ISSN (Print) : 2320 – 3765
ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

*(An ISO 3297: 2007 Certified Organization)*

**Vol. 5, Issue 9, September 2016**

# Level-Shifted Multicarrier Modulation Techniques for a Switched-Capacitor Seven-Level Inverter: A Comparative Study

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**ABSTRACT**:A multilevel inverter is a power conversion device that produces an output voltage in the desired levels by using DC voltage sources at the input. Due to adequate cost, simple implementation and high efficiency, they are very useful in modern drives and other medium and high power utilities. Here a switched-capacitor multilevel inverter is used. The switched-capacitor multilevel inverter can produce the desired output voltage. It can also boost the input voltage without any bulky transformer. Also, the number of switches and DC voltage sources are reduced in this topology. This reduces the size and cost of the inverter. In this paper, the operation and simulation results of a switched-capacitor seven-level inverter using level-shifted multicarrier modulation technique is presented. The simulation of Switched-Capacitor Seven-Level Inverter is done using MATLAB/Simulink software.

**KEYWORDS:**Multilevel Inverter, Switched-Capacitor Unit, T.H.D,Level-Shifted Multicarrier Modulation Technique, Pulses

## I.INTRODUCTION

A switched-capacitor power converter consists of only semiconductor switches and capacitors. It needs no magnetic element, so they always have small volume and light weight. They usually have an output voltage higher than the input supply voltage. The switched-capacitor multilevel inverter can produce the desired sinusoidal voltage waveform and boost the input voltage without any bulky transformer. By using this kind of inverter with fewer switching devices and simpler control methods, it is possible to achieve a greater number of voltage levels at the output. The switched-capacitor multilevel inverter consists of a combination of the conventional series and parallel switched capacitor units. The switched-capacitor multilevel inverter topology reduces number of switches and isolated DC voltage sources, the variety of the DC voltage source values, and the size and cost of the system in comparison with the conventional topologies. In addition, this topology can boost the input voltage without a transformer. The switched-capacitor multilevel inverters have applications in renewable energy systems, electric drives, etc. The hybrid source switched-capacitor topologies can be used in electric vehicle application and PV systems. There are many modulation techniques for multilevel inverters. Here different modulation techniques are compared with respect to a switched-capacitor seven-level inverter.

## II.SWITCHED-CAPACITOR SEVEN-LEVEL INVERTER

A switched-capacitor seven-level inverter is shown in figure 1. It consist of switched capacitor units and a cascaded H-Bridge unit. The switched-capacitor seven-level inverter consists of one DC source, two capacitors, two diodes and eight switches. The switches $S_{a1}$ and $S_{a2}$ are the parallel switches and the switches $S_{b1}$ and $S_{b2}$ are the series switches, which connects the capacitors $C_1$and $C_2$in parallel and series with the source. The switches $S_a$and $S_b$have complementary operation with each other, which means that, when the switch $S_a$ is ON, the switch $S_b$must be OFF and vice versa.The switches$T_1$,$T_2$, $T_3$ and $T_4$ form the H-Bridge unit. The switches $T_1$ and $T_4$ are operated to produce a positive voltage, while the switches $T_2$ and $T_3$ are operated to produce the negative level voltage at the output.

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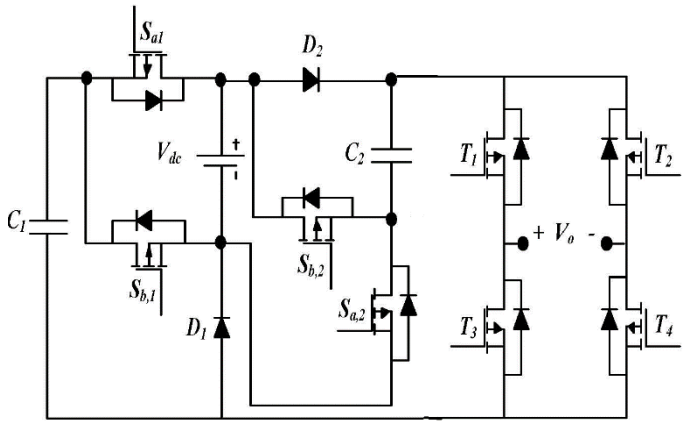


Fig. 1: Switched-Capacitor Seven-Level Inverter

*A. Operation of Switched-Capacitor Seven-Level Inverter*

The operation of a switched-capacitor seven-level inverter is described in table 1. In this table, 0 and 1 means OFF and ON switching states of the switches respectively. The operation of the switched-capacitor seven-level inverter is illustrated in figure 2. In order to get zero voltage level at the output, none of the switches are turned ON.

| $S_{a1}$ | $S_{b1}$ | $S_{a2}$ | $S_{b2}$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ | Output Voltage |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 1 | 0 | 1 | 0 | 0 | 1 | $V_{dc}$ |
| 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | $2V_{dc}$ |
| 0 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | $3V_{dc}$ |
| 1 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | $-V_{dc}$ |
| 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | $-2V_{dc}$ |
| 0 | 1 | 0 | 1 | 0 | 1 | 1 | 0 | $-3V_{dc}$ |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Table 1: Switching pattern of Switched-Capacitor Seven-Level Inverter

*B. Advantages and Applications*

The switched-capacitor multilevel inverter can step-up the input voltage without any bulky transformer. The number of DC voltage sources and switches are reduced. As a result, the size, installation area and cost is also reduced.

The switched-capacitor multilevel inverter can be used in PV systems, electric vehicles and DC-AC converter applications.

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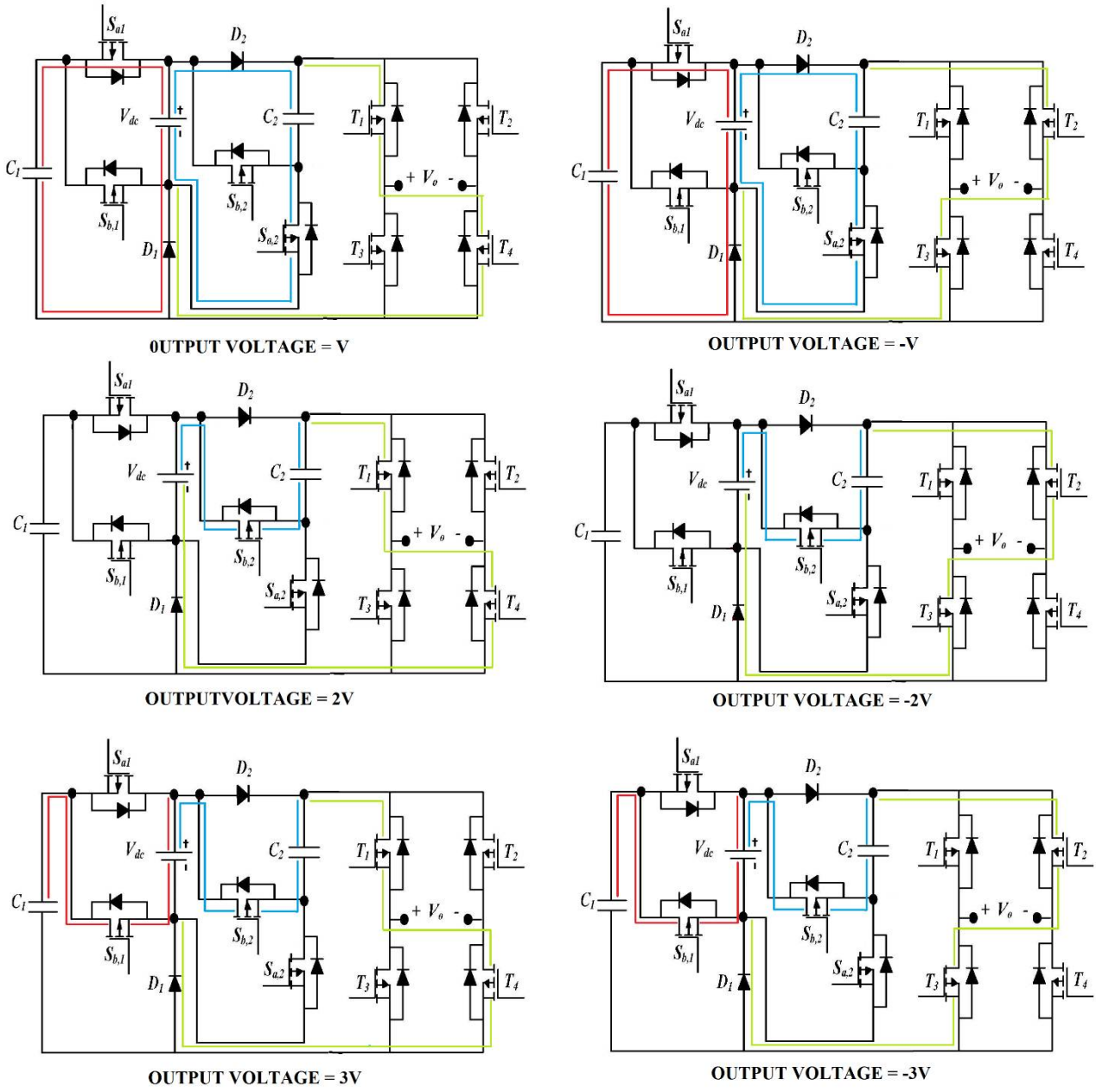


Fig. 2: Operation of Switched-Capacitor Seven-Level Inverter

## III.LEVEL-SHIFTED MULTICARRIER MODULATION TECHNIQUES

In this modulation scheme, the modulating signal is a sine wave and the carriers are triangular waves. An *m*-level inverter requires *(m-1)* triangular carriers. All the triangular carriers have same frequency and amplitude. There are three types of level-shifted multicarrier modulation techniques:

- In-phase Disposition (IPD) Modulation
- Alternative Phase Opposite Disposition (APOD) Modulation
- Phase Opposite Disposition (POD) Modulation

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*A. In-Phase Disposition (IPD) Modulation*

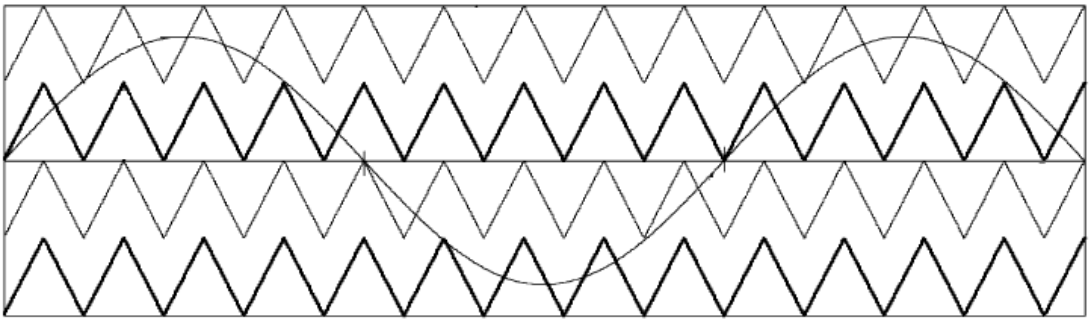

Fig. 3: In-Phase Disposition (IPD) Modulation

In this modulation scheme, all the triangular carriers are in phase. Figure 3 shows In-Phase Disposition (IPD) Modulation.

*B. Alternative Phase Opposite Disposition (APOD) Modulation*

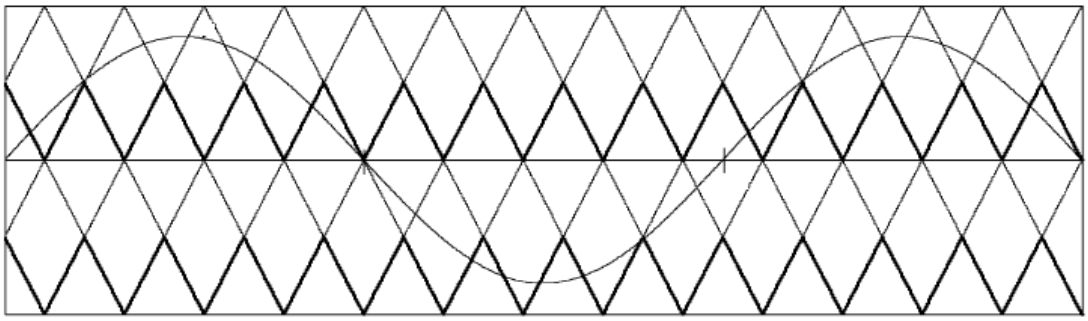

Fig. 4: Alternative Phase Opposite Disposition (APOD) Modulation

In this modulation scheme, all the triangular carriers are alternatively in opposite disposition. Figure 4 shows Alternative Phase Opposite Disposition (APOD) Modulation.

*C. Phase Opposite Disposition (POD) Modulation*

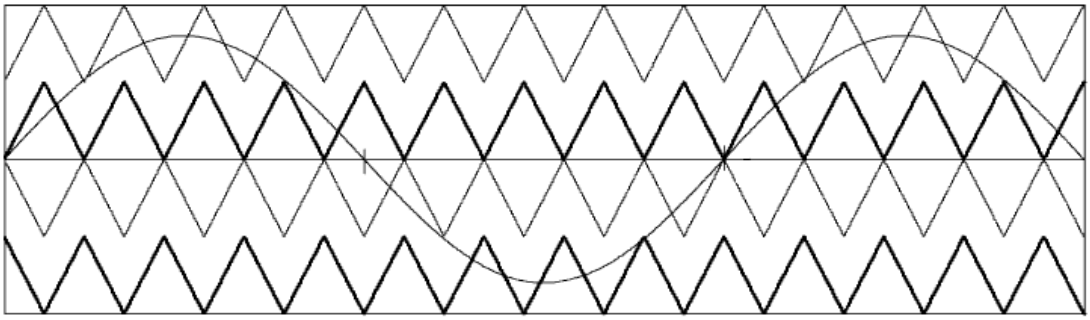

Fig. 5: Phase Opposite Disposition (POD) Modulation

In this modulation scheme, all the triangular carriers above the zero reference are in phase but in opposition with those below the zero reference. Figure 5 shows Phase Opposite Disposition (POD) Modulation.

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ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

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## IV.SIMULATION RESULTS

The simulation of switched-capacitor seven-level inverter is done using MATLAB/Simulink software. Figure 6 shows the Simulink Diagram of switched-capacitor seven-level inverter.

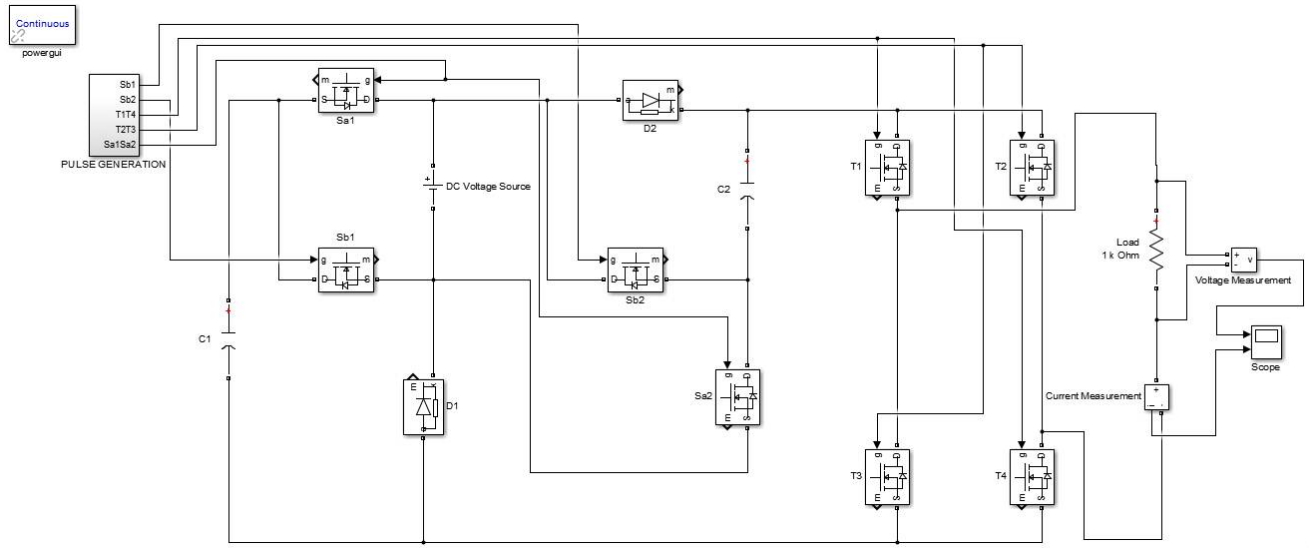


Fig. 6: Simulink Diagram of Switched-Capacitor Seven-Level Inverter

A switched-capacitor seven-level inverter requires eight switches. The switches used were MOSFETs. Two 1000 µF capacitors are used as the switching capacitors and a 1 kΩ resistor is used as the load. The switching pulses for the various switches $S_{a1}$, $S_{a2}$, $S_{b1}$, $S_{b2}$, $T_1$, $T_2$, $T_3$ and $T_4$were generated using level-shifted multicarrier modulation techniques. The modulating signal is a sine wave of 50 Hz frequency and the triangular carriers are of 10 kHz Frequency. The pulses were generated by comparing the modulating signal and with carriers with mathematical and logical operators. The simulation results of various level-shifted multicarrier modulation techniques for a switched-capacitor seven-level inverter is shown in the following subsections.

### *A. Simulation of Switched-Capacitor Seven-Level Inverter using In-phase Disposition (IPD) Modulation*

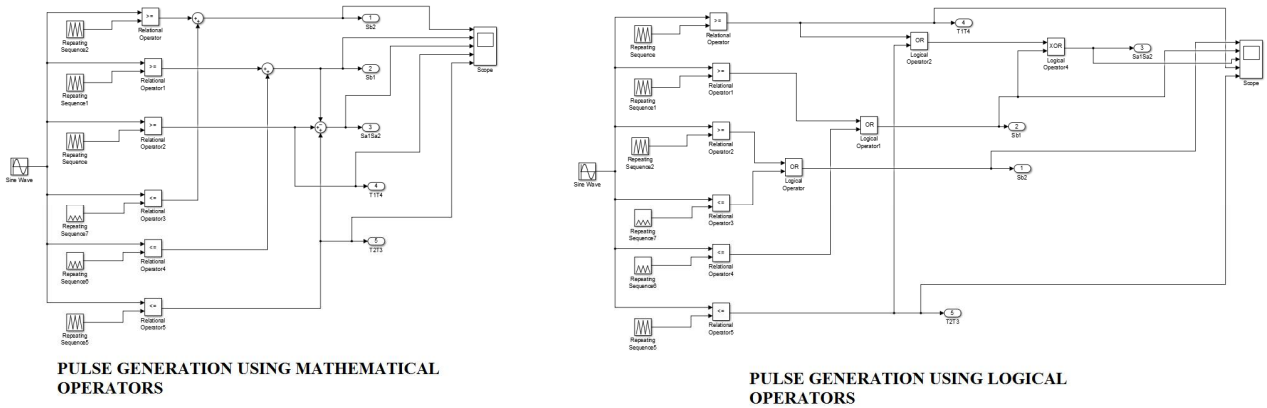


Fig. 7: Simulink Diagram of Switching Pulse Generation for a Switched-CapacitorSeven-Level Inverter using In-Phase Disposition Method with Mathematical and Logical Operators

Figure 7 shows the Simulink diagram of switching pulse generation for a switched-capacitor seven-level inverter using In-Phase Disposition modulation technique. The switching pulses are obtained by comparing sine wave with

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ISSN (Online): 2278 – 8875

International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering

*(An ISO 3297: 2007 Certified Organization)*

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triangular carriers using mathematical and logical operators. The switching pulses for the various switches are shown in figure 8.

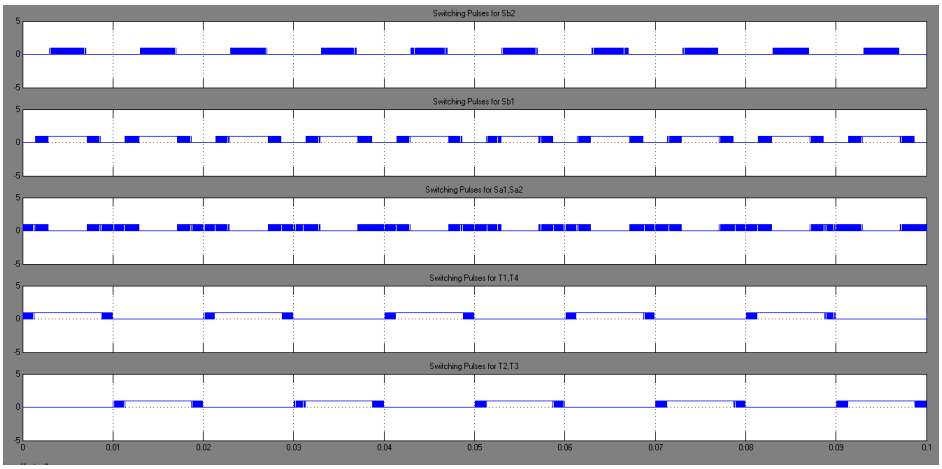


Fig. 8: Switching Pulses for a Switched-Capacitor Seven-Level Inverter usingIn-Phase Disposition Modulation

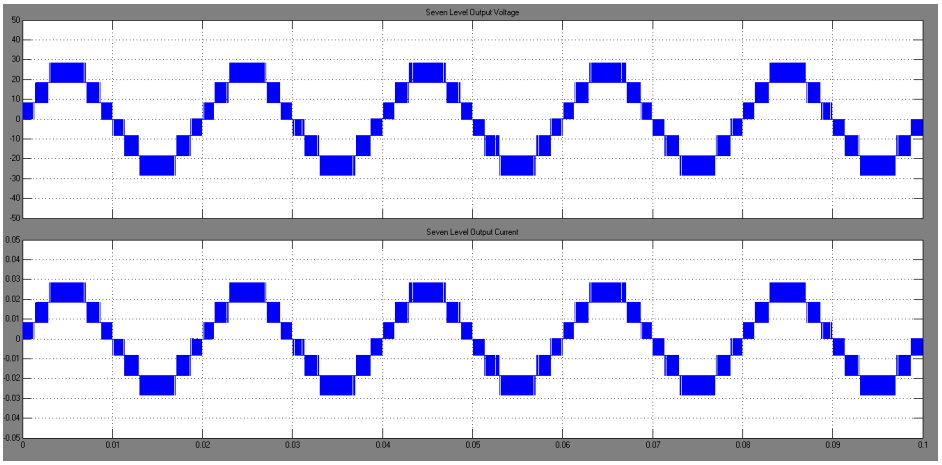


Fig. 9: Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

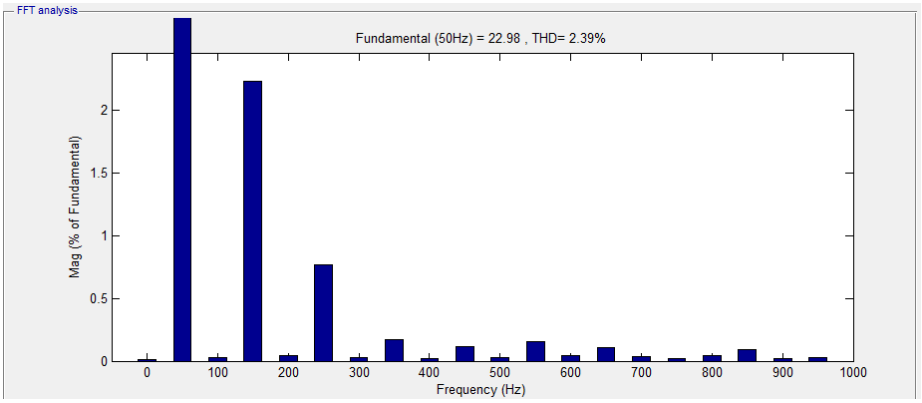


Fig. 10: Harmonic Spectrum obtained from FFT Analysis of a Switched-CapacitorSeven-Level Inverter using In-Phase Disposition Modulation

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Figure 9 shows the output voltage and current waveforms of a switched-capacitor seven-level inverter using In-Phase Disposition modulation technique. Since a resistive load is used the voltage and current waveforms have similar shapes. The harmonic spectrum of output voltage obtained from FFT analysis is shown in figure 10. The T.H.D obtained from FFT analysis is found to be 2.39%.

*B. Simulation of Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition (APOD) Modulation*

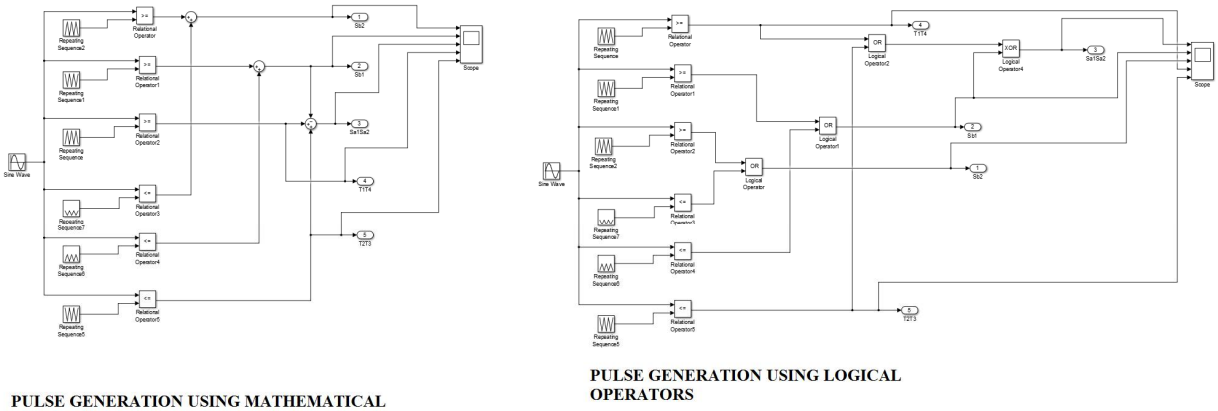


Fig. 11: Simulink Diagram of Switching Pulse Generation for a Switched-CapacitorSeven-Level Inverter using Alternative Phase Opposite Disposition (APOD) Modulation with Mathematical and Logical Operators

Figure 11 shows the Simulink diagram of switching pulse generation for a switched-capacitor seven-level inverter using Alternative Phase Opposite Disposition modulation technique. The switching pulses are obtained by comparing sine wave with triangular carriers using mathematical and logical operators. The switching pulses for the various switches are shown in figure 12.

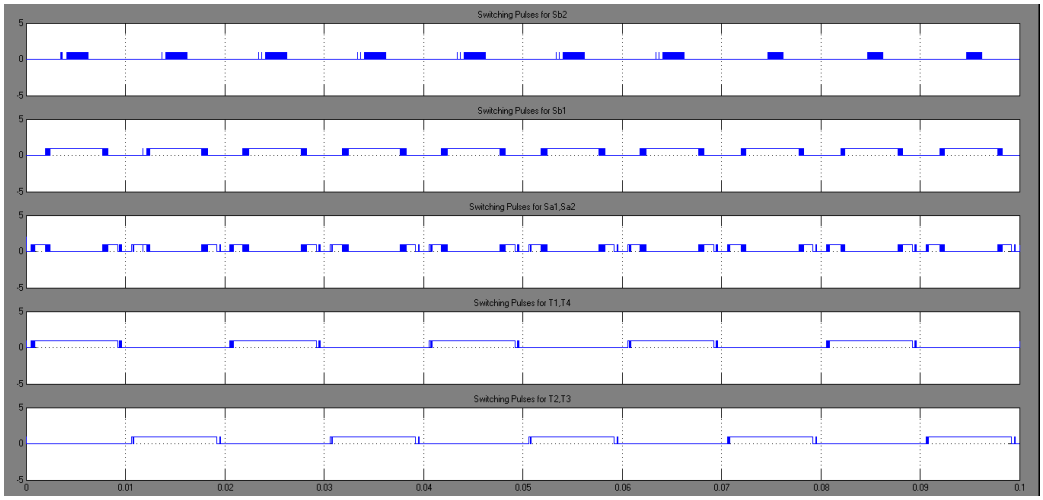


Fig. 12: Switching Pulses for a Switched-Capacitor Seven-Level Inverter usingAlternative Phase Opposite Disposition (APOD) Modulation

Figures 13 shows the output voltage and current waveforms of a switched-capacitor seven-level inverter using Alternative Phase Opposite Disposition modulation technique. The harmonic spectrum obtained from FFT analysis is shown in figure 14. The T.H.D obtained was found to be 7.55%.

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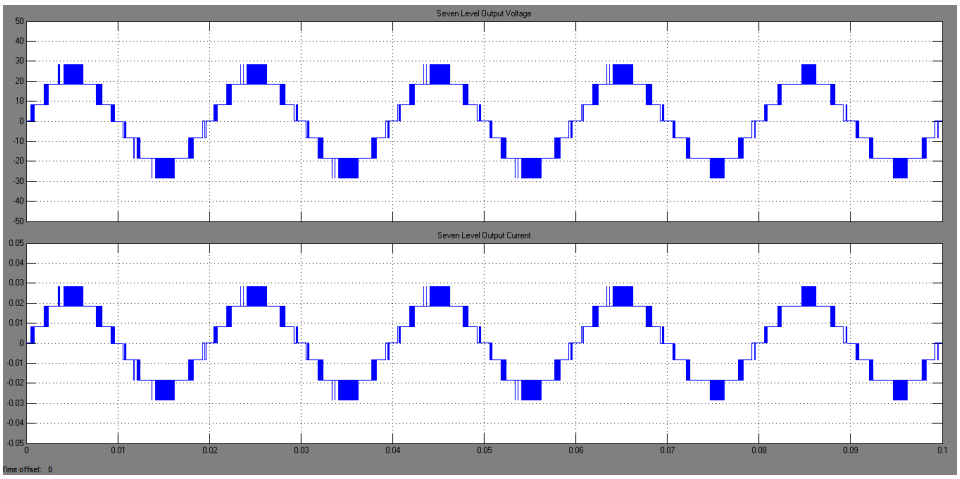


Fig. 13: Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition (APOD) Modulation

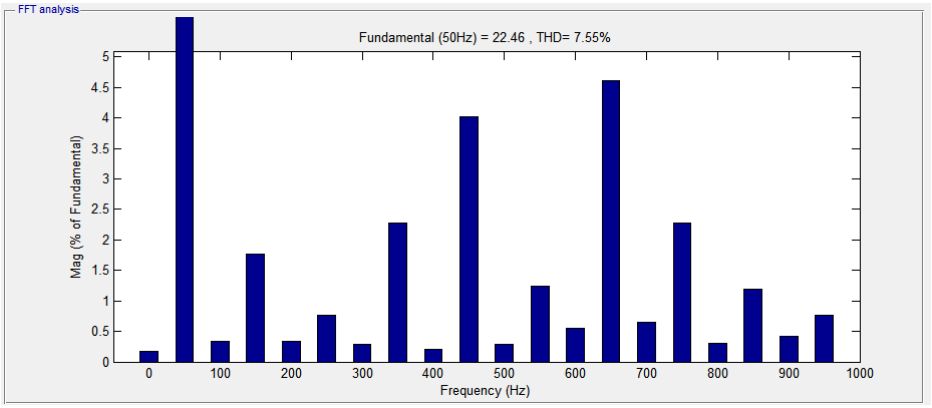


Fig. 14: Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition (APOD) Modulation

*C. Simulation of Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition (POD) Modulation*

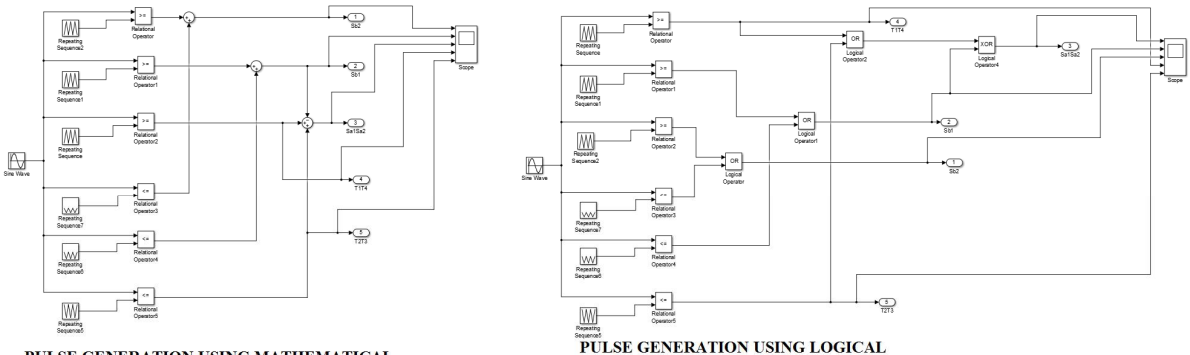


Fig. 15: Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition (POD) Modulation with Mathematical and Logical Operators

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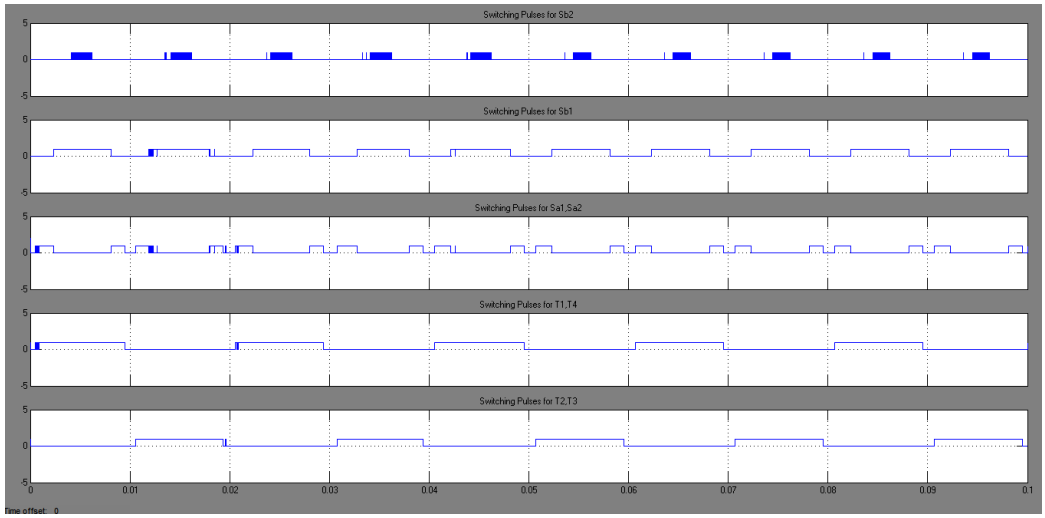


Fig. 16: Switching Pulses for a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition (POD) Modulation

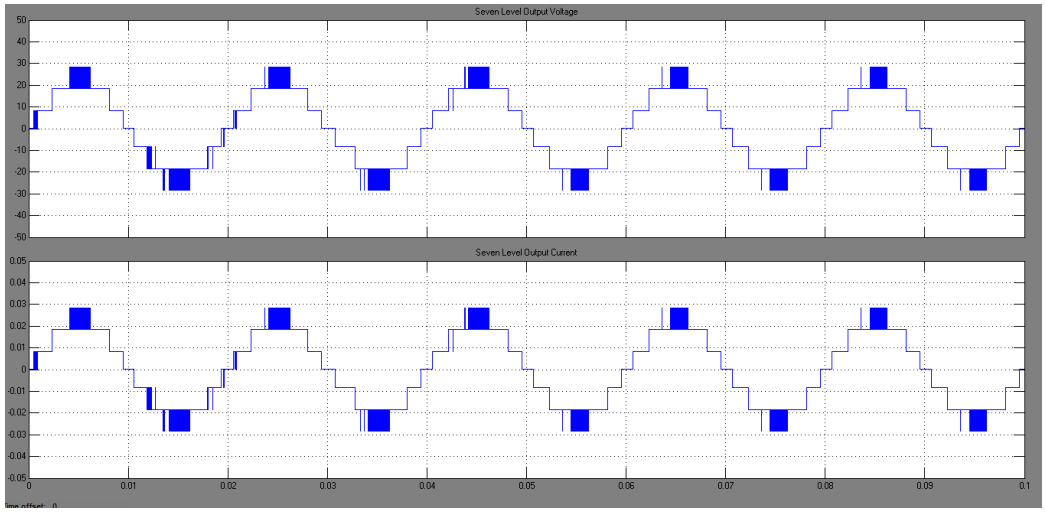


Fig. 17: Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition (POD) Modulation

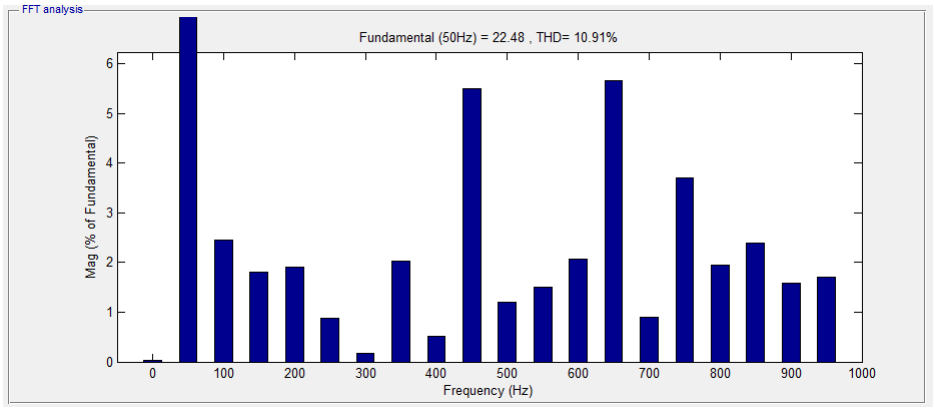


Fig. 18: Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition (POD) Modulation

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Figure 15 shows the Simulink diagram of switching pulse generation for a switched-capacitor seven-level inverter using Phase Opposite Disposition modulation technique. The switching pulses are obtained by comparing sine wave with triangular carriers using mathematical and logical operators. The switching pulses for the various switches are shown in figure 16.Tthe output voltage and current waveforms of a switched-capacitor seven-level inverter using Phase Opposite Disposition modulation technique is shown in figure 17. The harmonic spectrum obtained from FFT analysis is shown in figure 18. The T.H.D obtained was found to be 10.91%.

*Comparison of Different Level-Shifted Multicarrier Modulation Technique With Respect To T.H.D*

The comparison of different level-shifted multicarrier modulation technique with respect to T.H.D is shown in table 2.

| Level-Shifted Multicarrier Modulation Technique | T.H.D of Switched-Capacitor Seven-Level Inverter |
|---|---|
| In-Phase Disposition | 2.39 % |
| Alternative Phase Opposite Disposition | 7.55% |
| Phase Opposite Disposition | 10.91% |

Table 2: Comparison of Different Modulation Techniques with respect to T.H.D from Simulation Results of a Switched-Capacitor Seven-Level Inverter

## V.CONCLUSION

The operation of a switched-capacitor seven-level inverter was studied and the simulation of switched-capacitor seven-level inverter was done using MATLAB/Simulink software. The switching pulses were generated using level-shifted multicarrier modulation techniques. It can be concluded from the simulation results and from table 2 that the In-Phase Disposition modulation technique when used, produce the least T.H.D for a switched-capacitor seven-level inverter.

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