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*Original Research*

# Design And Study Of Stand-alone Multilevel Inverter Based On Switch Reduction Technique Fed By Photovoltaic And Wind Turbine Systems

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## ABSTRACT

Electricity stability is decreased and both harmonics and losses are increased throughout the power conversion procedures. while harmonic distortion and power losses tend to increase. The drawbacks of conventional inverters may be addressed with the help of new multilayer inverter designs. Lately, multilevel inverter techniques have become more and more well-liked as an affordable substitute for a range of industrial uses. Several notable characteristics of this design include its smaller component, decreased switching losses, and the ability to generate improved voltage and current waveforms. The most crucial prerequisite for multilayer inverters is the minimization of harmonic components in the output voltage/current. The three distinct power sources that make up the system proposed in the present research are two identical wind turbines and photovoltaic system. Each of these power sources has an output voltage of 1, 2/3, and 1/3 Vdc, respectively. A 7-level output voltage was created by combining all of the DC sources. This paper proposes several situations, all of which have harmonic distortion within acceptable limits, and shows that the suggested system can function even in the event that one of the aforementioned power sources is unavailable. Simulation and validation are conducted using MATLAB, demonstrating system stability even when one power source is unavailable.

**Keywords**: Multi-Level Inverter, Renewable Energy Sources, Photovoltaic, Wind Turbine, Harmonic, Contingency, Pulse Width Modulation.

## 1. Introduction

The issue of environmental pollution is a worldwide consequence of the widespread usage of fossil fuels. Furthermore, the cost of fossil fuels will rise as their supply runs out in the coming years [1]. Because it emits less pollution and fossil fuel energy is growing more expensive, Renewable Energy Sources (RES) becoming more significant. Meanwhile, RES has been getting cheaper in recent years. It is possible that in a few years, many applications may make extensive use of RES-distributed power production systems [2]. Energy sources include Photovoltaic (PV), wind, hydro, biomass, ocean, geothermal, and waste-to-energy conversion. PV and wind energies are usually used in power systems.

The PV system has several advantages as compared with a wind turbine system, such as easy installation, no moving components, and low maintenance. Whenever utilized in larger quantities, turbines are also cheaper than PV systems, but their upkeep and operation call for qualified personnel [3]. In RES the two techniques (PV and wind turbine) are usually coupled to provide continuous electricity under various conditions. The majority of electricity produced by RES is generated as DC power [4]. The power conversion link plays a crucial role in this process by converting the DC power into AC power, which is then fed into the electrical grid. Especially for stand-alone usage, hybrid PV and wind production systems are becoming a highly appealing choice. When the two energy sources solar and wind turbine are combined, the hybrid system is more reliable and more cost-effective to operate since the shortcomings of each source may be balanced by the strengths of the other [5]. The total economics and dependability of RES to meet its demand may be further enhanced by the incorporation of hybrid PV and wind power systems into the electrical system. In the same way, the amount of energy storage required to provide continuous power can be decreased when hybrid PV and wind power are combined in a standalone system [6].

Inverters are used to convert the DC power into AC power. Because the resultant voltage of RES is low, a RES generating system uses a DC-DC power converter to raise the output voltage so that it can meet the inverter's DC bus voltage. To make certain that there is no wasted energy produced by the RES, the power conversion interface's efficiency is crucial.

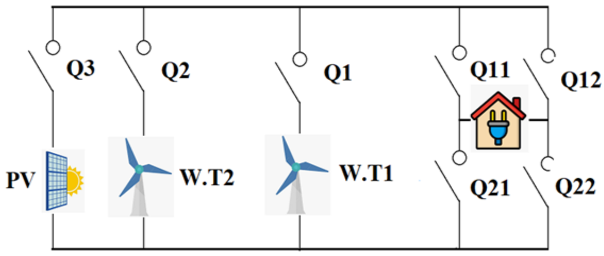
It is vital to maximize the energy given while the supplied energy from RES varies during the day. Two factors that affect the output power of PV panels and wind turbines are sun irradiance and the velocity of the wind. Variations in these variables therefore need to be managed properly by the control devices of those kinds of systems. To optimize the energy produced the available and guarantee that the system should be operated at "Maximum Power Point" (MPP), the velocity of the wind turbine needs to be adjusted in response to variations in wind speed. Likewise, to operate the PV systems at MPP, adjustments must be made to the DC voltage and current at the PV system's output [7], [8]. A wide range of applications is needed for high-power, minimally distorted sinusoidal waveforms. Relying only on a switch is problematic for medium- and high-power uses. Consequently, in 1975, the idea of Multilevel Inverters (MLI) was presented. The MLI's primary idea is to synthesize a staircase voltage waveform to accomplish the necessary power transformation and obtain more power by combining many low-voltage DC sources with power semiconductor switches [9]. MLIs are widely used in industry due to advantages such as decreasing harmonics, boosting output voltage, and removing reliance on step-up transformers [10]. New inverter designs and modulating approaches have been investigated in recent work. The most common inverter designs are Diode-Clamped (DC), Flying Capacitor (FC), and Cascaded H-Bridge (CHB) [11]. Multilevel inverters (MLIs) offer a promising solution to various power conversion challenges, especially in renewable energy systems, by reducing switching losses and improving output voltage quality. The integration of MLIs in systems like wind and solar energy has proven to enhance power quality and efficiency, making them suitable for a wide range of applications[12-14]. The comparisons between the proposed work and a sample of literatures are given as in Table (1). As previously said, this study designs and implements a single-phase switch reduction MLIs utilizing RES (photovoltaic system and wind turbine systems) for off-grid systems. Seven switches are used in the novel logical switching technique of pulse width modulation (PWM) to create an output voltage level with 7 levels in this work. Three power sources: one PV solar system produces 1/3 Vdc, while the two wind turbine systems based on Permanent Magnet Synchronous Generator (PMSG) are used to produce 1 Vdc and 2/3 Vdc. The logical operation of the proposed Pulse Width Modulation (PWM) is used to generate seven levels based on a multi-carrier methodology. MATLAB software is used to model the power sources. This paper consists of four main sections; the first one is the introduction as explained above, while the second section deals with the suggested system and its components. The third section discusses the results achieved by the MATLAB program and the last section discusses the obtained results.

Table 1. Comparison Of Literatures With The Proposed Work

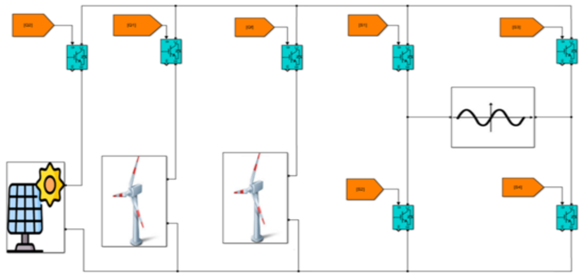
| Ref | Year | No. Of Switches | With RES | THD % | Contingency Study |
|---|---|---|---|---|---|
| [15] | 2020 | 10 | No | 17.3 | Not proposed |
| [16] | 2021 | 9 | No | 1.89 | Not proposed |
| [17] | 2022 | 12 | No | 5.1 | Not proposed |
| [18] | 2023 | 9 | Yes | N.A | Not proposed |
| [19] | 2024 | 6 | No | 17.98 | Not proposed |
| Our Work | 2025 | 7 | Yes | 0.99 | Yes |

## 2. Suggested System Components

Three dc sources and twelve switches are needed individually for a traditional cascaded 7-level MLI. The primary disadvantage of the traditional cascade is that additional electronic switches are needed as levels rise. Consequently, there must be certain changes performed to decrease the inverter's dimensions and switch number. In comparison to a traditional MLI, the next architecture produces a staircase waveform with less overall harmonic distortion [20]. It is constructed with three RES and seven switches. Switch reduction MLI employing an improved sinusoidal PWM approach with traditional and reduced semiconductor switches has been researched in this work. Figure (1-a) depicts the suggested system, which is made up of three separate power sources. The first one is the wind turbine system (W.T1), which has a voltage of 1 Vdc (100%). The second one is also the wind turbine system (W.T2), which has a voltage of 2/3 Vdc (66.66%). The PV system is next, with a voltage of 1/3 Vdc (33.33%).




(a)



(b)

Figure 1. (a) The suggested system, (b) The Implementation Of The Suggested System By MATLAB Program

The total DC sources are brought together in the form of (1, 2/3, and 1/3) Vdc to produce an output voltage that ranges from +3 Vdc to -3 Vdc that produce 7-voltage level. MATLAB software is utilized to model the proposed system, as illustrated in Figure (1-b). The proposed system components will be discussed in this section as below:

### 2.1. The Photovoltaic System

Direct current (DC) is produced by PV cells by using the photovoltaic phenomenon to transform sunlight. The PV cell is composed of a combination of P and N semiconductor components. Consequently, a PV cell may be conceptualized as a diode in reality. Currents can be produced via the photovoltaic phenomenon whenever light is absorbed by the diode [21]. To generate enough voltage and power for the majority of uses, a PV module needs an extensive amount of solar cells coupled in series or parallel. A system known as an array consists of many PV modules linked on the same plane to produce a sufficient amount of electricity to be useful. The maximum power of the PV system may be reached by managing the location of the photovoltaic panels utilizing the maximum power point tracking MPPT technique [22]. To obtain the MPPT in the present research, we will use the Perturb and Observe (P&O) approach. The situation of the forward bias for a single diode form paralleled diode connected to the current sources is displayed in Figure (2).

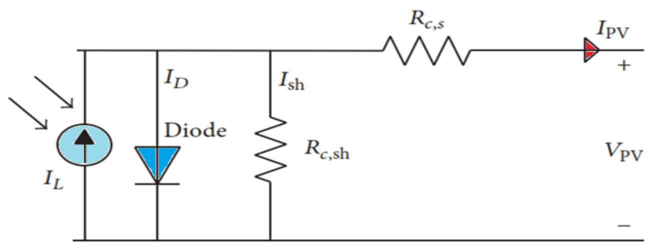



Figure 2. The Single Diode PV Cell Module

The photovoltaic module current at its output may be found in "Eq. (1)", "Eq. (2)"

$$I = I_L - I_D - I_{SH} \tag{1}$$

$$I = I_L - I_0 * [exp\ exp\left(\frac{q\,V_D}{nkT} - 1\right) - \frac{V_D}{R_{SH}}] \tag{2}$$

Whenever "VD" diode's operating voltage, "I0" is the reverse saturation of the diode current, "Q" is for the charge of the electrons and corresponds to (1.6X10-19), "k" for Boltzmann factor is (1.38X10-23) and "IL" stands for solar module current, "ID" for diode current, and "ISH" for shunt resistor current. The power output of the photovoltaic cell is given by the next formula is as in "Eq. (3)"

$$Ppv = V*I \tag{3}$$

Whereas "V" denotes the overall PV voltage, "I" denotes the output current of the photovoltaic cell, and "Ppv" is the output power in watts. The parameters of the voltage and current in the photovoltaic cell differ from reality because of losses in resistance elements.

### 2.2. Wind Turbine

Due to its high reliability and effectiveness, three-phase PMSGs that utilize changeable pitch wind may be the most important wind energy generators. A diode rectifier with three phases is used to transform the generated AC power to DC electricity [23]. A step-up called a boost converter is additionally needed to fulfill the essential DC bus and step up the output voltage; Figure (3) shows the main parts of the wind turbine.

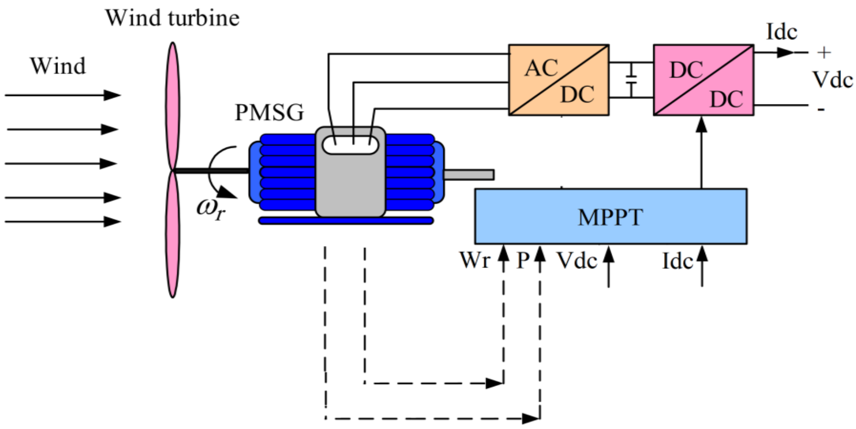



Figure 3. Wind Turbine PMSG Configuration

Whenever the power of the wind is transformed, the wind turbines create mechanical power, which may be determined via "Eq. (4)" follows [24].

$$P_{wind} = \tfrac{1}{2}\, \rho\, A\, V^3 \tag{4}$$

$$\lambda = w\, r / V \tag{5}$$

$$P_{wind} = \tfrac{1}{2}\, \rho\, C_p\, A\, V^3 \tag{6}$$

Whenever "ρ" density of the air, "A" area of blades or wings, "V" wind speed. "w" rotational blades speed, "r" radius of the area "A", power coefficient is "Cp" and the tip speed ratio is "λ", and "β" is pitch angle.
The characteristics equations of the selected wind turbine are given in "Eq. (7)", "Eq. (8)" as below [23]:

$$C_p\,(\lambda,\beta)=0.5\,[116/\lambda-0.4\beta-5]\; e\text{^}[21/\lambda] \tag{7}$$

$$1/\lambda\_i = 1/(\lambda+0.08\beta)- \ 0.035/(1+\beta^3\ ) \quad (8)$$

As shown in Figure (5-c), the curve corresponding to "Cp" and the "λoptimal" should be reached throughout the process of MPPT in order to guarantee that the wind turbine generator operates within its optimum power output.

### 2.3. Maximum Power Point Tracking in PV and Wind Turbines

An integral component of most PV-wind turbine systems is tracking the MPP for both the wind turbine and the solar panel array. RES energy is becoming more and more important as a result of the massive usage and depletion of fossil fuels. Additionally, the most accessible and cost-free sources of energy are solar and wind power. A new, less expensive, RES with lower carbon emissions is required in light of the recent changes in environmental circumstances, including global warming, and the sharp rise in the load for power. To deliver the optimum amount of electricity from the photovoltaic system to the demand, an MPPT is utilized [25].

To transmit the maximum amount of power from the photovoltaic cell to the load, a DC/DC conversion is utilized. The connection between the load and the module is a DC/DC converter. To transmit the greatest power, the duty cycle is changed to vary and meet the demand impedance as observed by the source at the moment of highest power output. For a PV system to produce its maximum electricity, an MPPT approach is therefore necessary. In PV systems, maximum solar array power generation is achieved by using different types of DC-DC converters such as buck, boost, and buck-boost combinations. This is achieved regardless of temperatures, irradiation, or electrical properties of the demand [26].

The P&O algorithm is used to achieve the MPPT, in this method, the MPPT can be reached if the ratio of the power/voltage changes is equal to zero as shown in Figure (4 – (a)). The same procedure is used for wind turbines and the P&O MPPT algorithm is employed here to achieve the MPPT, this algorithm can get the MPPT by comparing the output power, rotor speed, and boost output voltage and current, the MPPT curve of wind turbine is shown in Figure (4 - (b)). Each wind turbine have a mathematical model, the MPPT can be achieved when the curve of the power coefficient (Cp) – Lambda (λ) reach to the maximum point as shown in Figure (4 – (c)).

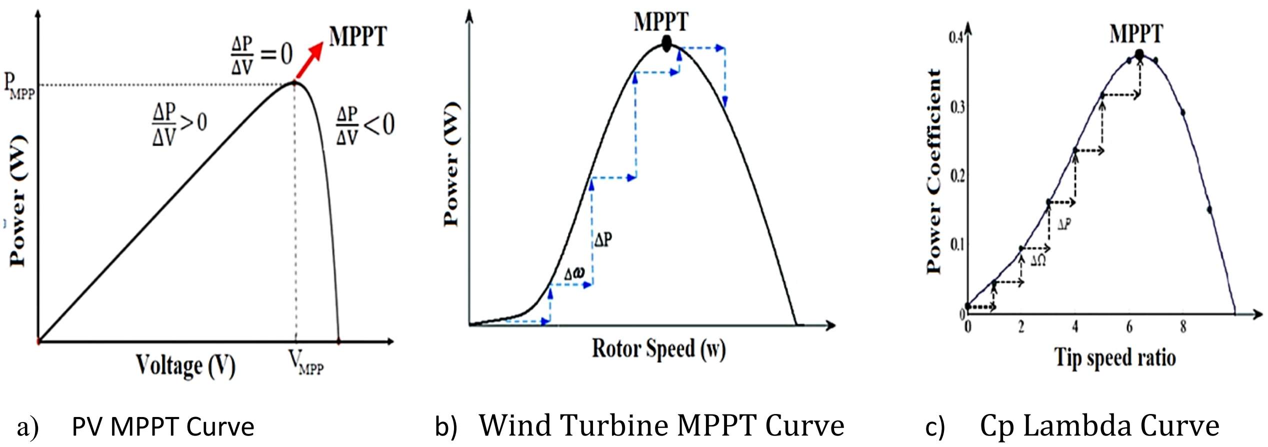



Figure 4. (a) MPPT of PV System, (b) MPPT For Wind Turbine, and (c) Power Coefficient-Lambda Curve Of Wind Turbine System

### 3. MLI Design

Power-electronic equipment called inverters is utilized to convert DC electricity to AC power. An MLI composed of many switches is becoming more and more common in high-power switching processes used in train power drives, electrical vehicles, and other sectors. Compared to traditional types, MLIs have several benefits including lower THD, EMI, and dv/dt switch stress [27], [28]. The main characteristics of MLIs are that they work at both high switching frequency PWM and essential switching frequency, and they generate output waveforms with little distortion due to harmonics. The sole drawback is that the system becomes bulkier and more complicated due to the need for more power switches. The goal of using fewer switches in the MLI architecture has emerged.

The MLI in the present research is designed based on switches reduction techniques with different DC voltage sources (two wind turbine systems and one PV system). To reduce the output THD value, a multicarrier PWM method with shifted levels based on Phase Disposition PWM (PD-PWM) method is employed [29]. The multicarrier PWM utilized to generate a 7-volt level with a sine wave standard is shown in Figure (5).

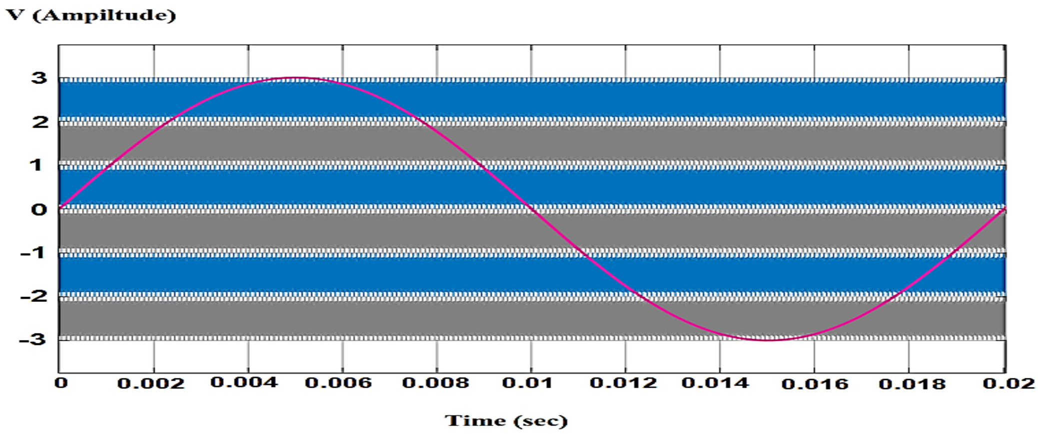



Figure 5. The PD-PWM Strategy Configuration

The voltage is produced by arranging the power sources in a ratio of (1*Vdc, 2/3*Vdc, 1/3*Vdc). The next expression (2n+1) is employed to generate a voltage level in the cascaded H-bridge MLI, for example, to generate 7 voltage levels (n is the number of voltage levels, (2*3+1 = 7) [30]. There are four switches per H-branch, so the overall number of switches needed is (4*n) = (4*3 = 12 switch), but in the suggested system, only seven switches are needed to generate seven voltage levels, the percentage of the switch reduction (size and cost) is about (7/12 = 41.6%), the suggested switches status of the proposed MLI that shown in Figure (1-a and b) is present in Table (2).

Table 2. Shown The Suggested MLI Switches Configuration

| DC Voltage Levels | Q1 | Q2 | Q3 | Q11 | Q12 | Q21 | Q22 |
|---|---|---|---|---|---|---|---|
| 1*Vdc | On-1 | Off-0 | Off-0 | On-1 | Off-0 | Off-0 | On-1 |
| 2/3*Vdc | Off-1 | Off-0 | On-1 | On-1 | Off-0 | Off-0 | On-1 |
| 1/3*Vdc | Off-0 | On-1 | Off-0 | On-1 | Off-0 | Off-0 | On-1 |
| 0 | Off-0 | Off-0 | Off-0 | Off-0 | On-1 | On-1 | On-1 |
| -1/3*Vdc | Off-0 | On-1 | Off-0 | Off-0 | On-1 | On-1 | Off-0 |
| -2/3*Vdc | Off-0 | Off-0 | On-1 | Off-0 | On-1 | On-1 | Off-0 |
| -1*Vdc | On-1 | Off-0 | Off-0 | Off-0 | On-1 | On-1 | Off-0 |

The implementation of the switch control the proposed MLI based on the switch status given in Table (2) is shown in Figure (6). The MATLAB Simulink program is used to implement the control circuit that convert the multi carrier and logic operation into PWM to feed the switches of the MLI.

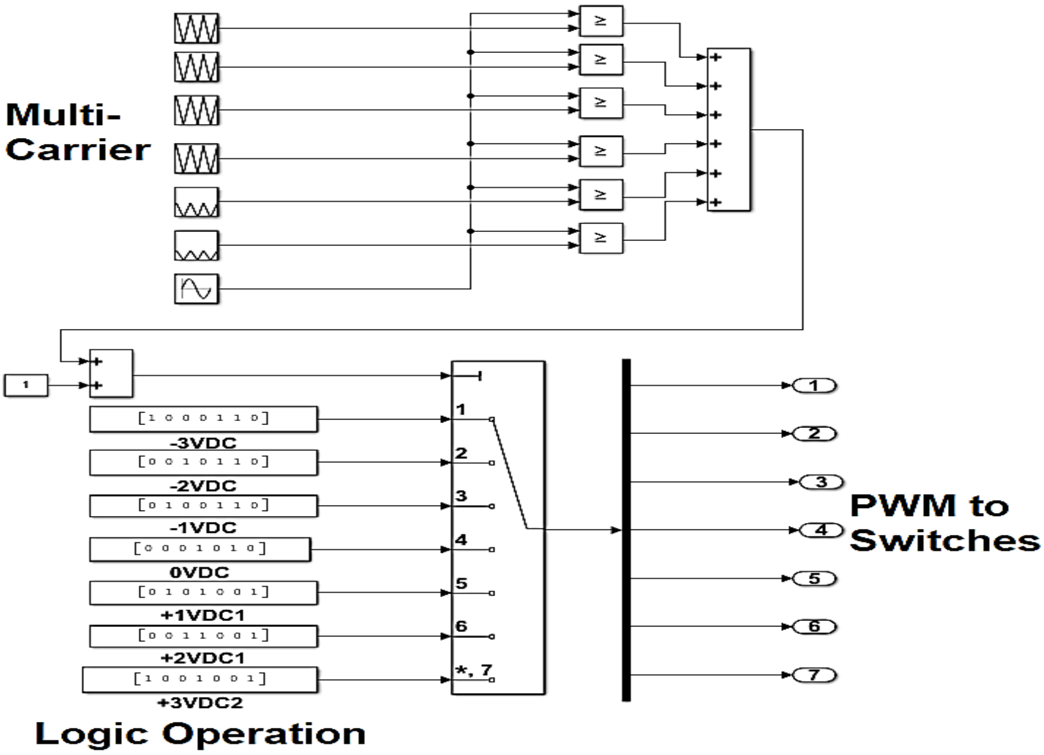



Figure 6. Implementations Of Switches Control

Using the suggested approach, the inverter's size is also decreased, and the THD generated for various scenarios was below the IEEE harmonic standards requirements (IEEE 519-2022) [31]. The number of switches decreased from 12 to 7, which lowers losses. In this project, the three RES are used to feed the MLI which are: two wind turbine systems and one photovoltaic system. In this study, the system is simple and the proportion of switches employed is (7/12 = 58.33%) contrasted to the typical MLI category, where an increase in voltage level may result in a gain in the system's complexity. The system's expense is decreased, as the aforementioned aspects have stated.

In this work, in addition to the normal operation of the MLI, different cases are considered, the loss of any source of the RES will not affect the output waveforms as possible, but it will reduce the voltage levels from seven to five. The first case deals with the loss of the PV system (33.33% of Vdc), while the second case presents with the loss of wind turbine-1 (100% of Vdc), and finally, the third case deals with the loss of wind turbine-2 (66.66% of Vdc). The proposed Vdc in this work is about (380V). For all proposed cases, the harmonics are still within the IEEE harmonic distortion standard (IEEE 519-2022) as will be discussed in the next section.

## 4. Simulation And Results

The selected PV panel type in this work is “A10Green Technology A10J-M60-220” The PV system consists of one panel in series and twelve panels in parallel, the output voltage in (volt), current in (amp), and the output power in (watt) as shown in Figure (7-(a)). The characteristics of the PV system and the individual panel are shown in Figures (7-(b)) and (7-(c)) respectively. The PV panel voltage is (30.12 V) and the PV current is about (7.3 A), the output PV panel power according to “Eq. (3)” is:

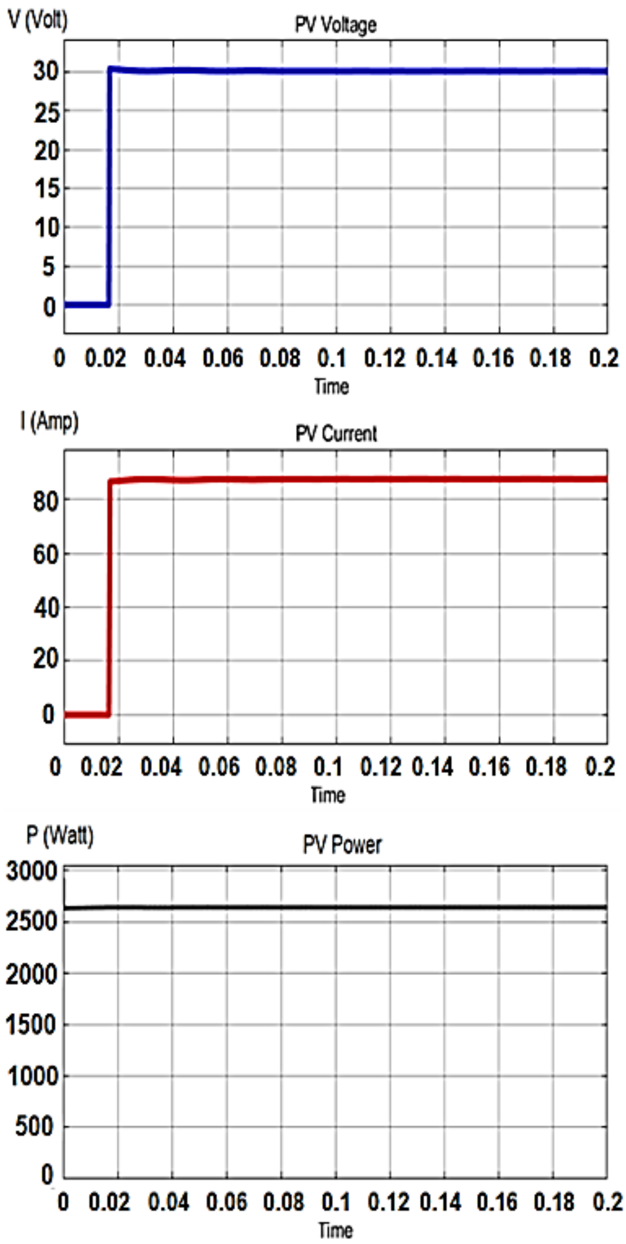
$P_{pv}$ = 30.12*7.3 = 219.876 Watt.

To find the overall power of the PV system the following procedure is used:

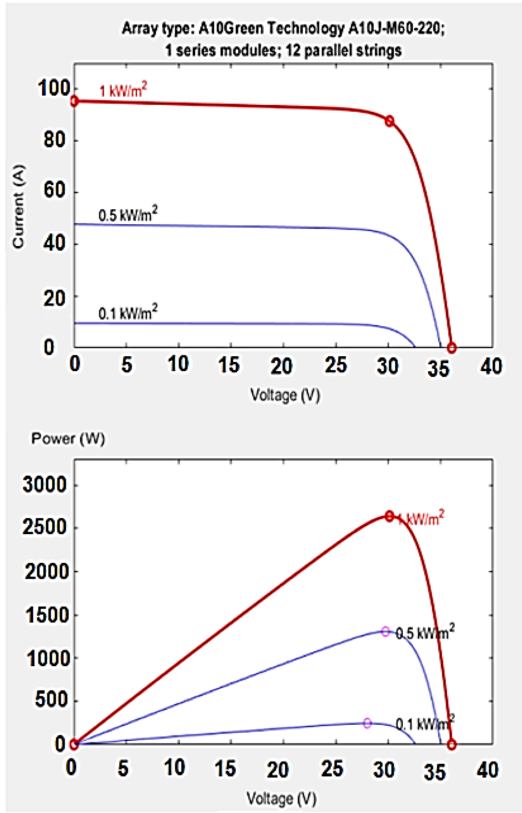
PV system voltage = Panel voltage * Number of series panels = 30.12*1 = 30.12 V

PV system current = Panel current * Number of parallel panels = 7.3*12 = 87.6 A

PV system Power = PV system voltage * PV system current = 30.12*87.6 = 2638.512 watt.




a)

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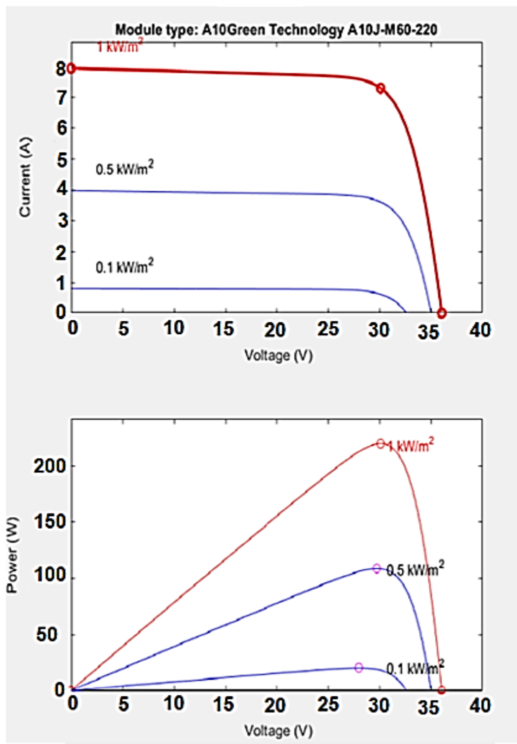


c)

Figure 7. (a) PV System Result, (b) Characteristics Of Proposed PV System (c) Characteristics Of The Proposed PV Panel

Based on the PV power achieved by MATALB Simulink as in Figure (7-(a)), the following equation is used to find the MPPT efficiency:

$$\eta_{P\&O} = \frac{Actual\ Maximum\ outpout\ Power}{Maximum\ rated\ power} *100\% \quad (9)$$

$$\eta_{P\&O} = \frac{2638.4\ W}{2638.512\ w} *100\%$$

$$\eta_{P\&O} = 99.99\%$$

The input/output of the wind turbine system based on PMSG is given in Figure (8) which explains the wind speed, pitch angle, single phase stator current, wind turbine torque, the rotating velocity of the wind turbine shaft, overall output power, three-phase stator current and finally the three-phase stator voltage of the wind turbine. With reference to the characteristics equations of the wind turbine (7) and (8) the MPPT of the wind turbine shown in Figure (4-(c)) should as follows, Cp = 0.48 and λ = 8, Figure (9) shows the Cp-λ curves, while the seven level of the MLI voltage is shown as in Figure (10).

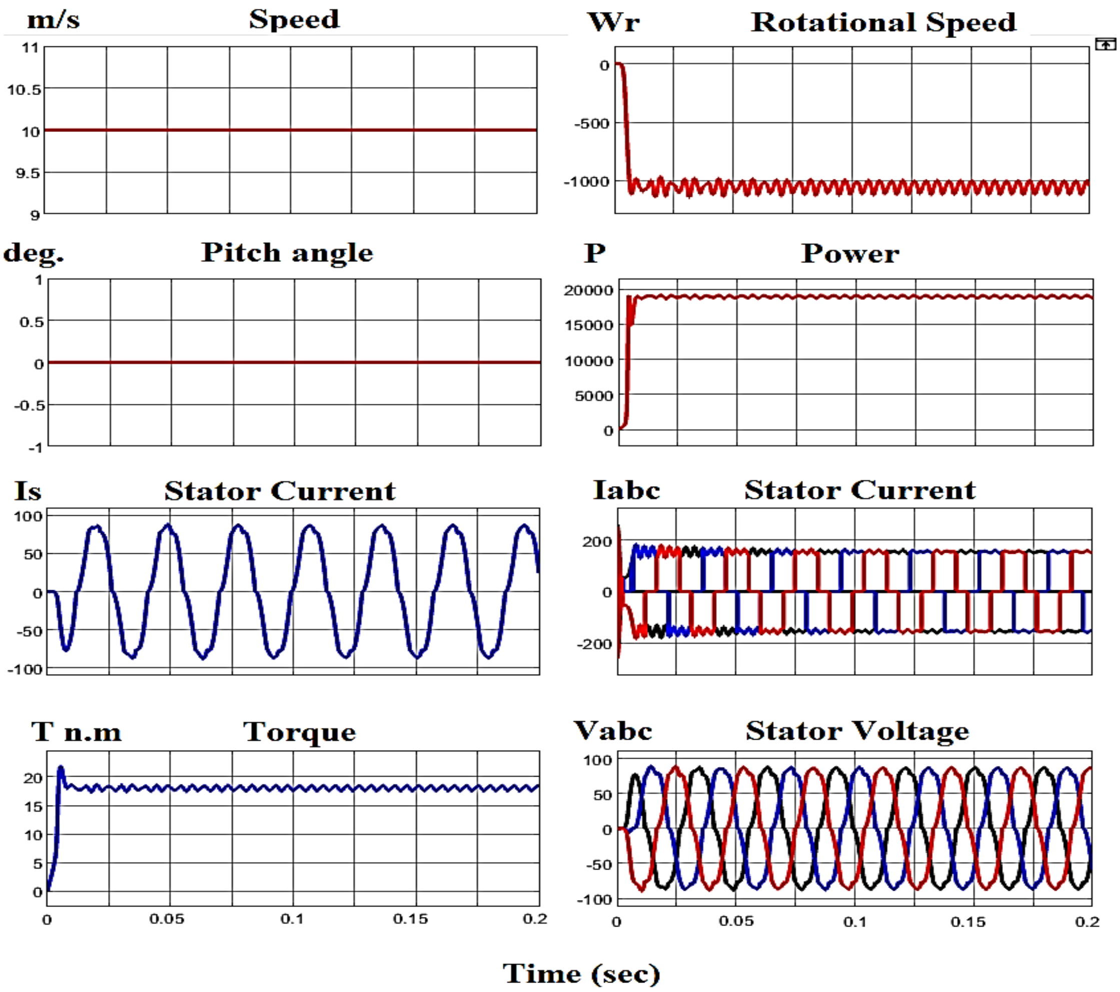


Figure 8. Input/Output Characteristics Of The PMSG Wind Turbine

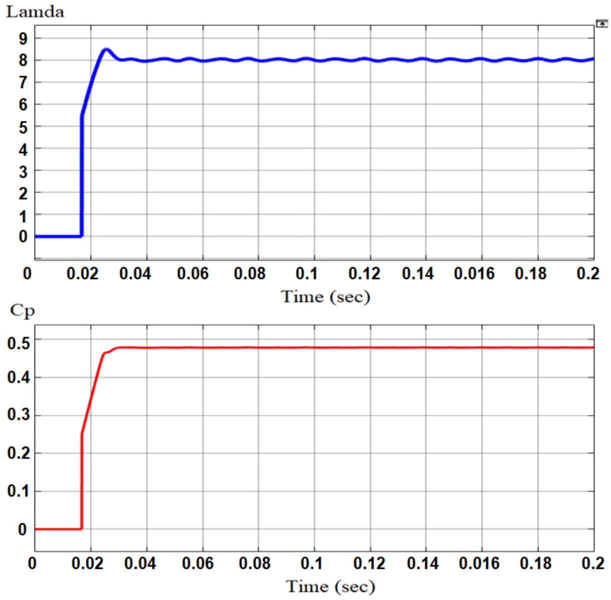


Figure 9. The Lamda and Cp Curves Of The Proposed Wind Turbine At The MPPT

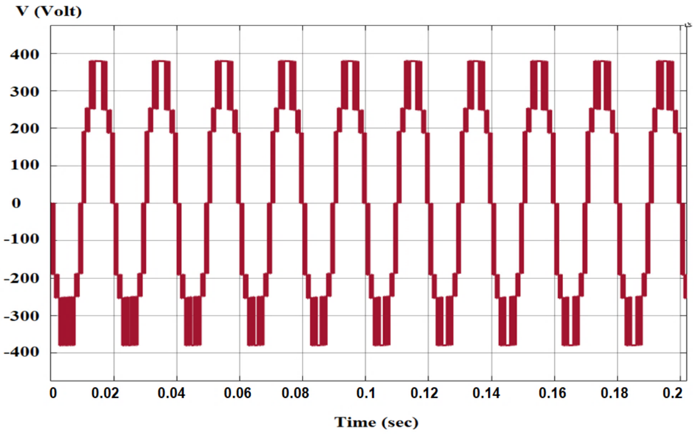


Figure 10. Seven levels Of The Suggested MLI

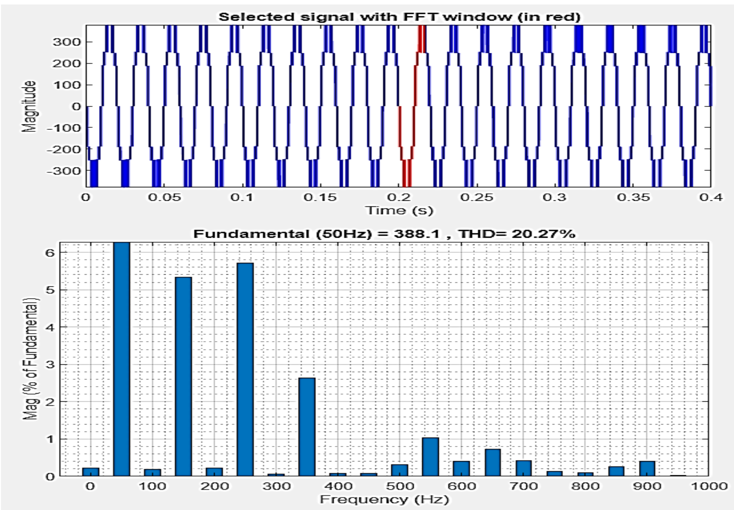


Figure 11. THD Of The Seven Levels Of The Suggested MLI

Figure (11) shows THD of the seven levels of the suggested MLI , To reduce the THD that is present in this case an L-C filter can be utilized at the load terminals to make the output voltage waveforms as pure as possible and the THD will be within the IEEE 519-2022 harmonic standards. Figure (12) shows the output voltage after using the L-C filter. Figure (13) will show the THD of the output voltage after using the L-C filter and it will reduce to 0.99% and it within the IEEE limits (below that 5% for a 1kV voltage system).

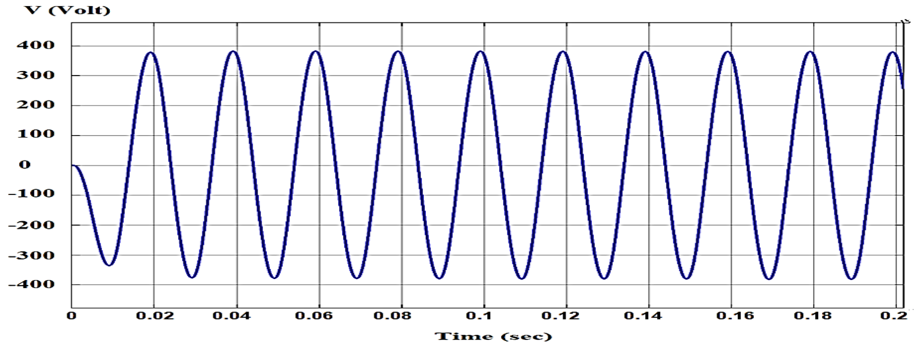


Figure 12. Seven Levels Of The Suggested MLI After Adding The L-C Filter

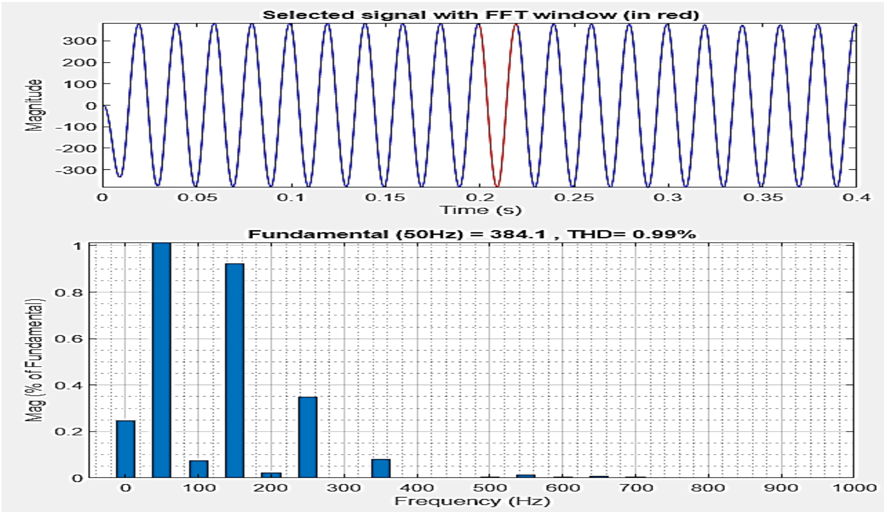


Figure 13. THD Of The Seven Levels Of The Suggested MLI After Adding The L-C Filter

Three different cases are suggested in this work, case one, when the PV is lost, case two loss of W.T1, and case three when the W.T2 is lost, the output voltage levels of the system of the mentioned above cases will be reduced to five levels, for case one (PV is loss) the output voltage waveform is shown in Figure (14).

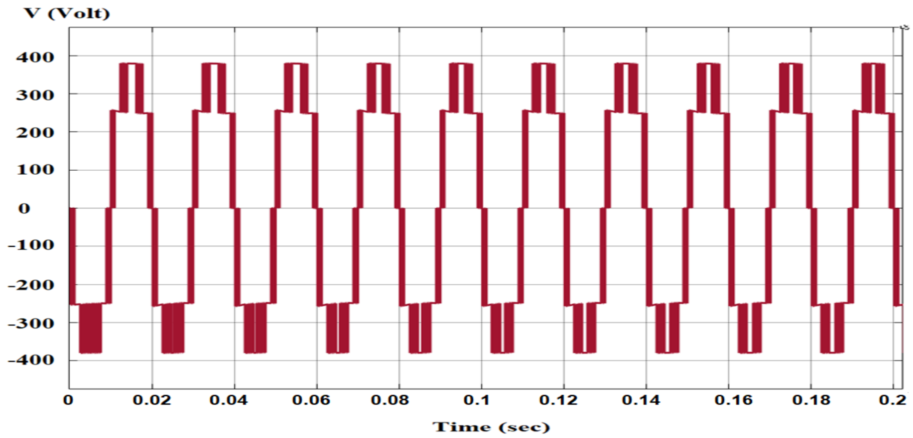


Figure 14. Five levels of the suggested MLI when PV system is loss

The THD of the sinusoidal output voltage waveform for case one (after adding the L-C filter) it will be about (2.01%) and the harmonic analysis window in the MATLAB program is shown in Figure (15).

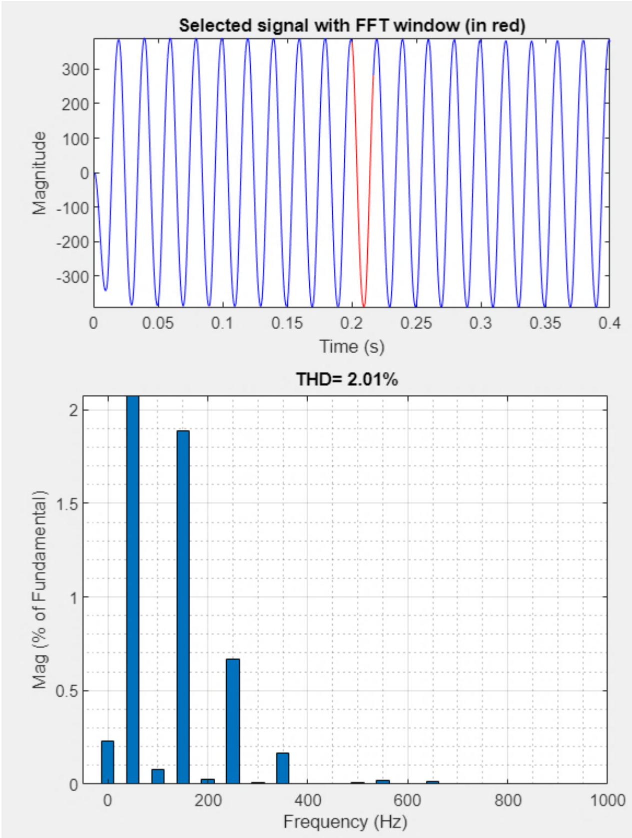


Figure 15. THD Of The Five Levels (Case One) After Adding The L-C Filter

For case two (W.T1 is loss) the output voltage waveform is shown in Figure (16).

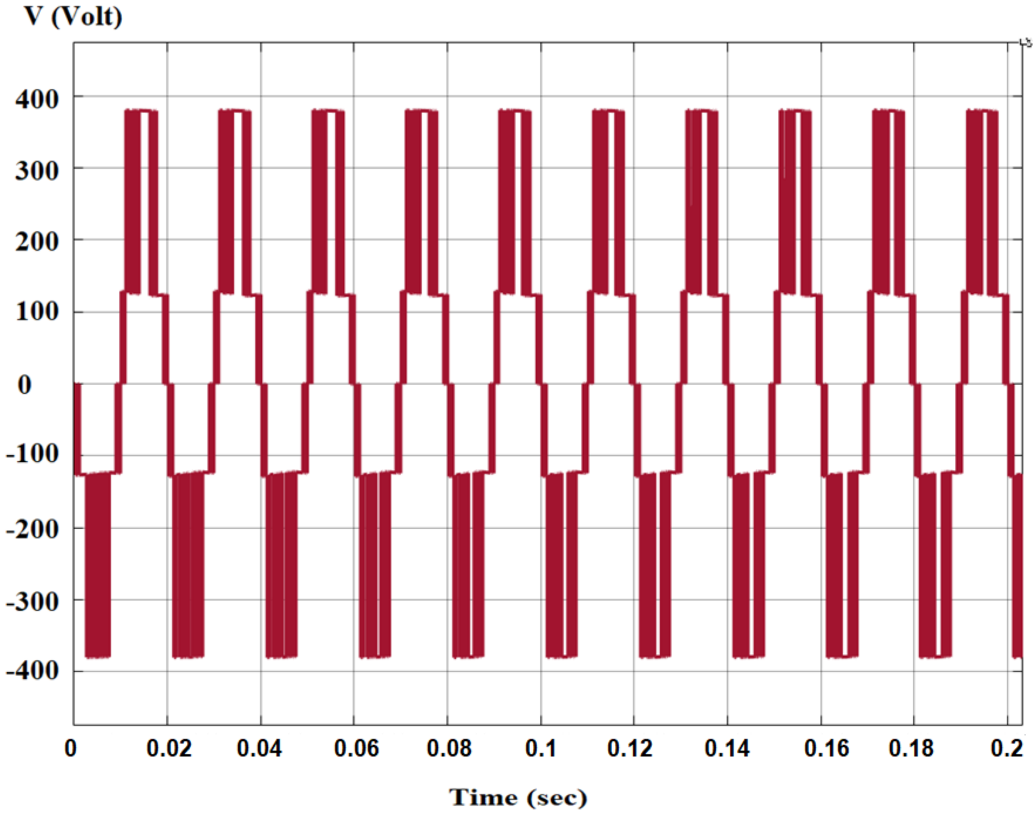


Figure 16. Five Levels Of The Suggested MLI When W.T-1 System Is Loss

The THD of the sinusoidal output voltage waveform for case two (after adding the L-C filter) will be about (2.07%) and the harmonic analysis window in the MATLAB program is shown in Figure (17).

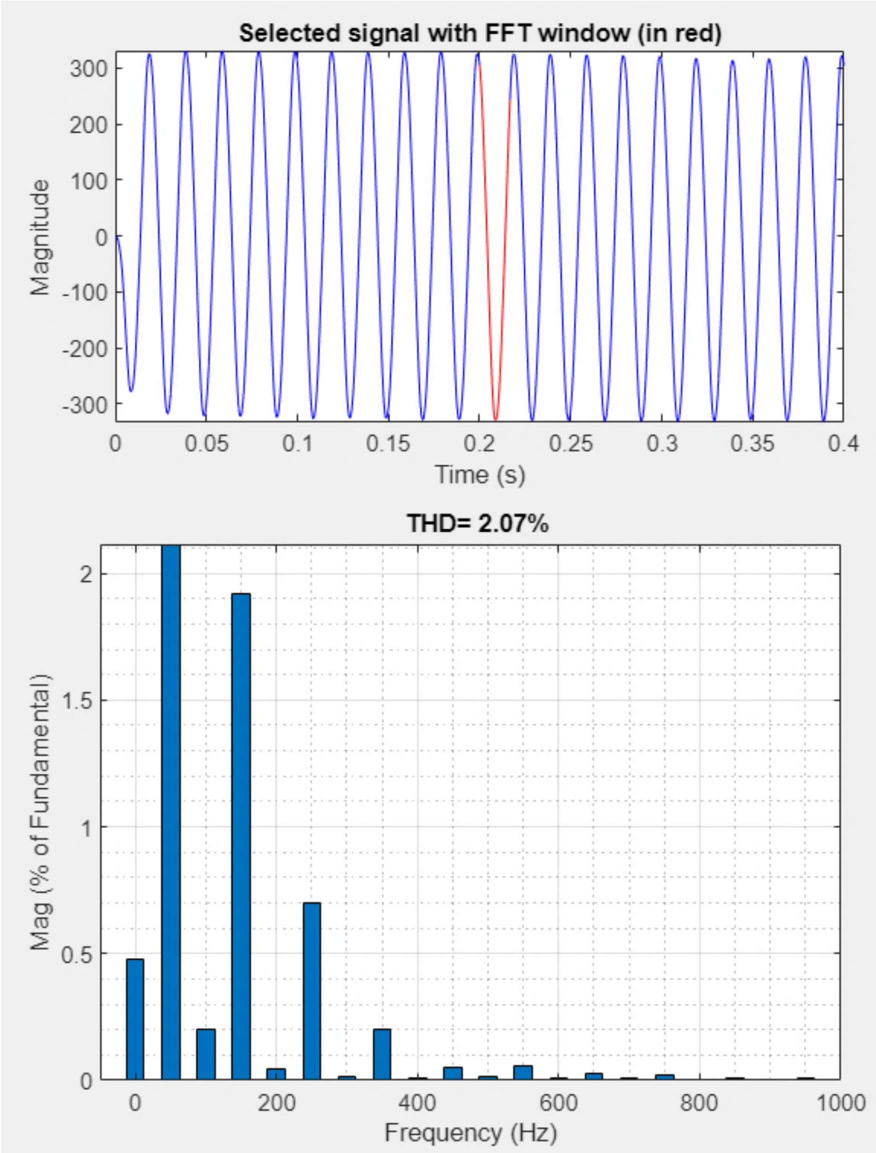


Figure 17. THD Of The Five Levels (Case Two) After Adding The L-C Filter

For case three (W.T2 is loss) the output voltage waveform is shown in Figure (18).

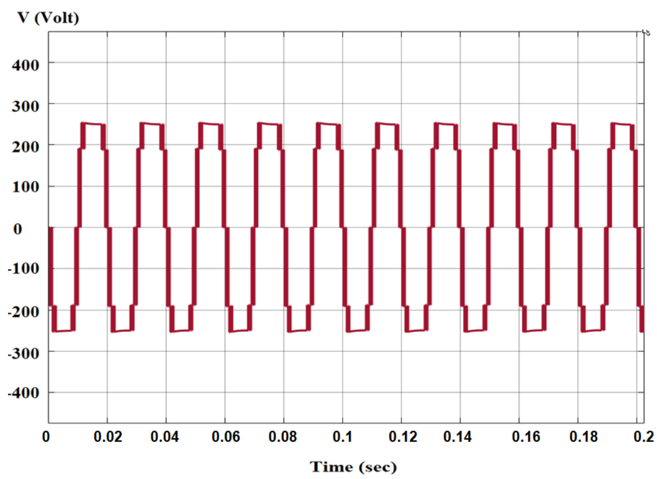


Figure 18. Five Levels Of The Suggested MLI When W.T-2 System Is Loss

The THD of the sinusoidal output voltage waveform for case three (after adding the L-C filter) it will be about (3.85%) and the harmonic analysis window in MATLAB program is shown in Figure (19).

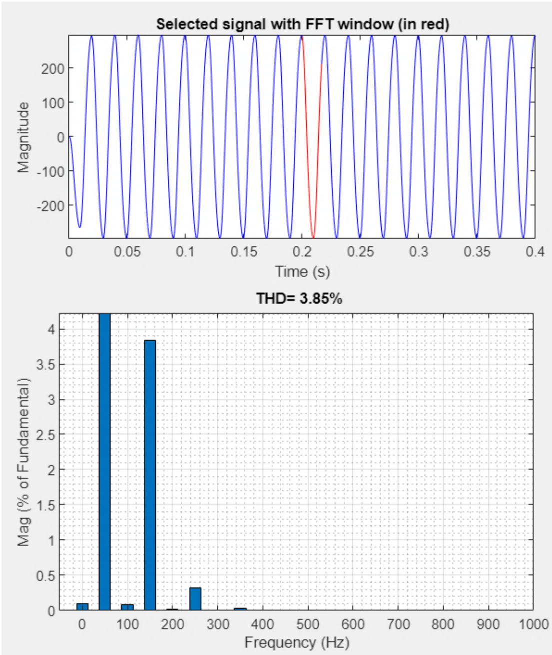


Figure 19. THD Of The Five Levels (Case Three) After Adding The L-C Filter

The compassion of the THD between three contingency case and the normal case can be explained as in Figure (20).

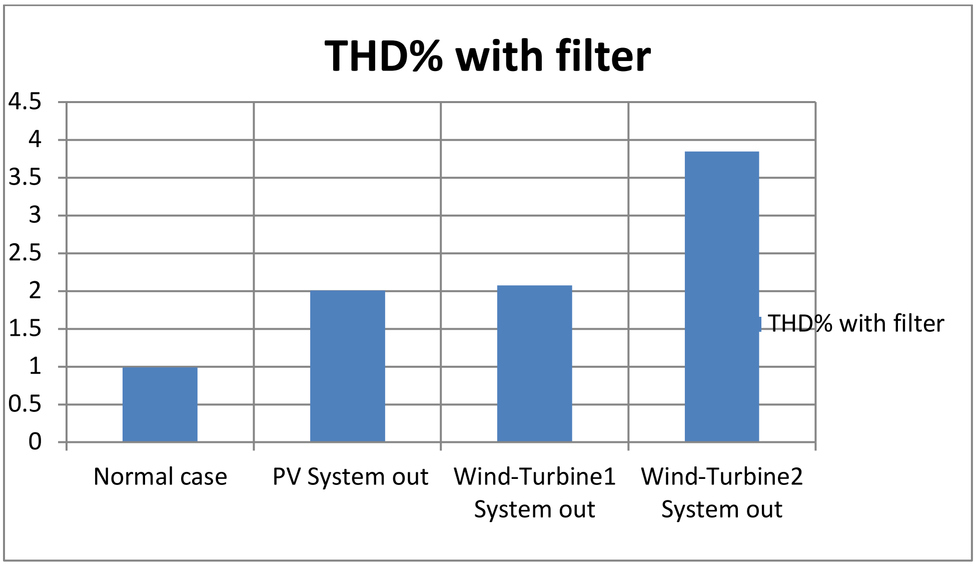


Figure 20. Comparison of (THD%) Under Different Scenarios With Filter Applied. ( Normal Operating Condition, PV System Disconnection, Wind Turbine 1 Disconnection, And Wind Turbine 2 Disconnection)

## 5. Conclusions

The rapid depletion of traditional forms of energy is severe due to the constant increase in the load of electricity. Significant research on RES-based electricity generation has also come from this. Despite their significant reliance on changing climatic circumstances, PV and wind energy are the two main RESs that are attracting increasing attention from the power electronics and power system research groups. To improve the power quality and extract the greatest possible power from RESs, new power converter technologies are needed for the intended operation, control, and power management. Switched waveforms with zero or little THD can be produced via MLI. As the number of output levels increases, it may generate the majority of sinusoidal voltage. However, when the level rises, more switches are needed, which raises the expense, the amount of space needed, and the complexity of the system. Our study presents a novel multilevel inverter architecture that involves fewer switches, resulting in significant size and cost reductions. MATLAB simulation results are used to validate the suggested inverter. The suggested approach will lessen the MLI limitations for real-time applications and make it feasible for an industrial item. The system presented in this study consists of three separate power sources: a solar system, two similar wind turbines, and one. The output voltages of these electrical sources are 1/3, 2/3, and 1 Vdc, in that order. Each of the DC sources was combined to provide an output voltage with seven levels. The THD of the suggested seven-level inverter based on the switch reduction method is (0.99%), in the case of the PV system loss, the THD is (2.01%), while in the case of the W.T-1 loss the THD is (2.07), the worst case is present when the W.T-2 is loss, in this case, the THD is about (3.85%). For all cases, the THD is within the IEEE harmonic standards 519-2022 (below 5% for 1 kV system voltage). According to the number of the eliminated switches as in the switches reduction method, that proposed work, the size and the cost are reduced about 42%.

## Declaration of Competing Interest

The author declares no conflict of interest.

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## Author Contributions

The author proposed the research problem. The work was fully conducted and prepared by the author.

## Notation list

| Abbreviations | Meaning |
|---|---|
| RES | Renewable Energy Sources |
| PV | Photovoltaic System |
| MPP | Maximum Power Point |
| MLI | Multilevel Inverters |
| DC | Diode-Clamped |
| FC | Flying Capacitor |
| CHB | Cascaded H-Bridge |
| PWM | pulse width modulation |
| PMSG | Permanent Magnet Synchronous Generator |
| W.T | wind turbine system |
| MPPT | maximum power point tracking |
| Ppv | The output power in watts |
| ISH | Shunt resistor current |
| THD | Total Harmonic Distortion |
| Q | The charge of the electrons |
| k | Boltzmann factor |
| ρ | Density of the air |
| A | Area of blades or wings |
| V | wind speed |
| w | Rotational blades speed |
| r | Radius of the area |
| Cp | Power coefficient |
| λ | The tip speed ratio |
| β | pitch angle |

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