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DEPARTMENT OF ELECTRICAL ENGINEERING

**APPLYING ACTIVE FRONT END TO MULTILEVEL
INVERTER**

Lappeenrannassa 28.4.2008

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ABSTRACT

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Subject: **Applying Active Front End to Multilevel Inverter**
Department: Department of electrical engineering
Year: 2008
Place: Lappeenranta

Lappeenranta University of Technology. 21 pages and 20 figures.

The aim of this work was to make an active front end from IGBTs for a multilevel inverter. The work was done for Mosart II, a long term still ongoing Vacon Oyj project. The purpose of the AFE is to balance the DC-voltage and to put the returning power back to the grid instead of the breaking chopper and the capacitor. With a diode rectifier the bridge only allows power to pass in one direction and the switching times are not controllable. That means the rectifier always takes the highest phase and the phases are always conducting the same 120° . With an AFE it is possible to actively change the rectifiers switching pattern. A diode bridge also generates much greater losses than an IGBT bridge. With these arguments it is rational to start researching the possibility of an AFE in a multilevel inverter.

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ABBREVIATIONS

AFE	Active Front End
C_{dc}	capacitance of the DC-link
i_d	d-axis current
$i_{d,ref}$	d-axis current reference
i_q	q-axis current
$i_{q,ref}$	q-axis current reference
IGBT	Insulated Gate Bipolar Transistor
$K_{p,dc}$	proportional gain of the PI-controller
u_{dc}	DC-voltage
t_0	switching time of the zero vector
T_α	time constant of the first-order model for the closed-loop current
$T_{i,dc}$	integral time of the PI-controller
t_m	switching time of the first vector
t_{m+1}	switching time of the second vector
T_s	switching period
$t_{U,on}$	switching time of the U phase
$t_{V,on}$	switching time of the V phase
$t_{W,on}$	switching time of the W phase
$U_{s,ref}$	voltage reference
v_m	first active reference voltage vector
v_{m+1}	second active reference voltage vector
\mathbf{V}_m	first active voltage vector
\mathbf{V}_{m+1}	second active voltage vector

ω_s grid frequency

$\psi_{1,ref}$ converter flux

1 Introduction

In these days the ways of saving the smallest amounts of energy is always an issue. It is calculated that about a half of the electricity of the world is used in motors. Almost all of those motors are driven without a frequency converter. Without a frequency converter a motor can only be driven full speed or not at all. A frequency converter gives the ability of control to motor usage. A frequency converter has an user interface that allows the modification of the driving frequency of the motor. It means that the motor can be driven with almost unlimited variety of frequencies. A frequency converter use can save up to thirty percents of energy. The total energy savings could thus be gigawatt hours per year.

A frequency converter contains four main parts that can be seen in figure 1. The first part from the grid is a line filter, it filters the current of the converter so that it does not interfere the grid too much. The second part is a converter, it converts the alternative current into a direct current form. The converter can be passive or active. A diode rectifier is a passive converter. After implementing the passive converter, nothing can be changed unless the bridge itself is changed. On the other hand an active converter or in other words an AFE is controllable. An IGBT bridge is one example of active converters, it allows active changing of the switching times. That way the power factor can be optimized to one and the DC-voltage can be controlled. An AFE also enables the possibility of returning power toward the grid, a diode rectifier only allows power to pass in one direction. A diode rectifier can be seen on the left side of figure 2 and an IGBT bridge on the right side of the same figure.

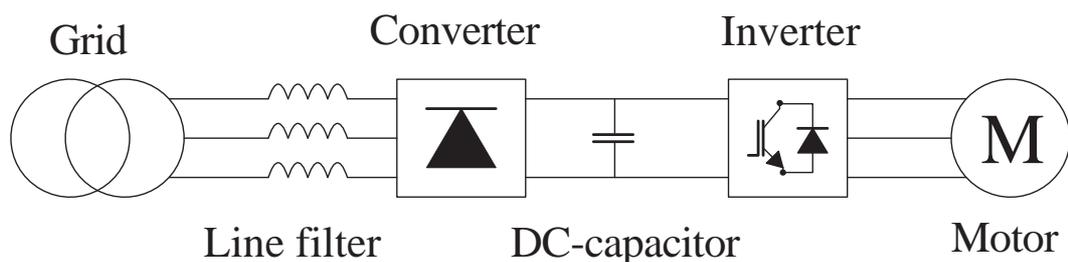


Figure 1: A block diagram of a frequency converter.

The converter can generate 6 active voltage vectors and 2 zero-vectors, which can be seen in figure 3. In that figure the diodes that are conducting are marked with their corresponding numbers next to the voltage vectors.

The third part of the frequency converter is a DC-capacitor, which balances the DC-voltage. Without a DC-capacitor the DC-voltage would fluctuate dramatically in every

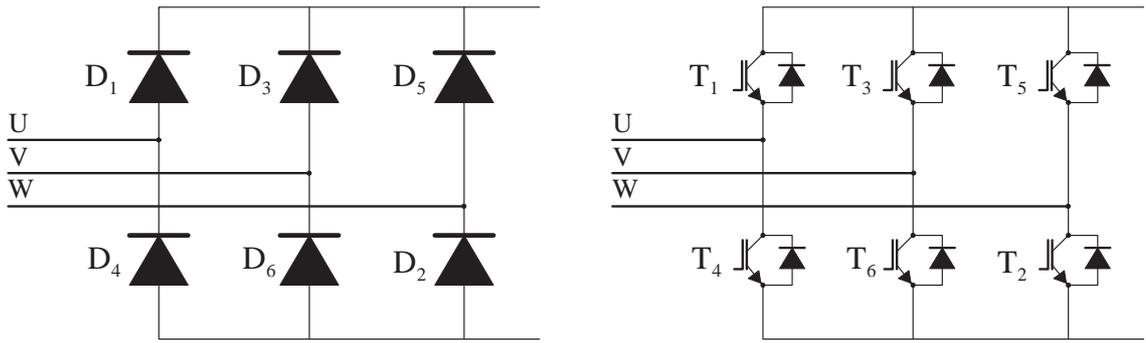


Figure 2: A full bridge diode rectifier on the left side and an IGBT converter on the right side.

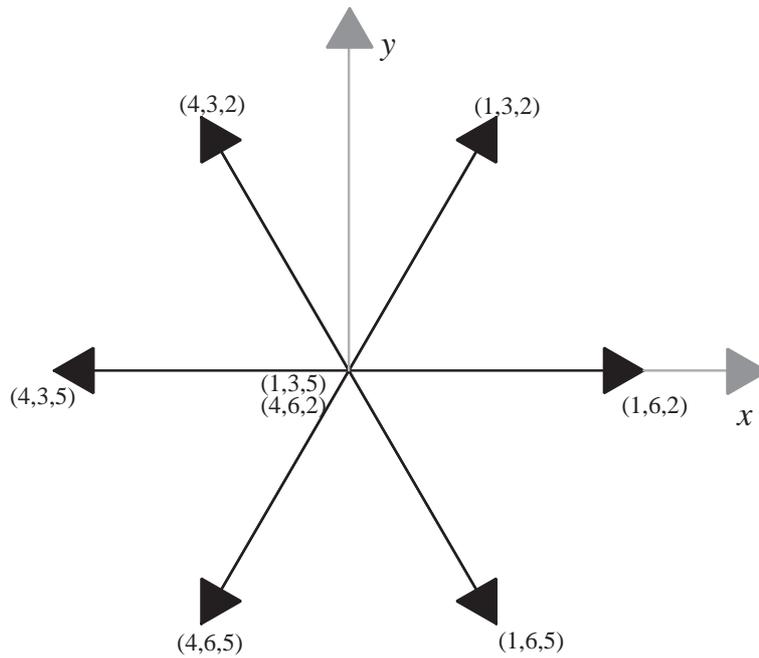


Figure 3: Active voltage vectors of the converter. The numbers describe the active diodes or switches as seen in figure 2.

switching. The last part of the frequency converter is an inverter. The inverter generates the wanted frequency from the DC-voltage, by switching phases to the higher DC-voltage and to the lower DC-voltage. Inverters have different modulation methods depending on the manufacturer and the product. Inverter needs to be active, because the wanted voltage needs to be adjustable. This document does not focus on the inverter part of frequency converters, but they could be easily reflected as a mirror image of the AFE with a slightly different control.

1.1 AFE for 2-level inverter

An AFE for a 2-level inverter is a common part of frequency converters. There are many applications in the current market with an AFE in it. That is why there can be found many articles on the issue. The AFE of this document was mainly developed by the principles from Riku Pöllänen's Dissertation.

1.1.1 AFE control

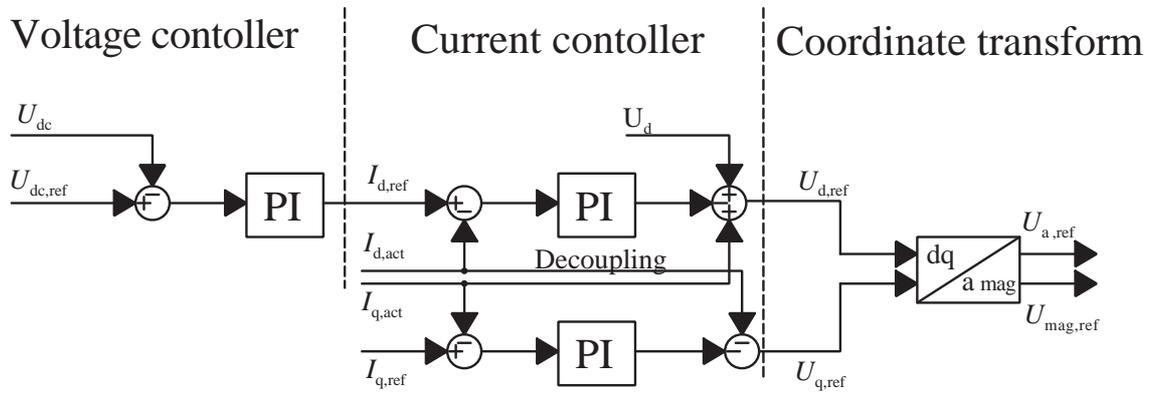


Figure 4: Control block of the AFE.

The control of the AFE consists of 3 main blocks as seen in figure 4. The first one in order is the voltage control. It consists of a DC-voltage comparison and a PI-controller as seen in figure 5. The PI-controller was designed using the symmetric optimum method described in Pöllänen's dissertation. In the symmetric optimum method, a design parameter α is calculated from the desired rise time.

$$t_r = \frac{\ln 9}{\alpha} \quad (1)$$

Time constant of the voltage controller can be calculated with the design parameter α and the desired phase margin φ , which is set to $\frac{\pi}{4}$,

$$T_{i,dc} = \sqrt{\frac{1 + \sin \varphi}{\cos \varphi}} T_\alpha \quad (2)$$

where $T_\alpha = \frac{1}{\alpha}$. The gain $K_{p,dc}$ for the PI-controller can thus be calculated

$$K_{p,dc} = \frac{C_{dc}}{k_{dc} \sqrt{T_{\alpha} T_{i,dc}}} \quad (3)$$

where $T_{i,dc}$ is the voltage controller time constant, T_{α} is the design parameter time constant, C_{dc} is the DC-capacitor,

$$k_{dc} = \frac{3\omega_s \psi_{1,ref}}{2u_{dc,0}}, \quad (4)$$

ω_s is the grid's frequency and $\psi_{1,ref}$ is the converter's flux. The PI-controller design process is commonly an easy process, since the only parameters you can choose are the wanted voltage rise time and the phase margin. The voltage rise time is chosen to be 2ms, which is 10 times faster than the grid's frequency. [1]

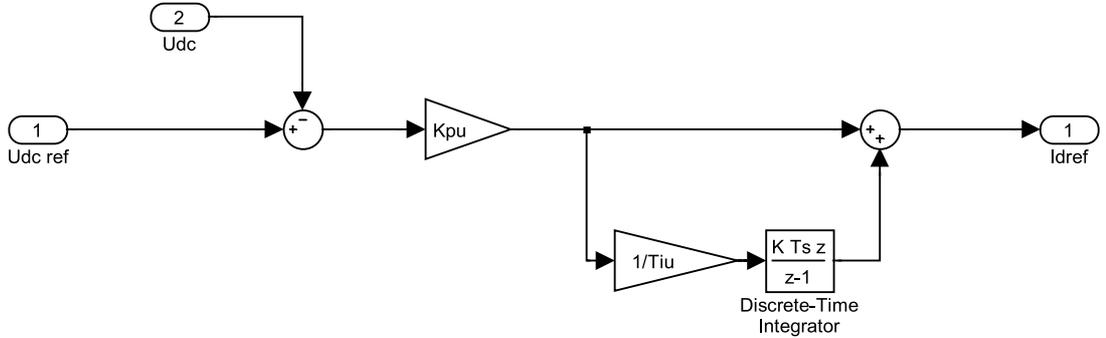


Figure 5: Voltage control Simulink block of the AFE.

The output of the voltage controller is the d-axis current reference $i_{d,ref}$ which goes to the current controller along with the measured currents from the grid side of the converter. The current controller also takes the voltages of the grid to synchronize the AFE control to the grid. That means the d-axis is always pointing in the direction of the grid's voltage vector.

The current controller uses a $i_q = 0$ control method, because that method forces the power factor to be 1. The method basically means that the $i_{q,ref} = 0$ and the $i_{d,ref}$ comes from the voltage controller. The Δi is calculated from the reference current and the active current. And it is fed into PI-controllers for both d- and q-axis as seen in the figure 6. The model also has decoupling for reducing the crossing effects of the d- and q-axis. The decoupling comes from the other axis current. The decoupling for d-axis is $\omega L_1 i_q$ and for the q-axis is $-\omega L_1 i_d$, where L_1 is the inductance of the L-filter and ω is the frequency of the grid. The decoupling can also be seen from figure 6. The output of the current controller also has the grid voltage summed in it. And because the grid voltage does not have a q-axis part,

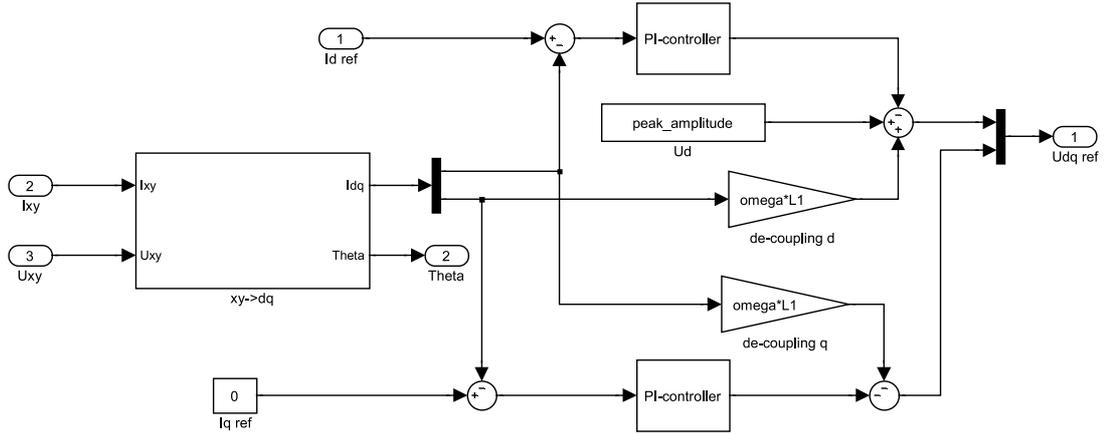


Figure 6: Current control Simulink block of the AFE.

only the amplitude of the grid voltage needs to be summed to the d-axis voltage reference. There we have the reference voltage vector in dq-coordinates.

The modulation of the voltage reference vector needs to be done in stationary coordinates. In the modulator the angle of the vector needs to be calculated for the sector selector block. So the easiest coordinates to do the modulation are in the polar coordinates. The polar coordinates can be easily transformed from the rotational coordinates by first transferring the reference vector to stationary xy-coordinates, and then making the rectangular to polar coordinate transform.

1.1.2 Space vector pulse width modulation

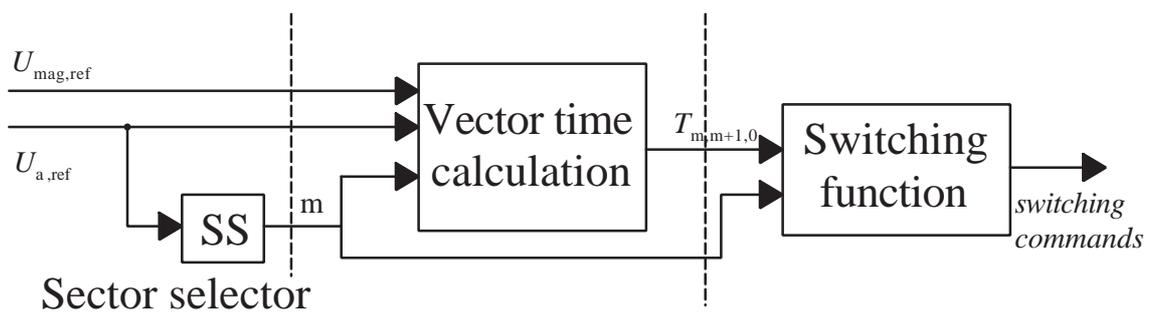


Figure 7: Space vector PWM block of the AFE.

The space vector pulse width modulation block also has 3 main parts in it, they can be seen in figure 7. The first part is the sector selector which indicates the sector we are dealing with. The possible voltage vectors can be divided into six sectors which can be seen in figure 8. The sectors are divided by the voltage vectors that are used in them. 8

voltage vectors can be used in the AFE, two of them are zero-vectors and rest of them are active voltage vectors as seen in figure 8. [2]

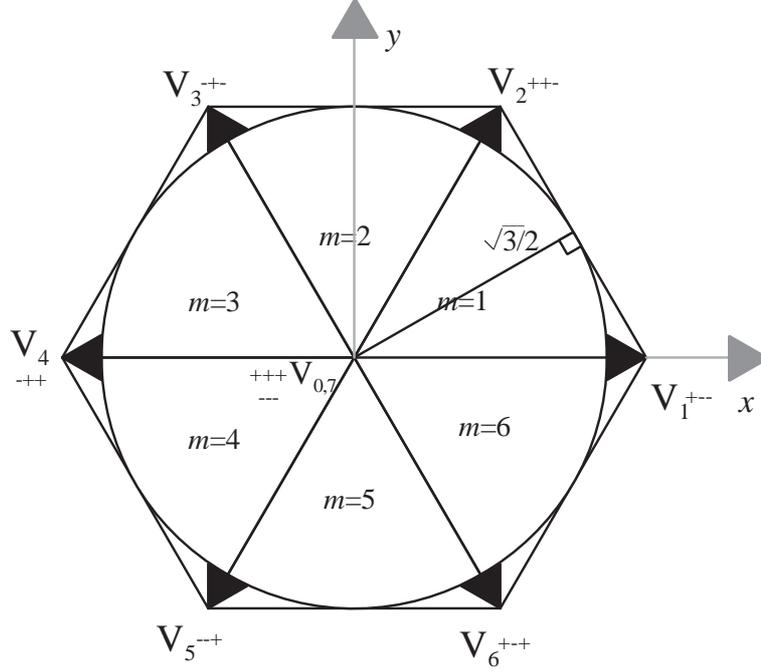


Figure 8: The eight voltage vectors \mathbf{V}_m , six of them are active voltage vectors $m \in \{1, 2, \dots, 6\}$. And two are zero-vectors $m \in \{0, 7\}$. The maximum sinusoidal reference voltage circle is in red and its amplitude is $u_{dc}/\sqrt{3}$. The sectors are marked with m .

The next block is the vector active time calculator. The active vector times can be calculated by using the voltage reference

$$U_{s,\text{ref}} = \frac{t_m}{T_s} \mathbf{V}_m + \frac{t_{m+1}}{T_s} \mathbf{V}_{m+1} \quad (5)$$

where

$$\mathbf{V}_m = \frac{2}{3} u_{dc} e^{j\frac{\pi}{3}(m-1)} \quad (6)$$

and

$$\mathbf{V}_{m+1} = \frac{2}{3} u_{dc} e^{j\frac{\pi}{3}(m)}. \quad (7)$$

The amplitude of the active vectors come straight from the DC-voltage. It can be seen in equations 6 and 7 that the amplitudes of the active voltage vector \mathbf{V}_m and \mathbf{V}_{m+1} are $\frac{2}{3} u_{dc}$. To get to the reference voltage we need to hold the active vectors the right amount of time, the rest of the switching period we need to use zero vectors. This can be seen in figure 9. [2]

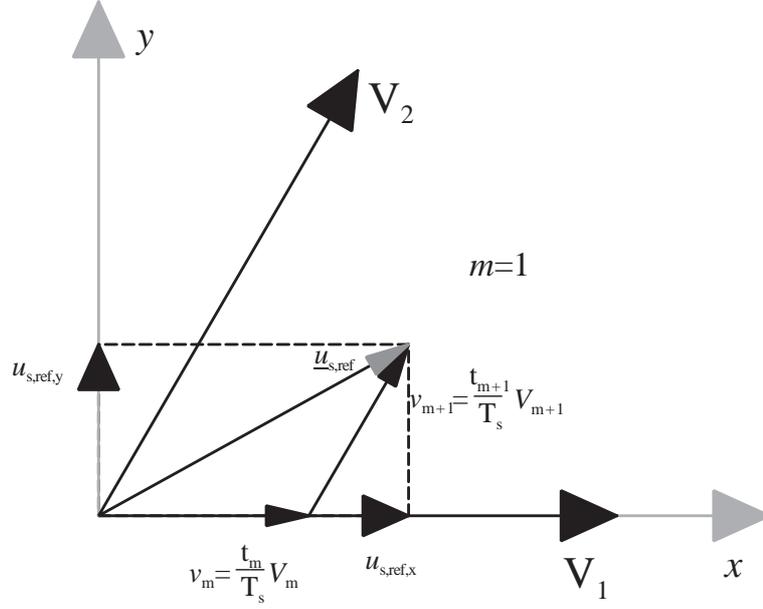


Figure 9: The wanted reference vectors v_m and v_{m+1} .

To get the maximum sinusoidal voltage, the reference voltage needs to make a circle. The maximum circle in the reference voltage level can be calculated with single trigonometry. The maximum sinusoidal circle can be seen in figure 8. [2]

$$|u_{s,ref}| = \frac{\sqrt{3}}{2} |\mathbf{V}_m| = \frac{u_{dc}}{\sqrt{3}} \quad (8)$$

From the equations 5, 6 and 7 can be calculated the voltage vector active times

$$t_m = \frac{|v_m| T_s}{|\mathbf{V}_m|} = \frac{|v_m| T_s}{\frac{2}{3} u_{dc}} \quad (9)$$

and

$$t_{m+1} = \frac{|v_{m+1}| T_s}{|\mathbf{V}_{m+1}|} = \frac{|v_{m+1}| T_s}{\frac{2}{3} u_{dc}}, \quad (10)$$

where v_m and v_{m+1} are the corresponding active vector lengths for achieving the reference voltage. The active vector lengths can be trigonometrically calculated from figure 9, thus

$$v_{m+1} = \frac{\sin \alpha |U|}{\sin 60^\circ} = \frac{2}{3} |U| \sin \alpha \quad (11)$$

$$v_m = \cos \alpha |U| - \frac{\sin \alpha |U|}{\tan 60^\circ} = \frac{2}{3} |U| \cos \left(\alpha + \frac{\pi}{6} \right), \quad (12)$$

where U is the magnitude and α is the angle of the reference voltage. The active times for the voltage vectors can now be derived from the equations 9, 10, 11 and 12.

$$t_m = \frac{\sqrt{3}}{u_{dc}} |U| \cos \left(\alpha + \frac{\pi}{6} \right) \quad (13)$$

$$t_{m+1} = \frac{\sqrt{3}}{u_{dc}} |U| \sin \alpha \quad (14)$$

The last task of the modulator is to change the switching times to switching functions. The switching instants are distributed symmetrically in the switching period. The zero-vector time is distributed into the middle of the period and into the start and the end of the switching period. With this decision it is made sure that the bridge is driving a zero vector when the switching period ends and the next starts, and the zero vectors 0, 7 are also distributed evenly. The zero vector in the middle of the switching period is the vector V_7 and the other zero vectors are the V_0 from the figure 8. The point of symmetrically distributing the switching times is that the switching can be done one switch at a time. For example in first sector the switching times can be seen in figure 10. [2]

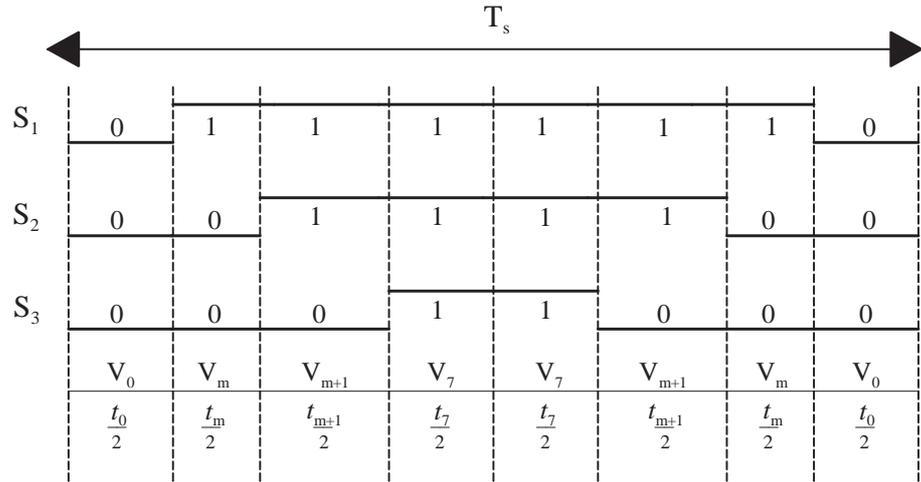


Figure 10: The switching times of a voltage vector in the first sector.

The switching times t_m , t_{m+1} and t_0 of the vectors are transferred to switching times for the phases $t_{U,on}$, $t_{V,on}$, $t_{W,on}$ with the formulas from table 1.

Table 1: The time instant for turning on the corresponding phase as a function of the sector. [2]

Sector, m	$t_{U,on}$	$t_{U,on}$	$t_{U,on}$
1	$t_0/2$	$t_0/2 + t_m/2$	$t_0/2 + t_m/2 + t_{m+1}/2$
2	$t_0/2 + t_m/2$	$t_0/2$	$t_0/2 + t_m/2 + t_{m+1}/2$
3	$t_0/2 + t_m/2 + t_{m+1}/2$	$t_0/2$	$t_0/2 + t_m/2$
4	$t_0/2 + t_m/2 + t_{m+1}/2$	$t_0/2 + t_m/2$	$t_0/2$
5	$t_0/2 + t_m/2$	$t_0/2 + t_m/2 + t_{m+1}/2$	$t_0/2$
6	$t_0/2$	$t_0/2 + t_m/2 + t_{m+1}/2$	$t_0/2 + t_m/2$

After the modulation, the safe time needs to be taken care of. The safe time disables the possibility of an IGBT phase short circuit. It is a short delay on putting IGBT's on. The IGBT switching command disabling happens immediately, but the activation has the safe time delay in it.

1.2 Multilevel inverter

The multilevel inverter was designed using 1-phase H-bridges, which are series connected in a phase. The main principle of the inverter is that it distributes the load equally to all phases. The main problem of the multilevel inverter is that the currents cannot travel from phase to phase. That makes the system much more unsteady than a normal 3-phase inverter, where currents balance each other from phase to phase. More about the modulation methods and other information of the multilevel inverter can be found in reference [3].

2 Simulation

The 2-level inverter model was built on to a Simplorers SimPowerSystem toolbox demo. Some changes needed to be done to the demo, the most important changes were that the voltage was changed from 60Hz 220V to 50Hz 400V. Originally the demo had a diode rectifier, so it had to be changed into an IGBT-bridge and the measurements had to be added to the model. The model did not have any filter in it so a L-filter had to be implemented. The model of the motor was also too small so it had to be changed to a bigger one and the mechanical torque for the motor had to be changed from 11 Nm to 50 Nm to get a greater stator current. For the AFE use the model's breaking chopper had to be disabled, but it was used when the bridge was driven without a control. The model can be seen in figure 11. And a closer look of the SVPWM and the motor can be seen in

figure 12.

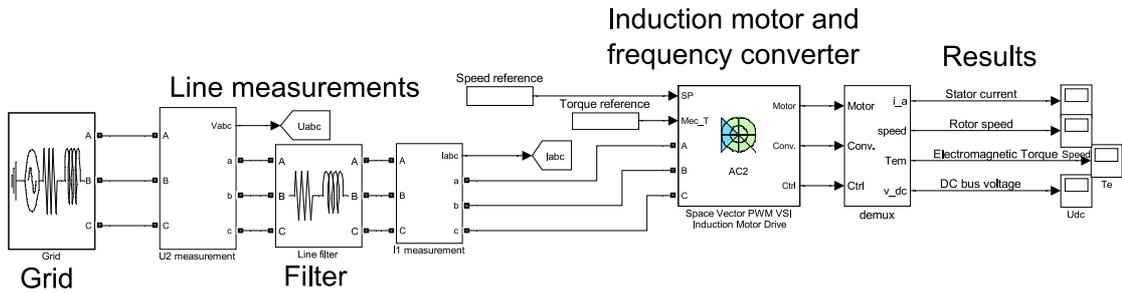


Figure 11: The 2-level inverter Simulink model.

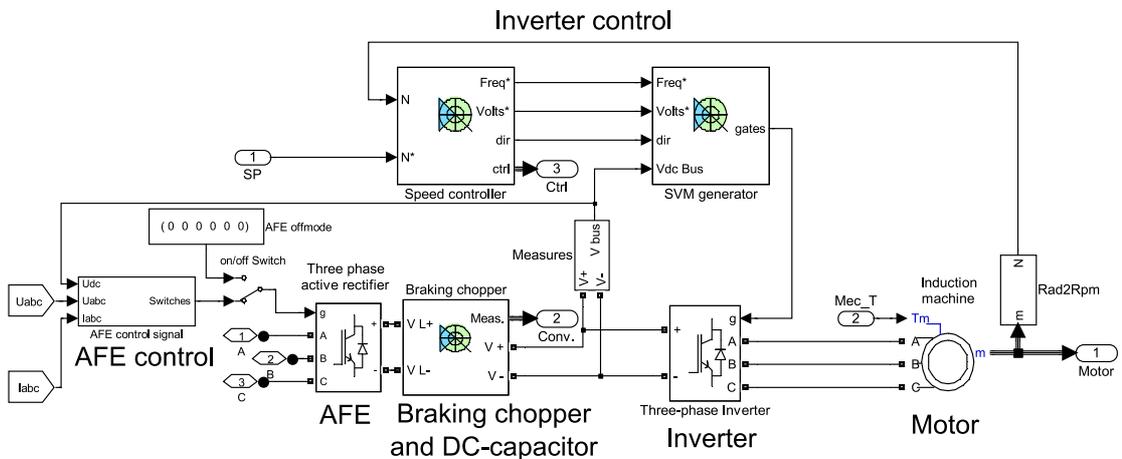


Figure 12: A closer model of the 2-level inverter SVPWM and motor.

The multilevel inverter model was self built. The load of the model was the one phase model of the motor, and its parameters were from the prototype motor of this project. The model of the multilevel inverter can be seen in figure 13.

2.1 Simulation principles

The AFE model was designed according to the Introduction section 1. The model can be seen in figures 14, 4, 5, 6, 7.

The simulations were first run with a diode rectifier on both models. The 2-level model was then driven by the simulation sequence that the model already had. The simulation sequence had three steps that can be seen in figures 15 and 17. First of all from the moment 0 second to 0.5 seconds the motor's speed reference is 1000 rpm and it is rising in a ramp with a slope of 1800 rpm per second until the motor reaches the reference speed. The other input to the motor control is the mechanical torque on the motor shaft.

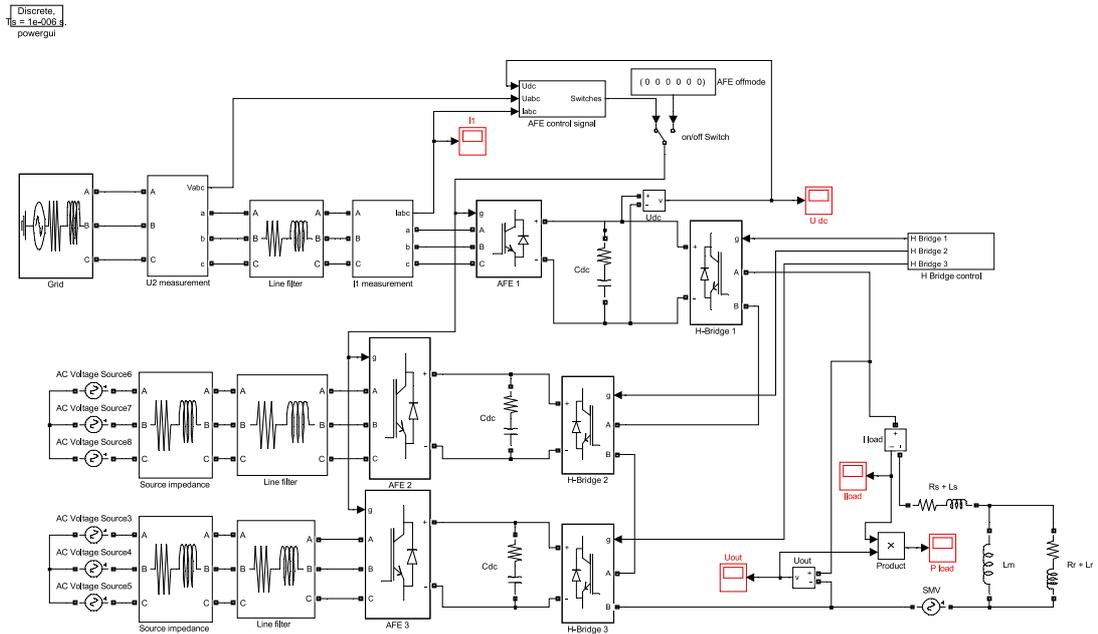


Figure 13: The multilevel inverter Simulink model.

The mechanical torque between 0 and 0.5 seconds is 0 Nm. Next at 0.5 seconds the mechanical torque changes to 50 Nm, but the speed reference stays at 1000 rpm. On the next step at 1 second, the speed reference starts to rise at the same slope to 1500 rpm, while mechanical torque is still 50 Nm. In the last step at 1.5 seconds the mechanical torque changes to -50 Nm and the speed reference stays at 1500 rpm until the end of the simulation. The negative mechanical torque means that the motor works as a generator transferring power to the grid. The reference speed can be seen as the green line in figure 15 (b) found in section 2.2.

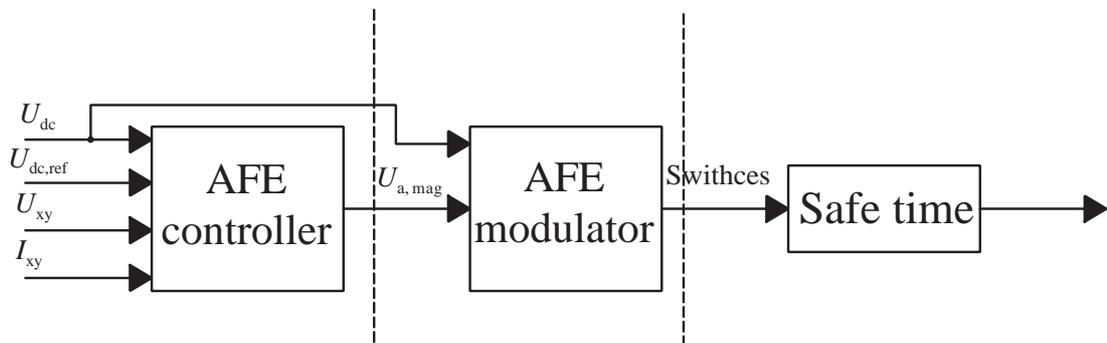


Figure 14: The block model of the AFE.

The multilevel inverter model was driven with 3 different setups. The first setup was a diode rectifier, and the power was at maximum with a direction toward the motor. This setup is later referred to as setup 1. Setup 2 was an AFE with a maximum power toward the motor. And setup 3 was an AFE with a maximum power toward the grid.

2.2 Results

The results for the three phase two-level inverter can be seen in figures 15 and 17. In figure 15 (a) the red color is the stator current measured with a diode rectifier, and the blue color is the stator current measured with the AFE. The current level in both cases is almost identical, the amplitude in a steady state is about 40A. Which is the same as in the multilevel inverter. The multilevel inverter stator current can be seen in figure 16, where red is the current with setup 1, blue is the stator current with setup 2 and green is the stator current with setup 3.

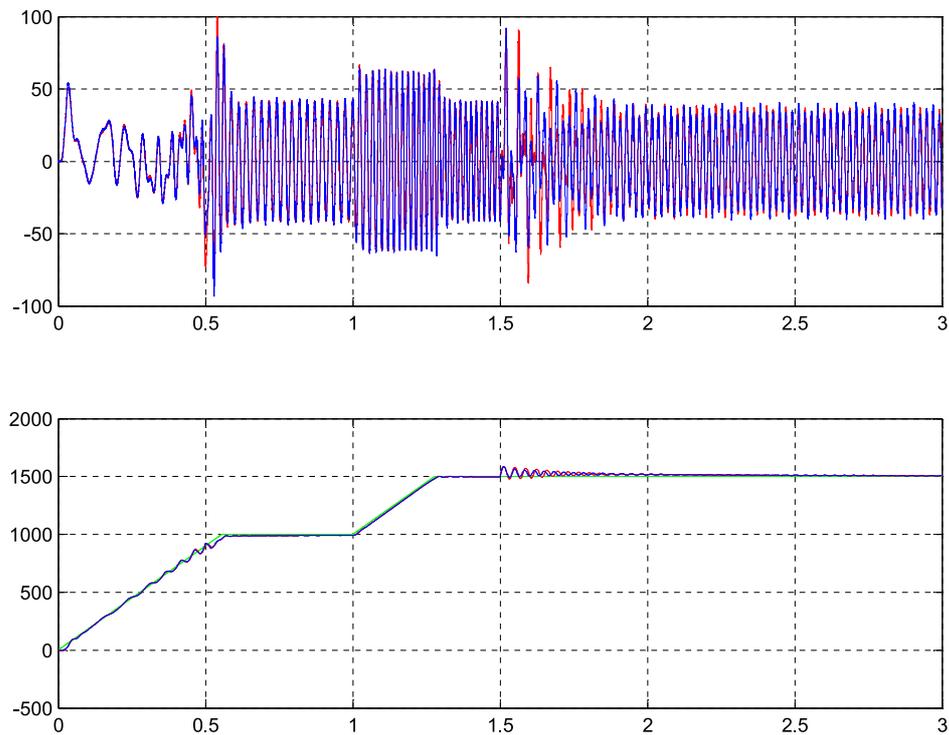


Figure 15: (a) The stator current of the 2-level inverter model where the red line is with a diode rectifier and the blue line is with an AFE. (b) The speed of the motor with a diode rectifier in red, with an AFE in blue and the reference speed in green.

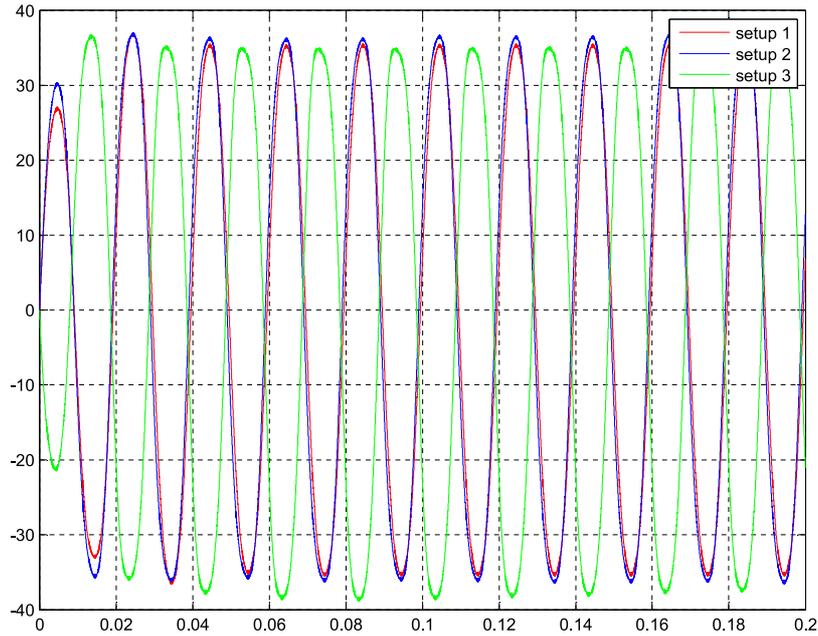


Figure 16: The stator currents of the motor in the multilevel inverter with setup 1 in red, with setup 2 in blue and with setup 3 in green.

The motor active speed can be seen in figure 15 (b) in red when using the diode rectifier and in blue with the AFE and also the motor's speed reference in green. The difference between the motor speed and the reference speed is almost undetectable until the 1.5 second mark, when the motor starts to act as a generator. Then the motor speed fluctuates much longer when using the diode bridge. The electromagnetic torque of the motor can be seen in figure 17 (a), where the torque with a diode rectifier is in red and the torque with an AFE is in blue. The 1.5 second transient is much larger with a diode bridge because the DC-voltage rises to the braking chopper's level. The steady state torque seems to be much more even with a diode rectifier, but that is only because the motor is not correct for the current and the torque and therefore the mechanical torque step causes the electromagnetic torque to fluctuate significantly. When the model was used with the original voltage and original mechanical torque the steady state torque was very stable with almost no variation.

The DC-voltage in the 2-level inverter can be seen in figure 17 (b), where red is the DC-voltage of the diode rectifier model and blue is the AFE model voltage. The AFE model was run without a braking chopper, but with the diode rectifier models the braking chopper's chopping voltage was 700 volts. The DC-voltage of the AFE model in a steady state was only ± 10 volts from the DC reference voltage 565 volts. And that was also

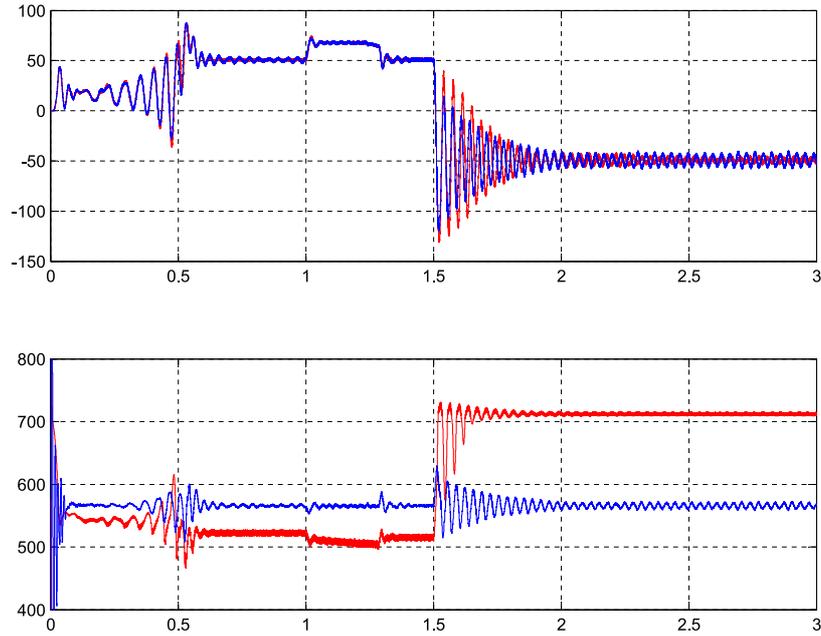


Figure 17: (a) The electromagnetic torque of the motor. The model with a diode rectifier is in red and the model with an AFE is in blue. (b) The DC-voltage of the model with a diode rectifier in red and with an AFE in blue.

because the motor model was not perfect and the motor did not actually have a control. With a better motor model the voltage fluctuation would be even smaller than that. It can be seen from figure 17 (b) that the diode rectifier model's DC-voltage is much lower than the wanted DC reference voltage all the way from the beginning until the motor starts to feed the grid. And that is when the DC-voltage rises to the breaking choppers activation voltage.

The DC-voltage of the multilevel inverter in the different setups can be seen in figure 18. There setup 1 is in red, setup 2 in blue and setup 3 in green. The DC-voltage is actually worse with the AFE than it is with the diode rectifier. That is because the AFE is trying to level the average voltage to the wanted DC-voltage reference. The setup 1 voltage as seen in red has an average of about 10 volts below the wanted 1000 volts. On the other hand the setup 2 DC-voltage has a 50 volts higher peak to peak voltage V_{pp} than setup 1. It can also be seen from figure 18 that setup 3 which is feeding the grid has a couple of dozens volts higher peak to peak voltage than setup 2, where the grid feeds the motor. But all in all the two setups where the AFE is active the DC-voltages do not differ much and the over 150 volts peak to peak amplitude of the DC-voltage is way too much.

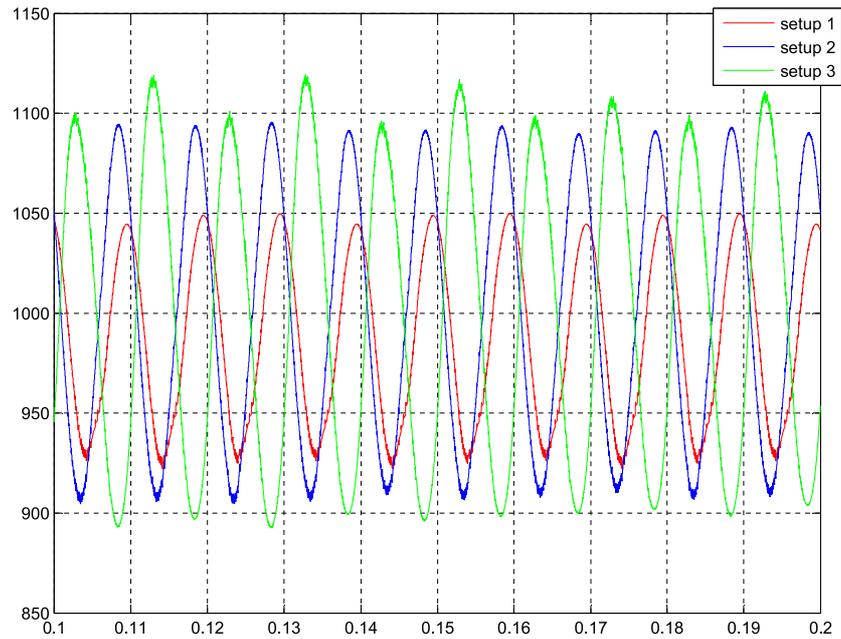


Figure 18: DC-voltages of the multilevel inverter. Setup 1 in red, setup 2 in blue and setup 3 in green.

The output voltage of the multilevel model can be seen in figure 19. The diode rectifier output is in figure (a) and setup 2 in red, and setup 3 in blue in figure (b). The DC-voltage is acting almost like it is supposed to. The output voltage fluctuation is 3 times greater than the fluctuation in the DC-voltage, because the output voltage is three times the DC-voltage at the maximum level. In lower levels the fluctuation is only so many times the fluctuation of the DC-voltage as there are cells on at the time. In figure 19 (a) the top of the output voltage is almost even, but in figure 19 (b) the DC-voltage's sinusoidal part can be seen on the maximum voltages. The phase differences of setup 2 and setup 3 cause the different output voltages. As seen on the maximum voltages setup 2 and setup 3 have a 180 degrees phase difference.

By multiplying the stator current and the output voltage, the load power can be calculated. The load power is in figure 20. Figure 20 (a) has setup 1 in red and setup 2 in blue, figure 20 (b) on the other hand has setup 3 in red. It can be seen from the figures that the load power of the setup 1 and setup 2 are almost identical. Setup 3 had the motor feeding the grid and therefore the power is mainly negative. The output power of setup 3 is almost a mirror image of the other output powers.

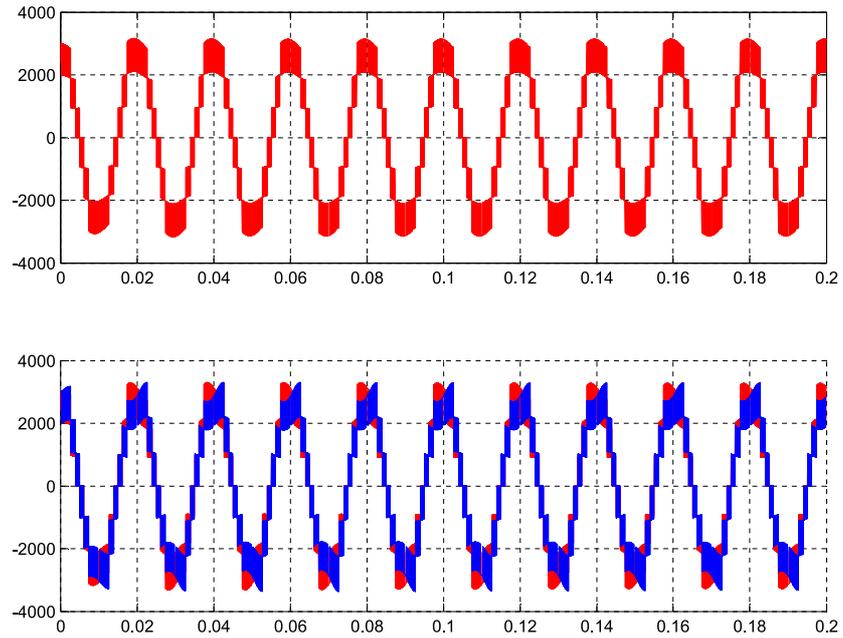


Figure 19: (a) Output voltage of the multilevel inverter model with setup 1. (b) Output voltage with setup 2 in red and with setup 3 in blue.

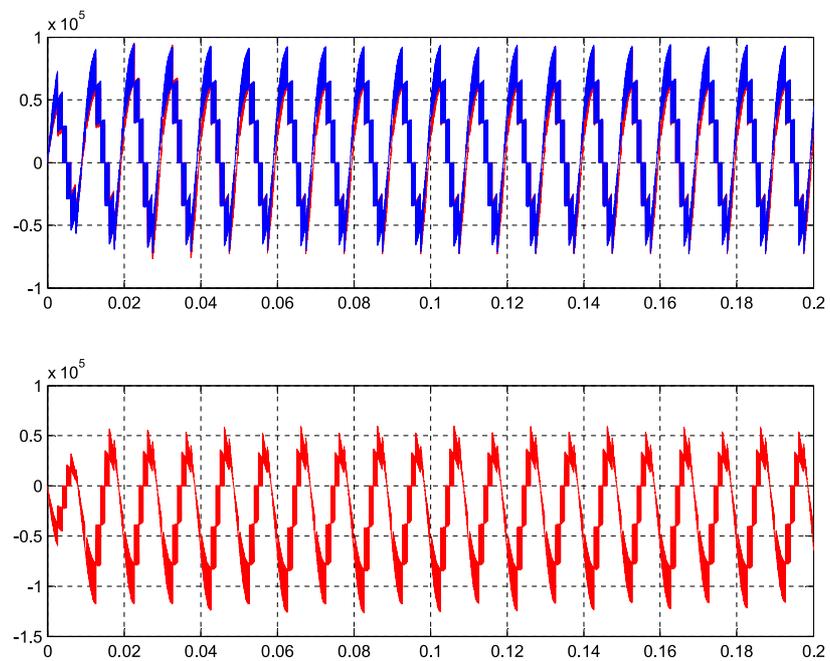


Figure 20: (a) The load power of the multilevel inverter model with setup 1 in red and with setup 2 in blue. (b) The load power with setup 3.

3 Summary

The project focused on a normal 2-level AFE and in its implementation to a multilevel inverter. The active front end's theory is well run through in section 1. The results from the 2-level inverter and the multilevel inverter have been conflicting each other. As seen in figure 17 (b) the DC-voltage of the 2-level inverter model with the AFE was desired. That proved the functionality of the AFE in a simple 3 phase 2-level usage. On the other hand the DC-voltage of the multilevel inverter model as seen in figure 18 is far from desired. The diode rectifier usage actually seems to be better than the AFE model when the motor is mainly feeding the grid. The DC-voltage fluctuation is with a diode bridge about 130 volts from peak to peak and with an AFE about 170 volts from peak to peak. Only when the motor is driven as a generator the AFE has advantages, because it can put the power back to the grid.

The conclusions of this project are that the regular 2-level inverter model AFE will not work in a multilevel inverter without modifications. The fact that the currents cannot pass through phases affect to the DC-voltage remarkably. The AFE for a multilevel inverter needs to have its own kind of control, probably with a signal from the inverter control. Further research is needed.

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