FINAL PROJECT

IMPROVING NEAPOLIS THEORY

LEGRIFFON Eric
JUNE 1999

T.E.I OF KAVALA- GREECE
Electrical Engineering department
Supervisor:
Prof. Dr. George KYRANASTASIS

IUT of BREST
Electrical Engineering Department
Supervisors:
M.Jean Pierre PICHAVANT and M. Florian CASSOL
First of all, I would like to thank all the teachers who gave me the opportunity to realize my final project in the Technological Educational Institute of Kavala, M. Florian Cassol, M. Daniel Beyaert, M. Joel Le Guen, Professor Dr George Kyranastasis and especially M-Jean Pierre Pichavant. I would also like to thank M. Autret who allowed me to go to Greece.

Moreover I would like to show my gratitude to all the Erasmus students, coming from Belgium, Spain, France, Holland, Germany, and Poland, participating in the Socrates European Program, and especially to Roland Le Gall and Aitor Garmendia, who taught me a lot of things in Data Processing.

Then, special thank to Tihon Parasoglou, M. Kyranastasis assistant, for his Friendship and his help in my final project.

Last but not least, I want to thank all my family, my girlfriend and my friends, for supporting me.

Eric Legriffon
Index

1. Geographical location
   1.1. A short introduction to GREECE
       a. Geographical situation
       b. Flag description
       c. Facts at a Glance
       d. My opinion about Greece
   1.2. About Kavala
       a. Description of the town
       b. What is interesting to see
       c. What I think about Kavala

T.E.I of Kavala
I.U.T of Brest
2. Presentation of TEI

2.1. The different departments

2.2. Electrical Engineering Department

2.3. Power Electronics Laboratory

The final project

3. Introduction

4. Introduction to Neapolis

4.1. What is Neapolis

4.2. Different parts of Neapolis

4.3. About the theory

5. Final project's subject

5.1. What I had to do

5.2. How to find the documentation

5.3. The figures

5.4. The links

5.5. The problems

5.6. About Internet

5.7. Technical Conclusion
AC: Alternative Current.
e.g.: For example
Dr. Drachma. It is the Greek currency. 1 franc = 50 Dr.
DC: Direct Current.
i.e.: That is (to say).
Inverter: An inverter is an apparatus for deriving AC power from a DC source.
NEAPOLIS 4.0: it is the name of the last version of an educational simulation package.
Rectifier: A rectifier is an apparatus for deriving DC power from an AC power.
Converter: it is a general term embracing rectifiers and inverters, but is often used specifically to denote an apparatus capable of functioning both as a rectifier and as an inverter.
Ph: Phase.
READIRIS: it is a name of an application capable of recognizing the characters.
Neapart: It is a new word that means a part of Neapolis.
RMS: Root Mean Square.
TEI: Technological Educational Institute.
### BOOKS

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics: Principles and applications</td>
<td><em>Joseph Vithayathil</em></td>
<td>Stephen W Director</td>
</tr>
<tr>
<td>Power Electronics Converters, Applications and design</td>
<td><em>Mohan Undeland Robbins</em></td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td>Power Electronics and AC Drives</td>
<td><em>B.K.Bose</em></td>
<td>Prentice-Hall</td>
</tr>
<tr>
<td>Power Electronics: Circuits, Devices and Applications</td>
<td><em>Muhammad h.Rashid</em></td>
<td>Prentice-hall</td>
</tr>
<tr>
<td>Introduction to POWER Electronics</td>
<td><em>Daniel W.Hart</em></td>
<td>Prentice-hall</td>
</tr>
<tr>
<td>POWER Electronics</td>
<td><em>Kjeld Thorborg</em></td>
<td>Prentice-hall</td>
</tr>
<tr>
<td>An Introduction to POWER Electronics</td>
<td><em>B.M.Bird</em></td>
<td>WILEY</td>
</tr>
<tr>
<td></td>
<td><em>K.G.King</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>D.A.Pedder</em></td>
<td></td>
</tr>
</tbody>
</table>
WEB SITES

For information about Greece and Kavala

http://www.lonelyplanet.com
http://www.viourist.com/Europe/Greece
http://kavala.forthnet.gr/kavala/kavala.htm
http://www.duth.gr/Kavala/kavala.htm

For information about the TEI

http://www.teikav.edu.gr

For a translation service

http://babelfish.altavista.com/cgi-bin/translate
http://www-rocq.inria.fr/qui/Philippe.Deschamps/CMTI_LFA.html

For French power electronics courses.

http://www.ac-grenoble.fr/get_index.htm

An HTML Initiation

http://www.ac-grenoble.fr/get_index.htm
This report is about the final project work, which must be done to pass the "Diplome universitaire de technologie" in "Genie Electrique et Informatique Industrielle".

I had the opportunity to do it at T.E.I (Technological Educational Institute) of Kavala, by participating in the Socrates European Program. I worked in the Electrical Engineering Department, in the Power Electronics & Electrical Drives Laboratory, directed by Professor Dr. George Kyranastasis.

First of all, I am going to make a short presentation of Kavala, GREECE and the Technological Educational Institute, that is, all the different departments in a first time, the department where I used to work, and then the Power Electronics & Electrical Drives Laboratory.

Then I will develop the project itself by starting to make a short introduction to Neapolis 4.0. After I will explain what I had to do, step by step, the materiel I could use, all the problems I had and the way I solved them. Finally I will make a special chapter about Internet and the way I used it for my final project and my report.

I will finish the report by speaking about the life in TEI, the everyday life, the working conditions, the Greek lessons, the relationships with Greek people, and the Erasmus students, i.e. the other students coming from everywhere in Europe so as to make their final project.
1. Geographical location

The Technological Educational Institution is located in Kavala, GREECE. Before an introduction to TEI itself, let's make a short introduction to GREECE and Kavala.

1.1. A short introduction to GREECE

a. Geographical situation

Greece lies at the southern extremity of the Balkan Peninsula in south-eastern Europe. To the north, it has borders with Albania, the Former Yugoslav Republic of Macedonia and Bulgaria, and to the east it borders Turkey (the European part) as you can see in the following map. The peninsula, which constitutes mainland Greece, is surrounded by about 1400 islands, of which 169 are inhabited. The most famous islands are Crete, Cyprus, Rhodes, Corfu, and Thasos not far from Kavala... Greece is divided in: 51 prefectures and 1 autonomous region, Ayion Oros (Mt. Athos).

b. Flag description

Nine equal horizontal stripes of blue alternating with white, there is a blue square in the upper hoist-side corner bearing a white cross; the cross symbolizes Greek Orthodox, the established religion of the country.
Full country name: Hellenic Republic
Area: 131,944 sq km
Population: 10.4 million
Capital city: Athens
People: 98% Greek with minorities of Turks, Slavic-Macedonians and Albanians
Language: demotic Greek
Religion: 97% Greek Orthodox
Government: multiparty democracy
Currency: Drachma (Dr).
1 FF=50 Drs.

d. My opinion about Greece

A for me, Greece is the most beautiful country I have ever seen. The landscapes and the monuments are beautiful and there are a lot of things to visit, because they have a very rich history. We can discover a lot of monuments such as columns, Amphitheaters, museums... The most beautiful things to see, are the islands, Athens and Chalkidiki where you can visit the Athos Mount, which is an autonomous region. But in three months, I didn’t have enough time to visit everything.

The weather is very nice, it has almost never rained during these three months, and there are a lot of sandy beaches, where we can go to sunbathe and swim in a hot water. Moreover there are more than one thousand islands, and the beaches are beautiful, very clean and peaceful, because there are not a lot of people living in the isles.
Unfortunately it is totally different in Greece, because Greek people do not respect their environment, and it is worse than in France, they throw papers everywhere and some beaches are quite dirty. In town, it is the same, the streets are sometimes quite dirty and polluted, because they have very old cars and very old buses. Moreover the motorcycle is often used because it is very fast and they can drive without a helmet.

The food is excellent, and you can have a good meal for a quite cheap price. You can eat a Greek salad with feta, moussaka, and drink the typical wine, retsina.

1.2. About Kavala

a. Description of the town

The city of Kavala is situated at the north of Hellas, in eastern Macedonia. Kavala is the second biggest town of Macedonia, after Thessaloniki. It is a beautiful town, with old and modern districts, mountains and sea. Kavala has also its own airport, a new one, named Alexander the Great, and people can take a plane everyday to Athens, or to go abroad, by charter. The city's port is very important for the economic development. It is Northern Greece's largest and most significant port, after Thessaloniki, servicing the transport of goods and persons. For example, people can go to Thasos by ferryboat or by the 'Dolphin' a very fast and modern boat. The port is also one of the largest and most important fish piers in Greece. Kavala has also a lot of industries such as: tobacco processing, a fertilizer production plant, which is one of the largest in Europe, textiles and clothing industries (today, the area's ready-to-wear sector is the most important in Greece)...
Moreover, they discovered oil in the bay area, unique in Greece, and it puts Kavala in the limelight once again. Its subsequent exploitation provided a significant boost to industrial development.

b. What is interesting to see.

Like the other towns, there are a lot of things to see, because the town has a very rich history, and everything is free for the students. As a matter of fact, we can see:

- the Byzantine walls and 16th century Castle.
- the Cathedral, built on the site of the earlier church.
- the Kamares Aqueduct, erected by Suleiman the Magnificent to guarantee the city's water supply.
- One of the cobbled streets of the district leads to the birthplace of Mehmet Ali (18th century), founder of the Egyptian royal line. The house is an appealing example of Turkish architecture, complete with harem.
- At a square near the house there is a bronze statue of Mehmet Ali.
- Imaret is another building of Mehmet Ali. It's an important architectural cluster of buildings with domes of 1817.
- Kavala's Archaeological Museum - one of the finest in Greece - contains impressive finds from Neapolis, Philippi, Amphipolis and Abdera.
- The city's other museums are also of interest: the Folk Art Museum and the Gallery of Fine Arts.

c. What I think about Kavala

Kavala is a quite nice city but it is a very big town, more or less similar to Brest in fact, with a lot of industries, an airport, a port, a university, a lot of beaches, and the same number of inhabitants.

What I don't really like in Kavala, is the pollution, because people have very old cars, and they are badly kept.

T.E.I of Kavala

I.U.T of Brest
As I said before, Greek people don’t respect their environment, and Kavala beaches are not the cleanest seas that I have ever seen. People drink, eat, smoke on the sand and throw everything.

As far as the TEI is concerned, it is worse, everything is broken, and there are a lot of papers and broken glasses on the floor.

In Kavala, life is expensive, and for everything you can buy in a supermarket, it is the same price as in France, because Kavala is a tourist town, and therefore the prices are very high. But the problem in Kavala is that almost all the shops are closed in the afternoon, except the supermarkets. It is not really easy to speak with the shopkeepers because they don’t speak English. But most of them know the German language, because they said us that lots of them worked in Germany several years ago.

On the other hand, you can make a lot of things in Kavala. First of all you can visit a lot of museums for free, and discover the Greek architecture. At the weekend you can go to a big market in the city where you can find lots of things such as, vegetables and fruits (very cheap and very good), tools, and clothes, that, the more often are false but very cheap. For example we can find a Lacoste tee shirt for 2000 Drachmas (40 FRS). It is very easy, to go to the town, because every 15 minutes, a bus is leaving the TEI bound for the city. Therefore you can take the bus and 10 minutes later you are in the City. Moreover a ticket costs only 130 Drachmas (2.60 FRS) for students. We can also move by taxi, and an eight kilometers distance costs only 600 Drachmas, so it is worth using it, because if you are four in a taxi it is the same price as the bus. It is very easy to find one because there are a great deal of red taxis everywhere in Kavala.

You can also take advantage of the sea and go to the beach for swimming in a very good water, diving, fishing, practicing canoe kayak, pedal boat... And if you want to be very peaceful, you can go to Thasos Island by ferryboat, and choose your beach, among the large beautiful beaches where you can be sure not to be disturbed.

As a conclusion, there are lots of things to do and for a very low price especially for students, we can discover a very fascinating culture, but it is a pity that Greek people and especially the young people do not respect their beautiful country.
2. Presentation of TEI

2.1. The different departments

The Institute was established in 1976 as a Center of Higher Education and Professional Education, and was granted the status of independent, self-governing Technological Educational Institute in 1983. As an institute of higher education it actively participates in a wide range of European Programs, and has made valuable contributions to applied research programs in Greece.

Technical Educational Engineering is a quite important campus of 136000m² in which we can find the students accommodations, the restaurant, a cafeteria, a football and athleticism field, a basketball ground, a tennis court, an amphitheater, a library under construction and of course the teaching buildings. It is about 8 kilometers far from the city. During the academic year 98/99, 6,652 students were registered. TEI Kavala is divided into three sections: two Faculties in Kavala and an annexed department in Drama.

At TEI, there are a lot of departments, and the students can either work in:

1. Department of Accounting
2. Department of Business Administration
3. Department of Foreign Languages
4. Department of Mechanical Engineering
5. Department of Petroleum Technology
6. Department of Industrial Informatics
7. Department of Science
8. Department of Electrical Engineering
2.2. Electrical Engineering Department

The students working in this department can study many subjects, which are more or less similar to the subject at IUT. As a matter of fact, the students study:

- Electrical Circuits and Measurements
- Electronics, Digital Electronics and Microcomputers
- Control Systems, Measurements Technology
- Electrical Machines
- Power Electronics and Motor Drives
- Electrical Installations
- Power Systems
- Electrical Applications

The studies in the Electrical Engineering department last 3 years, each one divided in two semesters. The students work about 35 hours a week and as far the English is concerned, they only learn it during 4 semesters, three hours a week.

The 6 semesters' studies are followed by a 6 months period of paid work-placement in industries, organizations and various enterprises, but they also have the opportunity, to do it in a foreign university, as we did. A lot of foreign teachers came to TEI to make a presentation of their university and to encourage Greek students to come in their country, to realize their final project, and the more often they make exchanges. Some of their students go to TEI and they received students from Kavala. We had to go to these lectures and that way I discovered the Basque country and Romania, because they came in TEI to incite students to come in their "beautiful country" as they said.
2.3. Power Electronics Laboratory

As far as I am concerned, I worked in a small laboratory, called "Power Electronics & Electrical Drives Laboratory", directed by Professor Dr. George Kyranastasis.

In this laboratory we can find four different rooms. The first room, the biggest one is a classroom (lecture room) in which M. Kyranastasis, and other teachers, can give Power Electronics and Electrical Drives courses, to Greek students. Unfortunately it was in Greek, so we couldn't go. There are also a lot of DC motors, AC motors, many drives, and some oscilloscopes, for the students to be able to make some experiments, like we can do in IUT. But the difference is that they don't make the manipulations themselves, because they look their teachers doing them while they are taking notes. At the end of one semester they have to make the manipulation themselves to pass the exam.

The second room (PCI) is composed of thirteen computers (three of them have an Internet connection) and one scanner, for Greek people to use them, either to work with word 97 to type their project, for example, to use Internet to find documentation, or to make simulation about Electronic devices with a special software.
But most of the time the students came to play informatic games or to use Internet that is to send E-mails or to send messages to a mobile. Because in TEI, every student has his own mobile, and it is not rare to see a student getting out of the classroom because someone is calling him. And the teachers don't seem to be disturbed and they are used to seeing such things.

The third one (PC II) is a small room, for students participating in the Socrates Program only, with five computers with Internet, a PC and a printer. It is for Erasmus students to work their final project, to use Internet to look for information, to write their final project but also to communicate with their family either by E-mail or by sending messages to the mobiles via Internet. In this small PC room, eight students making their final project or their practice (for the German) worked, so as to improve Neapolis (multimedia, new features, adding new devices...).

- 3 Basque students (Final Project) - San Sebastian
- 1 German student (Practice) - Wilhelmshaven
- 2 Belgian students (Final Project) - Ghent
- 2 French students (Final Project) - Brest

And the last room is the office of M. Kyranastasis and Tihon (a student studying in the Electrical Engineering Department). In this office, we can also find a library with many books of Electrotechnology and Power Electronics but also some computer software manuals, in English and in Greek.

As far as I was concerned I worked in the two computer rooms because I didn't have my own computer and I had to use the scanner everyday, because I needed a lot of pictures. Therefore I used to work in both.
3. Introduction

A lot of foreign students, coming from everywhere in Europe, come to the Technological Educational Institute, in order to make their final project or their practice. This project is about Neapolis 4.0, and most of them have to work for its development (multimedia, new features, adding new devices...). Therefore I am going to make a short introduction to Neapolis 4.0.

As far as I am concerned, I had to improve the theory part, with another French student, in order to help the user to learn about the device, he wants to simulate, and thus understand its behavior. Before starting with my project itself, I will make a presentation of this theory part in Neapolis.

Then I will speak about the final project's subject that is what I had to do exactly in the theory part. After I will explain how I proceeded step by step, the material I could use to realize my project, the problems I had with the computers and with Word, and the way I solved them, when it was possible. I will also make a special part about Internet, that is the way I discovered it and how I used it for my project.

I will conclude by saying what I have done, i.e. the theory of several converters and motor drives.
4. Introduction to Neapolis

4.1. What is Neapolis

The name “Neapolis” comes from the very old name of Kavala (over 2500 years), and means ‘new city’ (Nea=New, Polis=city).

It is a educational simulation package, which has been developed by Prof. Dr George Kyranastasis, responsible for the Power Electronics Laboratory of the Electrical Engineering Department in the TEI Kavala, in 1989, with the support of the Greek ministry of national education. It is continuously improved with the work of the students participating in the European Socrates program. The last version is used and tested in various universities and institutions, which collaborate with the TEI Kavala through Socrates and Leonardo programs.

Neapolis is used to simulate three kinds of devices: the converters, the motors and the motor drives.

With this program, not only can the students see the behavior of different models without any danger for the device and the user, but it can help him to understand how the real system work and especially what kind of results are expected in the laboratory. It is easier for the students to understand the curves on the computer screen than the measurement instruments in a laboratory. The users can simulate the behavior of the device, study it step by step, analyze the graphs and even change the parameters.

In general, let's say, that Neapolis is a very good teaching tool, which can allow the students to work alone, and which, moreover, can reduce the education cost and time.

4.2. Different parts of Neapolis

The program has three main parts: Neapart 1, Neapart 2 and Neapart 3. Neapart 1 is the main part of the program.
In Neapart 1, the user has the possibility to select the language. Then he can choose the model he wants to simulate among the converters, the motors and the motor drives. Let's say the 3-Ph rectifiers for example. The name of the model appears in the middle of the menu.

At last he can go to Define System, so that he could define all the parameters of the selected model: the supply, the converter, the motor, the drive, the load, the program (i.e. the simulation period), and the graphic; the user can select the number of areas, between 1 and 12, that are the number of graphics he can see in the same time, on the screen. Then he can choose the kinds of variables he wants to see, give it a symbol name choose a minimum and a maximum value, as shown in the following figure. As a simple example, we can choose the input and output voltage. But the user can also use the default values.
Neapolis 4.0 - Define project

Simulation periods

Time/Period steps

- 64
- 128
- 256
- 512
- 1024

Continue
Default values
Cancel

Neapolis 4.0 - Graphic selection

Variable list

- Input voltage
- Valve voltage
- Output voltage
- Input current
- Valve current
- Output current

Number of areas

[2] Areas

Clear Areas
Default values
Exit

Variables Selected

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Name</th>
<th>Min</th>
<th>Max</th>
<th>Area</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Input voltage</td>
<td>210</td>
<td>210</td>
<td>1</td>
<td>V_{in}</td>
</tr>
<tr>
<td>2</td>
<td>Output voltage</td>
<td>200</td>
<td>200</td>
<td>2</td>
<td>V_{out}</td>
</tr>
</tbody>
</table>

1. Select number of areas
2. Drag a variable on an area of the Simulation screen
3. Set minimum and maximum
4. Press Continue

T.E.I of Kavala
I.U.T of Brest
In Neapart 2, the **Simulate System** part, the user can see the waveforms (at a low or fast speed, by choosing in Simulation Speed) of all the variables, he selected in the first part. Each area has a curve with a variable in the vertical axis (defined in Define System) shown in function of the time.

In here you are also able to modify some parameters. And this is very important because you can watch the curves and decide which variables are interesting to change. Thus you don’t have to go back to Define System.

There is also one function very important in this part that makes possible to see the changes of one variable when another parameter is being modified. This option can be found on “Experiment” menu, and the function is called “Autoloading”. By clicking on this option the user makes the computer start an automatic and computer controlled changing of one predefined control parameter in constant steps.

At last he can print the waveforms, by clicking the Print button, at the top of the screen. The user has also the opportunity to read the help to know how to use the simulate system.
In Neapart 3, the Results processing part, we can analyze the waveform of the simulated device. As a matter of fact, we can plot rms value, replot the simulation value, and calculate harmonics.

- **Plot RMS Values** This procedure uses the data that have been produced from the “Autoloading” during the simulation process. The screen shows a list box with all the variables that their values have been calculated by the “Autoloading System”. Clicking on one of them you get the curve.

- **Replot Simulation Results** It gives the chance to plot again the results of simulation carried out at the second part under several combinations, but always as functions of time.

- **Harmonic Calculation** This is the procedure that can analyze all the simulation results and calculate the contained harmonics.

I haven’t used this part almost never in my project, I had only to implement the theory in Neapolis. If you want further details, you can download the DOS version in the TEI site:

4.3. About the theory

The Neapolis theory allows the students to use it before starting the simulation or to use it in an interactive mode, while he is using the Neapolis program, during the simulation. It is easier for him to understand the waveforms of the model that is simulated.

It is very simple to use it. First of all the user has to select the device in Neapart 1, by clicking the model at the top of the screen, and then he can reach the theory by clicking Theory. In the last version of Neapolis (Neapolis 4.0) there are four models of motors, nine converters, and nine motor drives, which are:

<table>
<thead>
<tr>
<th>Models</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-Ph Induction Motors</td>
<td>1-Ph Rectifiers</td>
</tr>
<tr>
<td>1-Ph Induction Motors</td>
<td>3-Ph Rectifiers</td>
</tr>
<tr>
<td>3-Ph Synchronous Motor</td>
<td>3-Ph Inverter</td>
</tr>
<tr>
<td>Direct Current Motors</td>
<td>3-Ph Frequency Converters</td>
</tr>
<tr>
<td></td>
<td>3-Ph Inverter</td>
</tr>
<tr>
<td></td>
<td>3-Ph Frequency Converters</td>
</tr>
<tr>
<td></td>
<td>3-Ph AC Controllers</td>
</tr>
<tr>
<td></td>
<td>3-Ph Cycloconverters</td>
</tr>
<tr>
<td></td>
<td>Chopper</td>
</tr>
<tr>
<td></td>
<td>Direct Current Link</td>
</tr>
<tr>
<td></td>
<td>1-Ph Rectifier DC Motor Drives</td>
</tr>
<tr>
<td></td>
<td>3-Ph Rectifier DC Motor Drives</td>
</tr>
<tr>
<td></td>
<td>Chopper DC Motor Drives</td>
</tr>
<tr>
<td></td>
<td>3-Ph Inverter Induction Motor Drives</td>
</tr>
<tr>
<td></td>
<td>3-Ph Frequency Converter Induction Motor Drives</td>
</tr>
<tr>
<td></td>
<td>3-Ph AC Controller Induction Motor Drives</td>
</tr>
<tr>
<td></td>
<td>3-Ph Cycloconverter Induction Motor Drives</td>
</tr>
<tr>
<td></td>
<td>Static Resistance Controlled Induction Motor Drive</td>
</tr>
<tr>
<td></td>
<td>Sub-Synchronous Cascade Controlled Induction Motor Drive</td>
</tr>
</tbody>
</table>

All the models have the same structure, with their name at the top of the page. Moreover, each model has its own page divided in those headlines:

- Description
- Construction
- Operation
- Control
- Applications
- Literature
- Parameters
- Modeling

---

T.E.I of Kavala
I.U.T of Brest
Once in Neapolis theory, the user can read all the theory about the simulated devices, but he can also access directly to one specific headline, by clicking in the menu, on the left side of the screen, on the links. For example, if he only wants to see the applications of the three-phase inverter, he just has to click Applications and thus he can see all of them. The user has also the possibility to see the theory of another device, without coming back to the main menu. To do it, he can click in the top right corner of the page to select a new model, as explained in the following figure. Some other options are also available that are the possibility to maximize the window, with full screen and thus read easily without the headlines. The user can also use the forward and back arrows, to go respectively in the navigation, like the buttons of the normal Internet browsers. Of course he can exit if he wants to return to the Simulation part.

Here the user can select
the headlines of the theory
he wants to read.

By clicking here, the user can select an other device.
5. Final project’s subject

5.1. What I had to do.

First of all, I had to find all the documentation, in order to fill the different parts of the document; that are described below, the description part, the construction part...

*In the description part,* I had to write the general description of the device, what it is made for.

*In the construction part,* I had to insert the picture of the device symbol, and also the main circuits, in which the device is used. For example, if the user goes to the description part of the three-phase rectifiers, he can see the different applications circuits of this converter that are, the three-phase single way rectifier and the three-phase bridge rectifier.

*In the operation part,* the devices are described more precisely, and we can understand the behavior of the device, thanks to the explications, the waveforms. For example, always with the three-phase rectifiers, we can see the output voltage waveforms with a three-phase supply, and the mathematical demonstration.

*In the control part,* we can see the way the devices are controlled, when it is possible. For example, the rectifiers use either uncontrolled switches like the diodes, or controlled switches like the thyristors. Therefore this fourth part explains why, we sometimes need to control the devices, and the way to do it.

*In the applications text,* we can see in which case the device is used, either in Industrial applications or in everyday life.

*In the literature part,* I only have to write the references of the books I used, to make the theory of the motors, the converters, and the motor drives, with the name of the book, the Author, the Editor.

*In the parameters part* we can see all the parameters, which can be changed before or during the simulation.

*In the modeling part,* I had to speak about the way to solve the differential equations.
5.2. How to find the documentation.

To find all the documentation, I could use a lot of books from the library. As all of them were in English, I also used Internet to find Electrotechnology and power electronics courses in French, because it was sometimes difficult to understand the entire technical vocabulary in English. Moreover I looked for a dictionary on Internet so that I could translate English into French, when it was possible because I didn't succeed in finding a technical dictionary, without paying.

Once I had found all the information to write the theory, I had to open an HTML file, in Word 97, in order to write the text and to insert the pictures. The HTML document was already created and saved to hard disk, in Nea 4. Before writing the theory, I started to customize the toolbars so as to earn time to reach the different tools of Word. For example I had a lot of pictures to insert so I put this command on the toolbars. I also inserted a bar for the equations, by going in Insert Field, and choosing 'equations and formulas'.

I wrote a lot of theory, and sometimes, I had to copy a whole page. Not to waste too much time I used an OCR application called Readiris that is capable to recognize the characters of a book. As a matter of fact, I just had to put the book in the scanner, to launch Readiris and select the appropriate language that is English. Once scanned, the software asks us to help him to correct some errors, so that it could improve itself. It was sometimes very fast to copy an entire page and I earned a lot of time with Readiris. But sometimes it was the opposite, because I worked with a lot of different books, and it was sometimes very long to make the right settings for each book. Moreover the software often missed some words on the right of the page, but it also often mixed the letters. For example the "i" and the "1" are quite similar and it couldn't see the difference between the two letters, so I had to correct all the letters. That is the reason why it was sometimes as long to make the good settings and to correct the words as to copy the whole page. That is nothing, because I learned a new tool, which, I think, will be very useful once improved.
5.3. The figures.

At the beginning, I drew the different circuits of the converters and the motors, with a software called "WinDraft Schematic Editor", which is very easy to use, because a lot of devices are already drawn and I had just to connect them together. To draw the circuits I could also use "Paint Shop Pro". But some circuits were very complex and it was very long to draw all of them.

Therefore, I decided to use the scanner to copy all the pictures from the books. As it was the first time I had to scan something, I had to learn the way to use it and to make the good settings, that are the type, the path, the brightness, the contrast, the scaling,..., in order to have a good quality picture. For the pictures I had to choose "Sharp B and White Photo" type and a very big scale so as to obtain the best picture otherwise it was impossible to recognize the characters written on the figure. After I could use "Paint Shop Pro" to erase some text or to modify something on the picture, like the number of a picture for example, or something else.

Like Readiris, it was very long to find the good settings, especially to find the right middle between the contrast and the brightness, because every book has a different style of paper, of drawings and of letters.

At last, I could insert the picture in my document by clicking Insert Picture From file..., or by choosing directly the command in the toolbars. After I could change the size and the position of the picture, by clicking it with the mouse right button and move it wherever I wanted. And I could also insert the picture in a text, at the right of the text or in the middle of the text, with Format picture option.
5.4. the links

As far the one-phase inverter file is concerned, for example, there are more than 16 pages of theory. Therefore it is difficult for the user, and very long to find exactly what he really needs. That is the reason why I had to create some hyperlinks for the theory to become more interactive. Some hyperlinks already existed, like those for choosing the headlines and for coming back to the headline. But now the user can also use hyperlinks in the text. As an example, if the student needs information about the sinusoidal pulse width modulation, in the control part he can see all the links, underlined and written in blue, to go directly to this course. It is really easy to use it, by clicking the link.

To create an hyperlink I had first to create a bookmark, by clicking Insert Bookmark at the very right place, in the text, I wanted to go. I had to give it a name without numbers and without spaces in this name. Then I had to write the name of the link, to click Insert hyperlink (or Ctrl+K) and to browse the bookmark name. That way it is very easy and very fast to find the specific part, we need to read.

I made the same, for the user to be able to see the cover of the books where I found the documentation so as to write the theory. As a matter of fact, in the literature part, all the books name are written, as well, as the Editor and the writer. By clicking the chosen name book, he can see the cover and thus find and read it so as to have further information. It is the same way to create such links. After scanning the cover, I put the picture in Word and save it with a specific name. After I created the hyperlink on the book tittle, and browsed in "Link to file or URL", the saved file. It is really useful for the user to be able to see the cover, because the books are more complete and it is sometimes very difficult to read a lot of pages on the computer screen.
5.5. The problems

I had a few problems that I didn’t succeed in solving, especially with Word 97 and I often lost my work because of them.

For example when I wanted to save my work some windows appeared like these two ones:

![MS Word Error Window](image1)

This kind of windows appeared when after created hyperlinks I wanted to save on the hard disk. But I had only this problem with some computers.

![Netscape Error Window](image2)

This message could appear at any time, without any reasons. When it appeared, I had to choose Close and the computer started again from the beginning, and of course all my work was lost.

I especially had this problem with one computer, but as I didn't have my own computer, I had different problems with each one, and I couldn't solve them. Because I had to change of computer very often, because all the students needed their computer to work. This is the main problem I had and nobody could tell me the way to avoid this problem.

T.E.I of Kavala

I.U.T of Brest
I also had this problem, and this window always appeared, when I wanted to save a document in English with special characters like $\alpha$, $\beta$ or $\pi$ but also with Greek letters. Because when I used Readiris, the software often confused the English characters and the Greek ones because some of them are very similar and I couldn't see the difference. So it took me a long time to discover where the problem came from. And when I asked the Word help what UTF-8 meant there were no answers.

To be able to change my work, I had to change the properties, in File Properties and to choose Multilingual (UTF-8)/Korean (KSC 5700), because the document was saved with the US/WESTERN European as a default language. Without this option I couldn't save my entire work, only the English characters. I thought the problem was solved, but when I opened my html file in a web browser, all the special characters disappeared or were replaced by "?". As a matter of fact, the English "o" and the Greek "ο" (omicron) are similar, and readiris often confused, and I couldn't see the difference. So I had to return to the US language and correct all the letters, after doing a web page preview, in File.

5.6. about Internet

Before coming in Kavala, I never had the opportunity to use Internet because I haven't got my own computer and we didn't use it at all in the IUT Brest. And that is one of the reason why I wanted to go to Kavala, because I knew that the project was about data processing and my knowledge in informatic was very bad. Therefore I had to discover Internet by my self and once I knew the way to use it, it was quite easy to find the documentation I needed. Internet was very useful, not only for my general knowledge, for communicating, but also for my project.
As a matter of fact Internet is a very good tool to communicate with people all over the world. With Internet I could not only send Email to my family, my friends, my teacher and receive some messages from them, but I could also chat with them as if I was calling them, because it is very fast especially at night.

And that is the reason why I spent a lot of nights at weekends to chat, with my friends but also with a lot of persons that I didn't know, about a lot of subjects.

Moreover it was very expensive to phone from Greece to Kavala, but it was free to use Internet as long as we wanted. There is also another way of communication with Internet, which consists in sending a message to a mobile with a special service, called "mtnsms." You can send a message everywhere in the world.

With the E-mail I also had the possibility to communicate with M. Pichavant to have information about my presentation and the French report. If we had to phone every time we had to communicate it would have been very long, and very difficult to arrange. I also used the Email to save my work because it was difficult to have a floppy, and as Roland lost all his work on his hard disk because his computer broke down, I could be sure not to loose my work with my E-mail. I just had to click File Send To Mail Recipient and write my E-mail address.

At last I especially used Internet for my project and my report. First of all, for the project, I had to read a lot of books and only in English, and it could be sometimes very difficult to understand every thing especially as far as the technical words are concerned. That is why I looked for some sites about Technology where I could find the same courses, but this time, in French. I could also copy some figures for my work. It was only at the beginning I used it, and at the end, I could understand almost everything, because the vocabulary is more or less the same for all the converters, for example. It was very long to find such a site because most of them are not free. I also used a dictionary on Internet, to find the translation of some English word, but also to translate French into English, for my report. Moreover as I worked with Html files, even if I didn't have to create them, because they already existed, I wanted to know what it was. And I found a very good initiation about Html. I also had the possibility to solve one problem because I couldn't use the tabulation, and I red that, as they wrote in the initiation, "Les espaces (plusieurs à la suite), tabulations, retours chariot n'ont pas de valeur en HTML."
I used Internet a lot for my report because I had to speak about Greece and I didn't have enough time to visit many things. Therefore I discovered Greece with Internet. It was useful to find some pictures to put in my report, like a map of Greece or a TEI picture or a Greek flag...

5.7. Technical conclusion

At the beginning, M. Kyranastasis told me that I had to make another project using Html files and the Visual Basic, but as I didn't know both of them, he told me it was impossible in two months to learn it and to make the whole project. Because most of the students coming here are engineers and they make either a four-month or a five-month final project. Therefore my project was very simple but I learned a lot of things. I especially used Word, Internet, the scanner, Readiris and PowerPoint for my presentation. And as far as I am concerned everything (except Word) was new and I had to discover all of them by myself.

Finally I had time to make 9 files, for the theory part of Neapolis.

I made 6 files about the converters that are:

- Three-Phase Rectifiers
- One-Phase Inverters
- Three-Phase Inverters
- Three-Phase Cycloconverters
- Three-Phase AC Controllers
- DC Choppers

and 3 files about the motor drives, that are:

- Chopper-DC-Motor Drives
- One Phase rectifier DC Motor Drives
- Three Phase rectifier DC Motor Drives

I also made the Subsynchronous Cascade Controlled Induction Motor Drive, but I didn't have enough time to finish it.

T.E.I of Kavala
I.U.T of Brest
6. The life at T.E.I

6.1. Welcome

Once arrived at TEI, the welcome was not very good, because I was given my room key, so that I could put my luggage inside and to have a rest. But nobody told me when I had to start, where I had to go, because a student welcomed me, and he had arrived only one week before me, so he didn't know the TEI very well. Nobody made me the TEI visit, and I had to discover it by myself. But it was not really important, because I lost my way two or three times in TEI, and after everything was all right because TEI is not so big. Moreover, that was the first opportunity to check my English knowledge, by asking my way to a Greek. At the beginning it was difficult to speak English, but the worst was to understand the Greek accent which is totally different from our teacher's accent. But after a few days, it was easier and easier. The welcome was not very good but a lot of foreign students come in TEI and at a different date and therefore it is difficult for M. Kyranastasis to organize all the arrivals. And it was easy to speak with M. Kyranastasis because he speaks English very well.

6.2. Everyday life

The life in TEI but also in Greece was very different from my life in Brest, and it was a great experience to live in TEI for almost three months, and to discover the Greek way of life.

First of all I lived in a very small twin bedded room with only two beds and two desks. It was a bit narrow but most of the time we were either outside or in the laboratory.

At the beginning, I shared my room with a Greek and it was a good way for me to learn some words. But after I shared my room with Roland Le Gall, the other French student. The rent was quite cheap; for the first month I had to pay 40,000 Drachmas (about 800 francs), for the room, the blanket and the pillow, and the two next months 25,000 Drachmas, each one.
It was very difficult to sleep at night, not only because it is very hot but especially because Greek students often organized parties either in their room or in the corridor. Because it was not rare to hear the music till 4.00 o clock in the morning, in one room, and to hear to another music, in another room at 8.00 the same day. Moreover I don’t really like Greek music because it is a bit too soft and a lot of songs are said to be very good, thanks to the lyrics and not to the melody. As I don’t understand Greek it was difficult for me to appreciate the music.

As far as the food was concerned, in the TEI restaurant, it was cheap too, about 17.000 Drachmas for one month and three meals a day, but it was not very good. On the other hand, Greek food is very good and you can eat very well in a restaurant for a low price.

But the rooms and the food, in TEI are more or less similar to the French ones. What was really different from the life in IUT was the way the students could express themselves. As a matter of fact, they were interested in politics, and we could see advertising everywhere in the TEI during the student elections. Moreover they could paint on the wall and organize as many concerts as they wanted, inside the university so as to promote their political tendencies.

During the month of June, for example, they organized a one week party (every night) in the TEI, with a lot of concerts with all the kinds of music, Greek music, English music, . . . , but also with theatre representations, or proceedings about peace . . . . It was really interesting and that way we learned a lot about their customs and their culture. Life in TEI is totally different from life in IUT because the students live inside the TEI. The students’ rooms are next to the classrooms. Moreover the students can move in the TEI by motorcycle, from one class to another one or from their classroom to the restaurant . . . . It is like a small village, and Greek people are very free, they can do a lot of thing that we can not do in France. As a matter of fact, I am not sure it is a good idea to paint the wall of IUT and to organize concert in the amphitheater. In a word, I enjoyed my stay in TEI, because it is very lively, you can meet a lot of people, you can discuss with all of them, you are very free and nobody is here to watch you. It is really worth living this experience, because there is a very good atmosphere.
6.3. Working conditions

As I have described before, in the TEI presentation, I worked in a small laboratory with only five computers with Internet, but we were sometimes more than ten to work in the laboratory, because the laboratory was used to work but also to write E-mail and every foreign students could use the computers. Therefore, as I didn't own a computer to work, it was sometimes impossible to work, but I could work in my small room to look for the information I needed for my project. Furthermore, I had to use a lot the scanner, and there was only one, not only for all the Erasmus students, but also for the Greek ones. There was also only one printer for all the students.

At last it was difficult to work in the afternoon because the laboratory was very small, without any windows, and from the beginning of June till the end, the temperature sometimes reached 30 degrees. I wanted to change my project and make another one about the way to install the air conditioning in the room but it was not possible. That is the reason why I used to work in the beginning from 8.30 to 13.00, and at night from 8.30 to more than midnight.

As a matter of fact, we could work whenever we wanted, 24h/24h everyday, even the weekend, because we had the keys of the laboratory, and I could go to the "lab", as we used to say, even when M. Kyranastasis was not there. And when I could work, it was in quite good conditions, because I could use Internet as much as I wanted and the computers were very good ones. As I said just before you are totally free in TEI and the teachers always trust the students, and that way you can work in better conditions.

I had to work alone, but when I had some problems I could ask for some help to Tihon a Greek student who was studying Electricity and working with M. Kyranastasis in the same time. He was very available and very friendly.

As a conclusion the working conditions were quite good because I could work whenever I wanted without any timetable, without any pressure and the only thing I had to do, was to finish my project in time. On the other hand, it would have been better if we had more computers, more scanners, and a good printer.
Twice a week we had Greek lessons with Mrs. Anna Mikailisou. Every Monday and Tuesday, we had to go to these lessons from 16.00 o'clock to 19.00. I personally think that it is impossible to learn Greek in only two months, because it is a very difficult language. The characters are totally different from our alphabet and it was the most difficult thing to learn.

But it was very important for me to learn because without it, I couldn't read anything, what was written on the advertising, for example, because nothing was written in English. And even if I could not understand the meaning of the words, I could know the main subject, because some words are very similar to English or French words. We learned a lot of things, not only the characters, but also the numbers, the colors, the time, the verbs...all the basics things so that we could try to answer a question or to be able to ask for something in a shop. But it fact it was very difficult to speak Greek, because even if we were able to ask something in a shop, for example, we were not able to understand the answer because they don't make efforts to speak slowly and simply. But it was a good experience to learn the language. We also had a very interesting debate about the Turkish and the Greeks, because Greece and Turkey had a lot of conflicts in the past, and a lot of Students in TEI hate Turkish people, but our teacher said it was not true, whereas the students said the opposite. So she explained that a part of their country belong to the Turkish in the past and now there are still some riots at the borders, but it is never very serious. That is her own opinion because when I said to Greek people that I had been in Turkey to visit Istanbul, they were very surprised and they couldn't understand why I had such a stupid idea as they said. A lot of Greek student don't like the Turkish and I don't really understand why, because the two countries were in war, but it was before 1821, and now the conflict is finished even if they are still arguing to share some islands, in the Aegean sea.

I learn a lot of things in these lessons, but unfortunately, I would have been very interesting in learning the Greek History, but we didn't have enough time to learn everything, the language and the history in the same time. I would have preferred to learn only the history, because the language is only spoken in Greece and it is not an international language.
Moreover a few months later I would forget the half of what I have learned.
At last Greece has a rich and very interesting history and it would have been interesting
to learn it.

At the end of the Greek lessons we had to make an exam to test our knowledge. Once
passed the exam we received a certificate proving that we went to the Greek lessons and that we
passed the exam.

7. Human relationships

7.1. Relations with Erasmus students

As I said before, I worked in a laboratory with a lot of Erasmus students coming from
everywhere in Europe, France, Spain, Belgium, Holland, Germany, and Poland. We spoke
English all together and we had very good relationships. Not only I could learn about their way
of life in their country but I also tried to learn new languages such as Spanish that I didn't know
before coming here. At the beginning it was difficult for me to understand the Spanish, because
their accent were special. For example, instead of pronouncing "I have", they said "I rave", and
they always pronounced an "r" before a "h", and it is the same for the 'j' they pronounced like an
'y'. I also had the opportunity to improve a little my German that I hadn't spoken for a very long
time, with the Germans who spoke French very well, so they were good teachers for me.
Moreover half of the shopkeepers speak German and not English. As a matter of fact, it was
very easy to learn with the other students because as far as the Belgians are concerned, for
example, they could speak several languages such as English, Dutch, German and French, so it
was impossible not to understand each others. When I couldn't find an English word, for
example, I could ask them by given the French word and they could translate. It was a very
good experience to speak with them, because we all tried to learn the other languages, and I
noticed that we were a bit late in France, because in other countries, they learn a lot of
languages at school, and very early. I learned a lot of things with them, especially with the
Belgians, because they have a very good culture. They spoke about their life in Belgium, and
about their tensions between Flemish people and the Walloons.
I also took advantage of the situation to ask them why they didn't like French people in general. And they answered that it was true that most of the Belgians didn't appreciate French people, because, as they said: "You always want to be different than the others, you always want to make different things, to think different... for example with the minitel, at the beginning you wanted to use the minitel, whereas every other countries use Internet, and now you are very late with Internet. In political decision too, you always think different than the others, just to be heard... You always try to contradict the International politic decisions, just to look important...". It was very strange to know what they thought about us, but what they really don't like in France is the politics and not the people. But they are not totally wrong. And they were very open minded, because I told some Belgian funny stories and they were laughing with me.

I also spoke a lot with Spanish students, because they were very friendly, and they knew France very well, because they were coming from San Sebastian in the Basque country. And Basque country is half in France and half in Spain, so they had good relationships with French people.

We made a lot of things together, we visited Greece and Turkey, but I shared good moments with the Greeks, too.

7.2. Relations with Greek people

Not only Greece is a very nice country, but Greek people are also very friendly. I mean it was very easy to get integrated to Greek life, because most of Greek students studying at TEI could speak English, more or less, and lots of them were interested in communicating with us, either to improve their language or to learn about France. At the beginning I though it would be all the more difficult to be welcomed, because of the war against NATO and the Serbia, as Political life is very important for them. But in fact, it was not a problem, because they are open-minded, and like the Belgians they don't like the French policy but not the people. They organized a party one day against NATO, and they knew that all the Erasmus students were for a NATO intervention in the Balkans, but we were inviting all the same, and nobody has never had any problems with the Greeks.
Moreover they are found of football, and they know that we are the world champions, that is also why we were accepted, because sport takes a very important place in their life, and they like French football team very much. It was for them and for us a very good discussion's subject. We have participated in a tournament, with all the Greek students, but we lost in the quarterfinal.

We had a lot of different relations with them, they were very friendly, we could speak with them, we could joke with them, we played football and basketball together, we made party at weekends... Some of them were sometimes too friendly and the Greek reputation was not totally wrong if you see what I mean.

It was sometimes difficult to communicate because some of them didn't speak English very well and as far as I am concerned I didn't know any words in Greek, before the Greek lessons.

In fact we only had relationships with the students, M. Kyranastasis was very busy, because he was in charge of a lot of Erasmus students, he has to give lessons to Greek students, and we didn't really need his help, because his assistant was totally available and most of the time we could work alone, because it was not very difficult. We had good relationships with Mrs. Valsamidou, the person in charge of the International Relations, and when we had some problems, she was always there to help us, and she was very friendly, and without her help, I couldn't have been able to recover my lost luggage, because she did everything she could to find it.

As a conclusion everything was all right, and we never had any problems with them, because I personally think that they are very friendly, and some of them were always with us (Erasmus students) rather than being with the other Greek students.
I would like to thank all the teachers who gave me the opportunity to go to the T.E.I to make my final project. Because it was a great experience, and I really enjoyed my stay in Kavala.

First of all I learned a lot of thing in Data processing, and for the first time in my life I used Internet, and that is one of the main reason why I wanted to come here because my Informatic knowledge was very bad. Moreover even if the project was a bit repetitive, I learned many things in Electrotechnology and Power Electronics, especially in technical vocabulary, about the converters and the motor drives.

Then, I have to say that the main reason to go to Kavala, as far as I am concerned, was to improve my English. I like this language and I think that nowadays it is very useful to be able to speak English to find a good job, because it is an international language. Moreover I learned Greek and I met a lot of students coming from everywhere in Europe, and I had very good relationships with all of them.

At last, I discovered a new country; a new culture, a new language and I do not regret anything.

As a conclusion the stage was really interesting, I learned a lot of things and I encourage not only the next students to realize their project in Kavala, but also everybody to go and visit Greece because it is a very beautiful country.
# Glossary

**Converters**
- One-Phase Inverters
- Three-Phase Inverters
- Three-Phase Rectifiers
- Three-Phase Cycloconverters
- Three-Phase AC Controllers
- DC Choppers

**Motor Drives**
- Chopper-DC Motor Drives
- One Phase Rectifier DC Motor Drives
- Three Phase Rectifier DC Motor Drives

**Under Construction**
- Subsynchronous Cascade Controlled Induction Motor Drives

---

T.E.I of Kavala

I.U.T of Brest
-AC: Alternative Current
-BJT: Bipolar Junction Transistor
-CMOS: Complementary Metal Oxide Semiconductor
-D.C: Direct Current
-GTO: Gate Turn Off
-HPWM: Harmonical Pulse Width Modulation
-IGBT: Insulated Gate Bipolar Transistor
-LCI: Load-Commutated-Inverter
-MCT: Metal-Oxide Controlled Thyristor
-MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor
-MRT: Mass Rapid Transit
-MSPWM: Modified Sinusoidal Pulse Width Modulation
-PWM: Pulse Width Modulation
-RMS: Root Mean Square
-SCR: Silicon Controlled Rectifier
-SIT: Static Induction Transistor
-SPWM: Sinusoidal Pulse Width Modulation
-UPWM: Uniform Pulse Width Modulation
Switch-mode dc-to-ac inverters are used in ac-motor drives and uninterruptible ac power supplies where the objective is to produce a sinusoidal ac output whose magnitude and frequency can both be controlled. Each type of inverters can use controlled turn on and turn-off devices (e.g., BJTs, MOSFETs, IGBTs, MCTs, SITs, GTOs), or forced-commutated thyristors depending on applications. These inverters generally used PWM control signals for producing an ac output voltage. An inverter is called a voltage-fed inverter if the input voltage remains constant.

The configurations of inverters are essentially the same as those employed in rectifiers. The following figure shows the basic single-phase arrangements—the bi-phase, bridge, and half bridge circuits. Discussion will initially be directed to the bridge circuit, which is not complicated by the necessity for a transformer and can operate in some modes which are not possible in the bi-phase circuit, or in the half-bridge, on its own.
3.1. Bridge inverter with resistive load

The simplest mode of inversion is the generation of an alternating voltage of square waveform across a resistive load. The thyristors are turned on and off in diagonal pairs, i.e. Th1 and Th4 alternately with Th2 and Th3, each pair for one half-period of the desired output, so that the D.C. supply is connected across the load alternately in opposite directions. In practice, however, an inverter is rarely, if ever, required to supply a purely resistive load, and it is essential that it should be capable of operating in a satisfactory and predictable manner with loads, which include greater or lesser amounts of reactance.

3.2. Bridge inverter with reactive feedback diodes

If the resistive load is replaced by one which includes inductance in a series circuit, operation in the terms described above becomes impossible, since the turn-off of one pair of thyristors and the turn-on of the other pair at the end of a half-cycle of the voltage waveform implies an instantaneous reversal of the load current which cannot be achieved without the generation of an infinite voltage across the inductance.

To put it another way, commutation of the output current is not possible, because there are no alternative paths for current in a given direction; operation as described for a resistive load is possible only with a load that permits the half-cycles of output current to coincide exactly with the half-cycles of voltage. Strictly speaking this does not exclude all loads that include reactance, but it does exclude virtually all-practical loads, and, if it could not be circumvented, would represent an intolerable limitation on the usefulness of the circuit.
The normal solution to the problem of accommodating loads in which the current is not in step with the voltage is to add a diode in parallel with each thyristor. This prevents the instantaneous output voltage from appreciably exceeding the supply voltage, and provides paths for load currents in opposition to the instantaneous output voltage.

3.2.b Bridge inverter with inductive load

The following waveforms illustrate the behavior of the single-phase bridge inverter with reactive feedbacks diodes, with a reactive load.

The voltage waveform, in conjunction with the impedance of the load, determines the current waveform, and the phase relationship between the current and voltage waveforms determines the apportionment of current between the thyristors and the diodes. The voltage waveform being square, the current waveform in this case comprises a sequence of exponentials.

For the purpose of considering the current loading of the thyristors and diodes in quantitative terms, it is convenient to postulate a load that draws a sinusoidal current, which, while it does not accurately represent many real loads supplied by a square-wave voltage source, is as
representative as any, and is not unlike some loads of practical importance. To make the discussion more general, one pair of arms of the bridge will be considered initially—a so-called half-bridge which may constitute part of a complete bridge or may be a complete inverter in the half-bridge configuration.

In many industrial applications, it is often required to control the output voltage of inverters (1) to cope with the variations of dc input voltage, (2) for voltage regulation of inverters, and (3) for the constant volts/frequency control requirement. There are various techniques to vary the inverter gain. The most efficient method of controlling the gain (and output voltage) is to incorporate pulse-width-modulation (PMW) control within the inverters. The commonly used techniques are:

1. Single-pulse-width modulation
2. Multiple-pulse-width modulation
3. Sinusoidal pulse-width modulation
4. Modified sinusoidal pulse-width modulation
5. Phase-displacement control

4.1 Single-pulse-width modulation

In Single-pulse-width modulation control, there is only one pulse per half-cycle and the width of the pulse is varied to control the inverter output voltage. The following figure shows the generation of gating signals and output voltage of single-phase full-bridge inverters.
The gating signals are generated by comparing a rectangular reference signal of amplitude, $A_r$, with a triangular carrier wave of amplitude, $A_c$. The frequency of the reference signal determines the fundamental frequency of output voltage. By varying $A_r$ from 0 to $A_c$, the pulse width, $\delta$, can be varied from 0 to 180°. The ratio of $A_r$ to $A_c$ is the control variable and defined as the amplitude modulation index. The amplitude modulation index or simply modulation index

$$M = \frac{A_r}{A_c} \quad (1)$$

The rms output voltage can be found from

$$V_o = \left[ \frac{2}{2\pi} \int_{-\infty}^{\infty} \frac{V_o^2}{V_c^2} d(\omega t) \right]^{1/2} = V_s \sqrt{\frac{\delta}{\pi}} \quad (2)$$

The Fourier series of output voltage yields

$$v_o(t) = \sum_{n=1,3,5,...}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\delta}{2} \sin n\omega t \quad (3)$$
The next figure shows the harmonic profile with the variation of modulation index, M. The dominant harmonic is the third, and the distortion factor increases significantly at a low output voltage.

4.2. Multiple-Pulse-Width Modulation

The harmonic content can be reduced by using several pulses in each half cycle of output voltage. The generation of gating signals for turning on and off of transistors is shown in the following (a) figure by comparing a reference signal with a triangular carrier wave. The frequency of reference signal sets the output frequency, $f_o$, and the carrier frequency $f_c$, determines the number of pulses per half-cycle, $p$. The modulation index controls the output voltage. This type of modulation is also known as uniform pulse-width modulation (UPWM). The number of pulses per half-cycle is found from

$$ P = \frac{f_c}{2f_o} = \frac{mf}{2} \quad (4) $$

Where $mf = f_c/f_o$ is defined as the frequency modulation ratio.

The variation of modulation index M from 0 to 1 varies the pulse width from 0 to $\pi/p$ and the output voltage from 0 to $V_s$. The output voltage for single-phase bridge inverters is shown in figure (b) for UPWM.
If \( \delta \) is the width of each pulse, the rms output voltage can be found from

\[
V_o = \frac{2p}{2\pi} \left[ \int_{p/p - \delta/2}^{(p/p + \delta)/2} V_s^2 d(\omega t) \right]^{1/2} = V_s \sqrt{\frac{p\delta}{\pi}}
\]  

(5)

The general form of a Fourier series for the instantaneous output voltage is

\[
v_o(t) = \sum_{n=1,3,5,...} B_n \sin n\omega t
\]  

(6)

The coefficient \( B_n \) can be determined by considering a pair of pulses such that the positive pulse of duration \( \delta \) starts at \( \omega t = \alpha \) and the negative one of the same width starts at \( \omega t = \pi + \alpha \). The effects of all pulses can be combined together to obtain the effective output voltage.
If the positive pulse of \( m \)th pair starts at \( \omega t = \alpha_m \) and ends at \( \omega t = \alpha_m + \pi \), the Fourier coefficient for a pair of pulses is

\[
b_n = \frac{1}{\pi} \left[ \int_{\alpha_m}^{\alpha_m + \delta} \cos n\omega t \, d(\omega t) - \int_{\pi + \alpha_m}^{\pi + \alpha_m + \delta} \cos n\omega t \, d(\omega t) \right]
\]

\[
= \frac{2V_s}{n\pi} \sin \frac{n\delta}{2} \left[ \sin n \left( \alpha_m + \frac{\delta}{2} \right) - \sin n \left( \pi + \alpha_m + \frac{\delta}{2} \right) \right]
\]

(7)

The coefficient \( B_n \) can be found by adding the effects of all pulses,

\[
B_n = \sum_{m=1}^{p} \frac{2V_s}{n\pi} \sin \frac{n\delta}{2} \left[ \sin n \left( \alpha_m + \frac{\delta}{2} \right) - \sin n \left( \pi + \alpha_m + \frac{\delta}{2} \right) \right]
\]

(8)

In this figure, the harmonic profile against the variation of modulation index for five pulses per half-cycle, is shown. The order of harmonics is the same as that of single-pulse modulation. The distortion factor is reduced significantly compared to that of single-pulse modulation. However, due to larger number of switching on and off processes of power transistors, the switching losses would increase. With larger values of \( p \), the amplitudes of lower-order harmonics would be lower, but the amplitude of some higher-order harmonics would increase. However such higher-order harmonics produce negligible ripple or can easily be filtered out.
4.3. Sinusoidal Pulse-Width Modulation

Instead of maintaining the width of all pulses the same as in the case of multiple-pulse modulation, the width of each pulse is varied in proportion to the amplitude of a sine wave evaluated at the center of the same pulse. The distortion factor and lower order harmonics are reduced significantly. The gating signals as shown below are generated by comparing a sinusoidal reference signal with a triangular carrier wave of frequency, fc.

This type of modulation is commonly used in industrial application and abbreviated as SPWM. The frequency of reference signal, fr, determines the inverter output frequency, fo, and its peak amplitude, Ar, controls the modulation index, M, and then in turn the rms output voltage, Vo. The number of pulses per half-cycle depends on the carrier frequency. Within the constraint that two transistors of the same arm cannot conduct at the same time, the instantaneous output voltage is shown in the next figure (a).

The same gating signal can be generated by using unidirectional triangular carrier wave as shown in figure (b).
The rms output voltage can be varied by varying the modulation index M. It can be observed that the area of each pulse corresponds approximately to the area under the sine wave between the adjacent midpoints of off periods on the gating signals.

If $\delta$ is the width of $m$th pulse, equation (5) can be extended to find the rms output voltage.

$$V_o = V_s \left( \sum_{m=1}^{p} \frac{\delta_m}{\pi} \right)^{1/2}$$

Equation (8) can also be applied to determine the Fourier coefficient of output voltage as

$$B_n = \frac{2V_s}{n\pi} \sin \frac{n\delta_m}{2} \left[ \sin n \left( \alpha_m + \frac{\delta_m}{2} \right) - \sin n \left( \pi + \alpha_m + \frac{\delta_m}{2} \right) \right]$$

(10)
The harmonic profile is shown in the next figure. The distortion factor is significantly reduced compared to that of multiple-pulse distortion modulation. This type of modulation eliminates all harmonics less than or equal to \(2p-1\).

The output voltage of an inverter contains harmonics. The PMW pushes the harmonics into a high-frequency range around the switching frequency, \(f_c\), and its multiples, that is, around harmonics \(m_0\), \(2m_0\), \(3m_0\), and so on. The frequencies at which the voltage harmonics occur can be related by

\[
f_n = (jm_f + k)f_c \quad (11)
\]

where the \(n\)th harmonic equals the \(k\)th sideband of \(j\)th times the frequency-modulation ratio \(m_f\).

\[
n = (jm_f - k)f_c \quad (12)
\]

\[= 2jp + k \text{ for } j = 1, 2, 3, \ldots \text{ And } k = 1, 3, 5\]
The peak fundamental output voltage for PWM and SPWM control can be found approximately from

\[ V_{m1} = dV_s \text{ for } 0 < d < 1 \quad (13) \]

For \( d = 1 \), Equation (13) gives the maximum peak amplitude of the fundamental output voltage as \( V_{m1(max)} = V_s \). In order to increase the fundamental output voltage, \( d \) must be increased beyond 1. The operation beyond \( d = 1 \) is called overmodulation. The value of \( d \) at which \( V_{m1(max)} \) equals 1.278\( V_s \) is dependent on the number of pulses per half-cycle \( p \) and is approximately 3 for \( p = 7 \), as shown in the following figure.

![Graph showing overmodulation](image)

4.4. Modified Sinusoidal Pulse-Width Modulation

Figure of the Sinusoidal-pulse-width modulation, indicates that the widths of pulses that are near the peak of the sine wave do not change significantly with the variation of modulation index. This is due to the characteristics of the sine wave, and the SPWM technique can be modified so that the carrier wave is applied during the first and last 60° intervals per half-cycle (e.g., 0 to 60° and 120 to 180°). This type of modulation is known as MSPWM and is shown bellow.
The fundamental component is increased and its harmonic characteristics are improved. It reduces the number of switching of power devices and also reduces switching losses. The harmonic profile is shown below, for five pulses per half-cycle. The number of pulses, \( q \), in the 60° period is normally related to the frequency ratio, particularly in the three-phase inverters, by

\[
F_c/f_0=6q+3 \quad (14)
\]
4.5. Phase displacement factor

Voltage can be obtained by using multiple inverters and summing the output voltages of individual inverters. A single-phase full-bridge inverter can be perceived as the sum of two half-bridge inverters. A 180° phase displacement produces an output voltage as shown in the following waveform (c), whereas a delay angle of \( \beta \) produces an output as shown in graph (e).

The rms output voltage,

\[
V_o = V_s \sqrt{\frac{\beta}{\pi}}
\]  

(15)

If

\[
u_{ao} = \sum_{n=1, 3, 5, \ldots} \frac{2V_s}{n\pi} \sin n\omega t
\]

(16)
Then

\[ v_{ba} = \sum_{n=1, 3, 5, \ldots}^{\infty} \frac{2V_r}{n\pi} \sin n(\omega t - \beta) \]  

(17)

The instantaneous output voltage,

\[ v_{ab} = v_{ao} - v_{bo} = \sum_{n=1, 3, 5, \ldots}^{\infty} \frac{2V_r}{n\pi} [\sin n\omega t - \sin n(\omega t - \beta)] \]

(18)

Since \( \sin A - \sin B = 2\sin\left(\frac{A-B}{2}\right) \),

\[ v_{ab} = \sum_{n=1, 3, 5, \ldots}^{\infty} \frac{4V_s}{n\pi} \sin \frac{n\beta}{2} \cos \left(\frac{\omega t - \beta}{2}\right) \]

(19)

The rms value of the fundamental output voltage is

\[ V_1 = \frac{4V_s}{\sqrt{2}} \sin \left(\frac{\beta}{2}\right) \]

(20)

Last equation indicates that the output voltage can be varied by varying the delay angle. This type of control is especially useful for High-power applications, requiring a large number of transistors in parallel.

5. APPLICATIONS.

For low and medium power applications, square-wave or quasi-square wave may be acceptable, and for high-power applications, low distorted sinusoidal waveforms are required.

Inverters are widely used in industrial applications (e.g., variable-speed ac motor drives, induction heating, standby power supplies, uninterruptible power supplies). The input may be a battery, fuel cell, solar cell or other dc source.
This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics, Principles and</td>
<td>Joseph Vithayathil</td>
<td>Stephen W Director</td>
</tr>
<tr>
<td>Applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Electronics, converters,</td>
<td>Mohan / Undeland / Robbins</td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td>Applications and design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>An introduction to power electronics</td>
<td>B M. Bird / K. G. King / D A G. Pedder</td>
<td>John Wiley &amp; sons</td>
</tr>
</tbody>
</table>

The 1-phase inverter has the following parameters:

- Output Frequency

- Inverter Control Method which may be one of the following
  - Rectangular wave
  - Semi-rectangular wave with the following parameter
    - Cutoff angle
  - Pulse Width Modulation of the following types
    - Sinusoidal (SPWM)
- Modified Sinusoidal (MPWM)
- Harmonical (HPWM), all with the following parameters
  - Relative Output Voltage Amplitude
  - Chop/Output Frequency Ratio
  - Chop Waveform Relative Amplitude
- Harmonic Elimination (HEMI) with the following parameter
  - Maximum eliminated harmonic class (3-15)

8. MODELING.

The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves, it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
In applications such as uninterruptible ac power supplies and ac-motor drives, three-phase inverters are commonly used to supply three-phase loads. It is possible to supply a three-phase load by means of three separate single-phase inverters, where each inverter produces an output displaced by 120° (of the fundamental frequency) with respect to each other. Though this arrangement may be preferable under certain conditions, it requires either a three-phase output transformer or separate access to each of the three phases of the load. In practice, such access is generally not available. Moreover, it requires 12 switches. The main 3-ph inverter used is the 3-ph-bridge inverter.

By further analogy with conventional rectifier circuits, an inverter to generate a three-phase output may comprise a bridge of six thyristors, together with associated reactive feedback diodes. Such a bridge may conveniently be considered as an assembly of three half bridges, each driven in the same manner as in the single-phase bridge, but with outputs mutually displaced in phase by \(2\pi/3\) radians.

![Three-phase bridge inverter diagram]
The output voltage waveforms in this circuit are illustrated in the following figure, which shows the phase voltages $v_x$, $v_y$, $v_z$ relative to the midpoint of the d.c supply and the corresponding interphase voltages.

![Waveform diagram]

The phase voltages, thus defined, are the same as those in the single-phase inverter, and include a third-harmonic component of one third of the amplitude of the fundamental component; the third harmonic does not, however, appear in the interphase output voltages, since the voltages are composed of pairs of phase voltage added with a phase displacement of $\pi/3$ at the fundamental frequency, and therefore of $\pi$ at the third-harmonic frequency. The whole series of triplen harmonics is similarly eliminated, and the harmonic content that remains is that represented by series $n=6r(\pm1)$, where $r$ is any positive integer, the $n$th harmonic having an amplitude $1/n$ relative to the fundamental component.

The interphase output voltage has a mean value of $2V_d/3$ and a r.m.s value of $\sqrt{(2/3)V_d}$, while harmonic analysis shows that the fundamental r.m.s component is $3/\pi$ times the total r.m.s voltage, i.e. $\sqrt{6V_d}/\pi$.

Alternatively, the fundamental-frequency interphase voltage may be calculated as the resultant of the outputs of two half-bridges, i.e.

$$2 \cos (\pi/6) \cdot \sqrt{2} \cdot V_d/\pi$$

If a balanced load is connected to the three-phase inverter, the neutral point of the load assumes a potential which at any instant is the mean of the three phase potentials, as shown in the following figure, and an alternating voltage of square waveform, at three times the inverter output frequency, appears between the load neutral point and the midpoint of the DC supply; this voltage contains all the triplen-frequency components eliminated from the inverter output voltage.
The load phase voltages contain the same harmonics as the interphase voltage, in the same proportions, but in a different pattern of phase relationships to the fundamental components.

With sinusoidal output currents and a load phase angle φ (lagging), the input current is of the form in the next figure, representing the sum of the currents drawn by the three half-bridges. The mean input current is

$$\bar{i}_d = I_s \frac{3 \cos \phi}{2} = I_s \frac{3 \sqrt{2} \cos \phi}{\pi}$$

The rms input current may be found by integration over a period $\pi/(3\omega)$ e.g. from 0 to $\pi/3$ in the next figure:

$$i_d = \bar{i}_d \sin \left(\omega t + \frac{\pi}{3} - \phi\right)$$

$$I_d = \sqrt{\frac{3}{\pi} \int_0^{\pi/3} i_d^2 \, dt}$$

$$= \bar{i}_d \sqrt{\frac{3}{\pi} \left[ \frac{\omega t}{2} - \frac{1}{2} \sin 2 \left(\omega t + \frac{\pi}{3} - \phi\right) \right]_0^{\pi/3}}$$

$$= I_s \sqrt{1 + \frac{3\sqrt{3}}{2\pi} \cos 2\phi}$$
The rms input ripple current is then:

\[ I_{ir} = \sqrt{I_d^2 - \bar{I}_d^2} \]

\[ = I_k \sqrt{1 - \frac{3\sqrt{3}}{2\pi} - \left( \frac{18}{\pi^2} - \frac{3\sqrt{3}}{\pi} \right) \cos 2\phi} \]
4. CONTROL.

Pulse-width modulation

Generating the commutation patterns required to eliminate an extended series of harmonics by
the method of selected harmonic reduction, with the necessary accuracy, entails considerable
complexity in the control system. Largely for this reason, the basically simpler technique
generally known as pulse-width modulation is more often considered as a means of producing an
improved waveform prior to filtering.

Pulse-width modulation for this purpose entails generating rectilinear output voltage pulses at a
repetition frequency considerably higher than the fundamental frequency and modulating their
duration so that the integrated value of each pulse is proportional to the instantaneous value of
the required fundamental component at the time of its occurrence: that is, the pulse duration is
modulated sinusoidally.

This is illustrated, for an inverter capable of producing three instantaneous levels of output
voltage (a bridge inverter for example) in the following figure.

![Sinusoidal pulse-width-modulation in a single-phase bridge inverter]

This depicts what might be regarded as an ideal scheme in which the pulse-repetition frequency
is an integral multiple of the modulating frequency and the output pulses are symmetrically
disposed, on the time axis, about regularly spaced ordinates. The duration of the pulses are
proportional to the corresponding ordinates of the modulating sine wave: thus:

\[ \frac{\beta_1}{y_1} = \frac{\beta_2}{y_2} = \frac{\gamma_1}{y_1} = \text{constant} \]

This might be regarded as an extension of the principle of multiple pulse-width control
described above, and it can easily be imagined that, if the repetition frequency of the pulses is
high enough in comparison with the modulating frequency, the resulting pulse train will have an
average effect, for most practical purposes, closely similar to that of the fundamental sine wave,
containing little or nothing in the way of low-order harmonics, and only a small degree of
filtering will suffice to produce a virtually sinusoidal waveform.

In fact, Fourier analysis confirms that unwanted frequency components below the pulse
repetition frequency in the waveform, are confined effectively to about three sidebands, and the
The lowest frequency likely to be noticeable is \((p-5)f_1\), where \(f_1\) is the modulating frequency and the pulse repetition frequency is \(pf_1\). Thus if \(p\) is, say, eighteen, the lowest frequency to be removed by the filter is the thirteenth harmonic. If the inverter system is capable of generating at a very high frequency, the requirements placed upon the filter can be so reduced that in material terms it becomes relatively insignificant.

A commonly adopted method of defining the pulse duration, which gives an approximation to the ideal modulation pattern referred to above, is illustrated in the next figure, in this case for a half-bridge.

At (a), a modulating sine wave is compared with a triangular wave, the 'carrier' at the required pulse repetition frequency, the relative amplitudes of the two signals being in proportion to those of the required fundamental-frequency output voltage and the d.c supply of the inverter. The switching instants are determined by the control at the points of coincidence of the two waveforms: hence, as a matter of geometry, the width of each output pulse (b) nearly corresponds to the average value of the required output potential during the period of the pulse. The approximation in this process lies in the slight irregularity in the timing of the instants due to the variation of the modulating signal within the pulse period: this becomes less significant as \(p\) is increased. The combination of two half-bridge outputs, generated by co-phasal triangular waves and antiphase modulating signals, produces a three-level waveform with a doubled carrier frequency, as shown below.
Unlike phase multiplication, methods of reducing harmonics such as selected harmonic reduction and pulse width modulation, which depend simply on modifying the output voltage waveform of an inverter by an increased frequency of commutation, have the disadvantage that the commutation losses are correspondingly increased, while the fundamental-frequency output obtainable is somewhat reduced. They are therefore generally less attractive for thyristor inverters than for transistor inverters in which commutation losses are less significant, and most useful for low frequency outputs.

[Bridge inverter output generated by pulse-width modulation in two half-bridges]

5. APPLICATIONS.

Three-phase inverters are normally used for high power applications. A major application of these inverters is the speed control of AC motors. The speed of an AC motor of the induction type or of the synchronous type is determined by the frequency of the AC. Therefore the speed could be conveniently adjusted by supplying the motor from an inverter of adjustable frequency. The type of motor that is popular for this application is the three phase induction type motor, which does have brushes since the rotor currents are induced by electromagnetic induction from the stator side. Present-day inverters are highly efficient and the control strategies are easy to implement.

The statements we have made regarding the use of AC motors for battery powered cars are also, valid for electric trains supplied from DC. The majority of rapid transit systems for city and suburban traffic are supplied by DC power, because they were originally designed to use DC motors. Therefore, here again, the trend now is to use inverter fed AC motors for future designs, the inverters being fed from the exciting DC supply.
6. LITERATURE.

This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics: Principles and Applications</td>
<td>Joseph Vithayathil</td>
<td>Stephen W Director</td>
</tr>
<tr>
<td>Power Electronics, converters, Applications and design</td>
<td>Mohan / Undeland / Robbins</td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td>An introduction to power electronics</td>
<td>B M. Bird / K. G. King / D. A. G. Pedder</td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td>Power electronics Circuits devices and applications</td>
<td>Muhammad Rashid</td>
<td>Prentice-hall International</td>
</tr>
</tbody>
</table>

7. PARAMETERS.

The three-phase inverter is a bridge circuit inverter.

The three-phase inverter has the following parameters:

- Output frequency

- Inverter Control Method which may be one of the following:
  - Rectangular wave
  - Pulse Width modulation of the following types
    - Sinusoidal (SPWM)
    - Modified sinusoidal (MPWM)
    - Harmonical (HPMW), all with the following parameters
      - Relative output voltage amplitude
- Chop/output frequency ratio
- Chop waveform relative amplitude
- Harmonical elimination (HEMI) with this parameter:
- Maximum eliminated harmonic class

8. MODELING.

The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves, it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
3-Ph Rectifiers

1. DESCRIPTION.

In industrial applications where three-phase ac voltages are available, it is preferable to use three-phase rectifier circuits compared to single-phase rectifiers, because of their lower ripple content in the waveforms and a higher power handling capability.

In this group we can find two different kinds: 3-Ph single way Rectifier and 3-Ph full bridge rectifier.

In the group of 3-Ph single way rectifier we can either find 3-Ph single way rectifier or 3-Ph single way rectifier with zig-zag transformer connection.

In the group of 3-Ph bridge rectifier we can also find 3-Ph full bridge rectifier and multiplex bridge rectifier.

2. CONSTRUCTION.

Virtually all practical power rectifiers comprises one or more groups of half-wave circuits, connected in parallel on the output side and supplied from different phases of a three-phase supply.

![Three-phase single way rectifier diagram](image)

Three-phase single way rectifier
Three-phase bridge rectifier

3. OPERATION.

A 3-Ph rectifier circuit is a circuit that converts a three-phase ac signal into a unidirectional signal. Diodes and thyristors are used extensively in rectifiers.

The 3-Ph single way rectifier is the simplest type, because a transformer is not essential to the operation of this rectifier arrangement if a neutral supply connection is available.

Three half-wave circuits are connected in parallel on the output side and supplied from different phases of a 3-phase supply. The three cathodes are connected. All the cathodes are reverse biased, and therefore non-conducting, except the one connected to the supply terminal at the highest potential with respect to the neutral. As each supply terminal in turns assumes the highest potential, the load current is transferred to the diode connected to it, and the output voltage waveform thus consists of a sequence of parts of supply phase voltages. The transference of current from one phase to another of higher potential is known as natural commutation, and the circuit is one of a class of naturally commutating or supply commutating system.
Waveforms of voltage and current in a three-phase single-way rectifier

2. 3-Ph single way rectifier with zig zag transformer

In practice, it is not normally used without a neutral supply connection, since the direct current in the supply lines—particularly the neutral line—which results from a direct connection is not usually considered acceptable at any appreciable power level, even if the desired output voltage is obtained without transformation.

However, a normal transformer connection—delta-star, for example—while keeping direct current out of the supply, only transfers the problem to the transformers, which will exhibit increased magnetizing current and iron losses if subjected to d.c. magnetization.

This problem is avoided in most cases by employing a special transformer connection, known as the zig-zag connection. Each secondary phase voltage is obtained from two equal-voltage secondary windings connected in series so that the d.c. magnetizing forces due to two secondary windings on any one limb are in opposite directions, and balance out.
Three-phase single-way rectifier with zig-zag transformer connection

Phasor diagram of transformer voltages
3.3. 3-Ph full bridge rectifier

The characteristics of the bridge rectifier can be simply deduced from those of its constituent commutating groups. On the d.c. side, the total output voltage, instantaneous or mean, is the sum of those of the two diode groups, while each group carries the whole load current.

The general expression for output voltage, in a three-phase bridge is:

\[ \text{V}_{\text{d moy}} = (3 \sqrt{3} / \pi ). \text{V}_{\text{phas max}} = (3 \sqrt{2} \sqrt{3} / \pi ). \text{V}_{\text{phas}} = (3 \sqrt{2} / \pi ). \text{V}_s \]
3.4. Multiplex bridge rectifier

The principles of phase multiplication may be extended to combinations of three-phase bridges with their inputs phase-displaced by half the interval between successive output voltage peaks, this technique leads to a variety of series/parallel combinations of three phase commutating groups. Two relatively common arrangements, combining two bridges to give a twelve-pulse output are possible.
Discussion so far has been confined to uncontrolled rectifiers, using only diodes as rectifying elements. If thyristors are substituted for the diodes in a rectifier circuit, an element of control is introduced whereby the direct output voltage can be varied by controlling the triggering inputs to the thyristor gates in a suitable manner.
4.1.3 Ph single way controlled rectifier

Discussion so far has been confined to uncontrolled rectifiers, using only diodes as rectifying elements. If thyristors are substituted for the diodes in a rectifier circuit, an element of control is introduced whereby the direct output voltage can be varied by controlling the triggering inputs to the thyristor gates in a suitable manner.

If each thyristor is triggered at the instant when the supply makes its anode potential positive with respect to its cathode—that is, at the instant when it would start to conduct by the process of commutation described earlier if it were a diode—the circuit behaves in the same way as the uncontrolled rectifier. If however the triggering pulses are withheld until some instant in the ensuing half-cycle, commutation is delayed, and the output voltage waveform is consequently modified.
Waveforms in a three-phase single-way controlled rectifier with delay angle $\alpha$

### 4.2. 3Ph half-controlled bridge rectifier

A bridge comprising a group of diodes in combination with a group of thyristor is known as a half-controlled bridge. The uncontrolled half of the bridge produces a fixed d.c. output voltage relative to the neutral point of the supply. The controlled half produces a d.c. voltage depending on the delay angle. The output voltage is therefore:

$$V_{d} = V_{ph} \sin\left(\frac{\pi}{3}\right) \left(\frac{\pi}{3}\right)^{1+\cos\alpha}$$
\[ \exists \nu > \alpha \]
4.3. 3Ph half-controlled rectifier with fully controlled and uncontrolled bridges in series

The principle of connecting a controlled converter in series with an uncontrolled one, can be extended in suitable cases to the use of a fully controlled thyristor bridge and a diode bridge, in series with considerably greater benefit to the input power factor.
4.3.3 Fully controlled rectifier with free-wheel diode

A fully controlled converter is sometimes furnished with a free-wheel diode—that is, a diode connected across its output to provide an alternative path for load current that excludes the converter thyristors, with effects which depends on the angle of delay \( \alpha \). If \( \alpha \) is so small that, without the diode, the instantaneous output voltage does not at any time become negative, the diode is always reverse-biased, and has no effect. With a larger value of \( \alpha \), however, such that the output voltage tends to become negative during parts of the cycle, the diode prevents the negative excursions, periodically carrying the load current, which would otherwise have to flow continuously in the converter. Since a negative output voltage cannot be produced, inversion is not possible.

4.3.3.a. three phase single way

4.3.3.b. three phase bridge

![Diagram](image)
The fully controlled converter, as described above, can produce a reversible direct output voltage current in one direction, and in terms of a conventional current/voltage diagram is said to be capable of operation in two quadrants, the first and second. Such a range of operation is useful for certain purposes, examples being the control of a d.c. torque motor, i.e., a motor used to
provide unidirectional torque with reversible rotation.

Equally, a converter may be used under steady-state conditions in the first quadrant only, but transiently in the second quadrant in order to extract energy from the load quickly and thereby improve the response of the system to changing command signals.

If four quadrant operation of a dc motor is required, i.e. reversible rotation and reversible torque, a single converter needs the addition of either a changeover contactor to reverse the armature connections or a means of reversing the field current in order to change the relationship between the converter voltage and the direction of rotation of the motor.

6. LITERATURE.

This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics: Principles and</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>Applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Electronics converters,</td>
<td>Mohan / Undeland / Robbins</td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td>Applications and design</td>
<td></td>
<td></td>
</tr>
<tr>
<td>An introduction to power electronics</td>
<td>B. M. Bird / K. G. King / D.A.G. Pedder</td>
<td>John Wiley &amp; sons</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power electronics Circuits devices and</td>
<td>Muhammad Rashid</td>
<td>Prentice-hall International</td>
</tr>
<tr>
<td>applications</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7. PARAMETERS.

The three-phase rectifier may be of the following circuit types:

- 3-pulse
- 6-pulse
- 12-pulse

The three-phase rectifier has the following parameters:

- Rectifier control type - No (with diodes)
- Sm (half diodes/half SCRs)
- Fu (with SCRs)

- Transformer turns ratio
- Firing angle

8. MODELING.

The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves, it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
A cycloconverter is a frequency changer that converts ac power at one input frequency to output power at a different frequency with one stage conversion. We can find two different kinds of circuits:

![Three-phase half wave circuit]  [Three-phase bridge circuit]

Three-phase half bridge circuit
3.1. **Three-phase half wave circuit**

A practical and commonly used cycloconverter uses the three-phase half-wave configuration, which is also known as 18-thyristor, three-pulse cycloconverter. The circuit consists of three identical half-wave antiparallel phase groups and is shown with a wye-connected ac machine load.
With the neutral connected, the phase groups operate independently. Each phase group functions as a dual converter with four-quadrant capability and therefore the load can sustain varying voltage and current of either polarity. The firing angle of each phase group is modulated sinusoidally but with a 120° phase shift so as to fabricate a mean sinusoidal output voltage, as shown below:

![Diagram](image)

This figure shows the phase voltage and current waves in the motoring condition, where the current lags the voltage by angle \( \phi \). The positive half-cycle of current flows through the positive converter, whereas the negative converter takes the negative half-cycle of current. A component converter operates in the rectification mode if the voltage and current are of the same polarity but in the inversion mode if these are of opposite polarity. Both of the component converters in a
phase group can be controlled simultaneously to fabricate the mean output voltage. This will permit the bi-directional phase current to flow freely through either converter. There will, of course, be an instantaneous potential difference between the outputs of two converters, which will tend to cause a short-circuit circulating current. This can be prevented either by blocking the nonconducting converter or allowing a limited amount of circulating current to flow through an intergroup reactor.

The next figure shows the relation between firing angles of positive and negative converters for the same output voltage under continuous conduction.

The output voltage of a converter is given by the general expressions:

\[
V_d = V_{do} \cos \alpha
\]

\[
V_{do} = \sqrt{2} V \frac{p}{\pi} \sin \frac{\pi}{p}
\]

where \( p \) is the pulse number. If the output voltage is positive, say for example, the voltage ratio \( K = 0.5 \), the positive converter operates as a rectifier with firing angle \( \alpha_p = 60^\circ \), and the negative converter operates as an inverter with firing angle \( \alpha_n = 120^\circ \), so that \( V_{do} \cos \alpha_p = V_{do} \cos \alpha_n \). If, instead, the voltage ratio is \( K = -0.5 \), the negative converter operates as a rectifier with \( \alpha_n = 60^\circ \) and the positive converter operates as an inverter with \( \alpha_p = 120^\circ \). In cycloconverter operation, the value of \( K \) is modulated between \( 1.0 \) and \( -1.0 \), maintaining the relation
The output voltage of the cycloconverter can be given in the form

\[ v_0 = \sqrt{2} V_o \sin \omega_s t = V_{d0} \cos \alpha_p = -V_{d0} \sin \alpha_N = m_f V_{d0} \sin \omega_s f \]

where \( V_o \) is the rms output voltage and \( m_f = \sqrt{2} V_o / V_{d0} \) is the modulation factor. The modulation factor is varied between 0 and 1, and correspondingly the firing angles are modulated by the relations

\[ \alpha_p = \cos^{-1}(m_f \sin \omega_s f) \]
\[ \alpha_N = 180^\circ - \alpha_p \]

### 3.2. Three-phase bridge circuit.

Although many different cycloconverter circuit configurations are possible, only one more practical circuit used for large drive applications will be described here. This is the 36-thyristor, six-pulse bridge circuit. Each phase group of the cycloconverter consists of a dual-bridge converter with IGR and the load is shown as wye-connected with isolated windings.

The sinusoidal output voltage can be controlled smoothly between zero and the maximum value by controlling the modulation factor between zero and one. The fundamental voltage can, of course, be increased by saturating the cycloconverter, and ultimately the maximum voltage may be obtained in the square waveform.

For lined-commutated operation of a cycloconverter, the output frequency should be less than the input frequency. Ideally, the lowest frequency may be zero (i.e., dc operation is possible). Zero-frequency operation is desirable for ac servo and slip recovery drives. As the output frequency increases, the harmonic quality of the wave deteriorates and for this reason the output frequency is usually limited to one-third of the supply frequency. The output frequency can be increased above the supply frequency by using forced or load commutation. For a cycloconverter-fed synchronous machine drive, line commutation can be used in the step-down frequency range, but the frequency may be increased to the step-up range using load commutation, where the machine is operated at leading power factor. In this mode, the cycloconverter can be visualized as a step-down frequency changer from output to input, with power flowing from the low-frequency to the high frequency side.
A synchronous motor powered by a cycloconverter can be used as a large low-speed reversing drive with a fast dynamic response. The naturally commutated cycloconverter delivers high-quality sine wave currents at low output frequencies; consequently, the low-speed performance is much superior to that of the LCI-synchronous motor drive with its intermittent dc link current and pulsating torque at standstill and low speeds.

The cycloconverter can function as either a voltage- or current-source supply, and it also permits regeneration to the ac supply network, so that four-quadrant operation is available with a smooth transition through zero speed. The speed range is limited by the usual restriction on the maximum usable ratio of cycloconverter output frequency to input frequency. Large cycloconverter drives are used in mine hoists, reversing rolling mills, and low-speed gearless mill drives.
This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics Principles and Applications</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>Power Electronics converters, Applications and design</td>
<td>Mohan / Undeland / Robbins</td>
<td>John Wiley &amp; Sons</td>
</tr>
<tr>
<td>Power Electronics and AC Drives</td>
<td>B.K. Bose</td>
<td>Prentice-Hall</td>
</tr>
<tr>
<td>Power electronics Circuits devices and applications</td>
<td>Muhammad Rashid</td>
<td>Prentice-hall International</td>
</tr>
</tbody>
</table>

The three-Phase Cycloconverter may be of bridge type with phase control

The three-Phase Cycloconverter has the following parameters:

- Pulse number (6 or 12)
- Output to Input Frequency Ratio
- Relative Output Magnitude
- Transformer turns ratio
The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves, it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
3-Ph AC Controllers

1. DESCRIPTION.

Most power semiconductor switching devices have capability for controlled switching for only one direction of current flow. However, employing a combination of devices, it is possible to use them as bi-directional switches, in AC circuits. In this chapter, we shall present some practical switching control techniques that are used in AC circuits using such switches. We shall first describe how AC switches can be implemented using conventional power devices.

2. CONSTRUCTION.

2.1. AC Switches Using Thyristors

The triac is a bi-directional thyristor that can be turned ON to conduct current in either direction. Its circuit symbol and terminal labels are shown in Fig (a). The power terminals of the triac are labeled main terminal 1 (MT1) and main terminal 2 (MT2). The gate is the control terminal. The gate pulse to turn ON the triac is to be applied between the gate and MT1. A triac can be turned ON by either a positive or a negative gate current pulse for either direction of current. Typically, for positive current direction, which we shall consider as from MT2 to MT1 in the triac, a positive current pulse is used. A negative gate current pulse is typically used for negative current. The triac is a latching device like a thyristor. Just a short gate pulse is sufficient to turn it ON. It turns OFF like a diode or thyristor. As in the case of a thyristor, the gate has no capability to turn OFF the device. After the device has turned ON, the gate loses control over the switching. It regains control after the current has fallen to zero, and needs another gate pulse to turn ON again. In these respects, it is like a thyristor. However, its dynamic switching characteristics are inferior to those of a thyristor. Also, triacs are not available in such high current and voltage ratings as thyristors. Therefore, for many switching applications, AC switches using thyristors may have to be used instead of triacs.

Figures (b), (c) and (d) show three AC switch implementations using thyristors. The arrangement in fig (b) consists of two thyristors in "antiparallel". Thyristor T1 is to be gated for currents in the direction shown in the figure, which we shall treat as positive. T2 should be gated during the negative half-cycle, for negative currents. In this scheme, the gate drive input terminal pairs are separate for the two thyristors: K1, G1 for thyristor T1; and K2, G2 for thyristor T2. This may be a disadvantage from the point of view of the gate firing circuit.
The scheme shown in (c) uses two diodes in addition to the two thyristors. This can be implemented using two switching modules, each module consisting of a thyristor and an antiparallel diode across it. In this scheme, the two thyristor gated can be tied together, and so also the two cathodes, so that there is only one pair of terminals for the gate drive of both thyristors. This may be convenient from the point of view of control circuit design. As can be verified from the figure, the positive current flow path is through T1 and D2, whereas the negative path is through T2 and D1. The current has to flow through two devices—a thyristor and a diode—which will involve more power loss, because of the forward voltage drop of two devices, instead of one in the circuit of (b).

Figure (d) shows an arrangement that needs only one thyristor for both directions of switching. As can be seen, the positive current path is through the diodes D1, D4 and the thyristor, whereas negative currents flow through D2, D3 and the thyristor. Control is simple, because there is only one thyristor to be fired for both positive and negative currents. But current has to flow through three devices, causing added power loss.

2.2. AC Switches Using Other Devices

Switching devices other than thyristors may also be employed to implement bi-directional switches. Figure (a) uses two switching modules in reverse series, each module consisting of a bipolar junction power transistor and an antiparallel diode. For each direction of current, the path consists of one transistor and the antiparallel diode of the other transistor. The base terminals of the two transistors can be tied together, and so can the emitters, so that there is only one pair of terminals for driving the switch. The scheme showed in (b) is similar, but uses power MOSFETs instead of BJTs. With the power MOSFETs, the antiparallel diode can be eliminated because the "body, diode" of the power MOSFET will serve the same function. In Fig. (c), a unidirectional switching device is shown without indicating any specific type of device. Other types of unidirectional switching devices like IGBTs or GTOs can also be used in the circuit arrangements shown in Figs (a) and (c). The switches in these figures have the advantage that turn OFF switching can be performed by means of the control terminal without waiting for the current to fall to zero naturally.
3.1 Series AC Line Switches With Y- or Δ-Connected Loads

In this scheme, there is a bi-directional AC switch in series with each line. The gating circuits of the thyristor should be designed to give the required range of control. A proper return should be available at each instant for the current in each line at each instant. This return path may be through one or both of the other two lines. The scheme may be used with either the Y- or Δ-connected loads shown in these figures. With Δ-connected loads, if the individual phase circuits can be separated, then this following alternative arrangement can be used:

In this circuit, the bi-directional switch is in series with each phase, inside the Δ configuration. Therefore the current in each switch is the phase current and not the line current. For this reason, the current of the thyristors needed may turn out to be smaller which is an advantage.

[Delta connected three-phase controller]
3.2 Neutral Point Controller

In the Y-connected load circuit of the figure (a) above, we notice that each load phase is in series with an AC line switch. Therefore the operation of the circuit will be unaffected if the positions of the switch and the load phase are interchanged. Such an arrangement is shown in the following figure (a). Figure (b) shows an alternative circuit in which the switches are Δ-connected. In these two schemes, the switching control is located in the position of the neutral. A further simplification of the neutral point controller can be done by using only three thyristors instead of six, by the circuit shown in Fig (c). If the gating circuit is suitably designed, a controlled bi-directional current path can be provided for each line current as by switches of the circuits (a) and (b).

![Neutral point switching control schemes]

4. CONTROL.

5. APPLICATIONS.

Reversing Switch for Three-Phase Motors

The direction of rotation of three-phase induction and synchronous motors is reversed by reversing the phase sequence of the three-phase AC connection to the motor terminals. A static switching scheme for doing this using AC thyristor switches is shown below. In this scheme, each of the switches labeled S1...S5 is a bi-directional thyristor switch. S1, S2 and S3 are to be ON for one direction of rotation. The switches that are to be ON for the reverse direction are S1, S4 and S5. It is important to ensure that S2 and S5 are never simultaneously ON at any instant. The same statement applies to S4 and S3. Such an event is short circuit across the lines B, and C.
6. LITERATURE.

This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics, Principles and Applications</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>Electric Machines and drives</td>
<td>Gordon R. Slemon</td>
<td>Addison-Wesley</td>
</tr>
<tr>
<td>Power electronics, Circuits devices and applications</td>
<td>Muhammad Rashid</td>
<td>Prentice-hall International</td>
</tr>
</tbody>
</table>
The three-phase AC Controller may be of the following circuit types:

- Star connection of anti parallel switches
- Delta connection of anti parallel switches

The three-phase AC Controller has the following parameters:

- Control type -S (semi-controlled: half diodes/Half SCRs)
  -F (fully controlled all SCRs)
- Firing angle

8. MODELING.

The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves; it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
In AC applications, the transformer serves to convert electric power efficiently from one voltage level to another. In DC/DC converters, the voltage conversion is achieved by power semiconductors, which function as static switches, switching at a high repetitive frequency. Static dc/dc converters using the switching principle are also known as choppers.

The circuit configuration of a chopper converter can be designed either to step down from a higher input voltage to a lower output voltage, or to step up from a lower input voltage to a higher output voltage. When the voltage conversion ratio \( a = \frac{\text{output voltage}}{\text{input voltage}} \) is less than 1, we call it a voltage step down chopper. If \( a > 1 \), it is a voltage step up chopper. A chopper converter can also be designed in such a way that its circuit incorporates both the steps down and step up switching schemes. Such a converter is called a two-quadrant chopper. Eventually we will also see the multiphase chopper and the thyristor chopper.
3. OPERATION.

3.1. Voltage step down chopper

a. Working principle

This figure shows the circuit configuration of the voltage step down chopper.

![Voltage step down chopper](image)

The chopper is delivering adjustable DC power into a resistive load from a fixed DC voltage source. The chopper power circuit is shown boxed inside broken lines. It consists of two power semiconductor devices, which function as static switches. Of these, the switch labeled S1 is a controlled switching device. This device can be turned on or turned off at will, by the appropriate control signal on its control terminal.

Besides the power circuit shown in this figure, the chopper has a control circuit (not shown for the sake of clarity). It is this control circuit that provides the switching signals to operate the power semiconductor static switch S1 to turn it on and off as required. The power diode is a static switch without a control terminal. It automatically turns on whenever ‘forward’ current flow is possible, and turns off to prevent reverse currents. Both S1 and S2 will be considered as ideal. This implies that their transitions between the on and off states are instantaneous without time delays and voltage drop across the switch terminals in its on state is zero. The load resistance R is connected to the output through an inductance L. The purpose of this inductance is to smooth out fluctuations in the output current caused by the switching process in the chopper.
To operate the chopper, we turn on and off the static switch S1 at a high repetitive frequency. When S1 is turned on, we notice two consequent effects. First, the voltage V1 is applied in reverse across the power diode. Therefore the power diode must stay off as long as S1 remains on. The on state of S1 always implies the off state of S2 (fig a). The second consequence of S1 being on is the build up of current (i2). The growth of i2 occurs exponentially because of the inductance L (fig d). The switch S1 is kept on for a time interval Ton, and then turned off. At this instant when S1 is turned off, i2 has a finite value. We have labeled this current magnitude as I_{p1}. It is the peak value of the output current during the first chopper cycle. This peak current occurs at the instant of turn off of the switch S1. This current cannot instantly fall to zero, because of the presence of the inductance L.

The decay of i2 causes an induced voltage Ldi2/dt to appear across the inductance. Because of this voltage, the diode gets forward-biased and causes the current flow to continue. The purpose of the diode S2 is to provide the freewheeling path when S1 is turned off. Therefore the turning off of S1 automatically causes the turning on of S2 when an inductance with stored energy is present (fig b). The current i2 decays exponentially as long as S1 remains off, that is, for duration Toff. The lowest value to which the current falls at the end of the first chopper cycle is labeled as the valley magnitude, I_{v1}.

Examination of the circuit configurations during the on and off periods of S1 show that, during Ton, the output current i2 is the same as the input current i1 (fig e, f). The second chopper switching cycle commences when S1 is turned on again at the end of the first Toff (fig a). The current again starts to build up. There is already an initial current equal to I_{v1}, and therefore the second peak I_{p2} will be larger than I_{p1}. Consequently, the valley magnitude I_{v2} at the end of the second cycle will also be larger than I_{v1}. In this way both the peak and valley magnitudes progressively increase. After several cycles, the differences between successive cycles become negligibly small.
b. Voltage relationship

On figure (c) we can see the voltage waveform at the output of the chopper. This is a train of rectangular pulses of duration $T_{on}$. This voltage consists of a DC component and an AC component. The AC component is the "ripple voltage". The magnitude of the output DC voltage at the load terminals will be given by the average height of the waveform of figure c. This will be:

$$V_2 = V_1 \cdot \frac{T_{on}}{T} = V_1 D$$

($D$ being the switching duty cycle of the chopper, defined as the ratio of $T_{on}$ time to total cycle time). Therefore the voltage conversion ratio $a$ of the chopper, defined as the ratio of output to input voltage, will be

$$a = \frac{V_2}{V_1} = D$$

The switching duty cycle can be varied in the range 0-1 by variation of the ON time.

c. Duty Cycle Range of practical Choppers

In practical choppers, it is impossible to achieve voltage ratio variation over the full 0-1 range, because the chopper switch, which is a power semiconductor, is non ideal. On the next figure we can see the actual and effective ON and OFF times.

3.2. Voltage step up chopper

a. Power Circuit Configuration

The circuit configuration of the chopper converter used for stepping up a DC voltage is shown in next figure.
The difference in the switching circuit configuration is that in the voltage step up scheme, the positions of the power diode and the controlled switching element are interchanged as compared with the circuit of the voltage step down chopper.

To operate the chopper, the controlled switch S2, is repetitively turned on and off at the chosen frequency.

The power input is from the DC voltage source $V_s$, which is shown on the right, and it feeds power into the load, which is at a higher voltage $V_l$ and is shown on the left. The chopper serves to raise the voltage from the source level to the output level.

There is also a filter circuit, consisting of the elements $C_i$ and $L_i$, used on the high voltage side. With this filter, the current flowing into the load will have reduced ripple. We will assume that these filter elements have large enough values to make the load ripple current negligible. The inductance $L_2$ functions as an interim reservoir of energy, drawing energy from the DC source during the on time of the chopper and feeding the same energy into the source at a higher voltage during the off time of the chopper. It also serves to smooth out ripple current on the low voltage side, which in this case is the input inside. $R_2$ is the unavoidable resistance of the inductive coil $L_2$ and includes the source resistance and wiring resistance.

**b. Analysis**

We shall simplify our analysis by assuming ideal circuit elements. To make the treatment simple, the filter elements $C_i$ and $L_i$ are not shown.

Figure (a) shows the circuit configuration during the on period of the chopper. The voltage across the switch S2 will be zero, and therefore the diode switch S1 will be reverse-biased by a
voltage of magnitude $V_1$ and will remain off. During this interval, current will build up in the inductance to a peak magnitude, which we shall label $I_p$, as a consequence of which some energy will be transferred from the voltage source $V_s$ into the inductor $L_2$.

The circuit configuration during the off period is shown in figure b. When the chopper is turned off, the decay of current in the inductor $L_2$ causes a voltage $Ldi_2/dt$ to occur across it. This adds to the source voltage $V_s$ to forward-bias the diode switch $S_1$ and turn it on. Current flows into the high voltage side, thereby transferring power to the latter from the low voltage side. During this time, the current decays to a valley magnitude, which we shall denote by $I_v$. Depending on the circuit parameters and the duty cycle, the current may decay to zero even before the end of the off period of the chopper switch. In such a case, the current flowing in the voltage source $V_s$ will be discontinuous. For the present, we shall assume that the chopper is operating in the continuous current mode.

c. Voltage ratio

Assuming continuous current flow mode, the waveform of the voltage occurring across the low voltage terminals of the chopper is shown in the next figure.

The DC component will be labeled $V_2$, and is given by the average height of the waveform. Therefore:

$$V_2 = V_1 \frac{Toff}{(Ton+Toff)} = V_1 (1-D)$$

The voltage conversion ratio $a$ of the chopper will be given by:

$$a = \frac{V_1}{V_2} = 1/(1-D)$$
There are some advantages if, instead of a single chopper, we employ several in parallel to supply current to a load. All the choppers will be identical and operating with the same switching frequency and the duty cycle. However, their switching periods will be phase-displaced with respect to each other.

The primary advantage is the higher ripple frequency in the ripple output, making it easier to filter off the ripple currents. Such a scheme, consisting of two or more choppers operating in parallel, with mutual phase displacement in their switching periods, is called a multiphase chopper. Figure (a) shows the general m-phase voltage step down chopper.

Two specific examples of multiphase choppers - the biphase chopper (m = 2) and the three-phase chopper (m = 3) - are shown respectively in Figs (b) and (c). The input filter consisting of L₁ and C₁ is shown in each circuit. Each chopper has a separate but identical output smoothing inductance labeled L₂. The resistance labeled R₂ is the unavoidable resistance of this inductive coil. An additional common inductance labeled L₃ is also shown in the load circuit. To make the circuit more general, we have also included a "back e.m.f." labeled Vs, such as will be present in a DC motor speed control application, in addition to the load circuit resistance Rs.
Each chopper in the general m-phase chopper will have the same switching frequency and duty cycle. However, the start of the switching period of chopper 2 will be delayed with respect to the start of the switching period of chopper 1 by an interval equal to $T/m$ seconds, which will correspond to a phase delay of $360^\circ /m$ in angular measure. Similarly, chopper 3 will have a phase shift of $360^\circ /m$ with respect to chopper 2 and so on. In the biphase, the phase displacement will be $180^\circ$, while for the three-phase chopper, it will be $120^\circ$.

The effects of this phase shift on the current waveforms of the individual choppers and on the resultant load current are illustrated in fig (a) and (b):

![Waveforms](image)

(a) Case of a biphase chopper  
(b) Case of a three-phase chopper

3.4. Thyristor Chopper

a. Need for Force Commutation

For the proper operation of the chopper circuits, or any power electronic circuit, the controlled switching elements have to be turned ON and turned OFF at the required instants of time. In most power semiconductor switching devices, this is done by providing the appropriate switching control signal input at the control terminal of the device. For example, an IGBT is turned ON by a positive voltage on its gate terminal and turned OFF by a zero volt signal at the same terminal.
The thyristor, which is an important power-switching device, is a singular exception to this rule. The gate terminal is useful only for the turn ON switching. It is ineffective for implementing the turn OFF switching. The practical method employed to turn OFF a thyristor that is already ON in a DC circuit is to impress a reverse voltage across its power terminals, namely, the anode, and the cathode. In this way, by "forcing", the anode to go negative, at least temporarily, it can be turned OFF or "commutated." (Commutation implies turn OFF switching in the terminology of Power Electronics).

The circuit that provides this force commutation impulse is in the power circuit, connected between the anode and cathode of the thyristor. Since the force commutation circuit is part of the power circuit of the converter, its operation will to some extent depend on the rest of the power circuit. Force commutation circuits are necessary when thyristors are employed as switching elements on a DC side in power electronic converters. For a thyristor converter, such as a rectifier for conversion from AC to DC, the reversals of the AC line voltage present will serve to reverse-bias and turn OFF the thyristors, and no force commutation circuits are normally necessary. The turn OFF switching in such converters takes place by "line commutation." In practice, line commutation is employed in AC/DC thyristor converters, and their switching frequencies are the relatively low power system frequencies, such as 50 or 60 Hz. For these, it is economical to use a category of thyristors, with longer turn OFF switching times, often classified as line commutated types. Another category of thyristors, with short turn OFF times, often called "fast turn OFF" type, has to be chosen for force commutated thyristor converters such as choppers.

Several types of force commutation circuits have been developed each with its relative merits and demerits. For the force commutated thyristor chopper that we are going to describe here, we have selected a practical circuit whose operation is relatively simple. The method of analysis that we shall present can generally be used with appropriate changes for other force commutation circuits also.

[Force commutated thyristor chopper]
b. Operation and Analysis

The figure above shows the circuit of a force commutated thyristor chopper for voltage step down conversion. The input is the DC voltage source labeled V. The load is the resistor labeled R_L. L_s is the smoothing inductance on the load side. An input filter is omitted for the sake of clarity. The power switching elements of the chopper are the freewheeling diode labeled D_F and the controlled switching element, which is the main thyristor labeled T_M. Turn ON switching of the main thyristor is achieved by the circuit block labeled G_F1, which supplies the gate firing pulses to the gate of T_M. The circuit block shown boxed inside the broken lines is the force commutation circuit, which serves to turn OFF the main thyristor T_M.

The force commutation circuit shown has five circuit elements. Two of these are the diodes labeled D_1 and D_2. Their role will be understood from the description that follows. Two other elements of the force commutation circuit are the "commutating capacitor" labeled C and the "commutating inductor" labeled L. L and C constitute an oscillatory circuit, whose oscillations serve to achieve the commutation of the main thyristor T_M in the manner to be described below. T_A is an auxiliary thyristor, for which the gate turn ON pulses are provided by the circuit block labeled G_F2. The turn OFF switching of the main thyristor is initiated by a gate pulse on the gate of the auxiliary thyristor T_A through the action of its gate firing circuit G_F2. Then follows an extremely fast sequence of circuit changes, usually lasting only some microseconds, culminating in the commutation of T_M. We shall now go through these circuit changes to give a clear understanding of the force commutation process. For this we shall assume that the chopper has been operating long enough to justify the assumption of repetitive conditions.

We shall also assume that the load smoothing inductance L_s is large and therefore the load current I_L can be assumed constant during the commutation sequence.

4. CONTROL

4.1. Switching control circuits for chopper converters

a. Functional Requirements of the switching control circuit

A chopper converter, like other power electronic converters, has a power circuit section and a switching control circuit section. The ultimate purpose of the switching control circuit section in a power electronic converter is to provide the necessary inputs to the control terminal of every power semiconductor switching element of the converter, so that it switches ON and OFF with the correct timing, to enable the converter to operate in the required manner.
Referring to this figure, which applies generally to a typical power electronic converter, the power circuit section consists of a configuration of power semiconductor switching elements through which power from its input terminals is delivered to a load circuit connected to its output terminals. Filter circuits, which may also exist on the input and output sides, are not included in this figure, since these are external to the power switching section. The power circuit section ordinarily has to handle relatively large voltages and currents. The switching control section, on the other hand, normally works from low voltage power supplies, and generally consists of integrated circuits and other low power electronic components, usually assembled on printed circuit boards. In this figure we have shown three functional circuit blocks within the switching control section. These are labeled as the control block, the timing block and the driver block.

The timing block actually generates the timing pulses, according to the required switching pattern of the converter. For example, in the case of a chopper, it should produce the pulses of the required frequency and duration needed for the controlled chopper switch (or switches if the chopper is multiphase). But if the chopper is used for a specific application, it will be necessary to vary the duty cycle to satisfy the needs of the application. For example, if the chopper is used for the speed control of a DC motor, we may use a closed-loop control circuit to maintain the speed at the wanted value. The closed-loop controller will sense the actual speed and compare it with the reference input to it. There may also be other inputs to the closed-loop controller, such as the motor current, because the controller may have to limit the motor current within safe limits. All of these are included in what we have grouped as the control circuit block. This block processes all the input information into it and decides the duty cycle at which the chopper should work at a given instant of time. It provides an input voltage to the timing circuit block to vary the widths of the timing pulses, and so achieve this duty cycle. What we want to point out here is that the controller block basically depends on the specific application of the chopper. Since this chapter is not intended to cover the applications of the chopper, we shall not give further consideration to the controller block here. The output pulses of the timing block, in general, may not be suitable for being directly applied to the control terminals of the semiconductor switching elements. The three main reasons for this are as follows.

1. The power capability of the timing pulses may be insufficient.

2. The nature of the timing pulses may not suit the particular type of switching element. For example, if the switching element is a GTO, what it needs to turn ON is a positive current pulse, of short duration only, into its gate terminal. An IGBT, on the other hand, requires a positive voltage input for the entire duration of the ON time.

3. There is usually a need to provide electrical isolation between the timing circuit (in fact, the whole control section) and the power circuit. The driver circuit block serves to meet these requirements.
The driver circuits employed depend, in general, on the type of power semiconductor switch employed. For these reasons, we shall limit further treatment in the present chapter to the timing circuit block only.

b. Generation of timing pulses for a single-phase chopper

The block schematic of a circuit scheme for generating the timing pulses for a single-phase chopper is shown in fig (a). The switching frequency of the chopper is set by programming the circuit block labeled "clock oscillator" to output pulses at this frequency. If there is a need to vary the chopper frequency then we may use a voltage-controlled oscillator for our clock and adjust the frequency as required, by adjusting the reference voltage to it. The output of the clock generator is used to synchronize the frequency of the ramp generator. The ramp voltage output is compared with an adjustable control voltage using a comparator chip. The comparator output serves as the timing pulses for the chopper. The ON period of the chopper will be the pulse width of the timing pulses from the comparator.

The output pulse width, and therefore the duty cycle of the chopper could be varied by varying the control voltage input to the comparator, as shown in the figure.

If the power semiconductor switch of the chopper is a latching device such as a GTO, what is mainly needed to turn it ON will be a pulse of short duration at each leading edge of the timing pulse of the train. For turn OFF switching, it will need another pulse at each trailing edge of the timing pulse train. These can be obtained by using two-monostable multivibrator chips- one triggered by the leading edges and the other triggered by the trailing edges. In the case of a force commutated thyristor chopper, the monostable outputs at the leading edges can be used to time the gate firing input of the main thyristor and the monostable outputs at the trailing edges to time the gate firing of the auxiliary thyristor.
c. Generation of timing pulses for multiphase choppers

A multiphase chopper will require one timing waveform for each phase. A scheme that achieves this, and ensures the exact phase shift between phases, is illustrated here for a three-phase chopper. For a multiphase chopper with m phase m, we shall use a clock oscillator frequency equal to m times the chopper frequency. We can then divide this frequency by m using an m-stage ring counter. Each of the outputs of the ring counter serves as the clock for each individual phase. The control voltage input to all the m comparators will be common, so that the duty cycles of all the choppers can be simultaneously adjusted by the same control voltage.
5. APPLICATIONS.

5.1 Two quadrant choppers

On this figure we can see the voltage step down and voltage step up modes. This figure is typical of a DC motor speed control application.
5.2 Four-quadrant chopper

For very fast reversals, in a fully static manner, without the use of mechanical switching, it is best to use a four-quadrant chopper.

For further information, go and see Chopper DC motor drives

6. LITERATURE.

This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power electronics: Principles and</td>
<td>Joseph Vithayathil</td>
<td>Stephen W Director</td>
</tr>
<tr>
<td>Applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Machines and drives</td>
<td>Gordon R. Slemon</td>
<td>Addison-Wesley</td>
</tr>
<tr>
<td>Power electronics Circuits devices and</td>
<td>Muhammad h. Rashid</td>
<td>Prentice-hall International</td>
</tr>
<tr>
<td>applications</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7. PARAMETERS.

The chopper has the following parameters:

- Chopper output voltage
- Chopper operation frequency
- Chopper capacitance
- Chopper inductance
The power electronic converter converts electric energy of one form to another. Thus there are many different kinds of converters from the simplest (a diode) to the most complicated (a multiphase cycloconverter).

Each converter is composed mainly of semiconductor valves, it is supplied from a voltage (or current) source and supplies a passive load or an electrical motor. Each converter valve is considered as a switch, which can be opened or closed. The state of each switch is characterized with a state variable the value of which can be one (switch closed) or zero (switch open). Each valve opens when its current becomes zero and closes when its anode to cathode voltage becomes positive (diode) and its gate gets a firing pulse (thyristor).

The converter output voltage is calculated from the input voltage, the state variables of the converter valves and the converter topology. The output current is calculated from the differential equations of the output load which, using the method of equivalent elements, are transformed to algebraic ones. The valve currents are calculated from the output current and the converter topology.
A set of chopper circuits capable of producing a controllable direct voltage in one, two, or four quadrants are described in DC chopper theory. These choppers can be combined with a commutator motor to produce a variable-speed drive. Two kinds of choppers are largely used in Industrial applications.

2. CONSTRUCTION.

A chopper drive system is shown here. The voltage $V$ at the chopper is constant. If the circuit inductance is sufficient to maintain continuous armature current, the average armature terminal voltage is:

$$<V_c> = \frac{(t_{on}/T)}{V}$$
3. OPERATION.

3.1 Two-quadrant chopper

This figure is typical of a DC motor speed control application. The motor is on the low voltage side of the chopper and the DC supply is on the high voltage side.

![The two operating modes of the two-quadrant chopper](image)

The polarity of the induced voltage in the motor depends on its direction of rotation. In both figures, the motor is spinning in the same direction, and therefore has the same polarity of terminal voltage. However, in fig a, the motor is driving a load, and is therefore drawing power through the chopper. It is therefore drawing current in the direction shown, which we shall consider as the positive direction. In fig b the motor is being regeneratively braked, and therefore the current is negative. If we plot on a graph the motor voltage along the vertical axis and the motor current along the horizontal axis, all the operating points on this graph for the driving mode will lie in the first quadrant (positive I and positive V).

For the braking mode, all the operating points will be in the second quadrant (negative I and positive V). This is illustrated in the next figure:

![Diagram of two quadrants](image)

A chopper designed for changeover from one mode to the other at will is called a two-quadrant
chopper. In a two-quadrant chopper the changeover between driving and braking can be implemented in one of two possible ways.

A. Mechanical change-over scheme.

We can physically change the connections to the controlled switch and the power diode. In this case, we need to have only one controlled switching element and one power diode for both modes of operation of the chopper. For example, we can implement the circuit change by either a manually operated or an electromagnetically operated switch. Such a scheme is illustrated by this figure.

![Mechanical change-over scheme](image)

The three terminals of the circuit that are connected to the static elements of the chopper are labeled X, Y and Z. The terminals of the static elements of the chopper are shown in Fig (b), with the terminals of the controlled switch labeled 1 and 2 and those of the power diode labeled 3 and 4. The changeover between driving (voltage step down mode) and breaking (voltage step up mode) is implemented using a four-pole double-throw switch, which may be designed for either manual or relay operation. In one position of the switch, the terminals X, Y and Z are connected to 1, 2, 3 and 4 as shown in Fig (c). This will give us the configuration for driving, that is, the voltage step down mode of the chopper. The interconnections between X, Y and Z and 1, 2, 3 and 4 as shown in the second position of the switch in Fig (d) will give us the braking or voltage step up mode.

B. Static changeover scheme.

In this scheme, we use two controlled switches and two power diodes. Each controlled switch has a power diode in 'antiparallel' with it as shown in the next figure. A controlled switch together with its antiparallel diode constitutes a switching block. For example switching block 1 consists of the controlled switch S1 and its antiparallel diode D1. Similarly, switching block 2 consists of S2 and D2. The controlled switches are IGBTs, but they could be any types of controlled power switching device such as power BJTs, power Darlington or GTOs. If the switch is a power MOSFET there is generally no need to have a separate antiparallel diode, because a power MOSFET functions as a diode for reverse current flow. To operate the two-quadrant chopper in the voltage step down (driving) mode, we block the switching control pulses to the gate of S2 and channel them to the gate of S1. S2 and D1 will be inoperative during this mode of operation. To change over to voltage step up (braking) mode, we block the gate pulses to S1 and channel them to S1. In this mode, S1 and D1 will be inoperative. The inhibition of
pulses to one switching block and the channeling of them to the other can be done in the gating control circuit of the chopper. There will be no need for mechanical switching in the power circuit.

If a battery-powered car is powered by a DC motor with two-quadrant chopper control, it is relatively easy to implement the changeover with the driving foot pedal itself. When the latter is pressed down, the gate pulses to S1 are inhibited and they are channeled to S1. The duty cycle will be controlled by the downward position of the pedal. Upward movement of the pedal, beyond a limiting position, will block the switching pulses to S1 and channel them to S2, thereby moving into regenerative braking. The duty cycle, and therefore the braking torque, will be dependent on the upward displacement of the pedal. This makes it possible to do normal driving and braking using a single pedal only, and use friction braking only for stopping and emergencies.

3.2 Four-quadrant chopper

For very fast reversals, in a fully static manner, without the use of mechanical switching, it is best to use a four-quadrant chopper, the circuit configuration of which is shown in this figure.
The static four-quadrant chopper has four switching modules, labeled by subscripts 1,..., 4. Each switching module consists of a controlled static switch, together with an antiparallel diode. The manner of switching control by pulse with modulation may be described as follows. For one direction of rotation, which we shall call the forward direction, the switches S2 and S3, will be kept OFF. S4 will be kept ON. The motor speed will be controlled through pulse width modulation of the switch S1. If now a change to a target speed in the reverse direction is to be implemented, the motor is first braked regeneratively until the speed falls to zero, and then accelerated in the reverse direction to achieve the target speed. The sequence of operation will be as follows. All the switches will be turned OFF at first. This will cause the motor current to flow through the diodes D2 and D3, causing the current in the motor circuit, consisting of the motor armature and the smoothing inductor, to fall to zero. After this, braking is initiated by the pulse width modulated switching of the static switch S3. During the ON period of S3, current will build up in reverse through D1 and S3 because of the induced e.m.f of the armature. During the OFF period of S3, energy will be fed back to the source by current flow through D1 and D4. The braking current will be controlled to give the desired braking torque characteristic by appropriate control of the duty cycle of the static switch S3 during the braking period. At the end of the braking period, when the motor speed has fallen to zero, the static switch S2 will be turned ON, and the operation will shift to the driving mode in the reverse direction by continuing the pulse width modulated switching of S3. The motor will accelerate and come to the desired speed in the reverse direction.

4. CONTROL.

5. APPLICATIONS.

Chopper drives are widely used in traction applications all over the world. A DC chopper can provide regenerative braking of the motors and can return energy back to the supply. This energy-saving feature is particularly attractive to transportation systems with frequent stops such as mass rapid transit (MRT). Chopper drives are also used in battery electric vehicles.
This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics, Principles and</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>Applications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric Machines and drives</td>
<td>Gordon R. Slemen</td>
<td>Addison-Wesley</td>
</tr>
<tr>
<td>Power electronics Circuits devices and applications</td>
<td>Muhammad R. Rashid</td>
<td>Prentice-hall International</td>
</tr>
</tbody>
</table>

The chopper has the following parameters:

- Chopper output voltage
- Chopper operation frequency
- Chopper capacitance
- Chopper inductance

The Direct Current Motor may be of the following four types:

- Compound field
- Series field
- Parallel field
- Independent field
The motor has the following parameters
- Stator Poles
- Rotor Inertia
- Rotor Friction Coefficient
- Armature Resistance
- Armature Inductance
- Series Field Resistance
- Series Field Inductance
- Series Field Constant
- Parallel/Independent Field Resistance
- Parallel/Independent Field Inductance
- Parallel/Independent Field Constant
- Mutual Inductance

The motor load can be of the following types (load Torque as function of motor speed)
 a. Step - Constant torque
 b. Line - Torque proportional to speed
 c. Square - Torque proportional to speed square
 d. Cube - Torque proportional to speed cube

The motor load has the following parameters
- Load Inertia
- Load Friction coefficient
8. MODELING.

Each motor drive is composed of a motor and a power electronic converter, which usually transforms electrical energy in the form which is needed to supply the electrical motor, which is used as a load of the converter. Thus the system model is composed of the models of individual components.

Each drive may also have a control system, which controls the motor speed and limits the motor input current.
Each of the single-phase circuit configurations of the following table can be used to control the armature voltage and current of a separately excited d.c. motor. For the half-wave semiconverter and full converter connections the armature current $i_a$ is unidirectional, whereas the double converter permits the flow of armature current in either direction. The polarity of the armature voltage $v_a$ is non-reversible for the half-wave and semi-converter circuits. The fully controlled converter enables positive or negative armature voltage to be applied while the double converter is completely comprehensive and permits operation in any of the four quadrants of the armature voltage-current plane.
## 2. CONSTRUCTION.

<table>
<thead>
<tr>
<th>Type</th>
<th>Circuit</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>half-wave</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>1 pulse</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>semi-convener</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>2 pulse</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>full converter</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>2 pulse</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>double converter</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
<tr>
<td>2 pulse</td>
<td><img src="#" alt="Circuit Diagram" /></td>
<td><img src="#" alt="Operation Diagram" /></td>
</tr>
</tbody>
</table>
3. OPERATION.

3.1 Single-phase semi-converter

The two versions of the semi-converter in the table result in identical load-side performance. The freewheel diode version of the converter is shown in the following figure, in which the d.c motor is represented by its equivalent circuit.

Consider the case in which the armature current is continuous, for which typical waveforms are shown in the next figure, when $\alpha = 60^\circ$. 
While $v_a$ is positive the freewheel diode is reverse biased and held in extinction.

While current flow is blocked in the SCRs, in the interval $0 < \omega t < \alpha$, for example, no supply current can flow and the load current freewheels through FWD. Each SCR carries one of the pulses of the supply current during each supply voltage cycle. The load voltage are given by:

$$v_a = i_a R_a + L_a \frac{di_a}{dt} + e_b, \alpha \leq \omega t \leq \pi$$

$$0 = i_a R_a + L_a \frac{di_a}{dt} + e_b, \pi \leq \omega t \leq \pi + \alpha$$

The time average value of the armature voltage is designated $V$ or $V_{\text{ averages}}$:

$$V = V_{\text{av}} = \frac{1}{2\pi} \int_0^{2\pi} v_a(\omega t) \, d\omega$$

$$= \frac{1}{\pi} \int_0^\pi E_m \sin \omega t \, d\omega$$

$$V_{\text{av}} = \frac{E_m}{\pi} \left( 1 - \cos \alpha \right)$$
The average load current:

\[ I_{av} = I_a = \frac{V_{in} - E_b}{R_a} = \frac{E_m}{\pi R_a} (1 + \cos \alpha) - \frac{E_b}{R_a} \]

For a separately excited d.c. motor the instantaneous speed is proportional to the instantaneous back e.m.f. Curve figure therefore also depicts the speed-time variation. The r.m.s. and harmonic properties of the current waveform can only be accurately determined if analytical expressions are known for the instantaneous variables \( i_d(\omega t), i_s(\omega t) \) and \( i_{FDP}(\omega t) \). Some approximation to the values of, for example, r.m.s armature current and load power can be obtained by neglecting the ripple component of \( i_s(\omega t) \) and assuming constant armature current. Alternatively one can calculate the harmonics of the load voltage and determine corresponding current harmonic by dividing by the appropriate harmonic impedance.

### 3.2 Single phase full converter

The two-quadrant, four-switch, full converter circuit is applied to a separately excited d.c. motor load, as shown in the following figure.

![Single phase full converter circuit](image)

Alternate switching of the pairs of SCRs \( Th1, Th4 \) or \( Th2, Th3 \) is used. If \( Th1, Th4 \) are conducting, for example, positive supply voltage is applied to the motor.

The applied voltage from the ideal supply, is defined as:

\[ e = E_m \sin \omega t \]

This voltage is applied across the elements \( R_a \) and \( L_a \) in series with the back e.m.f. \( e_b \) so that

\[ E_m \sin \omega t = i_a R_a + L_a \frac{di_a}{dt} + e_b(\omega t) \]

At an arbitrary instant of time defined by \( \omega t = \alpha \), the net voltage impressed across the series R-L elements.

\[ E_m \sin \alpha - e_b(\alpha) = i_a R_a + L_a \frac{di_a}{dt} \]
3.2.1 continuous conduction

If $E_m \sin \alpha > e_b (\alpha)$ then current $i_a (\omega t)$ will flow continuously. The continuous current mode is illustrated for the case $\alpha = 60^\circ$.

Instantaneous back e.m.f variation $e_b (\omega t)$ follows the curve of instantaneous speed variation $n (\omega t)$. With a fully controlled converter, conduction occurs in $180^\circ$ pulses of supply current from $\alpha < \omega t < \pi + \alpha$. Each pair of thyristors conducts, in turn, for one-half of a supply cycle so that all four thyristors must be equally rated. When thyristors $Th_2, Th_3$ are triggered at $\omega t = \pi + \alpha$, negative voltage is applied across $Th_1, Th_4$ which causes them to commute naturally.
3.2.2 Discontinuous conduction

Consider the conduction where the armature current ia (ωt) falls to zero before the next pair of SCRs is switched in. In the following figure, the conduction of armature current occurs between the limits α < ωt < X, where X is the extinction angle and X < Π + α. In the interval X < ωt < Π + α, for example, all the SCRs are switched off and the load and supply currents are zero. During the current extinction intervals the back e.m.f of the motor is the only component of load voltage and this maps the time variation of the instantaneous speed.

3.2.3 Power and power factor

The power dissipated in the load branches equal to:

\[ P_a = I_a^2 R_n + E_b I_a \]

Component of power \( E_b I_a \) represents the output power plus the motor friction and windage losses. In terms of motor developed torque \( T \),

\[ E_b I_a = TN = P_{out} \]
Neglecting the power loss in the rectifier switches and ignoring the motor core and rotational losses, the operating efficiency is

\[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{E_b I}{P_a} \]

Since the input current has a r.m.s value equal to that of the motor current the operating power factor is:

\[ PF = \frac{P_a}{\frac{E_m}{\sqrt{2}} \times I_L} \]

This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics Principles and Applications</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>Power Electronics converters, Applications and design</td>
<td>Mohan / Undeland / Robbins</td>
<td>John Wiley &amp; sons</td>
</tr>
</tbody>
</table>
7. PARAMETERS.

1. **Electrical supply.**
   
   1. Single Phase Rectifier Supply
      
      a. Symmetrical Sinusoidal with the following parameters
         
         - Phase amplitude
         - Frequency
      
      b. Symmetrical Sinusoidal Harmonical with the following parameters
         
         - Phase amplitude
         - Frequency
         - Additional Harmonic Class
         - Additional Harmonic Amplitude
         - Additional Harmonic Phase
   
   2. Independent field DC Supply
      
      - Constant Direct Voltage

2. **1-Phase Rectifier**

   - 1-pulse without freewheeling diode
   - 1-pulse with freewheeling diode
   - 2-pulse without freewheeling diode
   - 2-pulse with freewheeling diode
   - 2-pulse bridge without freewheeling diode
   - 2-pulse bridge with freewheeling diode
The **1-Phase Rectifier** has the following parameters

- Rectifier control type
  - No (with diodes)
  - Sm (half diodes half SCRs)
  - Fu (with SCRs)
  - Se (user selects the switching elements type)
- Transformer turns ratio
- Firing angle
- Elements type

The Direct Current Motor may be of the following four types

- Compound field
- Series field
- Parallel field
- Independent field

The motor has the following parameters

- Stator Poles
- Rotor Inertia
- Rotor Friction Coefficient
- Armature Resistance
- Armature Inductance
- Series Field Resistance
- Series Field Inductance
- Series Field Constant
- Parallel/Independent Field Resistance
- Parallel/Independent Field Inductance
- Parallel/Independent Field Constant
- Mutual Inductance

The motor load can be of the following types (load Torque as function of motor speed)

a. Step - Constant torque
b. Line - Torque proportional to speed
c. Square - Torque proportional to speed square
d. Cube - Torque proportional to speed cube

The motor load has the following parameters

- Load Inertia
- Load Friction coefficient

8. MODELING.

Each motor drive is composed of a motor and a power electronic converter, which usually transforms electrical energy in the form which ids needed to supply the electrical motor, which is used as a load of the converter. Thus the system model is composed of the models of individual components.

Each drive may also have a control system, which controls the motor speed and limits the motor input current.
Three-phase converters are extensively used in adjustable speed d.c. drives for a wide range of power. The three-phase, half-wave circuit, shown in the construction part, is not greatly used because of the d.c. components inherent in its line currents. The adoption of a full-wave bridge circuit not only eliminates the d.c. components in the supply lines but also permits optimum utilization of the principal electrode ratings of the switches.
2. CONSTRUCTION.

Here we can find four different kinds of Three-phase naturally commutated controlled converter circuits.

<table>
<thead>
<tr>
<th>Type</th>
<th>Circuit</th>
<th>Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>half-wave</td>
<td><img src="image1" alt="Circuit" /></td>
<td><img src="image1" alt="Operation" /></td>
</tr>
<tr>
<td>3 pulse</td>
<td><img src="image2" alt="Circuit" /></td>
<td><img src="image2" alt="Operation" /></td>
</tr>
<tr>
<td>semi-converter</td>
<td><img src="image3" alt="Circuit" /></td>
<td><img src="image3" alt="Operation" /></td>
</tr>
<tr>
<td>3 pulse</td>
<td><img src="image4" alt="Circuit" /></td>
<td><img src="image4" alt="Operation" /></td>
</tr>
<tr>
<td>full converter</td>
<td><img src="image5" alt="Circuit" /></td>
<td><img src="image5" alt="Operation" /></td>
</tr>
<tr>
<td>6 pulse</td>
<td><img src="image6" alt="Circuit" /></td>
<td><img src="image6" alt="Operation" /></td>
</tr>
<tr>
<td>double converter</td>
<td><img src="image7" alt="Circuit" /></td>
<td><img src="image7" alt="Operation" /></td>
</tr>
<tr>
<td>6 pulse</td>
<td><img src="image8" alt="Circuit" /></td>
<td><img src="image8" alt="Operation" /></td>
</tr>
</tbody>
</table>

With passive impedance loading, a three-phase full-wave bridge has twice the load voltage and four times the power capability, compared with the peak phase voltage for a half-wave bridge. But the bridge switches in a full wave circuit have to be rated for the peak line voltage compared with the peak phase voltage for a half-wave circuit. When reversible armature current is needed, to give four-quadrant operation, the double converter is used.

When the application involves medium size motors, either the semi-converter or full converter is used.

3. OPERATION.

3.1 Three-phase semi-converter

The semi-converter circuit includes a freewheel diode FWD to assist in maintaining continuous load current. A cost advantage is obtained by the use of diodes in the lower half of the bridge, compared with the full converter. A further advantage is realized in that the semi conductor circuit absorbs less reactive volt-amperes than the fully controlled converter. The average voltage, at the load contains a contribution from the controlled upper half-bridge plus a contribution from the uncontrolled lower semi-converter. With continuous current (corresponding to high inductance operation with passive loads), for all firing-angles, one may
represent the average load voltage.

\[ V_{L_{av}} = \frac{3\sqrt{3}E_m}{2\pi} + \frac{3\sqrt{3}E_m}{2\pi} \cos \alpha \]

\[ = \frac{3\sqrt{3}E_m}{2\pi} (1 + \cos \alpha) \]

When \( \alpha = 0 \) the average output voltage becomes identical to that of an uncontrolled three-phase bridge. The average armature current is equal to:

\[ I = I_{L_{av}} = \frac{V_{L_{av}} - E_b}{R_a} \]

\[ = \frac{3\sqrt{3}E_m}{2\pi R_a} (1 + \cos \alpha) - \frac{E_b}{R_a} \]

RQ: The two equations are not valid for discontinuous current operation.

### 3.2 Three-phase full converter

A circuit diagram is given in the next figure, in which the motor armature is represented by its equivalent circuit. With low armature inductance and large SCR firing-angle the armature current may become discontinuous especially if the d.c. motor speed (and therefore back e.m.f) is high. If the motor armature circuit contains substantial series inductance and the firing angle is small, then the armature current is likely to be continuous, even with a large motor back e.m.f.
3.2.1 Continuous conduction

Load voltage and current waveforms for continuous armature current operation are shown in the next figure, for a case when $E_b = E_m/4$. For all values of $\alpha$ the load voltage is defined by:

$$V = V_{Lm} = \frac{3\sqrt{3}}{\pi} E_m \cos \alpha$$

The average armature current therefore has the value:

$$I = \frac{V_{Lm} - E_b}{R_a}$$

$$= \frac{3\sqrt{3}}{\pi R_a} E_m \cos \alpha - \frac{E_b}{R_a}$$
3.2.2. Discontinuous conduction

Consider the conduction shown in the following figure, where the same e.m.f. condition applies as in the figure of the continuous conduction (i.e. $E_b = E_m / 4$), but now the motor operates with a much lower value of armature circuit inductance so that discontinuity of the armature current has occurred by the stage $\alpha = 60^\circ$. Individual pulsations of current now occupy a conduction period
\( \theta_c \) which is less than the corresponding interval of 60° obtained with continuous operation. At \( \alpha = 75^\circ \) the average load voltage is \( \cos \alpha = 0.26 \), which is only marginally greater than the back e.m.f. The current pulsations are therefore very small and become zero when \( V_{La} = E_b \).
3.3. Three-phase double converter

If control is required for both forward and reverse speeds and the production of positive and negative torques one can use a fully controlled bridge incorporating reversal of the applied armature voltage. A better solution is the use of the double or dual converter, which avoids the need for change-over switches.

The average motor voltage is required to be identical for both bridges, which sets up an ideal requirement that the firing-angles of the two sets of thyristors should sum to 180°. A series inductance is included in each of the four motor legs to accommodate the inevitable ripple voltage due to instantaneous inequalities. By controlled firing, negative armature voltage and current may be used to obtain reverse speed operation. If the two bridges operate consecutively so that conduction occurs in only one bridge at a time, with the other completely blocked, the mode of control is called "circulating current free operation". This mode of operation is realized provided that the motor current is continuous but serious difficulties arise if the current becomes discontinuous but serious difficulties arise if the current becomes discontinuous.

Alternatively, the two bridges can operate concurrently with a regulated degree of circulating current in a mode of control known as "circulating current operation". The circulating current acts to maintain armature current at all times with both converters in continuous conduction.
This information has been taken from different power electronics books. Those books are:

<table>
<thead>
<tr>
<th>Name of the book</th>
<th>Author</th>
<th>Editorial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Electronics: Principles and Applications</td>
<td>Joseph Vithayathil</td>
<td>Stephen W. Director</td>
</tr>
<tr>
<td>An introduction to power electronics</td>
<td>B.M. Bird / K. G. King / D. A. G. Pedder</td>
<td>John Wiley &amp; sons</td>
</tr>
</tbody>
</table>

1. **Electrical supply.**
   
   1. Three-Phase Rectifier Supply
      
      a. Symmetrical Sinusoidal with the following parameters
      
      - Phase amplitude
      - Frequency
b. Symmetrical Rectangular with the following parameters
- Phase amplitude
- Frequency

b. Asymmetrical Sinusoidal with the following parameters
- Phase amplitude
- Frequency
- Asymmetrical phase Number
- Asymmetry percentage

d. Symmetrical Sinusoidal Harmonical with the following parameters
- Phase amplitude
- Frequency
- Additional Harmonic Class
- Additional Harmonic Amplitude
- Additional Harmonic Phase

2. Independent field DC Supply
- Constant Direct Voltage

2. 3-Phase Rectifier
- 3-pulse
- 6-pulse
- 12-pulse

The 3-Phase Rectifier has the following parameters
- Rectifier control type
  - No (with diodes)
  - Sm (half diodes halfSCRs)
  - Fu (with SCRs)
- Transformer turns ratio
The Direct Current Motor may be of the following four types

- Compound field
- Series field
- Parallel field
- Independent field

The motor has the following parameters

- Stator Poles
- Rotor Inertia
- Rotor Friction Coefficient
- Armature Resistance
- Armature Inductance
- Series Field Resistance
- Series Field Inductance
- Series Field Constant
- Parallel/Independent Field Resistance
- Parallel/Independent Field Inductance
- Parallel/Independent Field Constant
- Mutual Inductance

The motor load can be of the following types (load Torque as function of motor speed)

a. Step - Constant torque
b. Line - Torque proportional to speed
c. Square - Torque proportional to speed square
d. Cube - Torque proportional to speed cube
The motor load has the following parameters

- Load Inertia
- Load Friction coefficient

8. MODELING.

Each motor drive is composed of a motor and a power electronic converter, which usually transforms electrical energy in the form which ids needed to supply the electrical motor, which is used as a load of the converter. Thus the system model is composed of the models of individual components.

Each drive may also have a control system, which controls the motor speed and limits the motor input current.
In the circuit of the Subsynchronous cascade, shown in the next figure, the d.c. link converter consists of a three-phase diode rectifier bridge which operates at slip frequency and feeds rectified slip power through the smoothing inductor to the phase-controlled thyristor inverter. The inverter returns the rectified slip power to the ac supply network. The rectifier and inverter are both naturally commutated by the alternating emfs appearing at the slip-rings and supply busbars, respectively.

[Induction motor and subsynchronous static converter cascade]
The rectification of the slip-ring voltages eliminates the problem of matching the frequencies of the injected emf and the rotor emf, because an adjustable dc back emf can now be used as the injected voltage for speed control.

In this figure, the average back emf of the inverter is the injected dc emf opposing the rectified rotor voltage. If commutation overlap is negligible, the direct voltage output of the uncontrolled three-phase bridge rectifier is equal to:

\[ V_{dc} = 1.35 V_r \cdot s \]  

where \( V_r \) is the line to line rotor voltage at standstill, and \( s \) is the fractional slip. For a line-commutated three-phase bridge inverter with negligible overlap, the average back emf is given by:

\[ V_a = 1.35 V_L \cdot \cos \alpha \]  

where \( \alpha \) is the firing delay (\( \alpha > \pi/2 \)), and \( V_L \) is the ac line-to-line voltage. At no load, the motor torque is negligible and the rectified rotor current is almost zero. Consequently, the two direct voltages of equations (a) and (b) must balance. Thus,

\[ 1.35 V_r \cdot s + 1.35 V_L \cdot \cos \alpha = 0 \]  

and hence

\[ s = - (V_L/V_r) \cdot \cos \alpha = -a \cos \alpha = a \cdot \cos \alpha \]  

where \( a \) is the effective stator-to-rotor turns ratio of the motor. Speed control is, therefore, obtained by a simple variation of the inverter firing angle. If \( a \) is unity, the no-load speed of the motor can be controlled from near standsstill to full speed, as \( \cos \alpha \) is varied from almost unity to zero.

In practice, the motor turns ratio, \( a \), is usually greater than unity, resulting in a low rotor voltage. Consequently, a transformer is often required between the ac supply network and the inverter in order to step down the utility voltage to a level that is appropriate for the slip-ring circuit. If the transformer turns ratio for the utility side relative to the inverter side is denoted by \( a_T \), then the ac line-to-line voltage applied to the inverter terminals is \( V_I/a_T \), and equation (d) as the modified form:

\[ s = a/a_T \cdot | \cos \alpha | \]  

Clearly, if a cascade transformer is not used, then \( a_T \) is unity.

In order to develop motor torque, a rotor current, \( I_{rt} \), is required, and the rectified rotor voltage must force current flow against the inverter back e.m.f. As the induction motor is loaded, the
speed falls slightly so that the resulting increase in rotor voltage can overcome the voltage drops in the rotor windings and the dc link circuit.

If the rotor resistance is small, the fundamental rotor slip power, \( sP_{ag} \), is approximately equal to the dc link power. Thus

\[
sP_{ag} = V_d I_d \quad (f)
\]

but, as therefore,

\[
\mathbf{P}_{ag} = T \omega \quad (g)
\]

And hence

\[
T = \frac{V_d I_d}{s \omega} \quad (h)
\]

If the speed droop on load is neglected, equation (d) for the no-load slip can be substituted in equation (h). Substituting also for \( V_d \) from Equation (b) gives the torque expression

\[
T = 1.35 \frac{V L I_d}{(a \omega)}
\]

This equation is also valid when a transformer is present in the cascade circuit. Thus, the steady-state torque is proportional to the rectified rotor current, \( I_d \), which, in turn, is equal to the difference between the rectified rotor voltage and the average back emf of the inverter divided by the resistance of the dc link inductor. For a fixed firing angle, the inverter emf is constant, and hence the rotor slip increases linearly with load torque, giving a torque-speed characteristic similar to that of a separately excited dc motor with armature-voltage control. In practice, the complete open-loop torque-speed characteristics have the form shown in the following figure.

![Open-loop torque-speed characteristics for the induction motor and static converter cascade](image)
3.1. Power factor

The principal disadvantage of the subsynchronous cascade drive is its low fundamental power factor, or displacement factor, particularly at reduced speeds. If the system is designed for wide range speed control, the full-load power factor at maximum speed may be as low as 0.5, decreasing to 0.3 or less as speed is reduced. This low power factor is partly due to the commutating reactive power that is drawn through the induction motor from stator to rotor by the three-phase bridge rectifier. However, the reactive power consumption of the line-commutated inverter is largely responsible for the low power factor of the cascade drive. The average back emf of the inverter is a maximum at the lowest controllable speed. Ideally, under these conditions, the inverter firing angle is 180°, but as usual, commutation overlap and thyristor recovery time are significant, and hence the inverter firing must be advanced to prevent a commutation failure. This firing advance causes the inverter output current to lead the corresponding phase voltage, and the inverter acts as a generator of leading reactive power—that is, a consumer of lagging reactive power. The reactive power consumption increases when the inverter firing point is further advanced to reduce the back emf and motor slip. At full speed, the inverter firing angle is 90°, and the inverter kVA is almost completely reactive. At a given firing angle, the net power drawn from the ac supply is the difference between the power delivered to the stator and the power returned by the inverter. However, the total reactive kVA is the sum of the reactive powers absorbed by the motor and inverter, and consequently, the system power factor is poor at low speeds when the active power consumption is small.

As explained in the next section, the cascade drive is frequently operated with a reduced subsynchronous range of speed control. In order to maintain the drive power factor at the highest possible value throughout the speed range, the inverter delay angle should be a maximum at the lowest controllable speed. Thus, at the maximum controllable slip, the rectifier has zero delay angle, and the inverter bridge has a delay angle of almost 180°. Consequently, when the inverter is connected directly to the ac supply network without a voltage-matching transformer, the slip-ring voltage at the greatest controllable slip, is approximately equal to the ac network voltage, \( V_L \). Hence

\[ s_{\text{max}} = \frac{V_I}{V_r} = a \]
4. CONTROL.

Here must be control text.

5. APPLICATIONS.

Here must be applications text.

6. LITERATURE.

Here must be literature text.

7. PARAMETERS.

Here must be text.

8. MODELING.

Here must be modeling text.