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Fault tolerant nine-level inverter topology for solar water pumping applications

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ABSTRACT

Diminished voltage pressure and occasional-general harmonic distortion are the essential causes for such a ways and extensive usage of multi-level inverters (MLIs) in numerous industrial applications. Nonetheless, unwavering quality is one of the significant worries of MLIs as it utilizes countless switches as contrasted to 2-level inverters. Here, a fault tolerant 9-level inverter setup for the use of photovoltaic (PV) system-water pumping applications is suggested. This fault tolerant 9-level inverter is accomplished by combining a 2-level inverter, a 3-level fault tolerant inverter alongside switches with bidirectional ability. The setup is taken care of with four PV fed sources. The arrangement suggested shows the behavior towards switch fault in at least one inverter legs under open circuit conditions. On account of source failure, it could use the better hotspot for introducing continuous power to the water pumping motor. Meanwhile, the suggested fault-tolerant inverter works as seven-level inverter. The activity related to proposed inverter in the course of various failure modes is mentioned and simulated the usage of MATLAB/Simulink.

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1. INTRODUCTION

Water is a need for enduring. It is required for drinking and home grown uses, and it is required for huge scope water system, development, and force creation. Water assumes an important feature within the advancement of any country. The non-public pride in any kingdom pretty is based on the quantity and nature of reachable water assets in that kingdom. It is classed that an ordinary of five liters of recent water is needed according to individual each day for day-by-day survival [1]. Although a lot of fine water is available in the world, regularly it is not always accessible at areas wherein it thoroughly can be directly applied. This increases the want to pump excellent water from its supply to the regions where it is miles popular. For this purpose, water pumping had been being used for quite a long term. Sun photovoltaic energy has been supplied in overdue eighties and has expanded excessive significance by mid-nineties. Earlier sunlight totally based photovoltaic (PV) cells had been very wasteful with the effectiveness as low as 5-6% and profoundly pricey [2]. Farmers in a country like India are subjected to difficulties with respect to water starting from lack of rainfall for months together in the summers to heavy, crop destroying rains in off seasons. This results in an inevitable drought leading to several socio-economic problems that affects the food chain of the whole country. Solar powered water pumping system will effectively terminate this problem with its ability to store solar power thereby strengthening the pumping system.

A multi-level inverter (MLI) is the acts as the source for powering a 3-Φ induction motor that is utilized in agricultural works. Any failure of MLI leads to a total shutdown of the system. Thus, addressing the failure of a MLI leads in effective working and makes the system less prone to shutdowns. The proposed fault-tolerant ability provides uninterrupted, quality power supply with less total harmonic distortion (THD) and helps in the functioning of the induction motor used. Nowadays, there are advanced progress in applying computing technologies [3]–[10] that have significant progress in different techniques

Sun based water pumping systems [11], [12] are picking up the fame in the field of rustic territories where the power is not accessible. The acquisitions of sunlight-based PV based water pumping frameworks are chance on the simple entry when contrasted with diesel based water pumping systems. Variable power restriction challenges arise when the motor drive system is directly powered by a PV source and demand generation of maximum energy and the amount of water required to be pumped [13]. In solar photo voltaic (SPV) exhibit took care of pumping systems; induction motor drive (IMD) shows great execution when contrasted with other industrial prime movers due to its rugged construction. The advancement is planned to create beneficial, dependable, upkeep free and less expensive SPV water pumping systems [14].

Several low-level direct current (DC) sources act as an input for a multilevel inverter which is a power electronic circuit to provide alternating current (AC) output. Obtaining a staircase yield voltage with the help of the inputs in the form of isolated DC sources constitutes of the prime objective. Multilevel inverters provide multiple output levels that can be a source for obtaining a sinusoidal waveform. With respect to high power applications, multilevel inverters have been in high demand as they possess characteristics like low harmonics, minimum switching losses, and better electromagnetic capability. The ability of a multilevel inverter to generate a higher-level in its output voltage waveform makes it an efficient one. By utilizing multiple DC sources, it provides the desired AC output. Total harmonic distortion at the output is minimized by the increase in the output level. Power grids, industrial motor drives, and power conditioning are some of the areas in which these inverters utilized at their best [15], [16].

Asynchronous motor drives are majorly utilized in multiple applications due to their rugged production, protection loose, smooth to toil around variety of speeds. Thereafter, the manipulation techniques of the power electronic converters resulted in a fruitful performance as they are used for the motor drives. However, these power digital converters liable to numerous faults at some stage in wide various working principles of the systems [17], [18]. This will immediately give a path for short & open circuit with respect to the power switches among the converters. Which ultimately results in redundancy in the drive performance as the motor loses its balancing operation. A sudden unplanned and unscheduled power down of drives is followed by this process. Thus, accurate fault identification and immediate action are important to hold power in regular operation. Fault-diagnostic strategies have been studied in a detail way in [19].

These strategies have helped in developing topologies for fault-tolerant systems. This literature in [20] has shaped many non-redundant and redundant topologies for fault-tolerant systems. Parallel connection between the switches and main legs constitutes of redundant topologies. The constraints like high cost and physical space however lower their efficiency. Whereas in non-redundant systems, the defective section terminal or neutral terminal of motor are connected to the direct current link capacitors [21], [22].

The referenced writing outline recommends that the PV water pumping framework driven by engine ought to be taken care of through a high-acquire financially savvy strength transformation course of action to decrease cost of the framework. Notwithstanding it, the proposed framework ought to be furnished with a successful issue open minded plan which needs to make up for switch failures occurred inside the inverter module. Plan and execution of a whole green water system framework the use of advantage single-level power change, Z-source inverter, and a photo-voltaic framework. The help of given regulation strategy, the ZSI shall utilize better adjustment record with lower voltage stress all through the exchanging gadgets contrasted with the presence non-coupled impedance organizations [23], [24].

To address the above issues a 9-level inverter is employed to feed power to an induction motor for pumping applications. The proposed nine-level fault tolerant ability is a new contribution. To address the mentioned issues a new nine-level inverter is “modeled” to incorporate the fault tolerant ability. As per the literature survey there are no solutions for dealing with the faults occurring in the functioning of a MLI fed induction motor drives for water-pumping application. The particular topology has the benefits in terms of switch and sources failures, requires less components and not having neutral point and capacitor voltage balancing issues compared to conventional multilevel inverters. Average operating modulation index and equivalent load demand are the factors on which PV modules are divided. For better source utilization, the ratings of the battery are confirmed with respect to the newer source ratings. Phase disposition pulse width modulation (PDPWM) is used to produce the control signals for the switches to generate nine level voltages. The total system is simulated using MATLAB.

2. SOLAR WATER PUMPING SYSTEM CONFIGURATION WITH FAULT TOLERANT ABILITY

The outline of the fault tough 9-L inverter is shown in Figure 1. The structure is taken care of with four separate direct current connections which are shaped by four separate PV clusters, outfitted with batteries and maximum power point tracking (MPPT) charge regulator. The immediate current connections are appraised at $1/4^{th}$ of the whole power rating concerning single brought together PVS. Benefit of utilizing four separate PV exhibits leads to diminish rating of voltage in devices and turns into flaw versatile within the occasion of any of the cluster failure that is examined in later piece of this part. Four separate equivalent DC sources i.e., V1=V2=V3=V4=0.25 Vdc, act as a reference for the inverter and the power circuit is shown in Figure 2. A regular inverter and a neutral point staggered inverter belonging to two-level and three-level respectively are cascaded thus cultivating a structure.

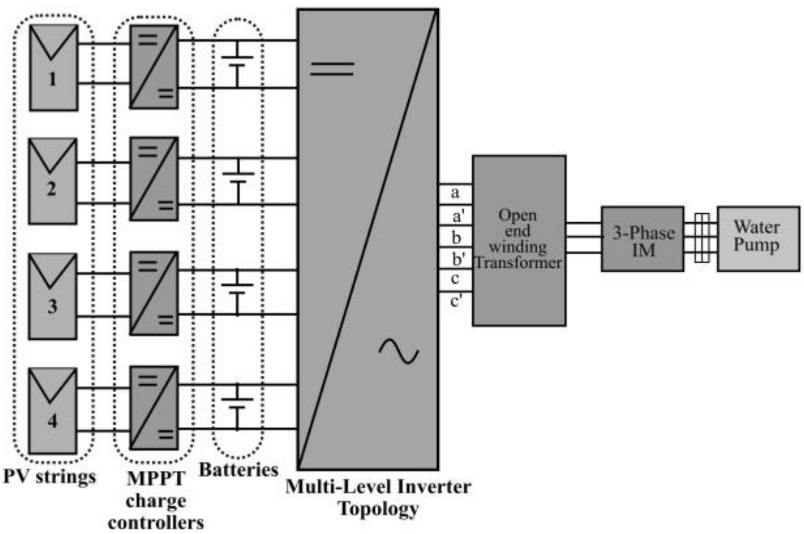


Figure 1. Schematic diagram of water pumping system fed by multi-level inverter

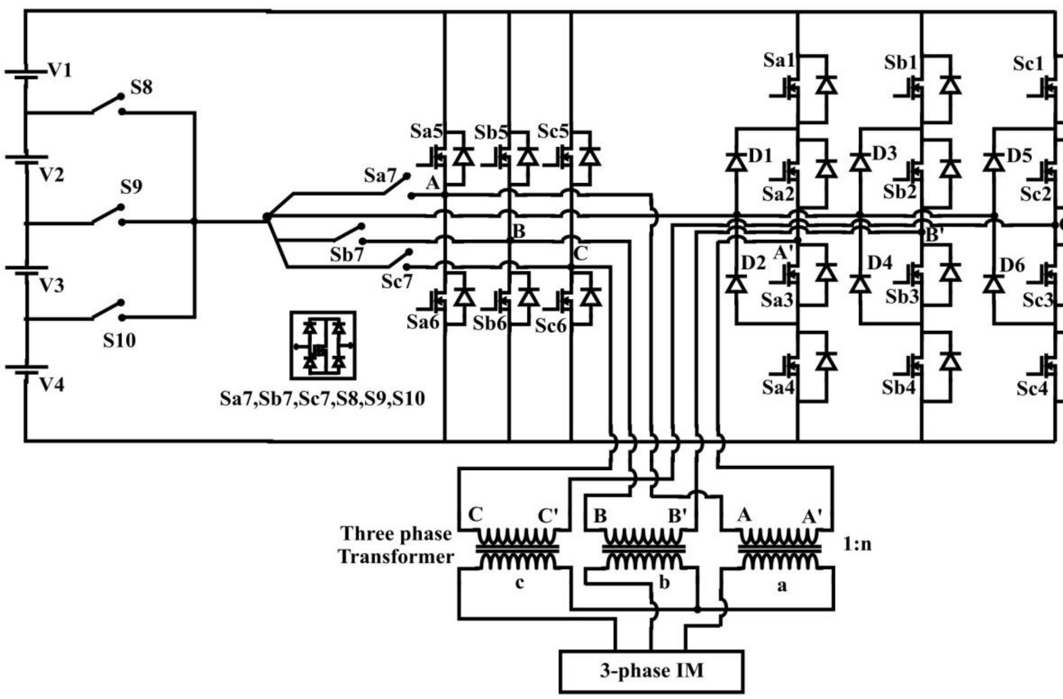


Figure 2. Power circuit of three-phase nine-level inverter

In Figure 2 the 4-quadrant switches are used to create halfway voltage levels for the length of fault and normal conditions. Each period of 2-level inverter and unbiased factor clamped inverter is given to the primary of transformer with open end winding to produce 9-L voltage. The induction motor is associated with the secondary part of open-end winding transformer. The changing blend to create 9-L voltage for a-phase is given in Table 1. The exchanging is same for b and c phases.

Table1. Control combination for 9-level operation

Voltage size	ON condition of switches
Vdc	Sa1, Sa2, Sa6
3Vdc/4	Sa1, Sa2, Sa7, S10
Vdc/2	Sa2, Sa1, Sa7, S9
Vdc/4	Sa1, Sa2, Sa7, S8
0	Sa1, Sa2, Sa5
-Vdc/4	S10, Sa7, Sa3, Sa4
-Vdc/2	S9, Sa7, Sa3, Sa4
-3Vdc/4	S8, Sa7, Sa3, Sa4
-Vdc	Sa5, Sa3, Sa4

Basically, inverter failures tend to occur because of source failure, semiconductor device short and open circuit failure, and drive circuit failure. Here, both source problem and open-circuit fault are talked about. As a result of lifting and breaking of holding semiconductor devices reasons the OC deficiencies. The exceptional kind of fault combinations and 3-ϕvoltage on open end winding of primary transformer utilizing reasonable exchanging for a-phase is given in Table 2. The gating pattern given in below is comparable for b and c stages under transfer open circuit fault. The given framework is contrasted and regular multilevel inverters are introduced in Table 3. The proposed framework is beneficial as far as number of parts, capacitor balancing issues and adaptation to internal failure contrasted with traditional topologies.

Table 2. Changing combination to generate voltage during fault

	Voltage size	Sequence of path of current and switches to turn “on”
Sa-4 &/orSa-6 Switch (Open fault) And/orV-4 Source open or (short circuit fault)	3 Vdc/4	Sa1, Sa2, Sa7, S10
	Vdc/2	Sa2, Sa1, Sa7, S9
	Vdc/4	Sa1, Sa2, Sa7,S8
	0	Sa1, Sa2, Sa5
	-Vdc/4	Sa5, Sa2, Sa3, Sa7, S8
	- Vdc/2	Sa5, Sa2, Sa3, Sa7, S9
	-3 Vdc/4	Sa5, Sa2, Sa3, Sa7, S10
Sa-1 &/or Sa-5 Switch (Open fault) And/orV-1 Source open or (short circuit fault)	3 Vdc/4	S8, Sa2, Sa3, Sa6
	Vdc/2	S9, Sa2, Sa3, Sa6
	Vdc/4	S10, Sa2, Sa3, Sa6
	0	Sa3, Sa4, Sa6
	-Vdc/4	S10, Sa7, Sa3, Sa4
	- Vdc/2	S9, Sa7, Sa3, Sa4
	-3 Vdc/4	S8, Sa7, Sa3, Sa4
Sa-5&Sa-6 Switch (Open fault)	3 Vdc/4	Sa1, Sa2, Sa7, S10
	Vdc/2	Sa2, Sa1, Sa7, S9
	Vdc/4	Sa1, Sa2, Sa7, S8
	0	Sa2, Sa3, Sa7
	-Vdc/4	S10, Sa7, Sa3, Sa4
	- Vdc/2	S9, Sa7, Sa3, Sa4
	-3 Vdc/4	S8, Sa7, Sa3, Sa4

Table 3. Contrast between proposed and other topologies

Inverter category	NPC	Flying capacitor	H-bridge	Suggested system
Switches	48	48	48	24
Diodes	144	0	0	24
Isolated power supplies/DC capacitors	8	8	12	4
Capacitors	0	72	0	0
Fault tolerant Ability	No	No	Tolerant (Not fully)	Yes

3. SIMULATION RESULTS AND DISCUSSION

The 3-Φ9-L inverter topology presented here is simulated with the use of MATLAB/Simulink. The parameters for simulation are given in Table 4. The inverter is being controlled by PDPWM. In PDPWM the reference signal is compared with 8-carrier signal depicted in Figure 3 to generate 9-L voltage output with the usage of gating aggregate as presented in Table 4. The logic to generate nine level voltages can be observed from Table 5. In case of fault the seven level voltages can be generated by changing the modulation index to 0.75 and can be compared with middle six carrier signals and Table 2 can be used for seven level voltage generation.

Table 4. Variables for simulation

Parameter	Specifications
PV Arra1, 2, 3 and 4 largest powers	2.5 kW
Irradiation	1000 W/m^2
Temperature	25 ^{0}C
Battery voltage (rated)	Vdc1=Vdc2=Vdc3=Vdc4=96 V
Frequency (modulating)	fm=50 Hz
Frequency (switching)	fs=2 KHz
Index (modulation)	Ma=0.98
Load	3-Φ I M, 415 V,1480 rpm

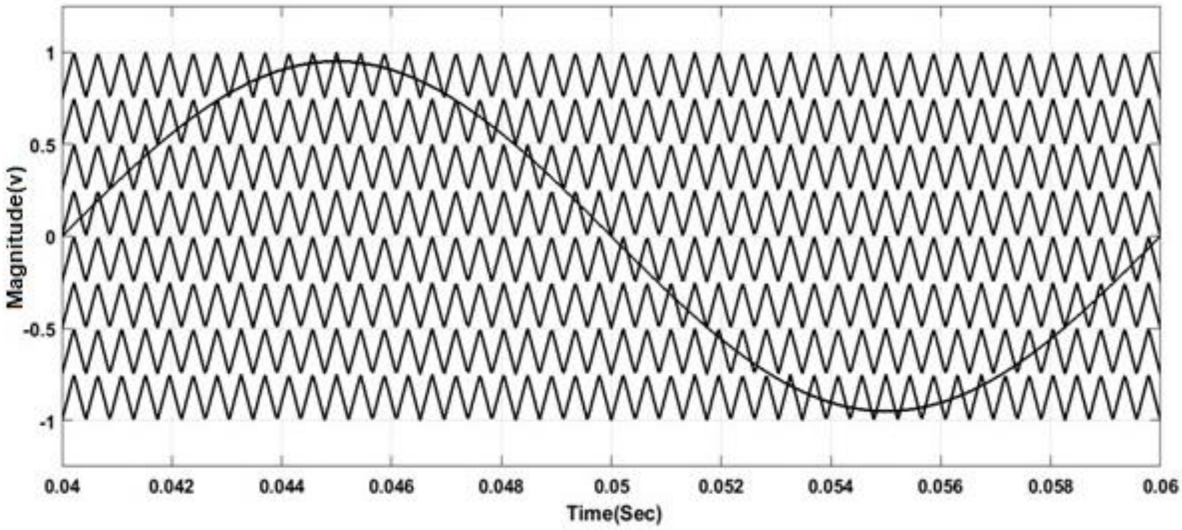
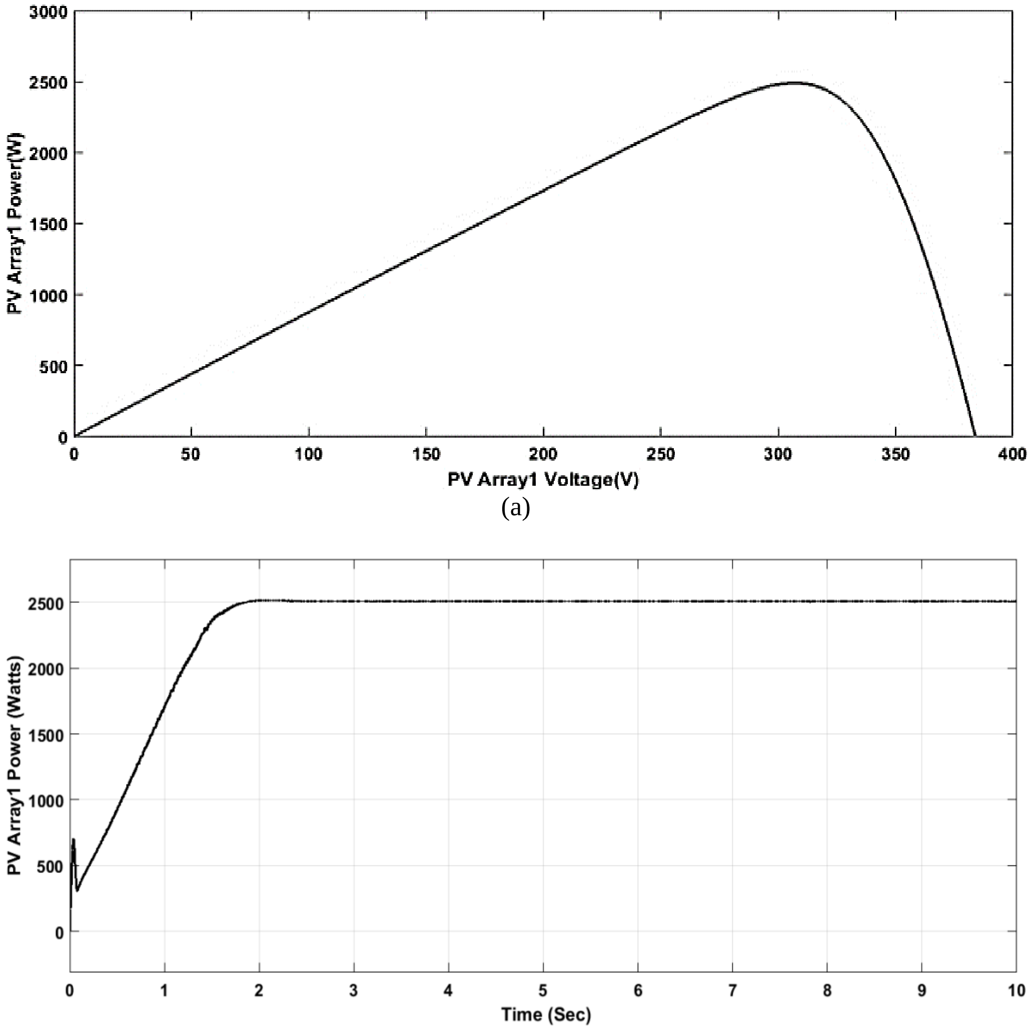


Figure 3. 9-level PD-PWM method (Y-Axis: 0.5 volts magnitude/div, X-axis: 0.002 sec/div)

Table 5. Logic for generation of 9-L voltage

Steps	Range	Value
Step 1	ma > Vcr1	Vdc
Step 2	Vcr1 < ma > Vcr2	3 Vdc/4
Step 3	Vcr2 < ma > Vcr3	Vdc/2
Step 4	Vcr3 < ma > Vcr4	Vdc/4
Step 5	Vcr4 < ma > Vcr5	0
Step 6	Vcr5 < ma > Vcr6	-Vdc/4
Step 7	Vcr6< ma > Vcr7	-Vdc/2
Step 8	Vcr7 < ma > Vcr8	-3 Vdc/4
Step 9	Vcr8< ma	-Vdc

The complete frameworks modeled in MATLAB/Simulink and perturb and observe algorithm is utilized in order to track the maximum power [25]. The characteristic of power and voltage of PV array1 and power output maximum is displayed in Figures 4(a) and 4(b). The nine-level voltage is depicted in Figure 5. The speed and torque performance traits are displayed in Figures 6(a) and 6(b) in the course of regular operation. The 7-level voltage throughout transformer number one aspect, the stator currents and voltages of induction motor are proven in Figure 7 at some stage in open circuit fault passed off in Sa-4 and Sa-6. The output voltage is maintained regular for the duration of fault by changing the tapings of transformer on primary side. The not changed torque and speed are displayed in Figure 8.



(a)

(b)

Figure 4. PV Array graph: (a) power vs voltage (X axis: 50 v/div, Y: 500 W/div) and (b) PV array1 power curve (X axis: 1 sec /div, Y: 500 W/div

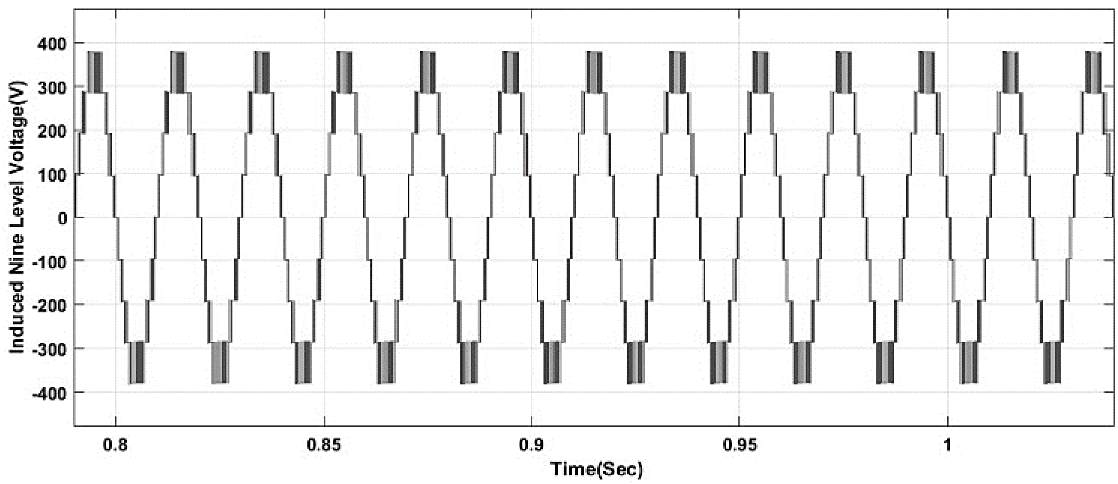
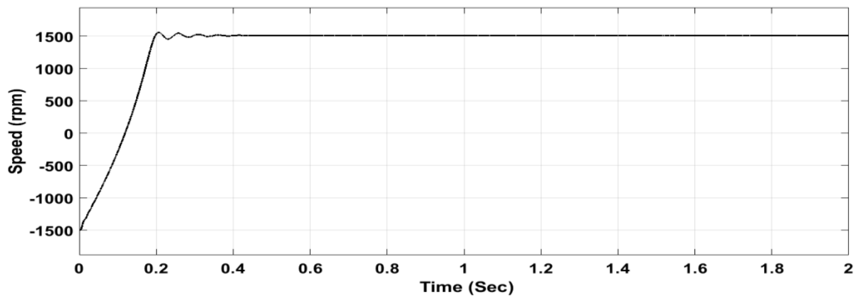
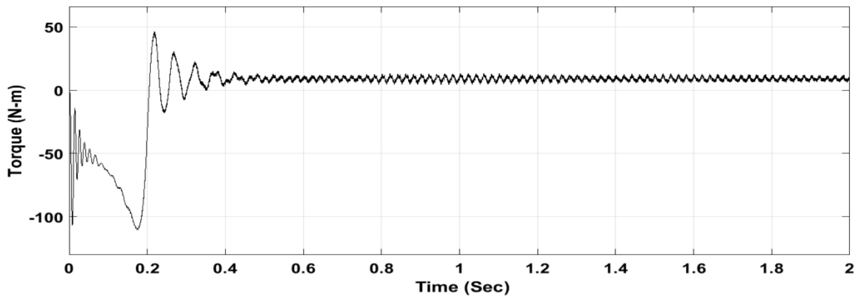


Figure 5. The Nine level voltage across primary side (Y axis: 10 A/div, 1000 V/div, 500 V/div X: 0.05 sec/div)



(a)



(b)

Figure 6. 3-Φ Induction motor (a) speed and (b) torque of IM- normal conditions (Y axis: 500 rpm/div, 50 N-m/div X: 0.2 sec/div)

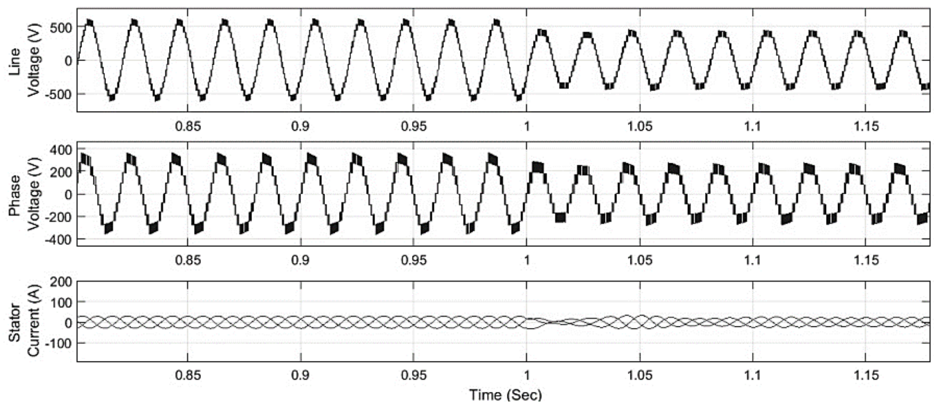


Figure 7. Nine- level voltage (primary side), induction motor (line voltage and currents) under fault conditions (Y-Axis: 10 A/div, 1000 V/div, 500 V/div X-axis: 0.05 sec/div)

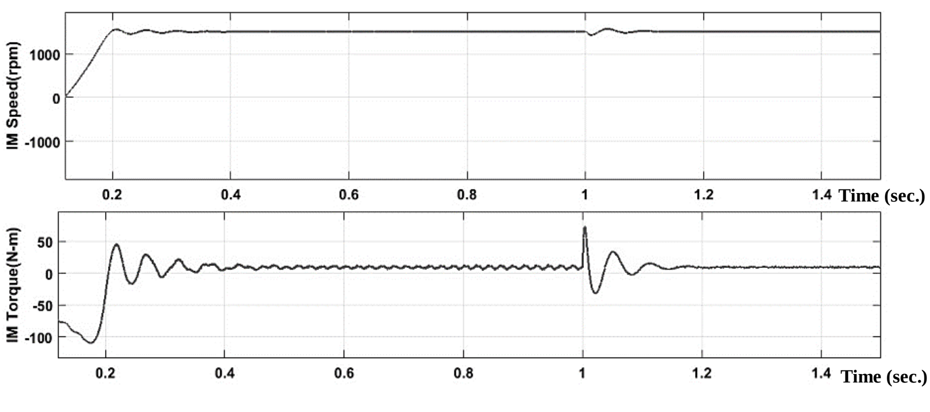


Figure 8. Speed and torque of induction motor under fault conditions (Y-Axis: 1000 rpm/div, 50 N-m/div X-axis: 0.2 sec/div)

Conventional nine-level MLI without fault tolerant ability: i) the results that are attained by considering irradiations and temperature levels related to solar PV array that is proposed above is on Figure 4, ii) from Figure 5 we understand that after a duration of 0.8 s the max output is generated in terms of power, iii) fhe duty cycle aids in achieving the maximum voltage after 0.8 s which is presented in Figure 5, iv) maximum power point tracking (MPPT) point aids in making it constant when the power is constant, v) the variation in the output power is changes accordingly, vi) The current of stator motor at 0.9 s is demonstrated in Figure 5, and vii) the change in current reaches the steady-state with the help of 150 rad/sec motor speed. Shaft torque and time are compared in Figure 5. The calculation of torque gives us a 14 N-m.

New proposed topology nine-level MLI with fault tolerant ability: i) the results that are attained by considering irradiations and temperature levels related to solar PV array that is proposed above is on Figure 4, ii) from Figure 5 we understand that after duration of 0.8 s the max output is generated in terms of power, iii) the duty cycle aids in achieving the maximum voltage after 0.8 s which is presented in Figure 7, iv) over 0.9 s gives the stator motor current as depicted in Figure 7, v) Figure 8 represents the difference in current till steady-state at 0.5 s due to motor speed, and vi) shaft torque and time are compared in Figure 8. The calculation of total pumps torque gives us a 10 N-m.

4. CONCLUSION

An original nine-level MLI with capacity of fault lenient for sun-based water applications are presented. The widespread acclaim with respect to the topology proposed is in variation to inner damage of the semiconductor switch failures and require much less quantity of parts. A thorough examination is finished concerning the altered inverter with the customary multilevel inverter. The exchanging procedure utilized in the new topology is pulse width modulation technique with phase disposition standard. This correlation activates and give up in which the shown multilevel inverter can be better selection for the applications related to water pumping systems. The flaw lenient capability of the given idea is verified by MATLAB results. The more desirable inverter with the ability of switching redundancy on the time of open circuit switch failure works to deliver energy by using operating on the voltage ranges. The consequences screen the capability of the topology working under single and multiple of switch failures. The running of the motor-drive combination is proved efficient at some point of starting, steady state, transient conditions, and switch failures.

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