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Analysis of different topologies of multilevel inverters

Master of Science Thesis

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Analysis of different inverter topologies

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Abstract

This thesis compares three different topologies of inverters (one level inverter, Diode clamped inverter, Flying capacitor clamped inverter and Cascaded H-bridge inverter). The multilevel inverters are 5-level and 9-level inverters. This comparison is done with respect of power losses, cost, weight and THD. The switching pattern for inverters is explained as well. These inverters are connected to a 400V, 75kW asynchronous motor. For each inverter, IGBTs and MOSFETs are used as switching devices to make the comparisons more accurate. The switches that are used for different inverters are the same for all of the inverters. (There is no control on inverter; also for loss calculation loading distribution is assumed.)

If the THD is important, the 9-level inverters should be used, since it has a lower THD than the 5-level and the two-level inverter. The 9-level multilevel inverters have the lowest THD when filters are not used. Their THD is about 7%. If the cost is important the two-level inverter should be used, since it has the lowest cost between all of the inverter topologies. If the power losses are important, the 5-level diode clamped is the best choice since it has the lowest power losses between all other inverter topologies. If the weight is important the two-level inverter is the best choice since it has the lowest weight between all other inverter topologies. Its weight is about 5Kg. If the power losses are important, the 5-level flying capacitor is the best choice, since it has the lower power losses between all the other inverter topologies. To select a multilevel inverter is a tradeoff between cost, complexity, losses and THD. The most important part is to decide which one is more important.

Acknowledgments

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1. Introduction

1.1. HEV configurations

A HEV is a vehicle that gets its propulsion energy from two different sources. One of them should be electrical. There are different topologies to couple the power sources to the wheels: Series configuration, Parallel configuration, Series-parallel configuration.

1.1.1. Series configuration

This configuration is the simplest variant of HEVs. The mechanical output of the internal combustion engine is converted to electricity through a generator. The power that is produced by the generator can operate the electric motor or charge the battery. This configuration has four operation modes: 1. Acceleration: During the acceleration mode the internal combustion engine and the battery operate the motor. 2. Light load: In this mode the energy that is produced by the internal combustion engine is more than the energy that is used by the motor, hence the extra power charges the battery. 3. Braking or deceleration: In this mode, the motor acts as a generator and charge the battery through the power converter. 4. Battery charging: The battery is charged by the internal combustion engine through the power converter when the vehicle is in complete stop. Fig. 1 shows the schematic of a series HEV configuration.

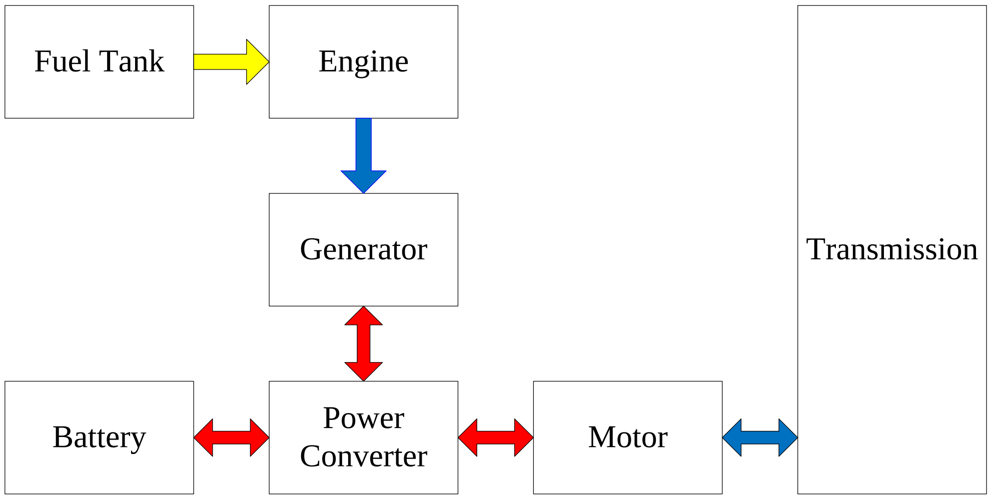

Figure 1. Series HEV configuration (Yellow: hydraulic, Blue: Mechanical, Red: electrical)

1.1.2. Parallel configuration

In this configuration, the engine and the motor are coupled to the transmission system, so they can work separately. This configuration has four operation modes: 1. Acceleration: In this mode the electric motor and the internal combustion engine drive the wheels at the same time. Normally 80 percent of the energy is supplied by the internal combustion engine and 20 percent is supplied by the electric motor. 2. Normal driving: In this mode, the electric motor is off while the internal combustion engine runs the wheels. 3. Braking or deceleration: During this operation mode the battery is charged through the power converter. 4. Battery charging:

The battery is charged by the internal combustion engine since the engine and the electric motor are coupled when the vehicle is in full stop. Fig. 2 shows the schematic of a parallel HEV configuration.

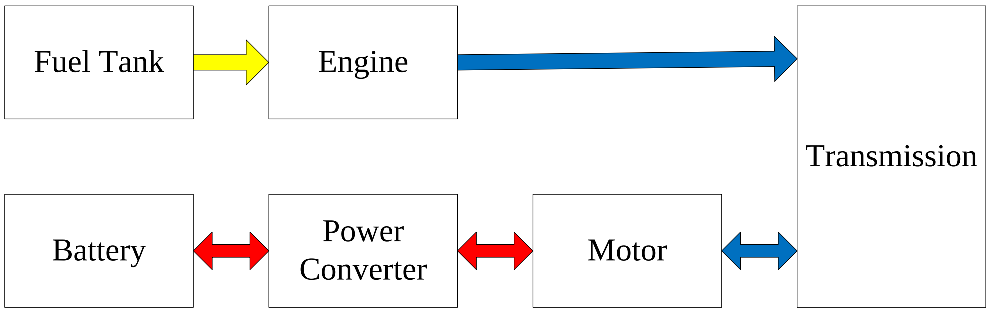

Figure 2. Parallel HEV configuration (Yellow: hydraulic, Blue: Mechanical, Red: electrical)

1.1.3. Series-parallel configuration

In this configuration, a generator is added between the engine and the power converter. The control method in this configuration is more complicated than the series and the parallel configurations. The operating modes in this configuration is divided in two groups, electric-heavy where the electric motor is more active and engine-heavy where the internal combustion engine is more active in the operation. The engine-heavy has six operation modes: 1. Startup: In this mode the battery drives the wheels through the electric motor while the internal combustion engine is off. 2. Acceleration: During the acceleration mode the internal combustion engine and the electric motor run the wheels at the same time. 3. Normal driving: The internal combustion engine drives the wheels while the electric motor is off. 4. Deceleration: The electric motor charges the battery through the power converter. 5. Battery charging in normal driving: In this mode the internal combustion engine should run the wheels and the generator at the same time to charge the battery. 6. Battery charging: The internal combustion engine charges the battery through the generator while the vehicle is in full stop. The electric-heavy has also six operation modes: 1. Startup: In this mode the battery drives the wheels through the electric motor while the internal combustion engine is off. 2. Acceleration: The internal combustion engine and the battery drive the wheels. 3. Normal driving: The internal combustion engine and the battery drive the wheels. 4. Deceleration: The electric motor acts as a generator to charge the battery through the power converter. 5. Battery charging in normal driving: The internal combustion engine should drive the wheels and the generator at the same time to charge the battery. 6. Battery charging: The internal combustion engine charges the battery through the generator and the power converter. Fig. 3 illustrates the schematic of a series-parallel HEV configuration.

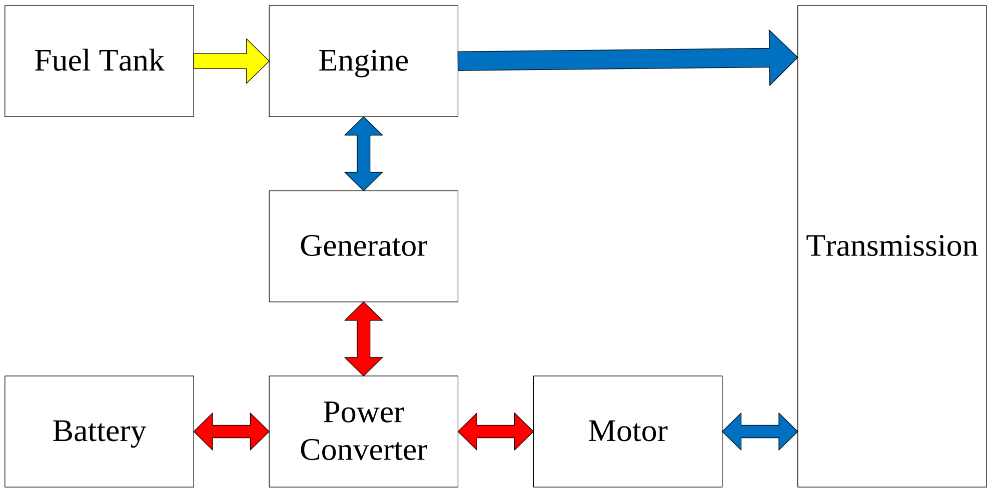

Figure 3. Series-parallel HEV configuration (Yellow: hydraulic, Blue: Mechanical, Red: electrical)

1.2. Inverters

The power in the battery is in DC mode and the motor that drives the wheels usually uses AC power, therefore there should be a conversion from DC to AC by a power converter. Inverters can do this conversion. The simplest topology that can be used for this conversion is the two-level inverter that consists of four switches. Each switch needs an anti-parallel diode, so there should be also four anti parallel diodes. There are also other topologies for inverters. A multilevel inverter is a power electronic system that synthesizes a sinusoidal voltage output from several DC sources. These DC sources can be fuel cells, solar cells, ultra capacitors, etc. The main idea of multilevel inverters is to have a better sinusoidal voltage and current in the output by using switches in series. Since many switches are put in series the switching angles are important in the multilevel inverters because all of the switches should be switched in such a way that the output voltage and current have low harmonic distortion.

Multilevel inverters have three types. Diode clamped multilevel inverters, flying capacitor multilevel inverters and cascaded H-bridge multilevel inverter.

The THD will be decreased by increasing the number of levels. It is obvious that an output voltage with low THD is desirable, but increasing the number of levels needs more hardware, also the control will be more complicated. It is a tradeoff between price, weight, complexity and a very good output voltage with lower THD.

1.3. Purpose and goal

The purpose of this thesis is to compare the diode clamped multilevel inverter, the flying capacitor multilevel inverter, the cascaded H-bridge multilevel inverter and the two-level inverter. These comparisons are done with respect to losses, cost, weight and THD. For these comparisons all of the inverters are simulated in MATLAB/SIMULINK. Moreover a goal is to compare three different switches for each type of inverter.

1.4. Previous works

The previous works that has been done on the multilevel inverters are more focused on the THD and the switching pattern of the multilevel inverters. Most of them are focused on to get a better output voltage and current with lower THD by different switching patterns. Switching angles in multilevel inverters are so important; since it can affect the output voltage and current THD. There are many interesting works on calculating the switching angles to eliminate the lowest order harmonics, such as “Active Harmonic Elimination for Multilevel Converters” (Tolbert), which is a study of different harmonic elimination methods. The newest method that uses for harmonic elimination is resultant theory. “Eliminating harmonics in a multilevel converter using resultant theory” (Chiasson) is more focused on the resultant theory for calculating the switching angles. There are also some works that are focused on different usages of the multilevel inverters. There are some other works that are related to this thesis that investigated different topologies of multilevel inverters for different electric applications.”Multilevel converters for large electric drives” (Tolbert) compares the cascaded H-bridge multilevel inverters with diode clamped multilevel inverters for large electric drives.

2. Multilevel inverters

Three types of multilevel inverter have been investigated in this thesis.

1. Diode Clamped multilevel inverters
2. Flying Capacitor multilevel inverters
3. Cascaded H-bridge multilevel inverters

2.1. Diode Clamped multilevel inverter

The main concept of this inverter is to use diodes to limit the power devices voltage stress. The voltage over each capacitor and each switch is V_{dc}. An n level inverter needs (n-1) voltage sources, 2(n-1) switching devices and (n-1) (n-2) diodes. 5-level diode clamped multilevel inverter

2.1.1. 5-level diode clamped multilevel inverter

In a 5-level diode clamped multilevel:

n=5

Therefore:

Number of switches=2(n-1) =8

Number of diodes= (n-1) (n-2) =12

Number of capacitors= (n-1) =4

A 5-level diode clamped multilevel inverter is shown in Fig. 4. Switching states are shown in Table.1. For example to have $V_{dc}/2$ in the output, switches S_1 to S4 should conduct at the same time. For each voltage level four switches should conduct. As it can be seen in Table.1 the maximum output voltage in the output is half of the DC source. It is a drawback of the diode clamped multilevel inverter. This problem can be solved by using a two times voltage source or cascading two diode clamped multilevel inverters. The output voltage of a 5-level diode clamped multilevel inverter is shown in Fig.5. As can be seen in Fig.5 all of the voltage level should have the same voltage value.

The switching angles should be calculated in such a way that the THD of the output voltage becomes as low as possible. The switching angle calculation method that is used in this thesis is the harmonic elimination method. In this method the lower dominant harmonics can be eliminated by choosing calculated switching angles. This method will be explained later in this thesis.

Table 1. The switching states of Diode clamped multilevel inverter.

V_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	0	1	1	1	1	0	0	0
0	0	0	1	1	1	1	0	0
$-V_{dc}/4$	0	0	0	1	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

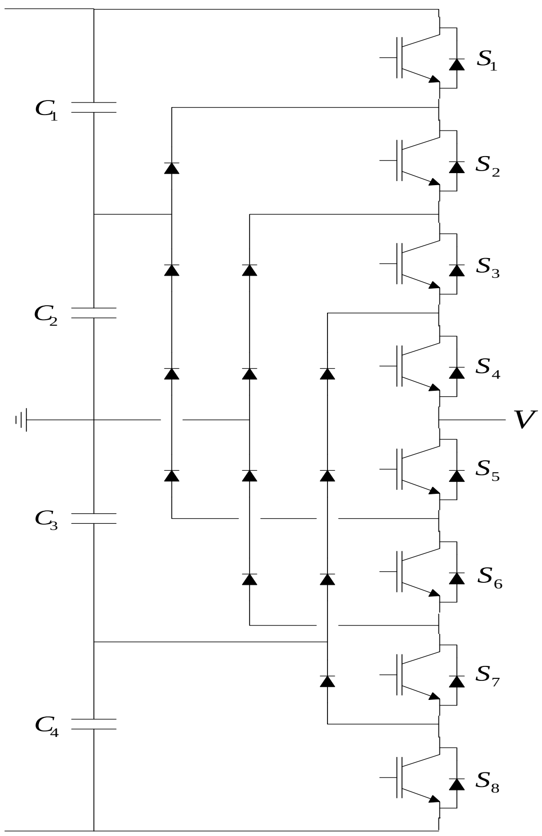

Figure 4. One phase of a diode clamped inverter

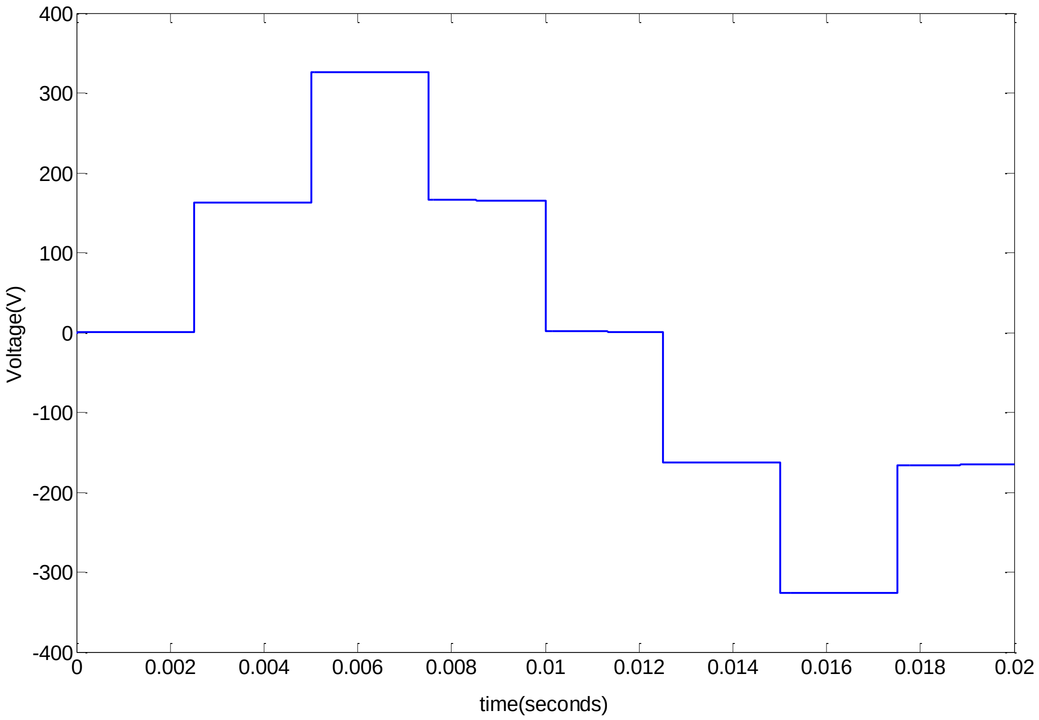

Figure 5. Output voltage of a 5-level multilevel inverter

2.1.2. 9-level diode clamped multilevel inverter

In this thesis a 9-level diode clamped inverter is made of two 5-level diode clamped inverters which are cascaded. Therefore the number of switches, diodes and capacitors are two times more than the 5-level diode clamped inverter. For a 9-level multilevel inverter:

n=9

Therefore:

Number of switches=2(*n*-1) =16

Number of diodes= (*n*-1) (*n*-2) =24

Number of capacitors= (*n*-1) =8

In this method switching angle should be calculated in such a way so that a 9-level output voltage is produced. The output voltages of each 5-level diode clamped multilevel inverter are added to each other, and then the output voltage is created. The output voltage of each diode clamped multilevel inverter is shown in Fig.6 and Fig.7.

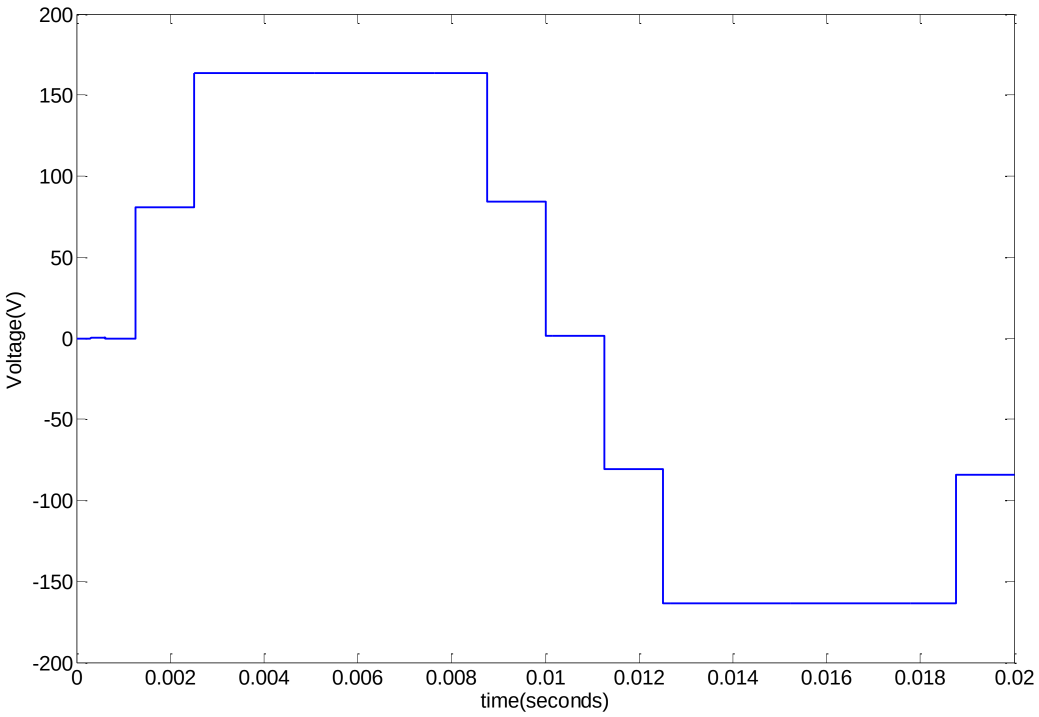

Figure 6. Output voltage of the first cell

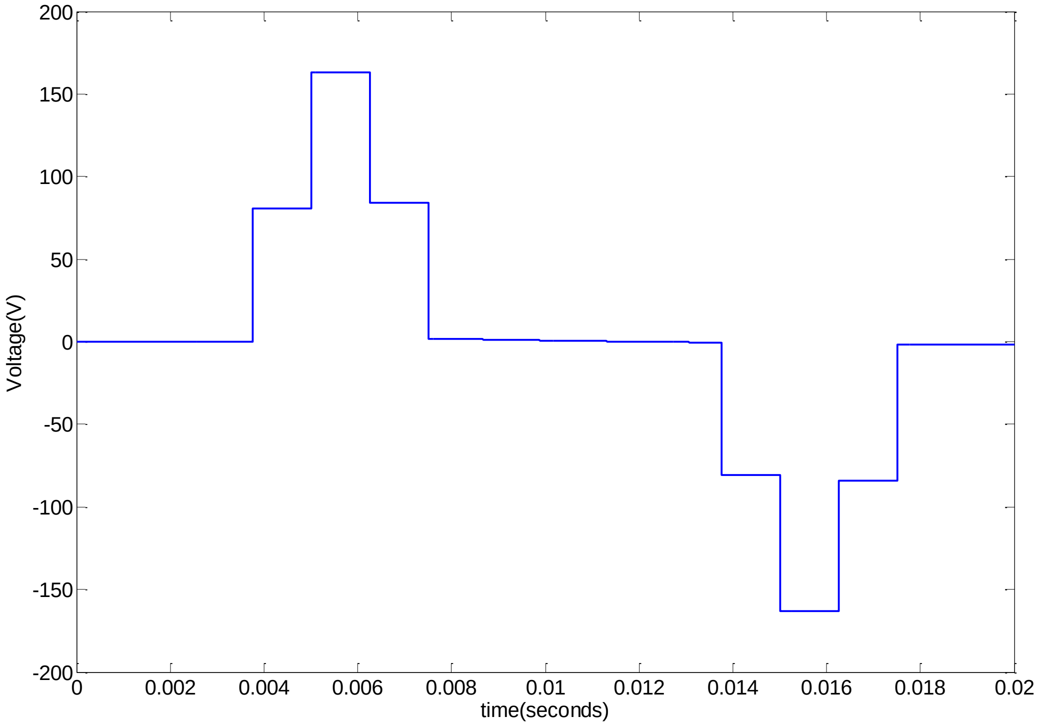

Figure 7. Output voltage of the second cell

And by adding these output voltages to each other, there will be a 9-level output voltage as it is shown in Fig.8.

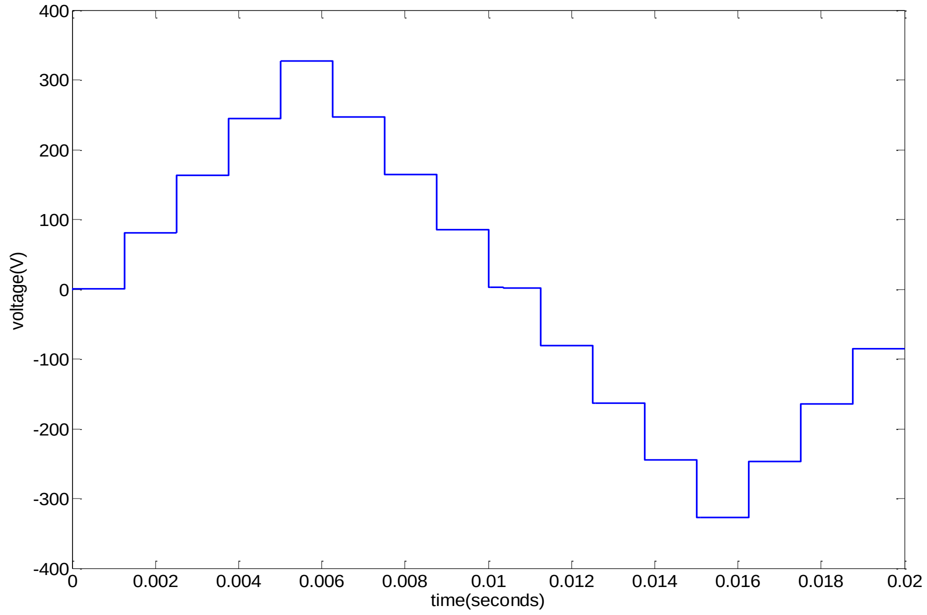

Figure 8. Output voltage of a 9-level multilevel inverter

2.2. Flying capacitor multilevel inverters

This inverter uses capacitors to limit the voltage of the power devices. The configuration of the flying capacitor multilevel inverter is like a diode clamped multilevel inverter except that capacitors are used to divide the input DC voltage. The voltage over each capacitor and each switch is V_{dc}.

2.2.1. 5-level flying capacitor multilevel inverters

For a 5-level flying capacitor multilevel inverter:

n=5

Therefore:

Number of switches=8

Number of capacitors= 10

Fig. 9 shows a five level flying capacitor multilevel inverter. The switching states in this inverter are like in the diode clamped multilevel inverter. It means that for each output voltage level 4 switches should be on. Table.2 shows the switching states for a 5-level flying capacitor clamped multilevel inverter. The output voltage was shown before in Fig.5.

The switching angles like the diode clamped multilevel inverter should be calculated in such a way that the THD of the output voltage becomes as low as possible. The method is the same as the diode clamped inverter.

Table 2. The switching pattern for capacitor clamped multilevel inverter.

V_0	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8
$V_{dc}/2$	1	1	1	1	0	0	0	0
$V_{dc}/4$	1	1	1	0	1	0	0	0
0	1	1	0	0	1	1	0	0
$-V_{dc}/4$	1	0	0	0	1	1	1	0
$-V_{dc}/2$	0	0	0	0	1	1	1	1

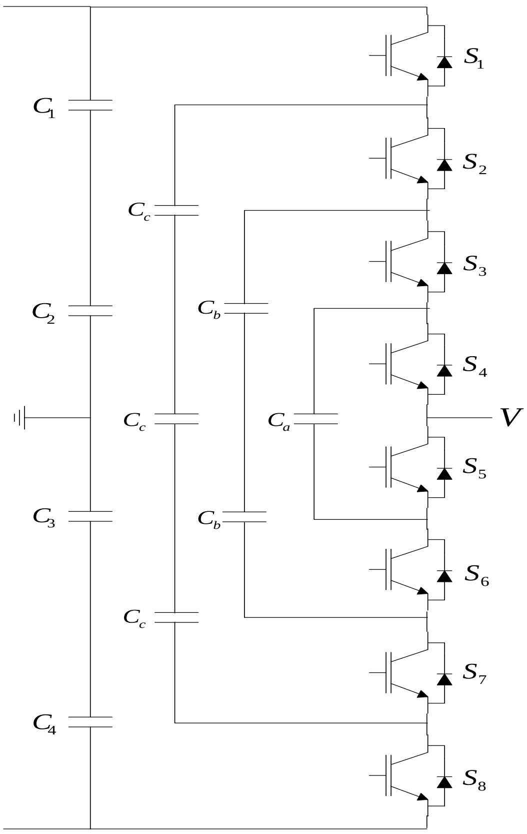

Figure 9. One phase of a 5-level Flying capacitor multilevel inverter

2.2.2. 9-level flying capacitor multilevel inverter

For a 9-level multilevel inverter:

n=9

Therefore:

Number of capacitors=8

Number of switches=16

Like the diode clamped inverter in this thesis, a 9-level flying capacitor clamped inverter is made of two 5-level flying capacitor inverters which are cascaded. Switching angles and output voltage of each 5-level flying capacitor inverter are completely the same as for the 9-level diode clamped inverter. The output voltage of each 5-level flying capacitor inverter was shown before in Fig.6 and Fig.7. Those two output voltages are added to each other to make a 9-level output voltage which is shown in Fig.8.

2.3. Cascaded H-bridge multilevel inverter

The concept of this inverter is based on connecting H-bridge inverters in series to get a sinusoidal voltage output. The output voltage is the sum of the voltage that is generated by each cell. The number of output voltage levels are 2*n*+1, where *n* is the number of cells. The switching angles can be chosen in such a way that the total harmonic distortion is minimized. One of the advantages of this type of multilevel inverter is that it needs less number of components comparative to the Diode clamped or the flying capacitor, so the price and the weight of the inverter is less than that of the two former types. Fig. 10 shows an *n* level cascaded H-bridge multilevel inverter. The switching angles calculation method that is used in this inverter is the same as for the previous multilevel inverters.

An *n* level cascaded H-bridge multilevel inverter needs 2(*n*-1) switching devices where *n* is the number of the output voltage level.

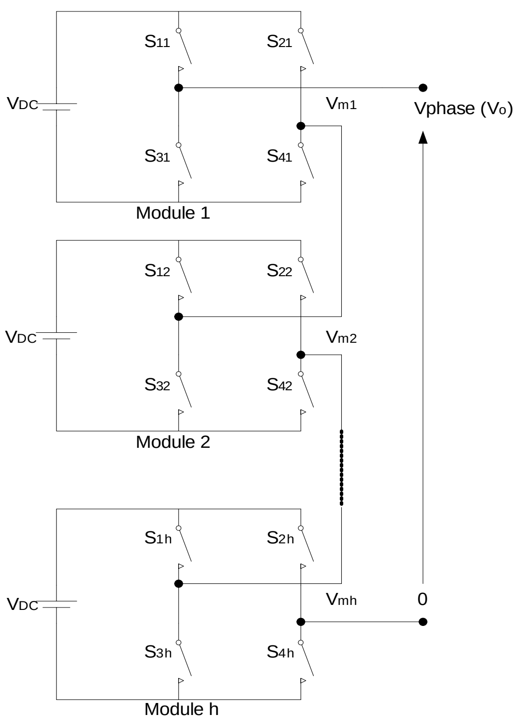

Figure 10. One phase of a cascaded H-bridge multilevel inverter

2.3.1. 5-level Cascaded H-bridge multilevel inverter

The output voltage of this inverter has 5 levels like in the previous multilevel inverters. This inverter consists of two H-bridge inverters that are cascaded. For a 5-level cascaded H-bridge multilevel inverter 8 switching devices are needed.

2.3.2. 9-level cascaded H-bridge multilevel inverter

The output voltage of the multilevel level inverter has 9 levels the like the previous multilevel inverters. This inverter consists of four H-bridge inverters that are cascaded. For a 9-level cascaded H-bridge multilevel inverter 16 switching devices are needed.

2.4. Harmonic elimination method

The switching pattern that is used in this thesis for all of the multilevel inverters is harmonic elimination method. In this method the switching angles for switches should be calculated in such a way that the lower dominant harmonics are eliminated. In this case 5-level and 9-level multilevel inverters will be investigated. For a 5-level inverter the 5th harmonic will be eliminated and for the 9-level inverter the 5th, 7th, 11th harmonics will be eliminated. The Fourier analysis needs to be calculated to determine the frequency spectra of the output waveform.

2.4.1. 5-level multilevel inverters

The Fourier series of a 5-level unity DC source is shown in (2-1).

$$f(t) = f_{\theta_1}(t) + f_{\theta_2}(t) = \frac{2V_{dc}}{\pi}\sum_{h=1}^{\infty}[\cos(h\theta_1) + \cos(h\theta_2)]$$

$$= \frac{2V_{dc}}{\pi}\sum_{h=1}^{\infty}\left[\sum_{i=1}^{2}⟦\cos(h\theta_i)]⟧\frac{\sin(h\omega t)}{h}\right] \qquad (2-1)$$

Where:

V_{dc}: Voltage of each voltage source that is unity

θ_i : The switching angles

h: The harmonic orders

From (2-1) four equations will be resulted for eliminating the harmonics 5th.

$$V_{dc} = V_1 + V_2$$

$$\frac{2V_{dc}}{\pi}(cos\theta_1 + cos\theta_2) = h_1 \qquad (2-2)$$

$$\frac{2V_{dc}}{\pi}(cos5\theta_1 + cos5\theta_2) = h_5 \qquad (2-3)$$

Equations (2-2) and (2-3) are for the harmonics that should be eliminated, so (2-3) should be equal to zero. The DC sources are constant, so

$$V_{dc} = 2V_1 \qquad (2-4)$$

$$M = \frac{h_1}{2V} \qquad (2-5)$$

The modulation index is 1 since the voltage that is used in these calculations is in per unit. From (2-2) to (2-5) the nonlinear equations will be calculated.

$$\cos(\theta_1) + \cos(\theta_2) = \frac{\pi}{2} \qquad (2-6)$$

$$\cos(5\theta_1) + \cos(5\theta_2) = 0 \qquad (2-7)$$

In this thesis equations are solved by the Newton-Raphson method.

In Newton-Raphson method the following matrixes should be created:

1. Switching angles matrix

$$\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix}$$

2. The nonlinear system matrix

$$F = \begin{bmatrix} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) \end{bmatrix}$$

$$dF = \begin{bmatrix} -\sin(\theta_1) & -\sin(\theta_2) \\ -5\sin(5\theta_1) & -5\sin(5\theta_2) \end{bmatrix}$$

3. The answers matrix

$$T = \begin{bmatrix} \frac{\pi}{2} \\ 0 \end{bmatrix}$$

$$d'F = \frac{T - F}{dF}$$

For each iteration loop

$$\theta_{new} = \theta_{old} + d'F$$

By some iterations in MATLAB, the switching angles for a 5-level and 9-level cascaded H-bridge multilevel inverter are calculated.

$$\theta_1 = 16.3286^0 \qquad \theta_2 = 52.3286^0$$

As can be seen in Fig.11 the 5^{th} harmonic was eliminated.

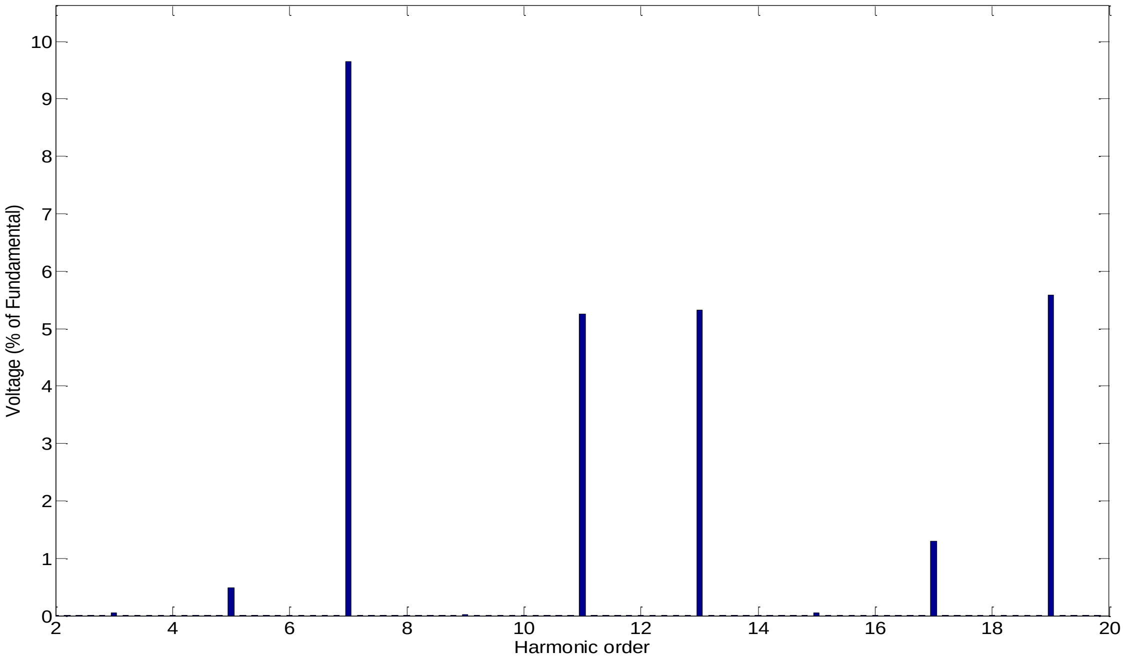

Figure 11. Output voltage harmonic spectrum for a 5-level multilevel inverter

2.4.2. 9-level multilevel inverters

The Fourier series of a 4 step unity DC source is shown in (2-8).

$$f(t) = f_{\theta_1}(t) + f_{\theta_2}(t) + f_{\theta_3}(t) + f_{\theta_4}(t)$$
$$= \sum_{h=1}^{\infty} [\cos(h\theta_1) + \cos(h\theta_2) + \cos(h\theta_3) + \cos(h\theta_4)]$$
$$= \frac{4V_{dc}}{\pi} \sum_{h=1}^{\infty} \left[\sum_{i=1}^{4} [\![\cos(h\theta_i)]\!] \frac{\sin(h\omega t)}{h} \right] \qquad (2-8)$$

Where:

V_{dc}: Voltage of voltage sources for each cell that is unity

θ_i : The switching angle

h: The harmonic order

From (2-8) four equations will be resulted for eliminating the 5th, 7th, 11th harmonics.

$$V_{dc} = V_1 + V_2 + V_3 + V_4$$

$$\frac{4V_{dc}}{\pi}\left(\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4)\right) = h_1 \qquad (2-9)$$

$$\frac{4V_{dc}}{\pi}\left(\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4)\right) = h_5 \qquad (2-10)$$

$$\frac{4V_{dc}}{\pi}\left(\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4)\right) = h_7 \qquad (2-11)$$

$$\frac{4V_{dc}}{\pi}\left(\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4)\right) = h_{11} \qquad (2-12)$$

Equations (2-9) to (2-12) are for the harmonics that should be eliminated, so (2-10) to (2-12) should be equal to zero. The DC sources are constant, so

$$V_{dc} = 4V_1 \qquad (2-13)$$

$$M = \frac{h_1}{4V} \qquad (2-14)$$

The modulation index is 1 since the voltage that is used in these calculations is in per unit. From equations (2-15) to (2-18) the nonlinear equations will be calculated.

$$\cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) = \frac{\pi}{4} \qquad (2-15)$$

$$\cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) = 0 \qquad (2-16)$$

$$\cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) = 0 \qquad (2-17)$$

$$\cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) = 0 \qquad (2-18)$$

For this method the following matrixes should be created:

1. Switching angles matrix

$$\theta = \begin{bmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \end{bmatrix}$$

2. The nonlinear system matrix

$$F = \begin{bmatrix} \cos(\theta_1) + \cos(\theta_2) + \cos(\theta_3) + \cos(\theta_4) \\ \cos(5\theta_1) + \cos(5\theta_2) + \cos(5\theta_3) + \cos(5\theta_4) \\ \cos(7\theta_1) + \cos(7\theta_2) + \cos(7\theta_3) + \cos(7\theta_4) \\ \cos(11\theta_1) + \cos(11\theta_2) + \cos(11\theta_3) + \cos(11\theta_4) \end{bmatrix}$$

$$dF = \begin{bmatrix} -\sin(\theta_1) & -\sin(\theta_2) & -\sin(\theta_3) & -\sin(\theta_4) \\ -5\sin(5\theta_1) & -5\sin(5\theta_2) & -5\sin(5\theta_3) & -5\sin(5\theta_4) \\ -7\sin(7\theta_1) & -7\sin(7\theta_2) & -7\sin(7\theta_3) & -7\sin(7\theta_4) \\ -11\sin(11\theta_1) & -11\sin(11\theta_2) & -11\sin(11\theta_3) & -11\sin(11\theta_4) \end{bmatrix}$$

3. The answers matrix

$$T = \begin{bmatrix} \frac{\pi}{4} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$d'F = \frac{T - F}{dF}$$

For each iteration loop

$$\theta_{new} = \theta_{old} + d'F$$

By some iteration in MATLAB, the switching angles for a 5-level and 9-level cascaded H-bridge multilevel inverter are calculated.

$$\theta_1 = 12.1260^0 \quad \theta_2 = 20.8465^0 \quad \theta_3 = 38.6570^0 \quad \theta_4 = 63.3546^0$$

As can be seen in Fig.12, 5^{th}, 7^{th}, 11^{th} harmonics of output voltage are eliminated.

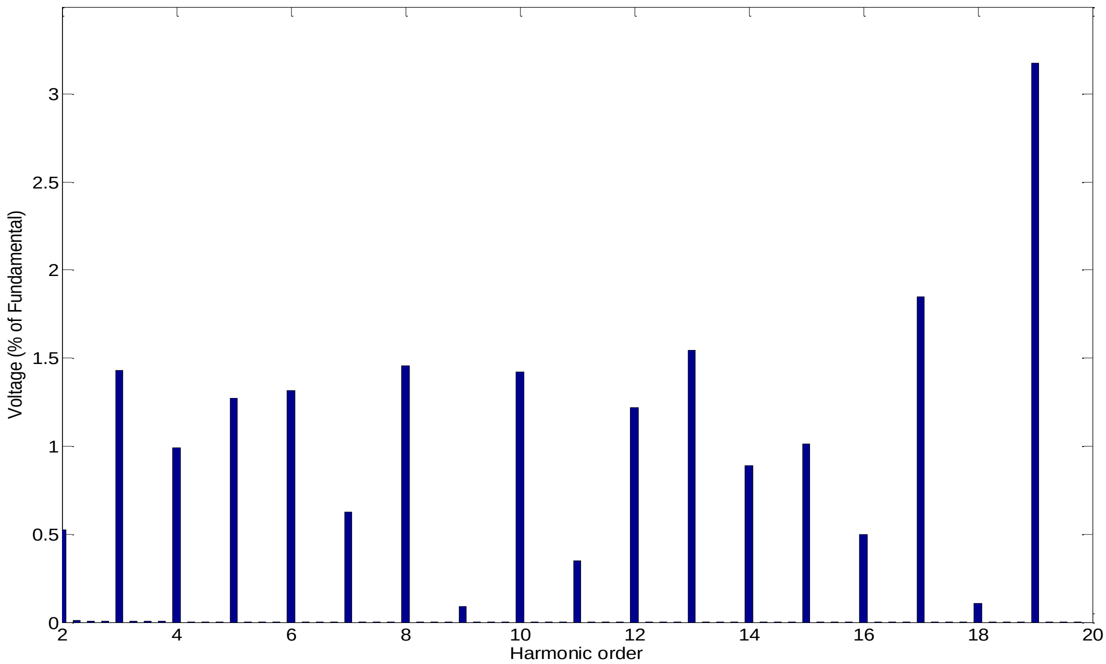

Figure 12. Output voltage harmonic spectrum for a 9-level cascaded H-bridge multilevel inverter

2.5. Power Losses calculations

Power losses in all of the switching devices can be divided in three groups

1. Conduction losses
2. Switching losses
3. Blocking(leakage) losses that is normally being neglected

In this thesis two types of switches are used: IGBT and MOSFET. Power loss calculations for the IGBT and the MOSFET are not done using the same method.

2.5.1. IGBT power losses calculations

The IGBT power losses like the other switching devices can be divided in three groups, but leakages power losses are neglected.

2.5.1.1.Conduction losses

Conduction losses occur in the switches and in the anti parallel diodes. Conductions losses for the switches can be calculated by (2-19) and the conduction losses for the anti parallel diode can be calculated by (2-20):

$$P_{ci} = u_{CE0}.I_{Iav} + r_c.I_{Irms}^2 \qquad (2-19)$$

$$P_{cd} = u_{D0}.I_{Dav} + r_D.I_{Drms}^2 \qquad (2-20)$$

where

u_{ce0}: on state zero current collector emitter voltage

I_{cav}: average switch current

r_c: collector emitter on-state resistance

I_{crms}: RMS switch current

u_{D0}: diode approximation with a series conduction of DC voltage sources

I_{Dav}: average diode current

r_D: diode on-state resistance

I_{Drms}: RMS diode current

u_{ce0} and r_c can be obtained from the diagram collector-emitter voltage versus collector current in the datasheet.

u_{D0} and r_D can be obtained from the diagram forward voltage versus forward current in the datasheet.

2.5.1.2.Switching losses

Switching losses are created in the switches and in the anti parallel diodes. Switching losses for the switch can be calculated by (2-21) and switching losses for the anti parallel diode can be calculated by (2-22).

$$P_{swI} = \left(E_{onI} + E_{offI}\right).f_{sw} \qquad (2-21)$$

$$P_{swD} = \left(E_{onD} + E_{offD}\right).f_{sw} \approx E_{onD}.f_{sw} \qquad (2-22)$$

where

E_{onI}: turn on energy losses in IGBT

E_{offI}: turn off energy losses in IGBT

E_{onD}: turn on energy losses in diode

E_{offD}: turn off energy losses in diode that normally is being neglected

f_{sw}: switching frequency

E_{onI}, E_{offI}, E_{onD} can be obtained from the datasheet of each IGBT.

2.5.2. MOSFET power losses calculations

The Mosfet power losses can as for the other switching devices can be divided in three groups when leakage power losses are neglected.

2.5.2.1.Conduction losses

Like in the IGBT, conductions losses are in the switches and in the anti parallel diodes. Conduction losses for the switch can be calculated by (2-23) and conduction losses for anti parallel diode can be calculated by (2-24).

$$P_{cM} = R_{DSon}.I_{Mrms}^2 \qquad (2-23)$$

$$P_{CD} = u_{D0}.I_{Dav} + R_D.I_{Drms}^2 \qquad (2-24)$$

where

$R_{DSon:}$ drain-source on-state resistance

I_{Mrms}: RMS value of the MOSFET on-state current

u_{D0}: diode approximation with a series conduction of DC voltage sources

I_{Dav}: average diode current

R_D: diode on-state resistance

I_{Drms}: RMS diode current

R_{DSon} should be obtained from the datasheet. u_{D0} and R_D should be obtained from the diagram "Forward character of reverse diode" in the datasheet.

2.5.2.2. Switching losses

Switching losses include switch-on transient and switch-off transient. Energy losses for on-transient can be calculated by (2-26) and energy losses for off transient can be calculated by (2-27). Total switching losses can be calculated by (2-25).

$$P_{swM} = \left(E_{onM} + E_{offM}\right).f_{sw} \qquad (2-25)$$

$$E_{onM} = V_{DD}.I_{Don}.\frac{t_{ri} + t_{fv}}{2} + Q_{rr}.V_{DD} \qquad (2-26)$$

$$E_{offM} = V_{DD}.I_{Doff}.\frac{t_{ri} + t_{fi}}{2} \qquad (2-27)$$

$$t_{rv} = \frac{t_{rv1} + t_{rv2}}{2} \qquad (2-28)$$

$$t_{rv1} = (V_{DD} - R_{DSon}.I_{Don}).R_G.\frac{C_{GD1}}{V_{(plateau)}}$$

$$t_{rv2} = (V_{DD} - R_{DSon}.I_{Don}).R_G.\frac{C_{GD2}}{V_{(plateau)}}$$

where

V_{DD}: Voltage across the MOSFET

I_{Don},I_{Doff} : The current passing through MOSFET during on-time or off-time

T_{ri}: Current rise time

T_{fi}: Current fall time

T_{rv}: Voltage rise time

T_{fv}: Voltage fall time

C_{GD}: Gate-Drain capacitor

$V_{(plateau)}$: Gate plateau voltage

R_G: Gate resistance that is depends on the drive circuit of the MOSFET

If V_{DS} is between 0, $V_{DD}/2$ the gate-drain capacitance will be C_{GD} ($R_{DSon}.I_{on}$) = C_{GD1}. If V_{DS} is between $V_{DD}/2$, V_{DD} the gate-drain capacitance will be C_{GD} (V_{DD}) = C_{GD2}.

V_{DD}, I_{Don}, I_{Doff} should be measured. t_{ri}, t_{fi}, C_{GD}, R_G, $V_{(plateau)}$ values should be found in the MOSFET datasheet.

3. Comparison between a 5-level diode clamped, flying capacitor, H-bridge and two-level inverters on Power losses, cost, weight and THD

In these simulations a balanced three phase system is assumed. The load for the system is a three phase asynchronous motor. The parameters of the asynchronous motor are listed below:

Nominal power = 75 KW

Line-line RMS voltage = 400 V

Frequency = 50 Hz

Rotor nominal speed = 1484 rpm

Stator resistance = 0.03552 Ω

Stator inductance = 0.335 mH

Rotor resistance = 0.02092 Ω

Rotor inductance = 0.335 mH

Mutual inductance = 15.1 mH

Pole pairs = 2

In this thesis three different IGBTs and one MOSFET and one diode and one capacitor were used. Characteristics for all of the devices are as follows:

IGBT FD300R06KE3

Collector-Emitter voltage= 600 V

DC-collector current= 300 A

Repetitive peak reverse voltage= 600 V

DC forward current= 300 A

u_{CE0}= 0.85 V

r_c=0.0022 Ω

u_{D0}=0.9 V

r_D=0.0014 Ω

Weight=340 g

Price: 132.48 €

IGBT FF200R12KE4

Collector-Emitter voltage= 1200 V

DC-collector current= 200 A

Repetitive peak reverse voltage= 1200 V

DC forward current= 200 A

u_{CE0}=0.8 V

r_c=0.0054 Ω

u_{D0}=1 V

r_D=0.0033 Ω

Weight=340 g

Price: 138.86 €

IGBT FMG2G300US60

Collector-Emitter voltage= 600 V

DC-collector current= 300 A

Repetitive peak reverse voltage= 600 V

DC forward current= 300 A

u_{CE0}=1.5 V

r_c=0.0029 Ω

u_{D0}=1.1 V

r_D=0.0027 Ω

Weight=360 g

Price: 117.7 €

MOSFET STE250NS10

Drain-Source voltage=100 V

Drain current (continuous) = 156 A

Drain current (pulse) = 880 A

R_{DSon}=0.0055 Ω

u_{D0}=0.9 V

r_D=0.0029 Ω

Weight=9 g

Price: 31.61 €

Diode 85HF60

Forward average current= 85 A

Maximum repetitive peak reverse voltage= 600 V

u_{D0}=0.7 V

r_D=0.0015 Ω

Weight=17 g

Price: 6.33 €

Capacitor FFV34E0107K

Nominal capacitance= 100 µF

Rated voltage= 100V DC

ESR, DC= 0.55 mΩ

Maximum RMS current= 24 A

Weight= 0.09 Kg

Price: 25.01 €

Capacitor C4DEFPQ6380A8TK

Nominal capacitance= 380 µF

Rated voltage= 400V DC

ESR, DC= 0.81 mΩ

Maximum RMS current= 100 A

Weight= 0.419 Kg

Price: 90.49 €

3.1. Power Losses comparison between 5-level diode clamped, 5-level capacitor clamped, 5-level cascaded H-bridge and two-level inverters

3.1.1. Loss calculations for IGBT FD300R06KE3

When the motor is operating in full load, the RMS and the average current that is passing through the diodes and switches are obtained from the SIMULINK file.

3.1.1.1.5-level Diode clamped multilevel inverter

The RMS current that is passing through one of the switches is 48.19A and the average current that is passing through one of the switches is 15.99A.

I_{Iav}=15.99A

I_{IRMS}=48.19A

No current passes through the anti parallel diodes in full load, so the conduction losses of anti parallel diodes are equal to zero.

According to (2-19) and for one switch, the power losses are:

P_{cI}= 17.7982W

There are 24 switches for three phases so:

P_{cI}=427.1566W

For the diode clamped multilevel inverter, the diode power losses should be calculated by (2-20). The power losses for one diode are:

P_{cD}= 7.0697W

There are 36 diodes in the 5-level diode clamped multilevel inverter, so the total power losses are:

P_{cD}= 254.5108W

Since the switching frequency is 50Hz, the switching losses are neglected in this thesis.

3.1.1.2.5-level flying capacitor multilevel inverter

The RMS current that is passing through one of the switches is 49.02A and the average current that is passing through one of the switches is 17.28A.

I_{Iav}=17.28A

I_{IRMS}=49.02A

No current passes through anti parallel diodes in full load, so the conduction losses of anti parallel diodes are equal to zero.

According to (2-19) and for one switch, the power losses are:

P_{cI}= 19.1105W

There are 24 switches for three phases so:

P_{cI}=458.6523W

3.1.1.3.5-level cascaded H-bridge multilevel inverter

There are 8 switches in each cell, but the current that passes through the switches is not the same for all of them. There are four different currents. It means that in each cell two switches have same current value. The values for full load are presented in Table.3.

Table 3. Currents that pass through different switches

Switches	IGBT RMS(A)	IGBT average(A)	Diode RMS(A)	Diode average(A)
S_{11},S_{21}	91	54.3	7.29	1.1
S_{31},S_{41}	93.2	58.9	21.5	5.6
S_{12},S_{22}	79	37.8	0	0
S_{32},S_{42}	93.5	60	50	22.1

According to (2-19) and (2-20) the power losses are:

P_{cI}= 1491.2W

P_{cD}= 209.3593W

P_{cTot}=1700.6W

3.1.1.4.Two-level inverter

There are 4 switches in each cell in one level inverter and the current that passes through each switch is the same for all of the switches.

I_{Iav}=63.56A

I_{IRMS}=100.7A

I_{Dav}=5.322A

I_{DRMS}=28.93A

According to (2-19) and (2-20) power losses are:

P_{cI}= 952.5267W

P_{cD}= 78.6561W

P_{cTot}=1031.2W

Fig.13 shows the power loss comparison when using IGBT FD300R06KE3.

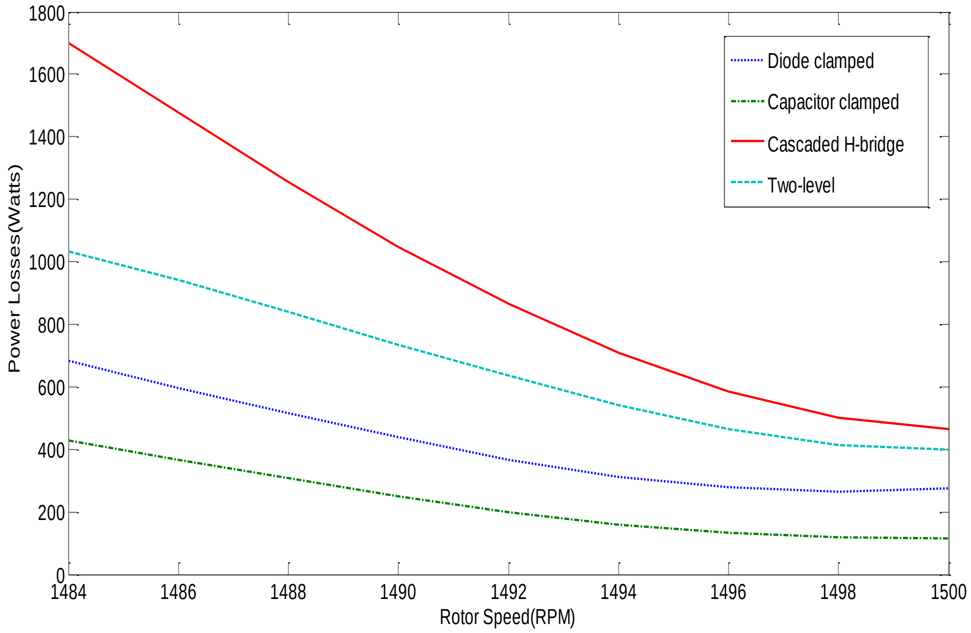

Figure 13. Power losses comparison for IGBT FD300R06KE3 for 5-level and two-level inverters

3.1.2. Loss calculations for IGBT FF200R12KE4

When the motor is operting in full load, RMS and average current that is passing through diodes and switches are obtained from SIMULINK file.

3.1.2.1.5-level Diode clamped multilevel inverter

The RMS current that is passing through one of the switches is 48.19A and the average current that is passing through one of the switches is 15.99A.

I_{Iav}=15.99A

I_{IRMS}=48.19A

No current passes through anti parallel diodes in full load, so conduction losses of anti parallel diodes are equal to zero.

According to (2-19) and for one switch power losses is:

P_{cI}= 26.029W

There are 24 switches for three phases so:

P_{cI}=624.6954W

For the diode clamped multilevel inverter, the diode power losses can be calculated as well by (2-20). The power losses of one diode are:

P_{cD}=7.0697

There are 36 diodes for three phases so:

P_{cD}=254.5108

Since the switching frequency is 50Hz, the switching power losses are neglected in this thesis.

3.1.2.2.5-level flying capacitor clamped multilevel inverter

The RMS current that is passing through one of the switches is 49.02A and the average current that is passing through one of the switches is 17.28A.

I_{Iav}=17.28A

I_{IRMS}=49.02A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) and for one switch, the power losses are:

P_{cI}= 27.5209W

There are 24 switches for three phases so:

P_{cI}=660.5010W

3.1.2.3.5-level cascaded H-bridge multilevel inverter

There are 8 switches in each cell, but the current that passes through the switches is not the same for all of them. There are four different currents. It means that in each cell two switches have same current value. Values for full load are given in Table.4.

Table 4. Currents that pass through different switches

Switches	IGBT RMS(A)	IGBT average(A)	Diode RMS(A)	Diode average(A)
S_{11},S_{21}	91	54.3	7.3	1.1
S_{31},S_{41}	93.2	58.9	21.5	5.6
S_{12},S_{22}	79	37.8	0	0
S_{32},S_{42}	93.5	59.9	50	22.1

The RMS current that is passing through one of the switches is 48.19A and the average current that is passing through one of the switches is 15.99A.

According to (2-19) and (2-20) power losses are:

P_{cI}= 1920.3W

P_{cD}= 242.3127W

P_{cTot}=2162.6W

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) the power losses are:

P_{cI}= 1700.6W

3.1.2.4.Two-level inverter

There are 4 switches in each cell in the two-level inverter and the current that passes through each switch is the same for all of the switches.

I_{Iav}=63.56A

I_{IRMS}=100.7A

I_{Dav}=5.322A

I_{DRMS}=28.93A

According to (2-19) and (2-20), the power losses are:

P_{cI}= 1376.8W

P_{cD}= 96.63W

P_{cTot}=1473.4W

Fig.14 shows the power losses comparison for IGBT FF200R12KE4.

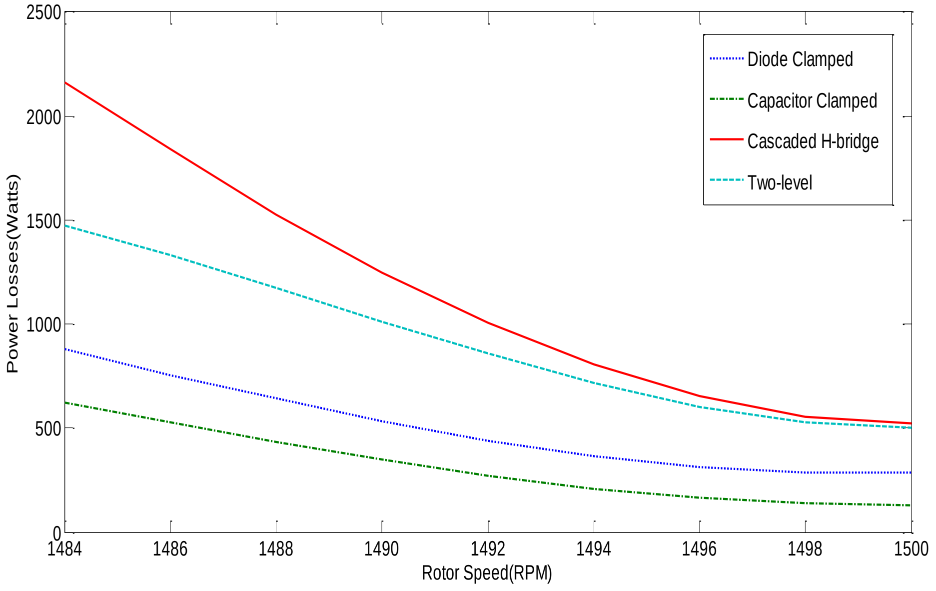

Figure 14. Power losses comparison for IGBT FF200R12KE4 for 5-level and two-level inverters

3.1.3. Loss calculations for IGBT FF200R12KE4

The power losses can be calculated like for the previous switches.

Fig.15 shows the power losses comparison for IGBT FMG2G300US60.

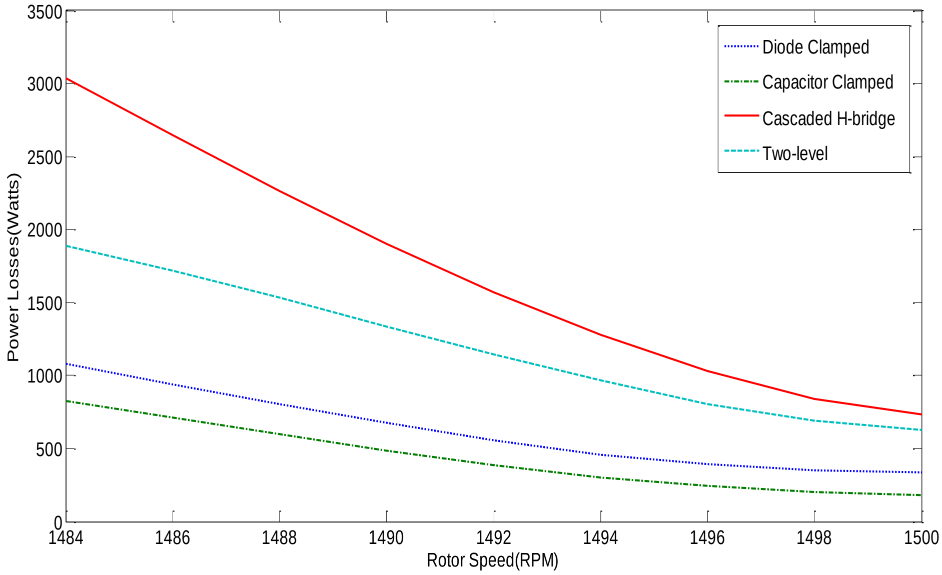

Figure 15. Power losses comparison for IGBT FMG2G300US60 for 5-level and two-level inverters

3.2. Power losses comparison between 9-level diode clamped multilevel inverter, 9-level flying capacitor clamped multilevel inverter and 9-level cascaded H-bridge multilevel inverter

The loss calculations method is like performed in (3-1), that current was obtained from the SIMULINK file and the data of switches were obtained from datasheets. By using the power losses calculations formulas, the power losses are calculated.

In this comparison two different IGBTs and one MOSFET were used.

3.2.1. Loss calculations for IGBT FD300R06KE3

When the motor is operating in full load, the RMS and the average current that is passing through the diodes and the switches are obtained from the SIMULINK file.

3.2.1.1.9-level Diode clamped multilevel inverter

As stated before in this thesis the 9-level diode clamped multilevel inverter are made by cascading two 5-level diode clamped multilevel inverters which are cascaded but their switching angles are different from each other. The RMS and the average current that is passing through one of the switches are 62.17A and 33.2A.

I_{Iav}=33.2A

I_{IRMS}=62.17A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) and (2-20) the power losses for one of the switches is:

P_{cI}= 35.95W

There are 48 switches for three phases so:

P_{cI}=1725.4W

For the diode clamped multilevel inverter, the diode power losses should be calculated as well. There are 24 diodes for a 9-level diode clamped inverter that conduction losses for one of them are calculated by (2-20).

For full load P_{cD}= 490.0986W

Since the switching frequency is 50Hz, switching losses are neglected in this thesis.

3.2.1.2.9-level flying capacitor multilevel inverter

The RMS current that is passing through one of the switches is 61.15A and the average current that is passing through one of the switches is 32.1A.

I_{Iav}=32.1A

I_{IRMS}=61.15A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) and for one switch power losses is:

P_{cI}= 35.46W

There are 48 switches for three phases so:

P_{cI}=1702.3W

3.2.1.3.9-level cascaded H-bridge multilevel inverter

There are 16 switches in each cell, but the current that passes through the switches is not the same for all of them. There are four different currents. It means that in each cell two switches have the same current value. The current values for full load are given in Table.5.

Table 5. Currents that pass through different switches

Switches	IGBT RMS(A)	IGBT average(A)	Diode RMS(A)	Diode average(A)
S_{11},S_{21}	81.66	47.89	6.826	1.321
S_{31},S_{41}	84.19	52.3	19.93	5.731
S_{12},S_{22}	79.37	44.65	2.299	0.2649
S_{32},S_{42}	84.44	53.35	27.66	8.963
S_{13},S_{23}	73.72	37.74	0	0
S_{33},S_{43}	84.47	53.62	40.39	15.88
S_{14},S_{24}	61.24	24.76	0	0
S_{34},S_{44}	84.47	53.62	57.58	28.85

According to (2-19) and (2-20) power losses are:

P_{cI}= 2498.2W

P_{cD}= 407.0097W

P_{cTot}=2905.2W

Fig.17 shows the power losses comparison for IGBT FD300R06KE3.

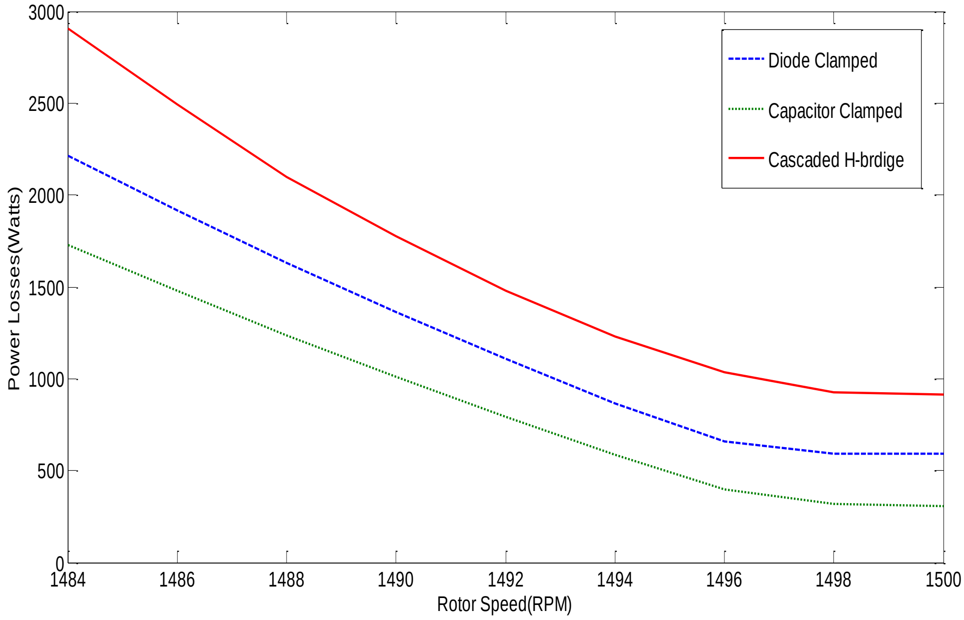

Figure 17. Power losses comparison for IGBT FD300R06KE3 for the 9-level inverters

3.2.2. Loss calculations for IGBT FF200R06KE4

When the motor is operating in full load, the RMS and the average current that is passing through the diodes and the switches are obtained from the SIMULINK file.

3.2.2.1.9-level Diode clamped multilevel inverter

As stated before in this thesis the 9-level diode clamped multilevel inverter are made by cascading two 5-level diode clamped multilevel inverters which are cascaded but their switching angles are different from each other. The RMS and the average current that is passing through one of the switches are 62.17A and 33.2A.

I_{Iav}=33.2A

I_{IRMS}=62.17A

No current passes through anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) and for one switch power losses is:

P_{cI}= 51.525W

There are 48 switches for three phases so:

P_{cI}=2473.2W

For the diode clamped multilevel inverter, the diode power losses should be calculated by (2-20). The power losses for one diode are:

P_{cD}=6.8069

There are 72 diodes in the 9-level diode clamped multilevel inverter, so the total power losses will be:

P_{cD}= 490.0986W

Since switching frequency is 50Hz, switching losses are neglected in this thesis.

3.2.2.2.9-level flying capacitor multilevel inverter

The RMS current that is passing through one of the switches is 61.15A and the average current that is passing through one of the switches is 32.1A.

I_{Iav}=32.1A

I_{IRMS}=61.15A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-19) and for one switch, the power losses are:

P_{cI}= 50.9W

There are 48 switches for three phases so:

P_{cI}=2443W

3.2.2.3.5-level cascaded H-bridge multilevel inverter

There are 8 switches in each cell, but the current that passes through the switches is not the same for all of them. There are four different currents. It means that in each cell two switches have the same current value. The values for full load are presented in Table.6.

Table 6. Currents that pass through different switches

Switches	IGBT RMS(A)	IGBT average(A)	Diode RMS(A)	Diode average(A)
S_{11},S_{21}	81.66	47.89	6.826	1.321
S_{31},S_{41}	84.19	52.3	19.93	5.731
S_{12},S_{22}	79.37	44.65	2.299	0.2649
S_{32},S_{42}	84.44	53.35	27.66	8.963
S_{13},S_{23}	73.72	37.74	0	0
S_{33},S_{43}	84.47	53.62	40.39	15.88
S_{14},S_{24}	61.24	24.76	0	0
S_{34},S_{44}	84.47	53.62	57.58	28.85

According to (2-19) and (2-20), the power losses are:

P_{cI}= 3213.4W

P_{cD}= 535.5721W

P_{cTot}=3748.9W

Fig. 18 shows the power losses comparison between the three different inverters for IGBT FF200R12KE4.

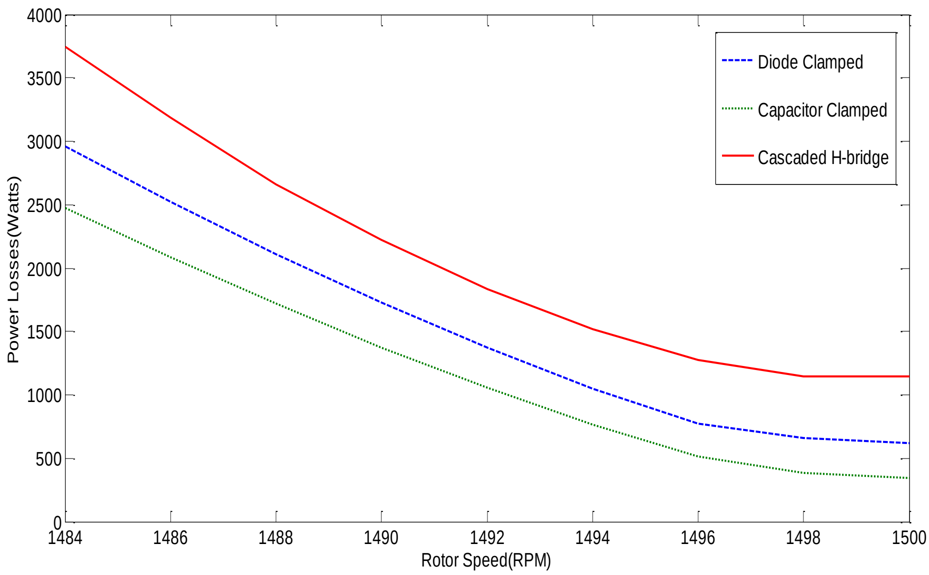

Figure 18. Power losses comparison for IGBT FF200R12KE4 for the 9-level inverters

3.2.3. Power Losses calculations for Mosfet STE250NS10

When the motor is operating in full load, the RMS and the average current that is passing through the diodes and the switches are obtained from the SIMULINK file.

The R_{DSon} in the Mosfet is slightly alternated with temperature and the current that is passing through the Mosfet. The Mosfet STE250NS10 "Static drain-source on resistance" diagram which is in the data sheet of the Mosfet shows that in the current range that the Mosfet operates, the variations of R_{DSon} are small. These variations are neglected in this thesis, so in this case it is assumed that R_{DSon} does not change during the simulations.

3.2.3.1.9-level Diode clamped multilevel inverter

As stated before in this thesis the 9-level diode clamped multilevel inverter are made by cascading two 5-level diode clamped multilevel inverters which are cascaded but their switching angles are different from each other. The RMS and the average current that is passing through one of the switches is 62.17A and 33.2A.

I_{Iav}=33.2A

I_{IRMS}=62.17A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-23) and for one switch, the power losses are:

P_{cI}= 10.63W

There are 48 switches for three phases so:

P_{cI}=510.1944W

For the diode clamped multilevel inverter, the diode power losses should be calculated by (2-24). The power losses of one diode are:

P_{cD}= 6.8069W

There are 72 diodes in the 9-level diode clamped multilevel inverter, so the total power losses will be:

For full load P_{cD}= 490.0986W

Since the switching frequency is 50Hz, the switching power losses are neglected in this thesis.

3.2.3.2.9-level flying capacitor multilevel inverter

The RMS current that is passing through one of the switches is 61.15A and the average current that is passing through one of the switches is 32.1A.

I_{Iav}=32.1A

I_{IRMS}=61.15A

No current passes through the anti parallel diodes in full load, so the conduction losses of the anti parallel diodes are equal to zero.

According to (2-23) and for one switch power losses is:

P_{cI}= 10.52W

There are 48 switches for three phases so:

P_{cI}=505.23W

3.2.3.3.9-level cascaded H-bridge multilevel inverter

There are 8 switches in each cell, but the current that passes through switches is not the same for all of them. There are four different currents. It means that in each cell two switches have the same current value. Values for full load are given in Table.7.

Table 7. Currents that pass through different switches

Switches	IGBT RMS(A)	IGBT average(A)	Diode RMS(A)	Diode average(A)
S_{11},S_{21}	81.66	47.89	6.826	1.321
S_{31},S_{41}	84.19	52.3	19.93	5.731
S_{12},S_{22}	79.37	44.65	2.299	0.2649
S_{32},S_{42}	84.44	53.35	27.66	8.963
S_{13},S_{23}	73.72	37.74	0	0
S_{33},S_{43}	84.47	53.62	40.39	15.88
S_{14},S_{24}	61.24	24.76	0	0
S_{34},S_{44}	84.47	53.62	57.58	28.85

According to (2-23) and (2-24) power losses are:

P_{cI}= 1671.2W

P_{cD}= 367.14W

P_{cTot}=2038.3W

Fig. 19 shows the power losses comparison between the three different inverters for MOSFET STE250NS10.

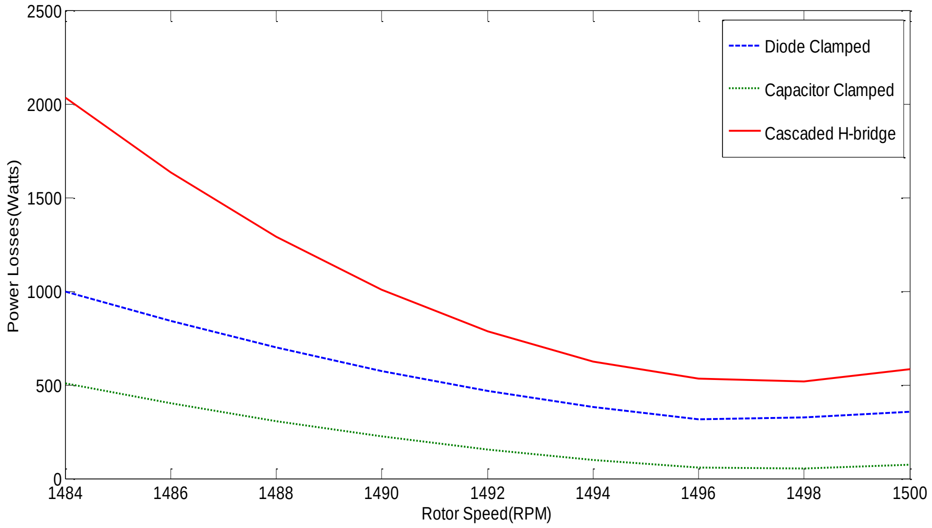

Figure 19. Power losses comparison for MOSFET STE250NS10 for the 9-level inverters

3.3. Weight and cost comparisons

Weight comparison is done for each topology by calculating the weight of all of the components of the inverters. The same switch is considered for all of the topologies to have a more accurate comparison. The IGBT FD300R06KE3 is used for all of the topologies. In the 5-level diode clamped multilevel inverter, the 5-level flying capacitor, the 5-level cascaded H-bridge and the two-level inverter, the capacitor C4DEFPQ6380A8TK is used, since the DC input voltages are higher, so a capacitor with higher voltage tolerance is needed. In the 9-level diode clamped multilevel inverter, the 9-level flying capacitor multilevel inverter and the 9-level cascaded H-bridge multilevel inverter the capacitor FFV34E0107K is used, since the DC input voltages are lower, so a capacitor with lower voltage tolerance is needed. Table.8 shows the total weight and the total cost of all types of inverters.

To have a better understanding of different types of inverters, weight and cost are shown in the charts in Fig.20 and Fig.21.

Table 8. Weight and cost comparison for all types of inverters

Type of inverter	Number of switches	Number of capacitors	Number of diodes	Weight(Kg)	Cost(€)
2-level	12	3	0	5.3	1861.2
5-level diode clamped	24	12	36	13.8	4493.3
5-level capacitor clamped	24	30	0	20.73	5894.2
5-level cascaded	24	6	0	10.67	3722.5
9-level diode clamped	48	24	72	19.704	7415
9-level capacitor clamped	48	60	0	21.72	7859.6
9-level cascaded	48	12	0	17.4	6659.2

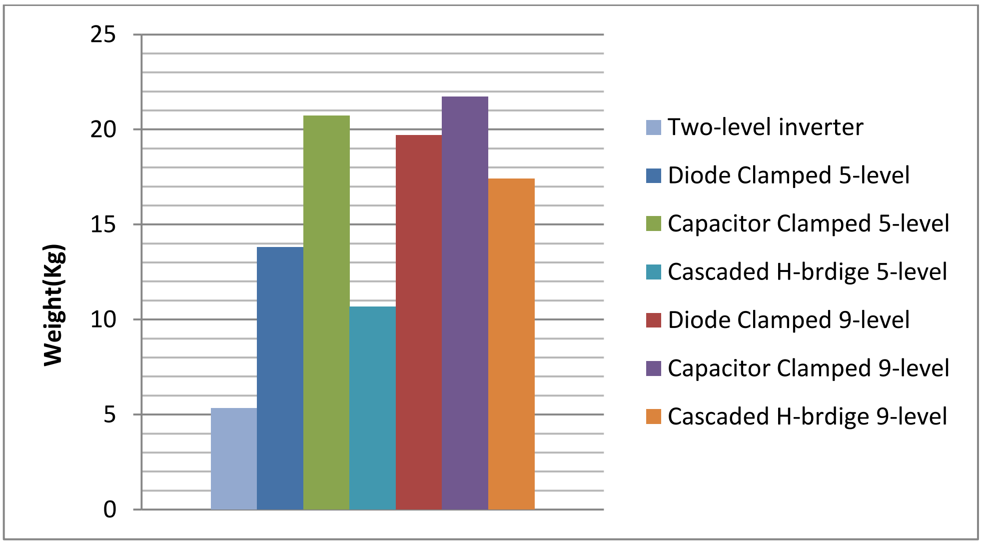

Figure 20. Weight comparison for all topologies of inverters

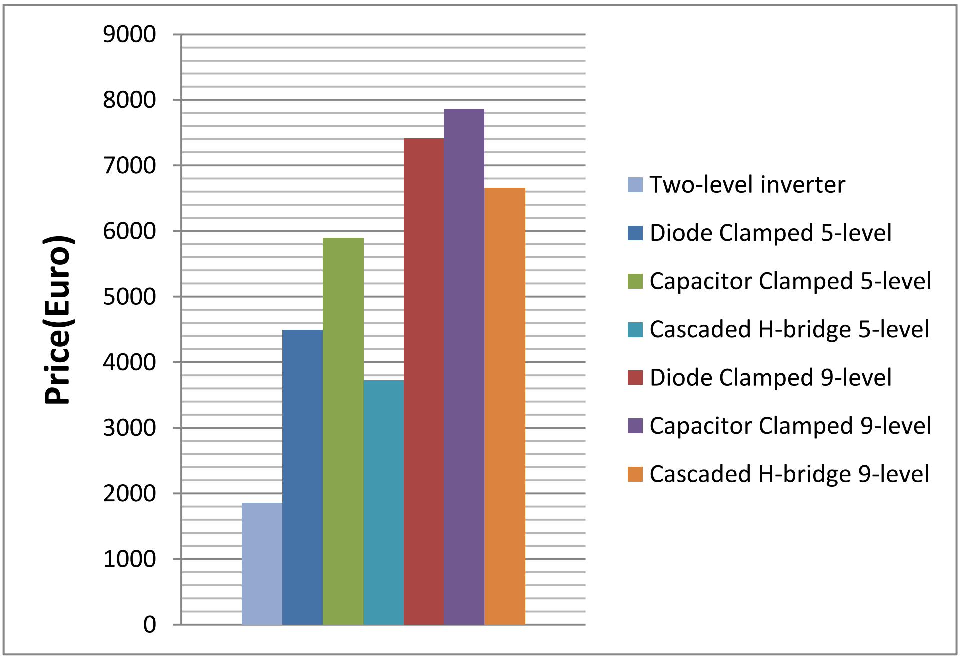

Figure 21. Cost comparison for all topologies of inverter

3.4. THD comparison for all of the inverter topologies

THD calculations obtained from the SIMULINK file. All of the THDs are for stator current in the electrical motor. The THD comparison between the 5-level inverters, the 9-level inverters and the two-level inverters is shown in Fig.22. The output voltage of all the 5-level topologies is the same, since the same switching pattern is used for all of them. The output voltage of all the 9-level inverters is the same, since the same switching pattern is used for all of them.

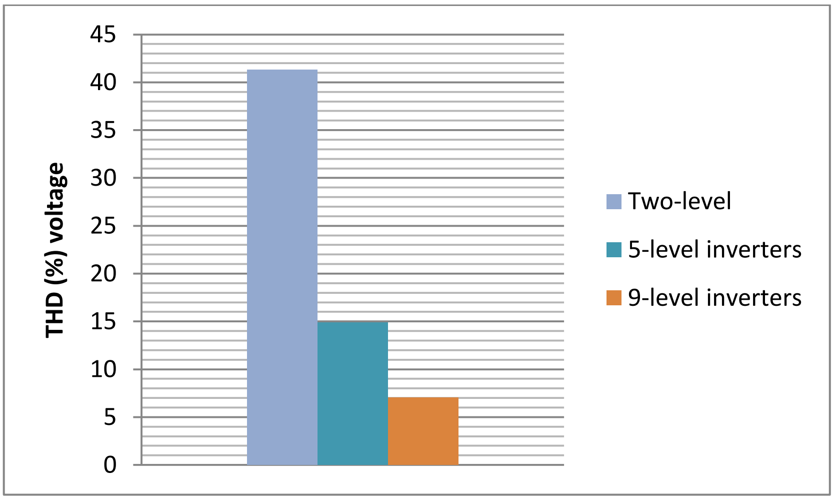

Figure 22. Voltage THD comparison for all inverter topologies

4. Conclusions

The choice of topology for each inverter should be based on what is the usage of the inverter. Each topology has some advantages and disadvantages. By increasing the number of levels, the THD will be decreased but on the other hand cost and weight will be increased as well. Also since the switching angles for switches are not the same, the drive circuit for each switch is separate from other switches.

The two-level inverter has the lowest cost and weight in comparison with the other topologies. But this inverter has a very high THD; its THD is about 40% when one switching event for fundamental period is used. In weight and cost calculations, the price and weight of the filter should be considered, since it is not practical to have an output voltage with 40% THD. The cost and the weight of the 5-level multilevel inverters seem better than the 9-level multilevel inverters. By increasing the number of levels, the cost and weight of the multilevel inverter will be increased. The advantage that the 9-level multilevel inverters have over the 5-level multilevel inverters is their THD before filters, thus a filter will be needed. The 9-level multilevel inverters have lower THD than the 5-level multilevel inverters. For example the THD in the 5-level multilevel inverters and the 9-level inverters are 15% and 7%. It seems that using the 5-level inverter and a filter is a better design.

The Flying capacitor clamped inverter has the lowest power losses between all of the other topologies, since there is no diode in its topology. For example the power losses in the 5-level flying capacitor multilevel inverter in full load are 625W, but it has two big problems. First is that it is heavier than the other topologies. It is not practical to use this heavy inverter in applications that are going to be used in applications that are not stable. Also the cost of this inverter is more than other inverters. It seems that the flying capacitor clamped multilevel inverter can be used in applications where the power losses are more important compared to the weight and cost.

The cascaded H-bridge has the lowest weight and cost between the multilevel inverters, but its power losses is more that all the other topologies. For example at compared to the other topologies its power loss is 3749W. This topology can be used in applications where the weight and the cost of the application is more important than its power losses.

The diode clamped multilevel inverter's power losses are lower than cascaded H-bridge. For example the power losses in the 9-level diode clamped multilevel inverter are 2963W. The diodes that were used in this thesis cost 6.95 Euros, so the cost will not be that much higher than the cascaded H-bridge. It seems that diode clamped inverter is a topology between all other topologies that THD, cost and power losses are between other types of inverters.

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