism of power devices; thus, a comprehensive fault-tolerant scheme should consider both failure conditions. The operation of 3L-ANPC inverters under device failure conditions and proposes the fault tolerant strategies to enable continuous operation of the inverters and drive systems for both single device open and short failure.

II WIND ENERGY CONVERSION SYSTEM

The turbine torque exhibits regular and random fluctuations due to blade tower interactions and to wind gusts. Neither pitch angle nor aerodynamic stall control can respond rapidly enough to compensate and so the machinery therefore must have a peak torque capability at least *50%* above the nominal rating. Compliance and damping in the power train are needed to avoid structural resonances excited by torque fluctuations or by electrical system disturbances. Compliant mounts for the gearbox are sometimes used, and induction generators provide additional compliance and damping. The direct drive generator must incorporate an effective alternative. Noise disturbance raises objections to the installation of wind farms. Eliminating the gearbox will eliminate a significant component with unpleasant audible characteristics. This is a major attraction of the direct drive concept; therefore the new machine should be as quiet as possible with predictable noise characteristics. An ambient temperature range of -30 to +40°C and possible internal condensation must be catered for. The temperature of all parts and differential temperatures will vary with time and with load. Nacelle cover, if fitted, would give some protection against rain, snow, ice, dust and chemical pollution but should not be relied upon.

III FAULT-TOLERANT DESIGN OF ANPC INVERTERS

A. Operation Analysis of ANPC Inverters under Device Failure Conditions

The operation of ANPC inverters under device failure conditions, and proposes the fault-tolerant strategies to enable continuous operating of the inverters and drive systems under single device open and short failure conditions. Therefore, the reliability and robustness of the electrical drives are greatly improved.

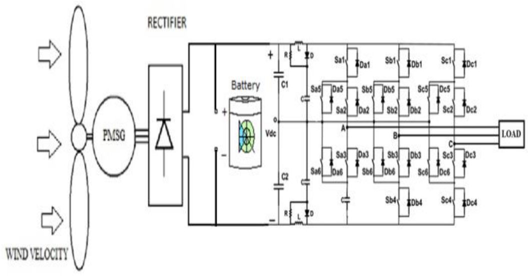

Fig.1 Circuit diagram of ANPC inverter

Multilevel inverters have found successful applications in medium-voltage high-power electrical drives, such as mining, pumps, fans, and tractions. Since multilevel inverters have a large number of power devices, any device failure may cause the abnormal operation of the electrical drives, and require shutdown of the inverter and the whole system to avoid further serious damage. However, in some critical industrial processes with high standstill cost and safety-aspect concern, a high reliability and survivability of the drive system is very important. Therefore, fault-tolerant operation of multilevel inverters has drawn lots of interest in recent years, and several researchers have addressed the fault-tolerant issues for the popular multilevel topologies, such as neutral-point-clamped (NPC) inverters, flying capacitor inverters cascaded H-bridge inverters, and generalized inverters. In most fault-tolerant solutions, additional components (such as power devices, fuses, or even phase legs) are required to be added to standard multilevel inverters for fault-tolerant operation. This will increase the cost and may even reduce the reliability of the inverters and drive systems due to employing more components. Moreover, both device open and short failure may occur in the inverters, depending on the characteristics and failure mechanism of power devices; thus, a comprehensive fault-tolerant scheme should consider both failure conditions. The ANPC inverters have higher reliability than NPC inverters when a derating is allowed for the drive system under fault-tolerant operation. If a derated operation is not allowed, the two inverters have similar reliability for device open failure, while 3L-NPC inverters have higher reliability than 3L-ANPC inverters for device short failure.

IV OPERATION ANALYSIS OF ANPC INVERTERS

a) Under Device Failure Conditions

Fig.1 shows the circuit of a ANPC inverter. The relation of switching states, switching sequence, and output voltage for phase

TABLE I
SWITCHING STATES, SWITCHING SEQUENCE

Switching states	Switching sequence					Output voltage
	Sa1	Sa2	Sa3	Sa5	Sa6	
+	1	1	0	0	1	+Vdc/2
0U2	0	1	0	1	0	0
0U1	0	1	0	1	0	0
0L1	1	0	1	0	1	0
0L2	0	0	1	0	1	0
-	0	0	1	1	0	-Vdc/2

Table.1 switching sequence

Under device failure condition, due to the symmetrical structure of ANPC topology, the failure of *Sa* 1 /*Da* 1 has similar effects on the inverter, and this is also valid for the other pairs: *Sa* 2 /*Da* 2 and *Sa* 3 /*Da*3 , *Sa* 5 /*Da* 5 , and Sa 6 /Da 6 .

b) Proposed Fault-Tolerant Strategies of ANPC Inverters

Therefore, only one from each pair of the devices in phase A will be analyzed in the following fault analysis. Fig.2 shows the examples of the current flow path at different output voltage levels under the open failure of *Sa* 1 /*Da*1,*Sa* 2 /*Da*2, and *Sa* 5 /*Da*5, respectively.

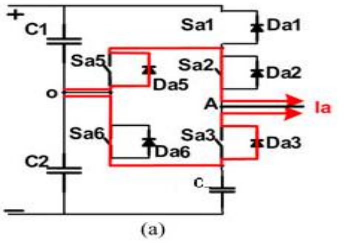

Fig.2 Modes of operation – (a) open circuit condition (Sa1 open fail)

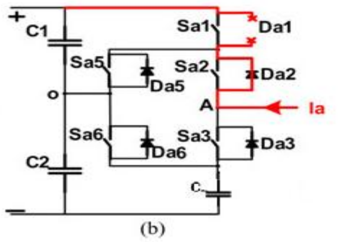

Fig (b) Open circuit condition (Da1 open fail)

The positive current direction is defined as flowing out of the phase. As seen, when *Sa* 1 open failure occurs at “+” state, if *Ia*> 0,

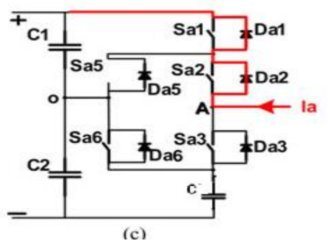

Fig (c) open circuit condition (Sa5 open fail)

If we assume that the capacitors and devices can survive in this condition, the inverter output currents will become unbalanced.Fig.2 (a), then the phase output is connected to
Neutral-point (NP) of dc- link instead of positive dc bus.
(b)When *Da* 1 open fault occurs at “+” state and *Ia*< 0, as shown.
(c), *Sa* 2 open failure occurs at “0U2/0U1” state when *Ia*> 0, then the phase output is connected to negative dc bus rather than NP of dc-link.
(d) Shows that *Sa* 5 open failure occurs at “0U2/0U1” state when Ia< 0, then the phase output is connected to positive dc bus instead of NP of dc-link

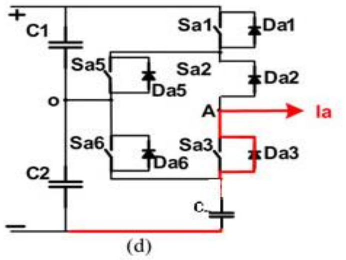

Fig.(d) open circuit condition (Sa2 open fail)

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Due to the incorrect output voltage, the output current will become unsymmetrical and the NP of dc-link will be unbalanced, the condition is even worse since the phase current *Ia* becomes discontinuous due to the cutoff of conduction path

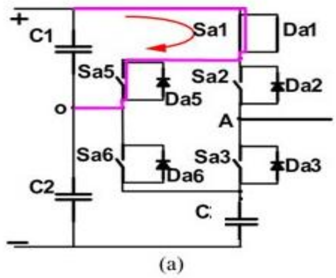


Fig.3 Modes of operation – (a) short circuit condition (Sa1/Da1 short fail)

then the induced voltage on load inductor and loop inductor may cause overvoltage on the inverter and cause damage. For other device failure cases, the circuit can be analyzed in the similar way. Device short failure can cause even more serious problems compared to open failure. The reason is that under short-failure Condition,

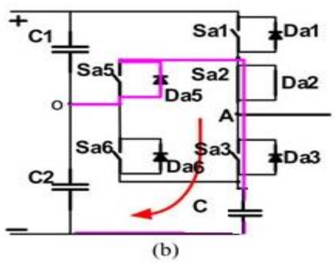
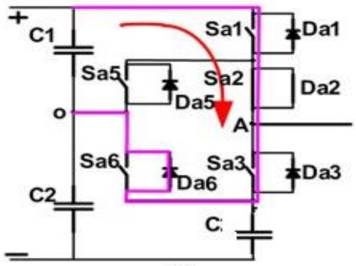


Fig (b) short circuit condition (Sa2/Da2 short fail,-ve)

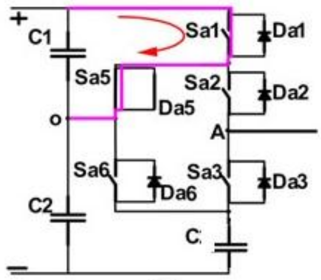
the dc-link capacitors may be discharged through a short current conduction path directly, and some devices may break down due to over current.Fig.3 shows the current flow path under short failure of *Sa* 1 /*Da*1 , *Sa* 2 /*Da* 2 , and *Sa* 5 /*Da* 5 ,respectively. When *Sa* 1 /*Da* 1 short failure occurs, if the switching state commutates to “0U1/0U2/−,” Moreover, because the voltage of one dc-link capacitor will drop to zero quickly, other devices may have to withstand the full dc bus voltage and break down due to overvoltage



(c)

Fig (c) short circuit condition (Sa2/Da2 short fail)

Fig. (a), the upper capacitor *C*1 will be shorted by *Sa* 1 /*Da* 1 and *Sa* 5.
Fig. (b) and (c) shows that if *Sa* 2 /*Da* 2 short failure occurs, state forms a short-current path for lower capacitor *C*2, while“0L1” state provides a short-current path for upper capacitor *C*1. If *Sa* 5 /*Da* 5 short failure occurs at “+/0L1” state,
Fig. 4.3(d), the condition is the same as Fig. 4.3(a).



(d)

Fig (d) short circuit condition (Sa2/Da2 short fail)

V. FAULTS-TOLERANT STRATEGIES OF ANPC INVERTERS

Besides the power loss balancing function, the ANPC switches Sa 5 and *Sa* 6 can also provide a fault-tolerant ability for the inverter. The modified switching states and switching sequences for the fault-tolerant operation under single device open failure are given in Table.2. After device open failure is detected, the 3L-ANPC inverter transits from normal operation into fault tolerant

TABLE II
SOLUTION FOR SINGLE DEVICE OPEN FAILURE

Fault device	Switching states	Switching sequence					Output voltage
		Sa1	Sa2	Sa3	Sa5	Sa6	
Sa5 /Da5	+	1	1	0	0	1	+Vdc/2
	0L1	1	0	1	0	1	0
	0L2	0	0	1	0	1	
	-	0	0	1	0	0	-Vdc/2
Sa6 /Da6	+	1	1	0	0	0	+Vdc/2
	0U2	0	1	0	1	0	0
	0U1	0	1	0	1	0	
	-	0	0	1	1	0	-Vdc/2
Sa1 /Da1	0U2	0	1	0	1	0	0
	0L2	0	0	1	0	1	
Sa2 /Da2	0L2	0	0	1	0	1	0
Sa3 /Da3	0U2	0	1	0	1	0	0

Table.2 switching sequence for open failure conditions

Operation. Knowing the position of the failed device, a new switching sequence is selected to generate certain switching state according to Table 4.2. As seen, if *Sa* 5 /*Da* 5 or *Sa* 6 /*Da* 6 fails open, the 3L-ANPC inverter is derived into a similar configuration as the conventional 3L-NPC inverter. The faulty phase is still able to output three voltage levels, and the maximum Modulation index and the output voltage waveform quality are the same as normal operation. Moreover, the device power loss balancing function can still be implemented to some extent during fault-tolerant operation.

5.1 Single Device Open Failure of ANPC Inverters

For example, if only *Sa* 5 fails, while *Da* 5 is healthy, then besides the “0L1” and “0L2” switching states, the faulty phase can still generate “0U1” and “0U2” switching states when the phase current is positive, which can be used for power loss balancing. If any single device open failure occurs among *Sa* 1 /*Da* 1 through the output terminal of the faulty phase needs to be connected to the NP of dc-link. The modulation signals also need to be modified in order to maintain the balanced three- phase line-to-line voltages. In carrier-based SPWM modulation of ANPC inverters, the references of the phase voltages in normal operation are expressed by (7). In this paper, we assume the maximum modulation index is 1 for linear modulation under normal operation.

$$\begin{cases} V_a = m\sin(wt) \\ V_b = m\sin\left(wt - \frac{2\pi}{3}\right) \\ V_c = m\sin\left(wt + \frac{2\pi}{3}\right) \end{cases} \qquad (1)$$

$$\begin{cases} V_a = 0 \\ V_b = -\sqrt{3}m\sin\left(wt + \frac{\pi}{6}\right) \\ V_c = \sqrt{3}m\sin\left(wt + \frac{2\pi}{3} + \frac{\pi}{6}\right) \end{cases} \qquad (2)$$

It is worth to mention that if zero-sequence component injection is used for SVPWM modulation, the maximum modulation index can reach 1.15 under normal operation. However, since zero-sequence component injection is not the focus of this paper, we do not discuss this aspect in the following sections. When the faulty phase can only output “0” voltage level, instead of using the balanced phase voltages as the reference signals, we must modify the reference signals to ensure that the line-to-line voltages are balanced in ANPC inverters.

5.2 Single Device Short Failure Of ANPC Inverters

For device short failure, we need to avoid using the switching states and switching sequences that can construct short-current path for the dc-link capacitors. Two solutions are proposed here.In solution I, the modified switching states and switching sequences are given in Table 4.3. In this scheme, when *Sa* 1 /*Da* 1 has short failure, the faulty phase can still output three voltage levels by choosing proper switching sequence; thus, the output voltage and current of the inverter are almost the same as those in normal operation. For the other device short-failure cases, we can use the similar method as that for device open failure to connect the faulty phase to the NP of dc-link, and modify the reference signals as (1). Accordingly, the maximum modulation index will be reduced to 0.577.

TABLE III
SOLUTION I FOR SINGLE DEVICE SHORT FAILURE

Fault device	Switching states	Switching sequence						Output voltage
		Sa1	Sa2	Sa3	C.	Sa5	Sa6	
Sa1 /Da1	+	0	1	0	0	0	1	+Vdc/2
	0	0	0	1	0	0	1	0
	-	0	0	1	1	0	0	-Vdc/2
Sa2 /Da2	0	0	0	0	0	1	0	0
Sa3 /Da3	0	0	0	0	0	0	1	0
Sa5 /Da5	0	0	1	0	0	0	0	0
Sa6 /Da6	0	0	0	1	0	0	0	0

Table.3 switching sequence for short failure conditions

However, the drawback of solution I is that certain devices have to withstand the full dc bus voltage under *Sa* 1 /*Da* 1 short-failure condition. For example, when *Sa* 1 /*Da* 1 fails short, overvoltage will appear across *Sa* 2 /*Da* 2 at "−" state according to Table 4.3. Similarly, when 'Fails short, the voltage across *Sa* 3 /*Da* 3 will be full DC bus voltage at "+" state. For a standard 3L-ANPC inverter, the voltage rating of the employed power devices is lower than the dc bus voltage (theoretically, equal to half of the dc bus voltage).To overcome the drawback of the first solution, Solution II is proposed, in this scheme, no matter which device fails in short, the faulty phase is always connected to the NP of dc-link, and the reference signals are modified according to (2). By doing so, the maximum modulation index will be reduced to 0.577 and the output power rating of the 3L-ANPC inverter will be reduced. However, overvoltage will not appear on any device, and it can be applied for any standard 3L-ANPC inverter without special requirement on the voltage rating of the inner devices.

VI SIMULATION ANALYSIS

Simulations were performed by using MATLAB-Simulink to verify that proposed fault-tolerant strategies to enable continuous operating of the inverters and drive systems under single and multiple device open- and short-failure conditions. Therefore, the reliability and robustness of the electrical drives are greatly improved. It will convert the DC to AC voltage and given to the load.

Simulation Results

A. Normal Operation

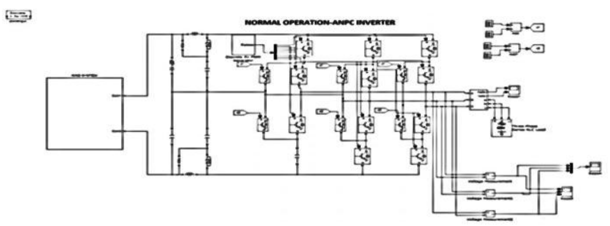


Fig.4 Normal operation of ANPC inverter (without fault)

B. Output Voltage

The below waveform shows the final output phase current of the Normal operation of the inverter output..

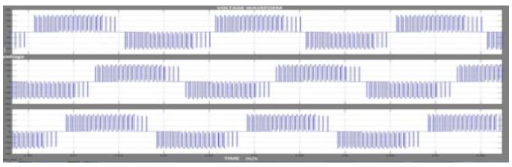


Fig.5 Output current waveform

C. Output Current Waveform

The output phase voltage of the Normal operation.

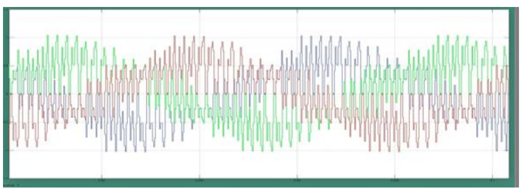


Fig.6 Output current waveform

The fig.5.8, 5.10 Shown below is the proposed circuit diagram of Fault tolerant operation of the inverter where it has both SC & OC conditions. In any one of the switches is under fault condition, then it provide the continuous output from the faulty switches this will improve the reliability and quality of the circuit compared with normal three phase inverter which found applications in industrial area. The output current and voltage waveform of the Fault tolerant operation of inverter are shown in below,

D. Open Circuit Operation

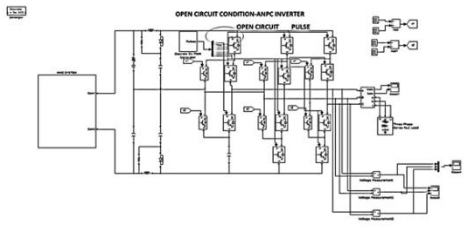


Fig.7 Open circuit operation of inverter

Compared with the conventional circuit, the proposed circuit has less component count which is responsible for increasing fault tolerant capability for open circuit condition.

E. Output Voltage

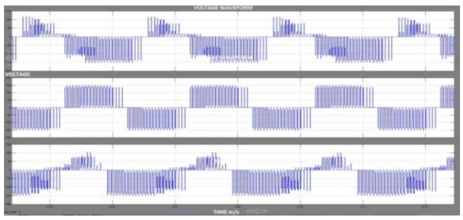


Fig.8 Output voltage waveform

F. Output current

Output currents, faulty phase voltage, and line-to-line voltage wave forms control for single device open failure on *Sa* 1 /*Da* 1 ,*Sa*2/*Da* 2 , and *Sa* 5 /*Da* 5 , respectively. The corresponding gate pulses of the switching device with 120° conduction mode...Each switch conducts for 120°. Only two switches remain on at any instant of time. The conduction sequence of switches is 61, 12, 23, 34, 45, 56, and 61 for normal operation. Since one switch conducts for 120°, the switches are less utilized as compared to that of 180° conduction for the load condition.

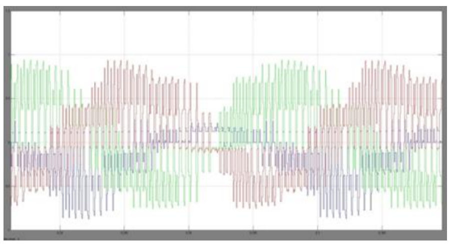


Fig.9 Output current waveform

The control of output voltage is done using pulse width modulation. The commonly used techniques are SPACE vector pulse width modulation technique.

G. Short Circuit Operation

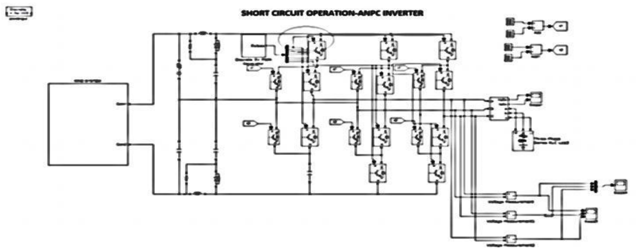


Fig.10 Short circuit operation of inverter

For device short failure, we need to avoid using the switching states and switching sequences that can construct short-current path for the dc-link capacitors.When*Sa* 1 /*Da* 1has short failure, the faulty phase can still output three voltage levels by choosing proper switching sequence; thus, the output voltage and current of the inverter are almost the same as those in normal operation. For the other device short-failure cases, we can use the similar method as that for device open failure to connect the faulty phase to the NP of dc-link, and modify the reference signals. Therefore, the faulty phase voltage, the line-to-line voltage, and the output currents are almost the same as those in normal operation. The NP voltage of dc-link is still balanced. When the device failure occurs in *Sa* 1 /*Da* 1 or *Sa* 2 /*Da* 2 regardless of open or short failure, the output currents are still stable and continuous by using the proposed control. However, the current amplitude is reduced, which is limited by the maximum modulation index. The NP voltage ripple becomes slightly larger compared to normal operation because the current of the faulty phase is always connected to the NP of dc-link. However, the voltage and current waveforms show that this NP voltage ripple will not impact the proper operation of the 3L-ANPC inverters.

H. Output Voltage Wave Form

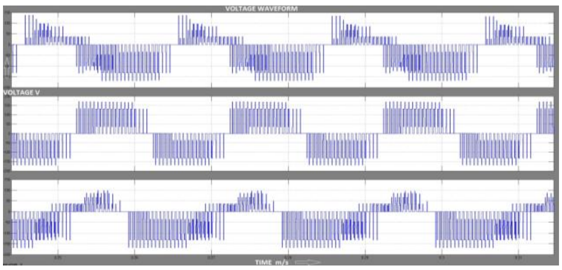


Fig.11 Output voltage waveform

I. Output Current Wave Form

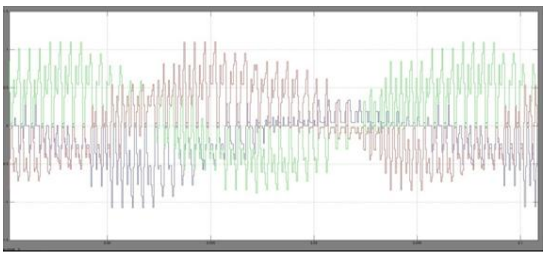


Fig.12 Output current waveform

6.1 Simulation of Subsystem Block

Variable speed operation yields 20 to 30 percent more energy than the fixed speed operation, providing benefits in reducing power fluctuations and improving variable supply.

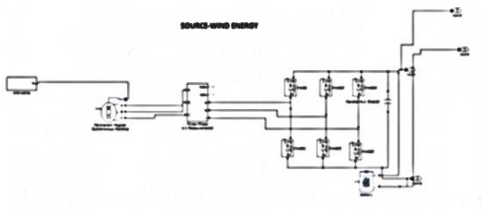


Fig.13 PMSG based wind system

Falling prices of the power electronics have made the variable speed technology more economical and common. Such a wind turbine system as other types of dispersed generation is mostly connected to distribution feeders and the generation system cannot be easily connected to the electric power network without conducting comprehensive evaluations of control performance and load impacts. This requires a reliable tool for simulating and assessing dynamics of a load connected variable speed wind turbine. The purpose of the work is to provide the capability of design, modeling, simulating and analyzing the dynamic performance of a variable speed wind energy conversion system using MATLAB / SIMULINK.

J. Battery Voltage Input of Inverter

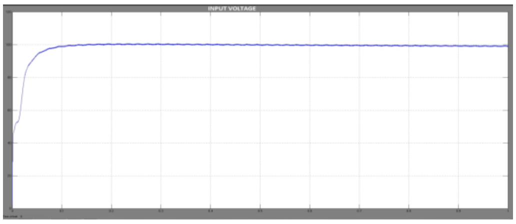


Fig.14 Output voltage from battery

VII CONCLUSION

Reliability and survivability of power electronics converter based electrical drives are very important in terms of safety and economic cost. This paper analyzes the operation of 3L-ANPC inverters for high-power drives under device failure conditions, and proposes the fault tolerant strategies to enable continuous operating of the 3L-ANPC inverters under both open- and short failure conditions for device failure. The analysis, simulation, results show that the reliability and robustness of the inverters and electrical drives are greatly improved by using the proposed solution. Moreover, since no additional components are added to standard 3L-ANPC inverters, the cost for robust operation of drives is lower.

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