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DESIGN AND SIMULATION OF A SOLAR-WIND STAND-ALONE SYSTEM WITH A SEVEN-LEVEL INVERTER

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Abstract. During an energy conversion process, the total harmonic distortion and losses will increase while its power stability decreases. Multilevel inverter technology can be utilized to alleviate the shortcomings of conventional inverters. These technologies have become recognized as cost-effective solutions for a wide range of industrial applications. Reduced component losses and lower switching losses, as well as improved output voltage and current waveforms are the first advantages of this design. In multilayer inverters, elimination of harmonic components in the inverter output voltage and current is crucial. This paper proposes a system that consists of three different renewable energy sources. Two of them are PV solar systems while the third is wind turbine simulated in MATLAB Simulink. Seven-level inverters based on switch reduction techniques are proposed in this paper. The proposed system design is verified in the absence of PV systems to produce five voltage levels as a contingency in PV systems.

Keywords: seven-level inverters, photovoltaic system, wind turbine, maximum power point tracking, pulse width modulation, permanent magnet synchronous generator (PMSG)

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ПРОЕКТИРОВАНИЕ И МОДЕЛИРОВАНИЕ АВТОНОМНОЙ СОЛНЕЧНО-ВЕТРОВОЙ СИСТЕМЫ С СЕМИУРОВНЕВЫМ ИНВЕРТОРОМ

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Аннотация. Во время процесса преобразования энергии в инверторе общие гармонические искажения и потери будут увеличиваться, в то время как его мощность снижается. Многоуровневая инверторная технология может быть использована для устранения недостатков обычных инверторов. Такая технология получила признание в качестве экономически эффективного решения для широкого спектра промышленных применений.

Снижение потерь при переключении, а также улучшенные формы сигналов выходного напряжения и тока являются основными преимуществами предлагаемой конструкции. В многослойных инверторах решающее значение имеет устранение гармонических составляющих в выходном напряжении и токе инвертора. В этой статье предлагается система микрогенерации, состоящая из трех различных возобновляемых источников энергии. Две из них представляют собой фотоэлектрические солнечные системы, а третья – ветряная турбина, смоделированная в MATLAB Simulink. В данной публикации предложены семиуровневые инверторы, основанные на методах уменьшения количества переключений. Предлагаемая конструкция системы инвертирования проверяется в отсутствие фотоэлектрических систем для получения пяти уровней напряжения как аналог аварийной ситуации.

Ключевые слова: семиуровневые инверторы, фотоэлектрическая система, ветряная турбина, отслеживание точки максимальной мощности, широтно-импульсная модуляция, синхронный генератор с постоянными магнитами (PMSG)

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Introduction

Renewable energy sources (RES) have become very important in recent years owing to their non-degradability, eco-friendliness and self-sufficiency. Systems using RES are reliable and can replace conventional generation techniques. Fossil fuels are degradable, non-renewable and contribute to climate change and ecological imbalance. Solar, wind and geothermal energies, as well as other renewable energy resources, are forms of RES. Solar and wind energy are the most commonly used RES [1]. The benefits of a solar photovoltaic systems over wind turbines include their minimal maintenance, lack of moving parts and ease of installation. Wind-turbine systems are less expensive than solar panels, especially when used in large quantities. However, they require a professional staff for operation and maintenance. The two technologies are typically combined using multiple RES so that they may deliver continuous power under various situations [2].

Since the amount of energy provided by renewable systems changes throughout the day, it is critical to maximize the delivered energy [3]. The output power of wind turbines and photovoltaic arrays is influenced by wind speed and solar irradiation. As a result, changes in these parameters must be handled appropriately by system control mechanisms. With variable wind, the turbine speed must be adjusted to optimize the generation of power to ensure that the system runs at its maximum power point (MPP). Similarly, the DC voltage and current at the output of the PV system must be modified to run the PV systems at their MPP [4]. The biggest issue that some RES encounter is they produce DC electrical energy. This requires equipment to convert DC to AC power. Inverters serve this role. However, there are switching components utilized during power conversion that reduce the stability and quality of the electricity [5].

Multilevel Inverter (MLI) technology is used at the DC output terminals of RES to convert the generated electricity into AC power and improve the power quality and stability. The benefits of MLI include improved voltage and current output waveforms, less electro-magnetic interference (EMI), their small size, and lower total harmonic distortion (THD) [6]. MLI switches are used to interrupt the DC so that it is produced at different levels. They are essential because they determine circuit size, installation dependability, control complexity and cost. In conventional MLIs, the size, cost and complexity of inverters increase with the output voltage level [7]. In this research, MLI switch reduction is used to provide a larger number of output levels with fewer switching components, thereby lowering costs. The proposed MLI circuit reduces the voltage stress on the switches, enhancing protection against overvoltage [8].

There are three main types of reduced switch MLIs that can be used. The first is a reduced switch symmetrical MLI (RSS-MLI) that produce many DC levels with equal magnitude. This method is a lower cost option. A reduced switch symmetrical MLI (RSA-MLI) produces DC of different magnitudes. Typically, this technology is used in a cascaded H-bridge method. Finally, a reduced switch modified MLI (RSM-MLI) does not use a cascaded H-bridge configuration. It cannot be used for high power applications due to its excessive voltage stress on H-bridge switches [9]. Fig. 1 shows the conventional and reduced switch MLIs.

Design and implementation of a single-phase switching reduction MLI in a stand-alone system fed from multiple individual RES are presented in this work. A new logical switching method, pulse width modulation (PWM), is used to create a seven-level output voltage. In this research, two PV-solar systems and one wind-turbine generator with a permanent magnet synchronous generator (PMSG) are offered as distinct energy sources. The proposed method is used to reduce the number of switching devices, thereby decreasing losses and THD.

The MATLAB Simulink program is used to simulate a seven-level inverter for use with renewable

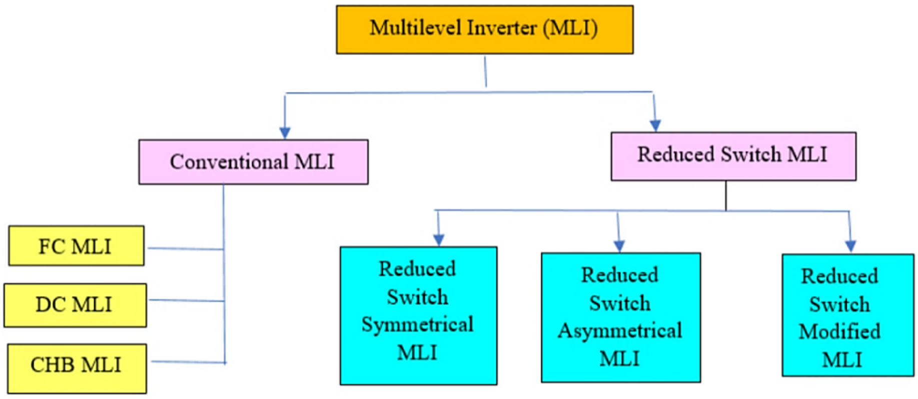

Fig. 1. Conventional and reduced switch MLIs [9]

energies. RES continue to be more dominant in local power production for stand-alone networks than fossil fuel units. In this research, PV and wind turbine technologies are used to create a self-contained system with high reliability and security that can work under a variety of operational conditions. The contingency of reduced PV solar system performance (due to cloudy winter days, nighttime or fault event) is taken into consideration in this work. Multilevel inverters are an ideal way to employ inverters for stand-alone use in systems that produce just a few kilowatts.

Literature review

Table 1 summarizes the suggested seven-level PWM inverter and contemporary MLI designs using several performance metrics. These metrics include the numbers of semiconductor switches, elements (such as diodes and/or capacitors), transformers and input DC sources, as well as THD before and after incorporation of an LC filter, in addition to contingency analysis. Each MLI design uses a different number of components to achieve the same output-voltage level, as seen in the comparison below.

Proposed system

The proposed system, shown in Fig. 2, is comprised of three distinct RES inputs. Two of them are PV solar systems and the third is a PMSG-type wind turbine generator. The PV solar systems are both connected to a DC-DC boost converter to increase the output voltages of the two systems to the same level (E/3, and 2E/3). A perturb and observe (P&O) algorithm approach is employed to accomplish maximum power point tracking (MPPT) of the PV solar system and the wind energy conversion system (WECS). The wind turbine output power is AC and thus, an AC-DC rectifier is needed to convert it to DC. A DC-DC boost converter is needed to boost the voltage (E). The wind turbine generator is a three-phase PMSG.

A. PV solar systems

Photovoltaic (PV) systems utilize the photovoltaic effect to convert sunlight into direct current (DC). A combination of P- and N-type semiconductor materials make up the PV cell. As a result, a PV cell can be represented as a diode. When the diode absorbs light, the photovoltaic effect creates current [19]. In most applications, a PV module requires a large number of solar cells connected in parallel or series to provide sufficient voltage and power. An array is a system made up of a large number of PV modules connected on the same panel to generate sufficient power. The MPPT algorithm approach is used to manage the position of the PV system panels so that the maximum

Table 1

Comparison of MLI topologies

Reference	No. of switches	No. of elements	No. of DC voltage sources	THD before LC filter	THD after LC filter	Use RES as inputs	Contingency analysis
[10]	10	–	3	–	3.53	Not used	Verified
[11]	8	–	2	–	1.83	Not used	Not verified
[12]	6	11	1	–	3.9	Not used	Not verified
[13]	8	–	2	–	2.8	Not used	Not verified
[14]	10	3	1	–	1.11	Used	Not verified
[15]	12	–	3	19.28	–	Not used	Not verified
[16]	8	–	2	18.05	–	Not used	Not verified
[17]	12	–	3	32.1	–	Not used	Verified
[18]	9	–	3	–	2.38	Not used	Not verified
In this work	7	–	3	20.51	2.09	Used	Verified

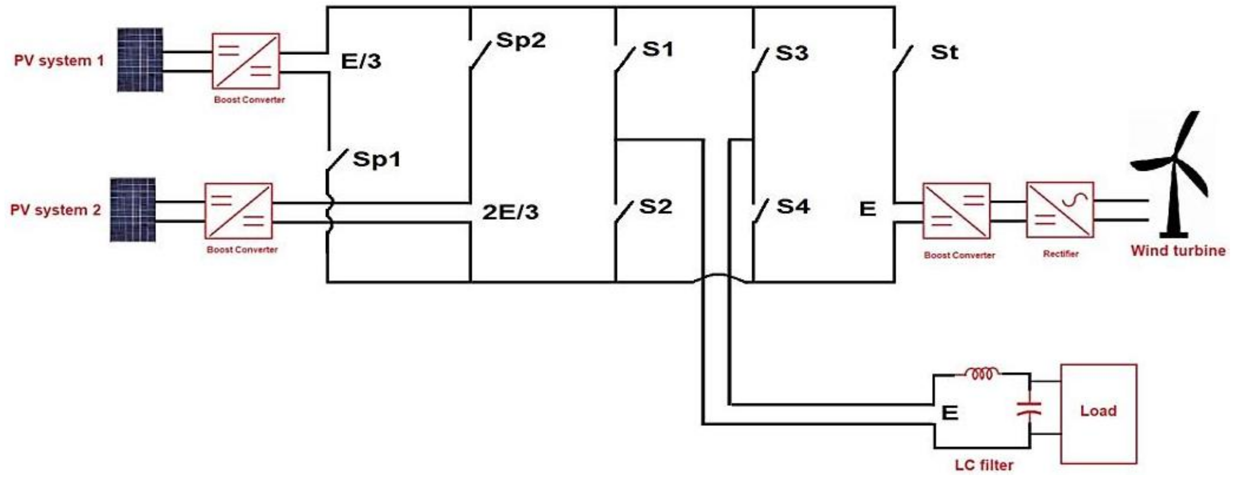

Fig. 2. The proposed system

generation power of a PV solar system can be obtained [20]. In this study, we will apply the P&O algorithm method to achieve the MPPT.

B. Wind turbine

Three-phase PMSGs powered by adjustable pitch wind turbines are considered the best choice for wind energy producers because of their great efficiency and dependability. The output AC power is converted to DC using a three-phase uncontrolled rectifier. To step up the output voltage and supply a DC bus, a boost converter is also required. Fig. 3 depicts the key components of the WECS [21].

The MPPT of a wind turbine is achieved using the P&O algorithm. Fig. 4 shows the operational principle of this algorithm [22].

C. Switch reduction MLI

Inverters are devices that convert DC to AC power. They are often used in household power applications such as motors, UPSs and similar devices. In high-power switching applications, MLIs are becoming more popular. To enhance power quality, high switching frequencies are employed to eliminate ripple in the output voltage or current waveform. Due to switching losses and device rating constraints, switch

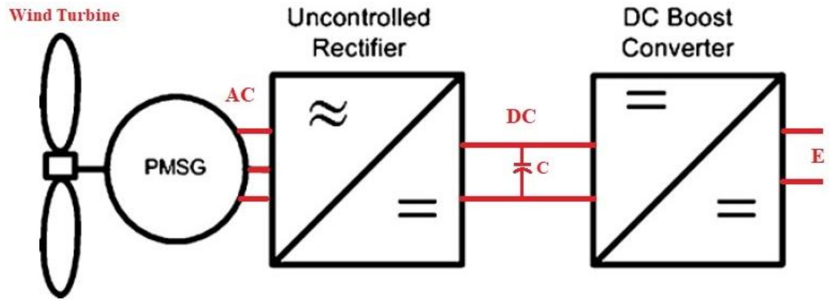

Fig. 3. Wind Energy Conversion System WECS

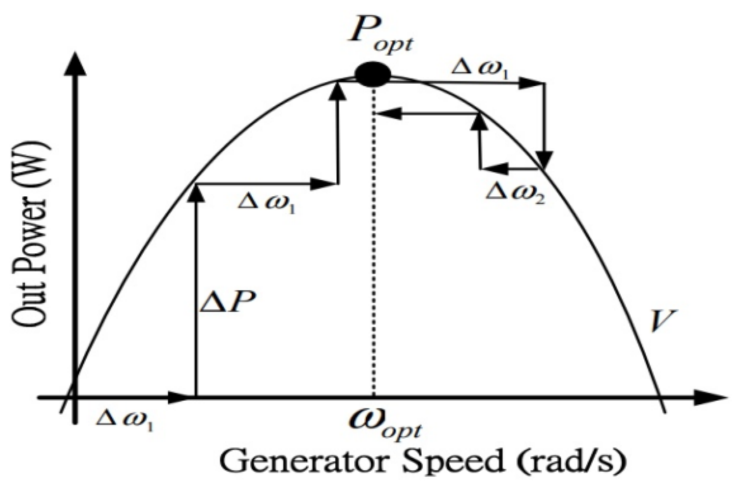

Fig. 4. Operational principle of the P&O algorithm [22]

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reduction MLIs have significant challenges in high-frequency high-power and medium-voltage applications [23].

Among the inverter internal voltage control approaches, pulse width modulation (PWM) is one of the most effective control strategies. In essence, pulse width refers to the width of an inverter's output pulse, which is dictated by the conduction period of each switch. This is especially true for bridge inverters, where each switch conducts for the duration of its gate pulse and the output pulse width is directly proportional to the gate pulse period [24]. As a result of changing the gate pulse duration, the output pulse width changes, thus modifying or regulating the voltage. PWM may be classified into two groups based on the approaches for adjusting gate pulse duration. Fig. 5 depicts a multicarrier PWM used to generate seven-voltage levels using a reference sine wave.

Fig. 6 shows the implemented PWM control system for a switch reduction MLI of the proposed system. A simple PWM approach is used to regulate gate pulses. The gate pulses for the switches are generated by a PWM pulse generator. Different modulation indices (Ma) are explored under varying output-voltage levels to highlight the influence of various modulation ratios on output-voltage levels. The output voltage has just three values when Ma is less than 0.33 (+E/3, 0, –E/3). The output voltage has five levels with a modulation index of 0.33 to 0.67 (+2E/3, +E/3, 0, –E/3, –2E/3). A seven-level output voltage may be generated with a modulation index of 0.67 to 1 (+E, +2E/3, +E/3, 0, –E/3, –2E/3, –E).

The switching functions are separated into six modes of operation that are linked to the output-voltage levels considering one output-voltage / reference signal cycle, with the entire switching states based on a comparison of the reference and carrier waveforms, as indicated in Table 2.

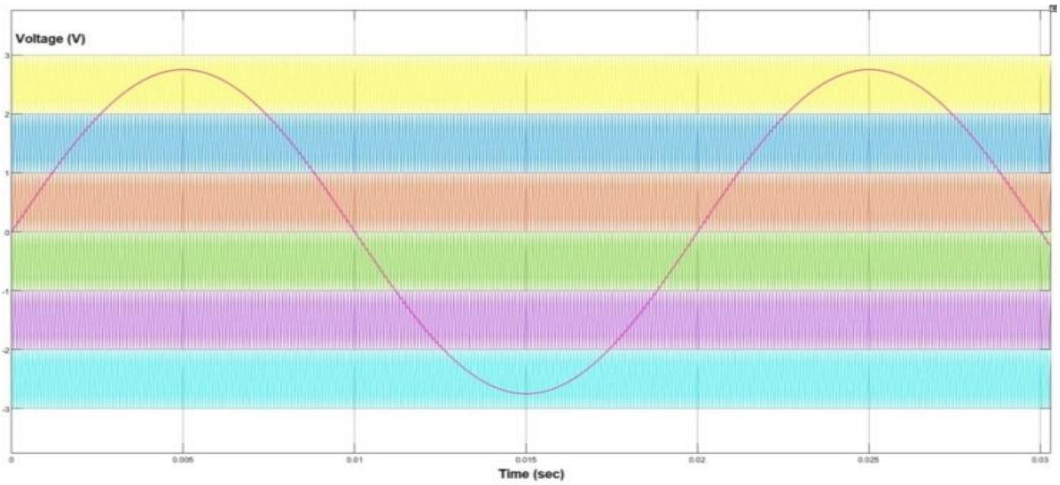

Fig. 5. Multicarrier PWM seven-shifted levels of a sine wave

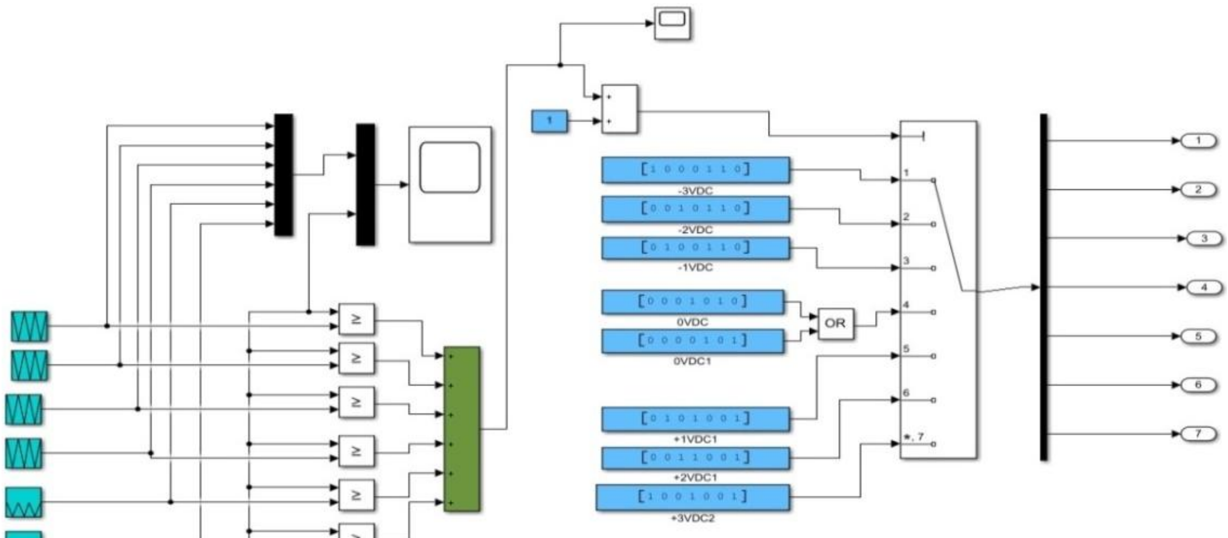

Fig. 6. Proposed control based on PWM

Table 2

Switching status and output voltages of the proposed MLI

Voltage Level	Sm	Sp1	Sp2	S1	S2	S3	S4
E	1	0	0	1	0	0	1
2/3E	0	0	1	1	0	0	1
1/3E	0	1	0	1	0	0	1
0	0	0	0	0	1	1	1
–1/3E	0	1	0	0	1	1	0
–2/3E	0	0	1	0	1	1	0
–E	1	0	0	0	1	1	0

The switches (Sp1, Sp2 and St) are connected in parallel with the solar PV system-1, solar PV system-2 and the turbine generator. The pairs of switches (S1, S4) and (S2, S3) operate alternately to provide the MLI of voltages across the load. The three RES are connected to switch reduction MLI consisting of seven switches. The output voltage is equal to turbine voltage E (400 V), while PV source-1 (1/3 · 400 = 133.3 V) and PV solar source-2 (2/3 · 400 = 266.6 V) are the algebraic sum of the two PV sources and is equal to the output voltage of the WECS.

D. Auxiliary circuits

DC-DC step-up and AC-DC rectifier converters are the main auxiliary circuits used with PV and wind turbine systems.

DC-DC step-up converter. One of the most widely used converters to enhance DC output voltage of a PV solar systems to match the needed DC bus voltage is the DC-DC step-up, or boost converter. System losses are reduced as the voltage is increased. Fig. 7 depicts a boost converter circuit diagram. When the switch is "ON" and the diode is an open circuit, the inductor "L" charges the power. However, when the switch is "OFF", the diode conducts while the input and inductor voltages are received at the output side. Capacitor "C" is used in the output waveform [25] to lower the ripple factor.

The following equation gives the duty cycle (D) of a step-up converter [26]:

$$D = 1 - \frac{V_{in}}{V_{out}}. \quad (1)$$

Inductance (L) and capacitance (C) of a step-up converter are given in Equations (2) and (3), respectively [11]:

$$L_{\min} = \frac{D\,(1-D)^2\,R}{2\,f}; \quad (2)$$

$$C = \frac{D}{R\left(\frac{\Delta V_o}{V_o}\right)f}, \quad (3)$$

where R is output resistance calculated from the output power and voltage. $\left(\frac{\Delta V_o}{V_o}\right)$ is the output ripple voltage, normally about 1% to 2%, and f is the switching frequency [10].

DC-AC rectifier circuit. This is a power electronic circuit that used to convert or transform DC power into AC. This three-phase circuit is made up of three parallel branches. Each branch has two diodes in series. The anode of the upper diode is connected to the cathode of the lower diode. A rectifier circuit is used to convert the generated AC wind turbine power to DC, which is then stepped up by a boost converter. The primary purpose of this conversion is to manage the DC voltage and to achieve the maximum power point [27–29].

A DC link capacitor is used to fix the voltage and reduce the ripple. An LC filter is used at the output of the MLI to reduce the harmonics to acceptable IEEE 519-2014 standard limits.

Simulation and results

Fig. 8 shows the proposed system modeling using MATLAB Simulink.

The system consists of a WECS with an output DC voltage of 400 V and two PV systems with output DC voltages of 133.3 V and 266.6 V, respectively. The temperatures of the two PV systems were assumed to be constant at 25 °C and the irradiance was 1000 W/m^2. The output power of each system was 2000 W, and the (I-V) and (P-V) characteristics of

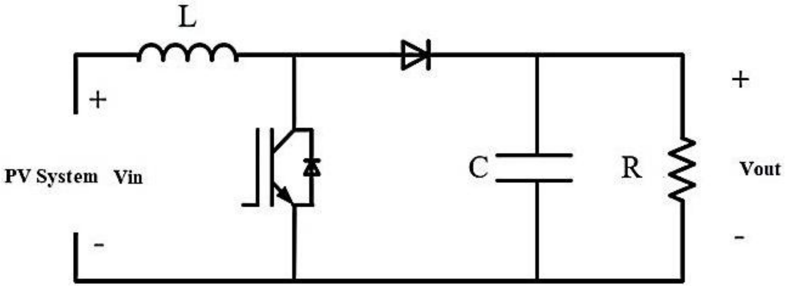

Fig. 7. A schematic of a DC-DC boost converter

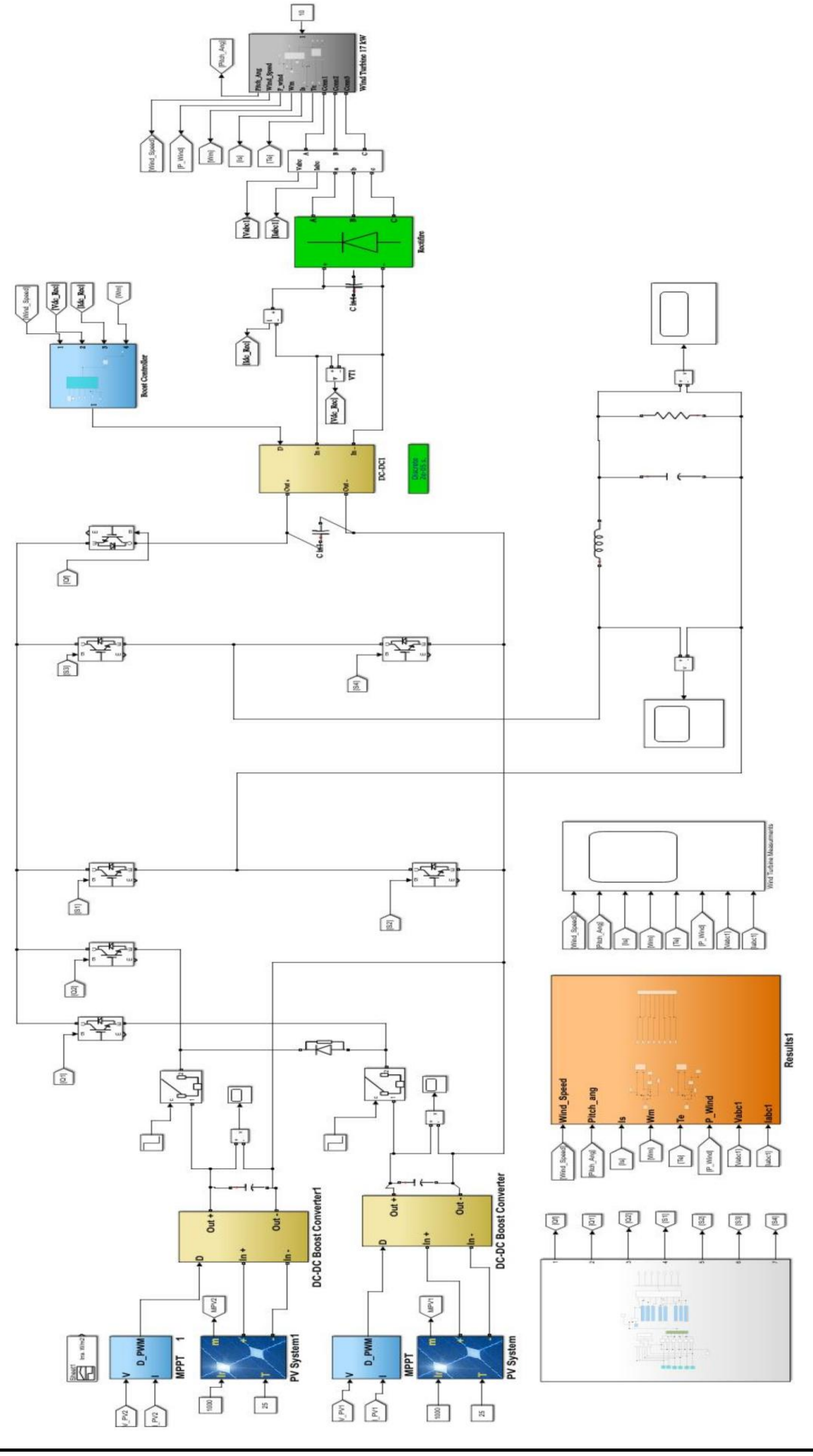

Fig. 8. The proposed system modeled using MATLAB Simulink

the selected PV panel are given in Fig. 9. Each PV system consists of 10 solar panels connected in parallel, the output voltage of the system is 37.26 V and current is 53.7 A (10 · 5.37 A). The total power is 2 kW for each solar system. Fig. 10 shows the output voltage, current and power of each PV system. An LC filter is used to reduce the harmonics and make the output waveform as sinusoidal as possible so that it is within the IEEE 519-2014 standard.

The output voltages of the DC-DC boost converters are (E/3) 133.3 V and (2E/3) 266.6 V for PV-system-1 and PV-system-2, respectively. The DC-DC boost converter circuit of the WECS is (E) 400 V DC. Parameters of the step-up converters are given in Table 3. The selected switching frequency is 4 kHz and the ripple voltage is about 1%. Fig. 11 shows the output voltage of the three boost inverters.

The wind speed was assumed to be constant in the current work at 10m/s and the rated output power at this speed is 17 kW. Fig. 12 shows curves of the input/output characteristics of the wind speed, electrical torque, output power, stator current, three-phase stator voltage, and turbine speed in rad/sec as well as pitch angle.

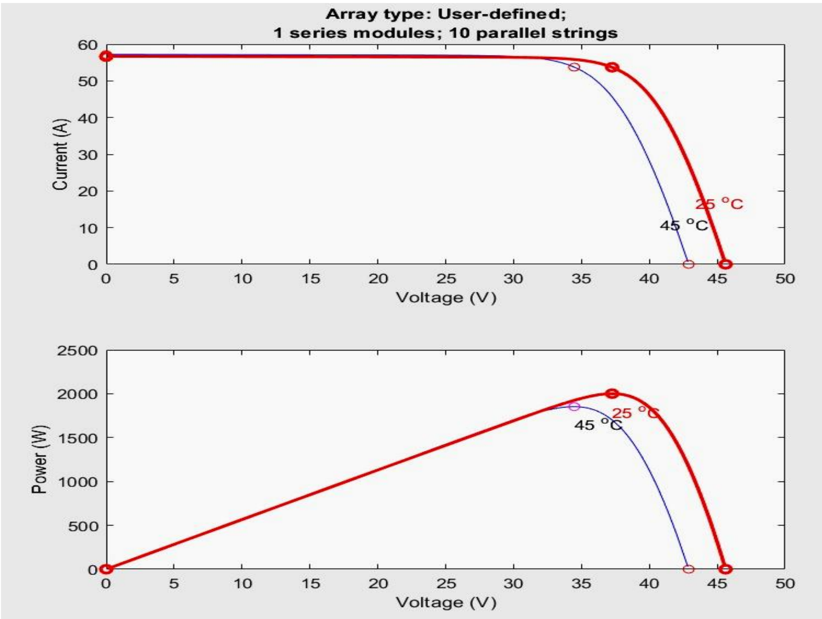

Fig. 9. The (V-I) and (P-V) characteristics of each PV system

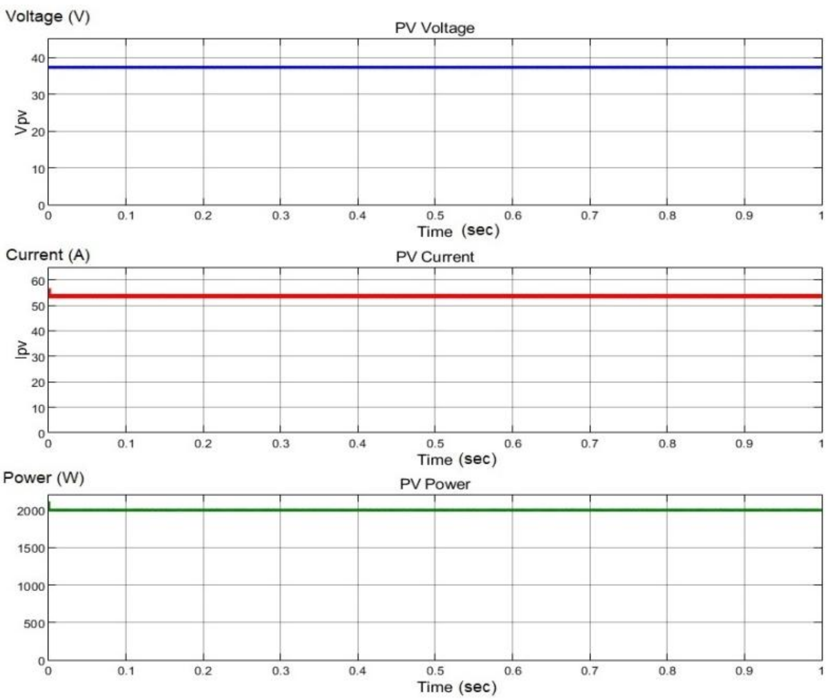

Fig. 10. Output voltage and current for each PV system

Table 3

Step-up converter parameters

Converter No.	Input voltage (V)	Output voltage (V)	Power (W)	Duty cycle	Inductor (mH)	Capacitor (uF)
1	37.26	133.3	2000	0.72	0.125	0.02
2	37.26	266.6	2000	0.86	0.15	0.6
3	160	400	17 000	0.6	0.22	0.79

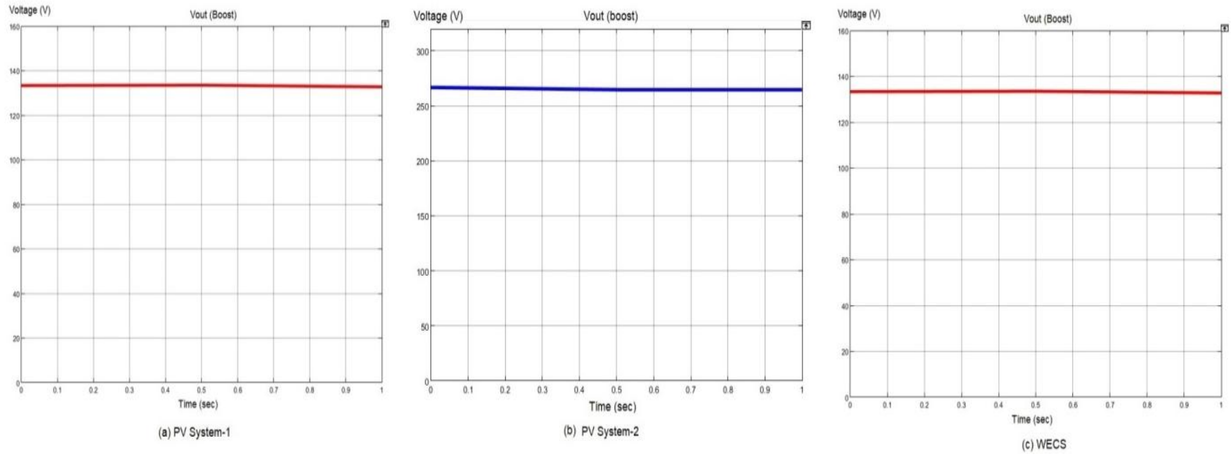

Fig. 11. The output boost voltages of the PV systems

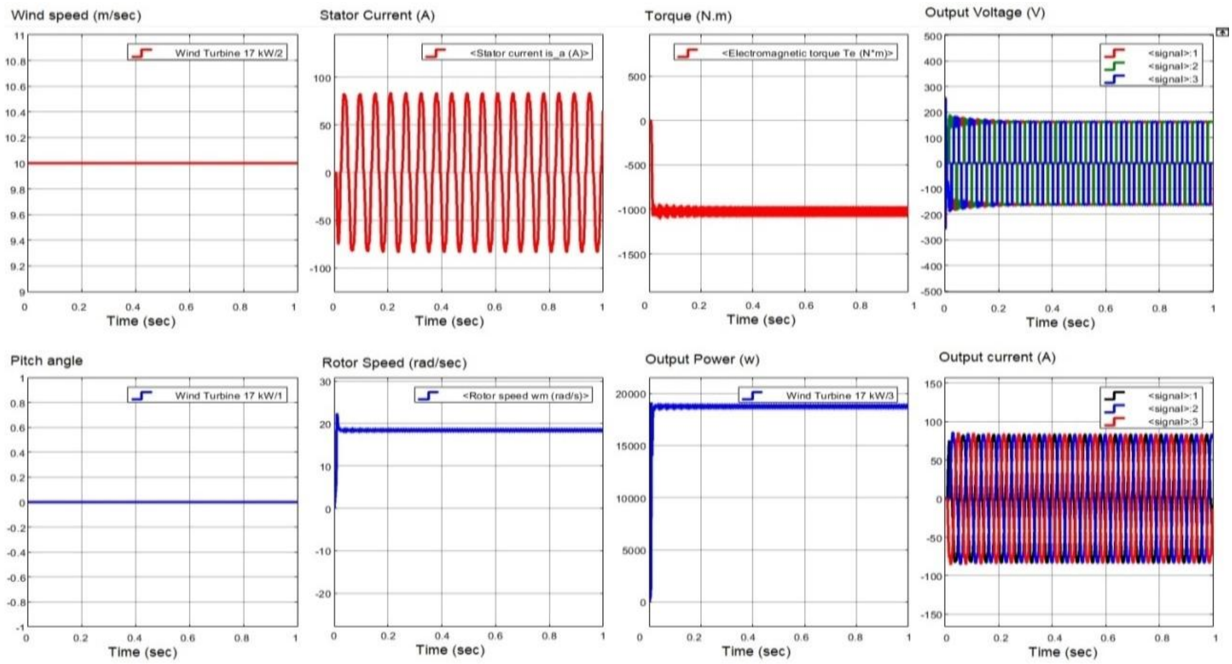

Fig. 12. Characteristics of the WECS

A seven-level voltage waveform without a filter is shown in Fig. 13. The same waveform after connecting an LC filter is shown in Fig. 14.

Harmonics on the low voltage side (below 1 kV) should have a maximum value of less than 5%, according to IEEE519-2014. It is clearly seen in Fig. 15 and 16 that the LC filter reduces the THD, making the output waveforms as sinusoidal as possible. The THD values of the output voltage are 2.09% and 20.51% with and without an LC filter, respectively.

Contingency analysis is important when the system has multi-RES to ensure the reliability of the overall system. When PV solar system-1 is out of service for any reason, the system must still provide the required output voltage. However, the voltage will decrease from seven to five levels and the THD will increased. Fig. 17 shows the output voltage without an LC filter at $t = 0.1$ sec when the PV solar system-1 is out of service. The THD of the five level inverter, which consists of wind turbine and PV solar system-2, is increased to 47.87%. When an LC is used, the THD is reduced to 5.16%. If PV solar system-2 is out of service, the output voltages without an LC filter are as shown in Fig. 18. The THD of a five level inverter, consisting of wind turbine and PV solar system-1, is increased to 31.39% and the THD is reduced to 3.72% when an LC is used.

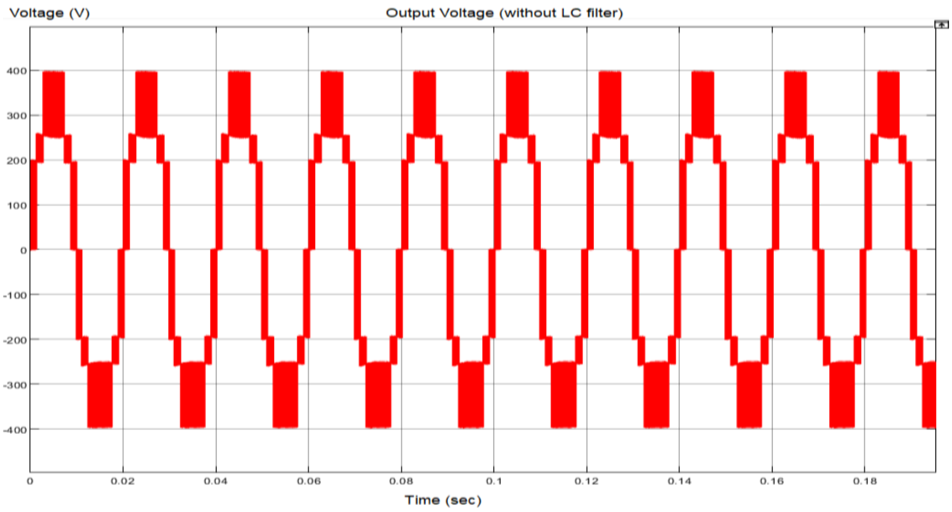

Fig. 13. Output voltage of a seven-level inverter without an LC filter

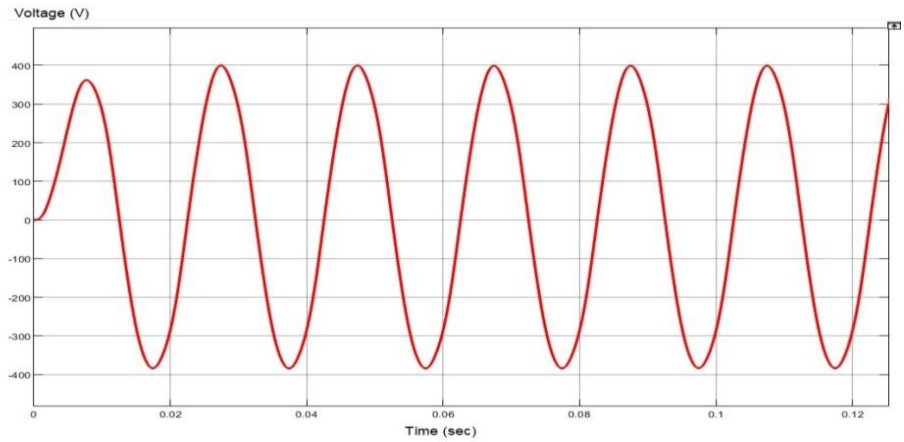

Fig. 14. Output voltage of a seven-level inverter with an LC filter

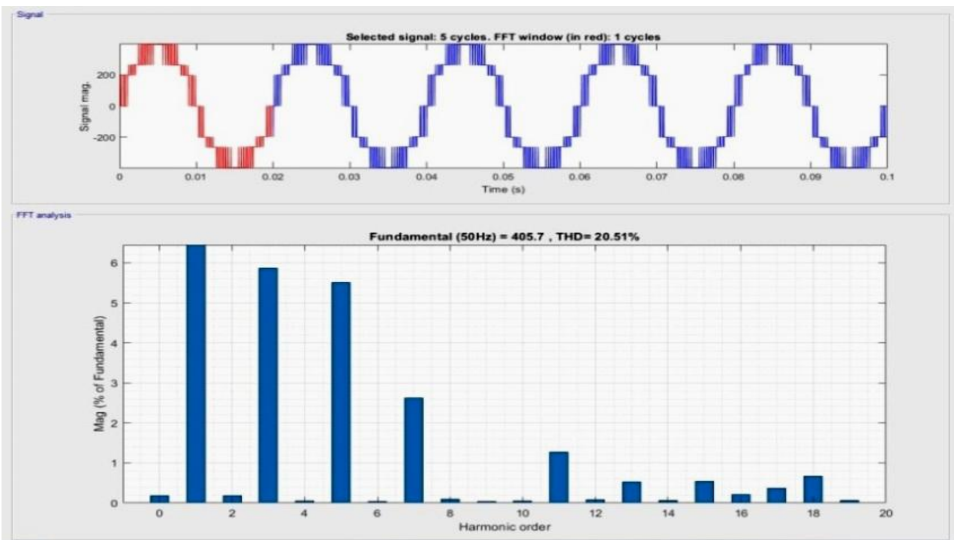

Fig. 15. THD of the output voltage waveform without an LC filter

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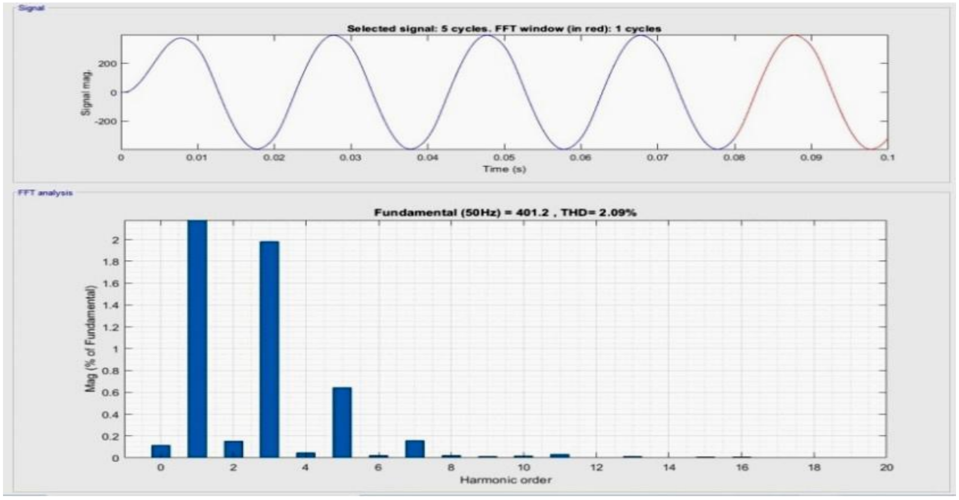

Fig. 16. THD of the output voltage waveform with an LC filter

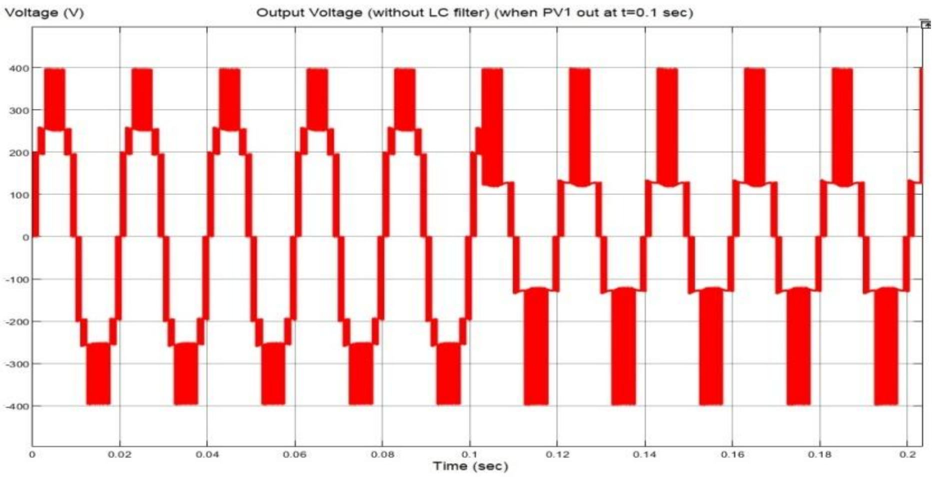

Fig. 17. Output voltage transition from seven to five levels (PV system-1 out of service)

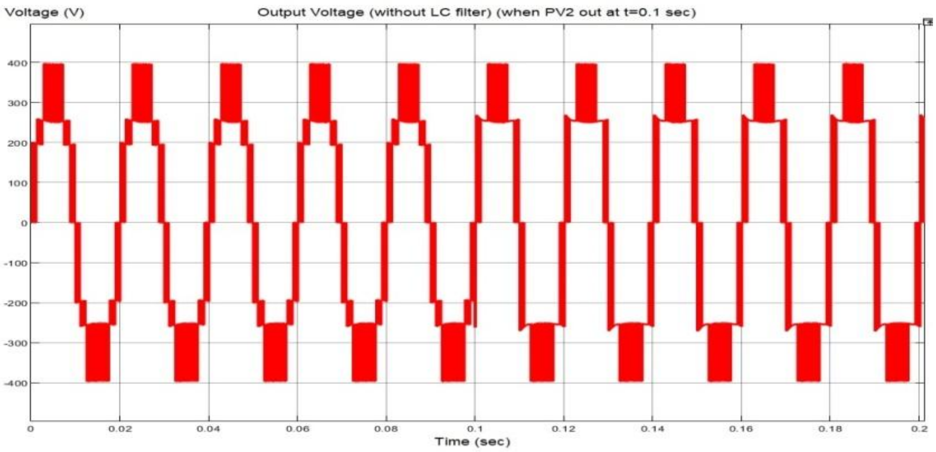

Fig. 18. Output voltage transition from seven to five levels (PV system-2 out of service)

Conclusions

In this study, a seven-level inverter fed by solar-wind systems was designed and simulated using MATLAB Simulink. Three RES are suggested. Two of them are PV systems with output voltages (E/3 and (2E/3), while the third is a wind turbine with voltage (+E). A multicarrier PWM approach was used to build the control circuit. The THD of the voltage waveform with an LC filter is about 2.09%, meeting the IEEE519-2014 standard. When one of the PV systems is removed from the system, the voltage level of the output waveform will have five levels. However, the THD will increase. Good design of an LC filter keeps the THD within standards during contingencies. The system performed well, demonstrating the efficiency of the designed control and power circuits.

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