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# A Switched-Capacitor Seven-Level Inverter using Level-Shifted Multicarrier Modulation Techniques

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**Abstract:** ***A multilevel inverter include an array of power electronic devicesthat generate output voltage in the form of stepped waveform. In this paper, a seven-level inverter using switched-capacitor units is presented. The switched-capacitor multilevel inverter can produce the desired output voltage levels with reduced number of DC voltage sources and switches. It can also step-up the input supply voltage without using a bulky transformer. The level-shifted multicarrier modulation techniques are used for the modulation purpose. Also two modified level-shifted multicarrier modulation techniques are analyzed and compared with respect to T.H.D for a switched-capacitor seven-level inverter. The simulation of switched-capacitor seven-level inverter using level-shifted multicarrier modulation techniques is done using MATLAB/Simulink software.***

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

## 1. Introduction

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. A switched-capacitor multilevel inverter consists of only semiconductor switches, capacitors and diodes. There are no magnetic elements and hence they occupy small volume and are light in weight. This type of multilevel inverters can produce a greater number of voltage levels at the output using switched-capacitor units. The switched-capacitor multilevel inverter can produce the desired sinusoidal voltage waveforms at the output using a fewer switching devices and simple control methods. It can also boost the input supply voltage without using a bulky transformer. Three different types of level-shifted multicarrier modulation techniques are used for the modulation purpose. Also, two new modified level-shifted multicarrier modulation techniques are analyzed and compared with respect to T.H.D for a switched capacitor seven-level inverter.

## 2. Switched-Capacitor Seven-Level Inverter

A switched-capacitor seven-level inverter is a combination of several switched-capacitor units with a cascaded H-bridge. Figure 1 shows a switched-capacitor seven-level inverter. It consists of one DC source, two capacitors, two diodes and eight semiconductor switches. The switches $S_{a1}$ and $S_{a2}$connects the capacitors $C_1$and $C_2$in parallel with the source whereas the switches $S_{b1}$ and $S_{b2}$ connects the capacitors $C_1$and $C_2$in series with the source. The capacitors $C_1$and $C_2$ are charged when they are connected in parallel with the source and are discharged when they are connected in series with the source. Thus the switches $S_a$and $S_b$have complementary operation with each other, which means that, when the switch $S_a$ is turned 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.

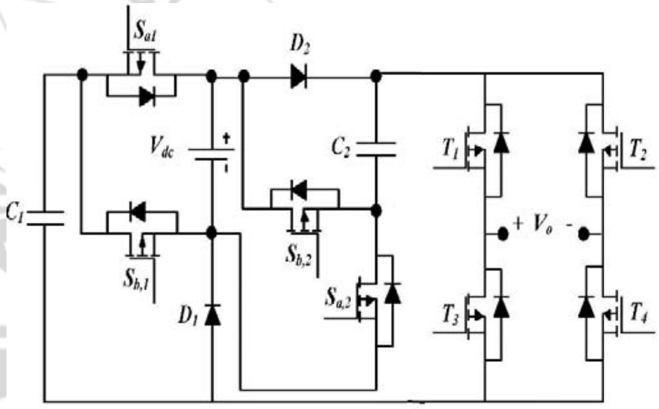


**Figure 1:** Switched-Capacitor Seven-Level Inverter

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.

### 2.1Operation of Switched-Capacitor Seven-Level Inverter

**Table 1:** Switching States for Different Output Levels

| $S_{a1}$ | $S_{b1}$ | $S_{a2}$ | $S_{b2}$ | $T_1$ | $T_2$ | $T_3$ | $T_4$ | Vo |
|---|---|---|---|---|---|---|---|---|
| 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 | $-3V_{dc}$ |

The operation of the switched-capacitor seven-level inverter is illustrated in table 1. Table 1 shows the switching states of different switches to generate the desired output voltage.

Here 1 indicates the ON state of the switch and 0 indicates the OFF state of the switch. $V_{dc}$is the input voltage and $V_o$ is the output voltage. A zero voltage is generated at the output by turning off all the switches. Figure 2 shows the operation of the switched-capacitor seven-level inverter.

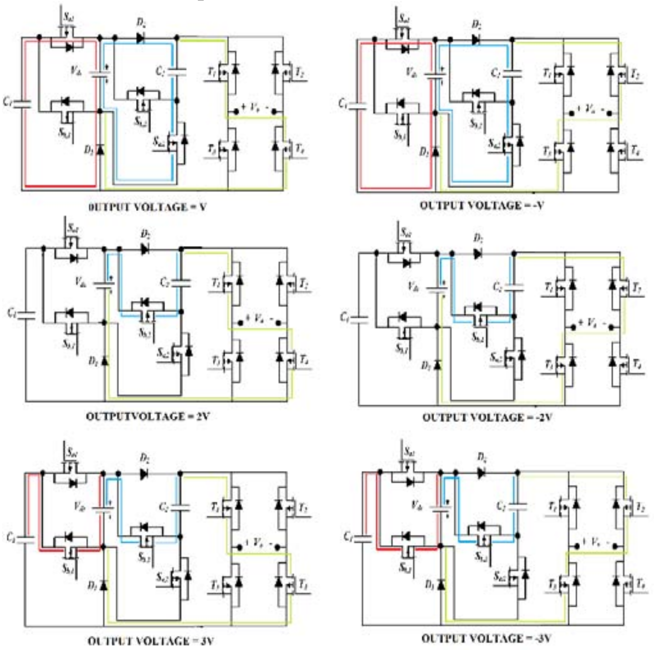


**Figure 2:** Operation of Switched-Capacitor Seven-Level Inverter

### 2.2 Advantages and Applications of Switched-Capacitor Multilevel Inverter

The charging and discharging of capacitors in the switched capacitor unit adds up the input voltage. Thus the switched-capacitor multilevel inverter can step-up the input voltage without any bulky transformer. Moreover, 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.

## 3. Level-Shifted Multicarrier Modulation Techniques

In level-shifted multicarrier modulation techniques, the modulating signal is a sine wave and the carriers are triangular waves. As the name suggests, there are several carriers which are level-shifted. An *m*-level inverter requires *(m-1)* triangular carriers. All the triangular carriers have same frequency and amplitude.

### 3.1 In-Phase Disposition (IPD) Modulation

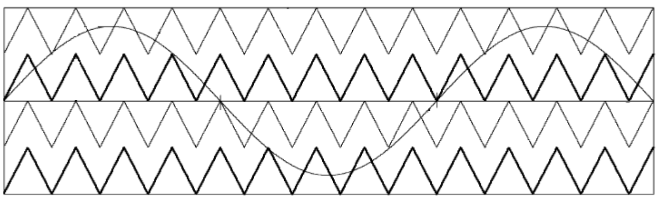

**Figure 3:** In-phase Disposition (IPD) Modulation

In this modulation scheme, all the triangular carriers are in phase. An *m*-level inverter requires *(m-1)* triangular carriers. Figure 3 shows In-Phase Disposition (IPD) Modulation.

### 3.2 Alternative Phase Opposite Disposition (APOD) Modulation

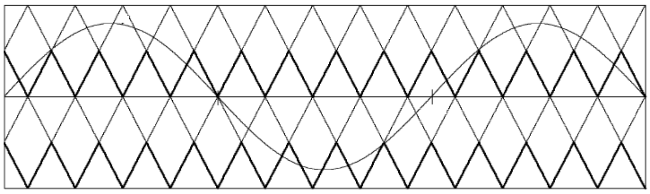

**Figure 4:** Alternative Phase Opposite Disposition (APOD) Modulation

In this modulation scheme, all the triangular carriers are alternatively in opposite disposition. An *m*-level inverter requires *(m-1)* triangular carriers. Figure 4 shows Alternative Phase Opposite Disposition (APOD) Modulation.

### 3.3 Phase Opposite Disposition (POD) Modulation

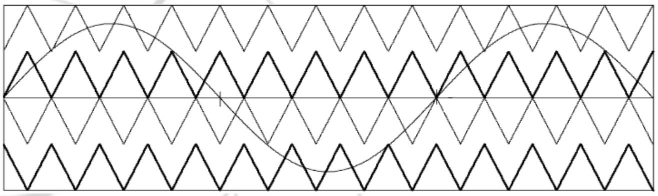

**Figure 5:** Phase Opposite Disposition (POD) Modulation

In this modulation scheme, all the triangular carriers above the zero reference are in phase but in opposition with those below the zero reference. An *m*-level inverter requires *(m-1)* triangular carriers. Figure 5 shows Phase Opposite Disposition (POD) Modulation.

### 3.4 Modified In-Phase Disposition Modulation

**Figure 6:** Modified In-Phase Disposition Modulation

In this modulation scheme, all the triangular carriers are in phase and the modulating signal is a rectified sine wave. An *m*-level inverter requires $\frac{(m-1)}{2}$triangular carriers. Figure 6 shows Modified In-Phase Disposition Modulation.

### 3.5 Modified Alternative Phase Opposite Disposition Modulation

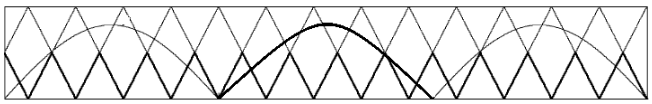

**Figure 7:** Modified Alternative Phase Opposite Disposition Modulation

In this modulation scheme, all the triangular carriers are alternatively in opposite dispositionand the modulating signal is a rectified sine wave. An *m*-level inverter requires

$\frac{(m-1)}{2}$ triangular carriers. Figure 7 shows Modified Alternative Phase Opposite Disposition Modulation.

## 4. Simulation of Switched-Capacitor Seven-Level Inverter using Level-Shifted Multicarrier Modulation Techniques

The simulation of switched-capacitor seven-level inverter using level-shifted multicarrier modulation techniques is done using MATLAB/Simulink software. Figure 8 shows the Simulink Diagram of switched-capacitor seven-level inverter.

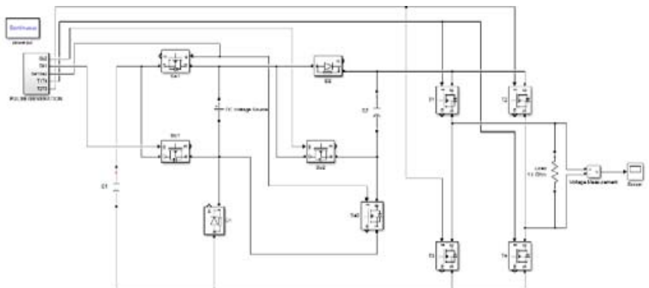

**Figure 8:** Simulink Diagram of Switched-Capacitor Seven-Level Inverter

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. An input supply of 10V DC is given. 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 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.

### 4.1 Simulation of Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter is generated using In-Phase Disposition Modulation technique. Figure 9 shows the Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation.

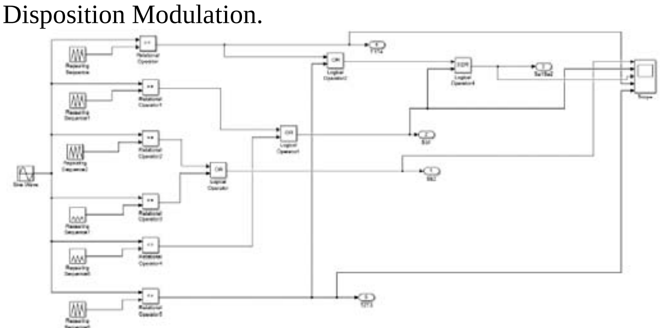

**Figure 9:** Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter using In-Phase Disposition Modulation is shown in figure 10. Figure 11 shows the seven-level output voltage and current waveforms of a switched-capacitor seven-level inverter using In-Phase Disposition Modulation. The harmonic spectrum obtained from FFT analysis is shown in figure 12. The T.H.D obtained was found to be 2.39%.

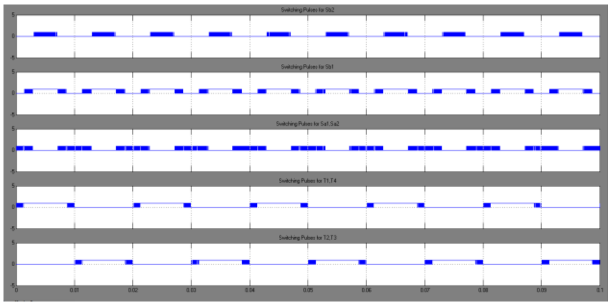

**Figure 10:** Switching Pulses for a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

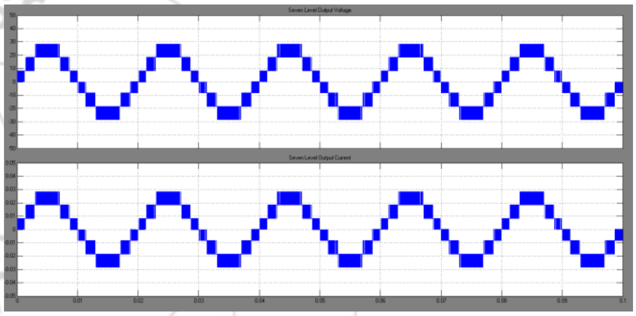

**Figure 11:** Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

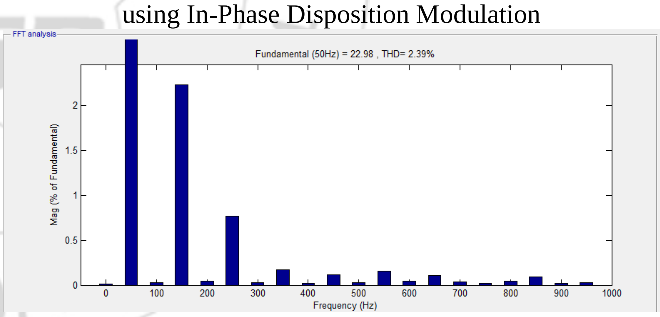


**Figure 12:** Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using In-Phase Disposition Modulation

### 4.2 Simulation of Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation

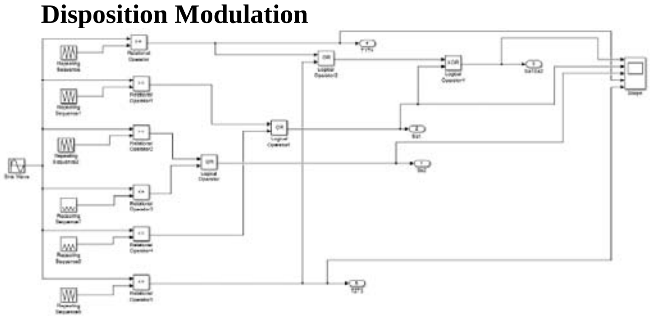

**Figure 13:** Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter is generated using Alternative Phase Opposite Disposition Modulation technique. Figure 13 shows the Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation.The switching pulses for the various switches of a switched-capacitor seven-level inverter using Alternative Phase Opposite Disposition Modulation is shown in figure 14. Figure 15 shows the seven-level output voltage and current waveforms of a switched-capacitor seven-level inverter using Alternative Phase Opposite Disposition Modulation. The harmonic spectrum obtained from FFT analysis is shown in figure 16. The T.H.D obtained was found to be 7.55%.

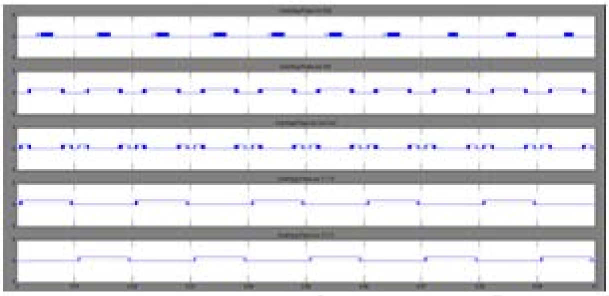

**Figure 14:** Switching Pulses for a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation

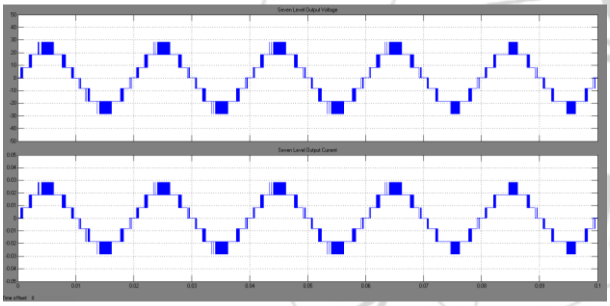

**Figure 15:** Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation

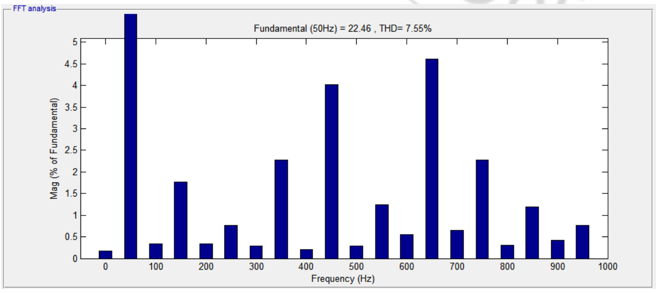


**Figure 16:** Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Alternative Phase Opposite Disposition Modulation

### 4.3 Simulation of Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter is generated using Phase Opposite Disposition Modulation technique. Figure 17 shows the Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation.

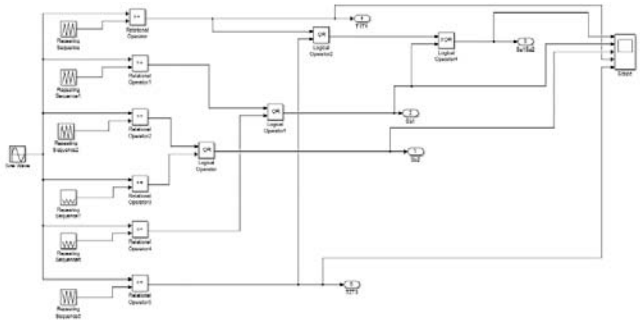

**Figure 17:** Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter using Phase Opposite Disposition Modulation is shown in figure 18. Figure 19 shows the seven-level output voltage and current waveforms of a switched-capacitor seven-level inverter using Phase Opposite Disposition Modulation. The harmonic spectrum obtained from FFT analysis is shown in figure 20. The T.H.D obtained was found to be 10.91%.

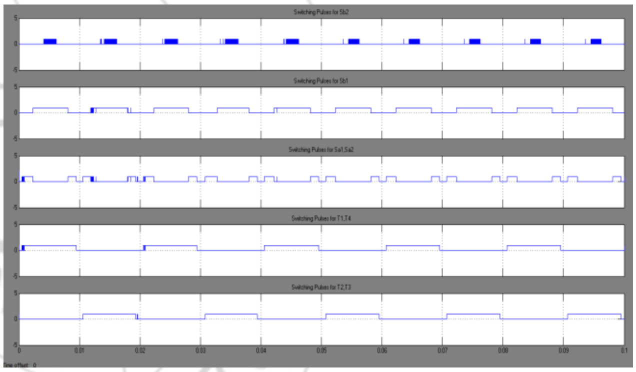

**Figure 18:** Switching Pulses for a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation

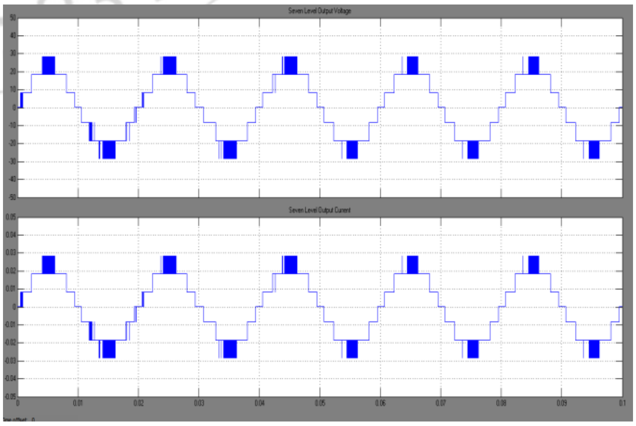

**Figure 19:** Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation

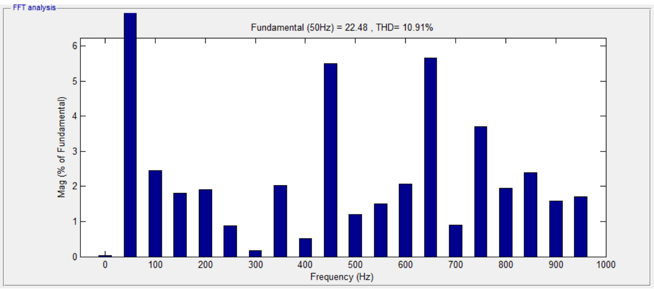


**Figure 20:** Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Phase Opposite Disposition Modulation

### 4.4 Simulation of Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter is generated using Modified In-Phase Disposition Modulation technique. Figure 21 shows the Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation.

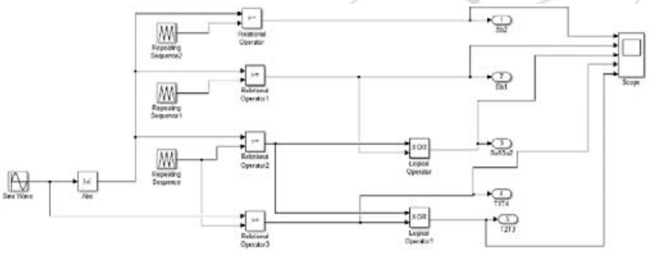

**Figure 21:** Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation

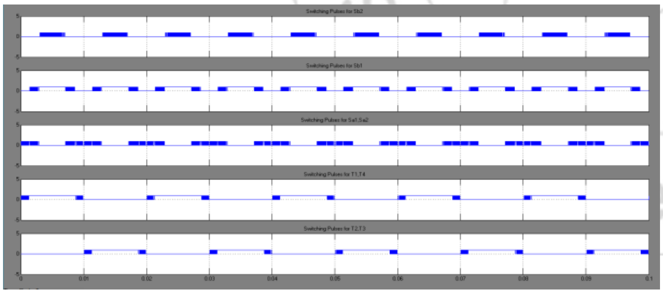

**Figure 22:** Switching Pulses for a Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation

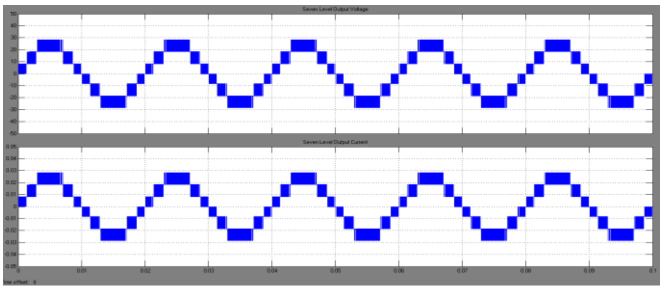

**Figure 23:** Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation

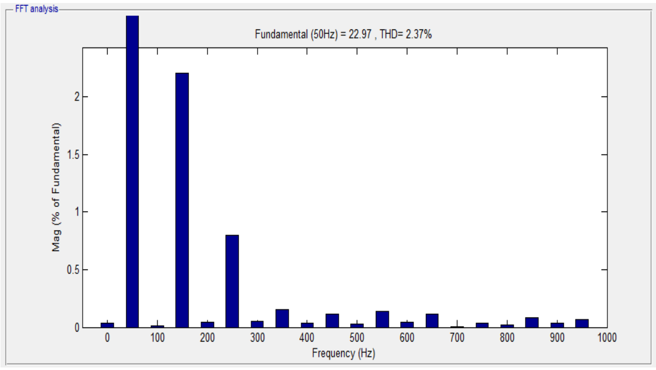


**Figure 23:** Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Modified In-Phase Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter using Modified In-Phase Disposition Modulation is shown in figure 22. Figure 23 shows the seven-level output voltage and current waveforms of a switched-capacitor seven-level inverter using Modified In-Phase Disposition Modulation. The harmonic spectrum obtained from FFT analysis is shown in figure 23. The T.H.D obtained was found to be 2.37%.

### 4.5 Simulation of Switched-Capacitor Seven-Level Inverter using Modified Alternative-Phase Opposite Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter is generated using Modified Alternative Phase Opposite Disposition Modulation technique. Figure 24 shows the Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Modified Alternative Phase Opposite Disposition Modulation.

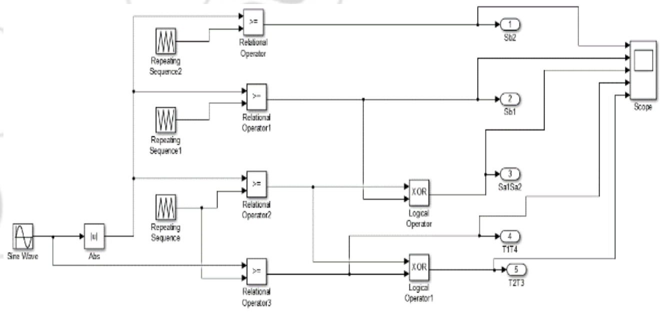

**Figure 24:** Simulink Diagram of Switching Pulse Generation for a Switched-Capacitor Seven-Level Inverter using Modified Alternative Phase Opposite Disposition Modulation

The switching pulses for the various switches of a switched-capacitor seven-level inverter using Modified Alternative Phase Opposite Disposition Modulation is shown in figure 25.

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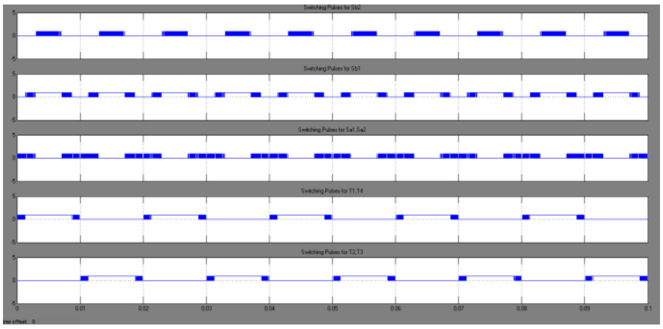

**Figure 25:**Switching Pulses for a Switched-Capacitor Seven-Level Inverter using Modified Alternative Phase Opposite Disposition Modulation

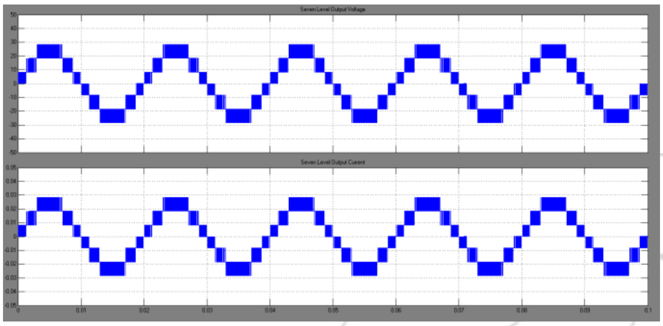

**Figure 26:** Seven-Level Output Voltage and Current Waveforms of a Switched-Capacitor Seven-Level Inverter using Modified Alternative Phase Opposite Disposition Modulation

Figure 26 shows the seven-level output voltage and current waveforms of a switched-capacitor seven-level inverter using Modified Alternative Phase Opposite Disposition Modulation. The harmonic spectrum obtained from FFT analysis is shown in figure 27. The T.H.D obtained was found to be 2.38%.

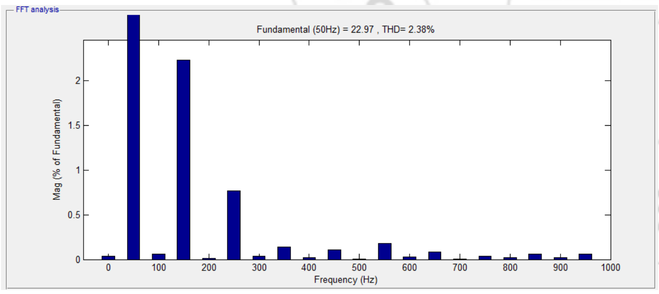


**Figure 27:** Harmonic Spectrum obtained from FFT Analysis of a Switched-Capacitor Seven-Level Inverter using Modified Alternative Phase Opposite Disposition Modulation

## 5. Observations

From the simulation results of a switched-capacitor seven-level inverter using level-shifted multicarrier modulation techniques, a comparison on different modulation techniques can be made with respect to the T.H.D obtained. Table 2 shows the comparison between different level-shifted multicarrier modulation techniques for a switched-capacitor seven-level inverter.

**Table 2:** Comparison of Different Level-Shifted Multicarrier Modulation Techniques for a Switched-Capacitor Seven-Level Inverter

| 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% |
| Modified In-Phase Disposition | 2.37% |
| Modified Alternative Phase Opposite Disposition | 2.38% |

## 6. Conclusion

The operation of a switched-capacitor seven-level inverter was analyzed and studied. The different types of level-shifted multicarrier modulation techniques was studied and compared. Thesimulation of switched-capacitor seven-level inverter using level-shifted multicarrier modulation techniques was done using MATLAB/Simulink software. It can be concluded from the simulation results that the Modified In-Phase Disposition modulation technique when used, produce the least T.H.D for a switched-capacitor seven-level inverter.

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