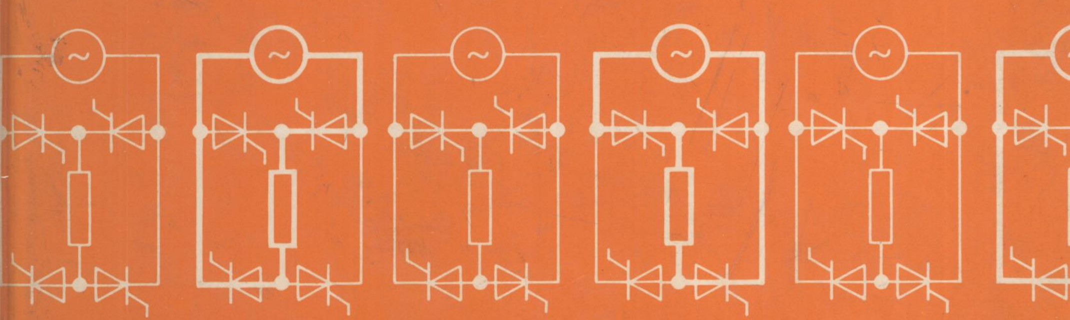
A Basic Guide to Power Electronics



Albert Kloss

A BASIC GUIDE TO POWER ELECTRONICS

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A BASIC GUIDE TO POWER ELECTRONICS

List of Symbols

CURRENTS

Instantaneous values

i	Alternating current, transformer current, valve current
$i_{\sim}$	Alternating current, supply (source) current
$i_{R,S,T}$	Phase currents
i_k	Short-circuit current, commutating current
i_{Th}	Thyristor current
$i_{1,2,\ldots,}$	Valve currents
i_1	Fundamental current
i_g	Triggering (gate) pulse
i_E	D.C. voltage-source current
i_d	Direct current
i_R	Current in resistor
i_C	Current in capacitor
i_m	Maximum value
I_m	Amplitude
I_F	Foward current, maximum value
i_{rr}	Reverse current peak

Relative values

i_d	Direct current

Mean values

I_d	Direct current
I_{do}	Direct current with $\alpha = 0^\circ$
I_{dN}	Rated (nominal) direct current
I_{dk}	Short-circuit direct current
I_{VAV}	Valve current
I_{ThAV}	Thyristor current

R.M.S. values

I	Alternating current, transformer current
I_N	Rated (nominal) transformer current
I_k	Short-circuit current

I_{Vrms}	Valve current
I_{Thrms}	Thyristor current
I_1	Fundamental component
I_n	Harmonic current
I_s	Supply current

VOLTAGES

Instantaneous values

v	Alternating voltage, line voltage, valve voltage
$v_{R,S,T}$	Phase voltages
v_{ph}	Phase voltage
v_n	Harmonic voltage
v_s	Supply voltage
v_{sec}	Secondary voltage
v_V	Valve voltage
$v_{1,2,\ldots}$	Valve voltage
v_{Th}	Thyristor voltage
$v_{L,Lk}$	Voltage across inductance
v_C	Capacitor voltage
v_d	Direct voltage
v_D	Diode voltage
v_{rr}	Reverse recovery voltage peak
V_{Vm}	Valve voltage, maximum value

Relative values

v_d	Direct voltage
$\mathrm{d}x$	Inductive d.c. voltage drop
$\mathrm{d}r$	Ohmic d.c. voltage drop
e_k	Total short-circuit voltage
e_{kt}	Transformer short-circuit voltage

Mean values

V_d	Direct voltage
V_{dio}	Ideal no-load direct voltage, $\alpha = 0°$
V_{do}	Direct voltage with $\alpha = 0°$
E	D.C. voltage source
A	Voltage–time integral (area)

R.M.S. values

V	Line voltage
V_i	Fundamental component
V_{Vrms}	Valve voltage
V_{ph}	Phase voltage

V_{sec}	Secondary voltage
V_p	Primary voltage
V_0	Source voltage, no-load voltage

POWERS

P	Active power (mean)
S	Total apparent power
S_1	Fundamental frequency apparent power
S_t	Transformer rated power (VA)
Q	Total non-active power (reactive power)
Q_1	Fundamental frequency reactive power
Q_H	Harmonic non-active power, distortion power
Q_T	Transformer short-circuit volt-amperes
Q_s	Supply short-circuit capacity
p	Relative active power, instantaneous power
q_1	Relative fundamental frequency reactive power
q_C	Relative capacitive reactive power
s_1	Relative fundamental frequency apparent power
W	Energy

PARAMETERS, ABBREVIATIONS

L	Inductance in d.c. circuit
L_k	Commutating inductance
C	Capacitance
R	Resistance
R_i	Equivalent resistance
x_k	Commutating reactance
V	Valve
D	Diode
L_F	Filter inductance
L_μ	Transformer no-load (magnetising) inductance
K	Cathode
A	Anode
p,n	Semiconductor conductivity types
REC	Rectifier
INV	Inverter
G	Generator
M	Motor
ASM	Asynchronous (induction) motor
SM	Synchronous machine
HVDC	High-voltage d.c. (transmission)
Hg	Mercury
Si	Silicon
Se	Selenium
n	Harmonic order, rotational speed

ANGLES, ANGULAR INTERVALS, FACTORS

α	Delay angle
α'	Natural delay angle
ϕ	Phase angle
ϕ_1	Phase angle of fundamental component
ωt	Angular interval at supply frequency
ω	Angular frequency of alternating (supply) voltage
ω_0	Natural angular frequency of oscillatory circuit
λ	Conduction angle, power factor
μ	Overlap (commutation) angle
f	Frequency
T	Period
τ	Time constant

HEAT

R_{th}	Thermal resistance (steady state)
r_{th}	Transient thermal resistance
P	Loss in valve
v_0	Threshold voltage
r	Equivalent (incremental) resistance
θ	Temperature
k_f	Current form factor

Preface

This book is directed both to students and to practising engineers and technicians.

The pillars of the book are the diagrams. They carry the most important information and it is possible as a first step to use the work as a picture book.

The main emphasis is placed upon a physical understanding of the problems considered. Practically oriented mathematical relationships are associated with, but separated from, individual sections of text. The reader can study the book in its essentials without having to become involved with mathematics.

The book is intended to serve as a textbook, with systematically structured material, and also as a practical work of reference.

The discussion concerns the most important aspect of power electronics—converter circuits for three-phase systems—and is centred on the three-phase bridge circuits with natural commutation which are the most widely used. Systematic treatment of the fundamentals is supported by the latest findings from industry and research. Many of the diagrams are based upon computer calculations.

The author has drawn upon long experience as an engineer with Brown Boveri and Co. at Baden, Switzerland, since 1969, and as delegate laecture at the Winterthur Technical and Engineering College (1971–1983).

The author would like to thank Mrs. M. Lochner for the painstakingly drawn diagrams and Mr. G. Lochner (Dipl. Ing.) for his critical checking of the manuscript.

IMPORTANT NOTICE

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Contents

1

The Structure of Power Electronics

FUNDAMENTALS

The principles of power electronics cover electrical circuits and apparatus which achieve the control or conversion of electrical energy by means of electronic valves.*

Power electronic equipments are generally referred to as 'converters', and the valves are accordingly termed 'converter valves'.

Valve action takes place in solid-state semiconductors. Because power electronic apparatus contains no moving parts, it is often referred to as 'static' equipment. The term 'power electronics' stems from the development of high-power semiconductor valves during the nineteen-sixties. The expressions converter or rectifier technology were previously used.

CONVERTERS

Converters constitute the hardware of power electronics. According to their basic functions, converters can be divided into the following groups:

Rectifiers (a.c.–d.c. converters)
Inverters (d.c.–a.c. converters)
A.C.–a.c. converters
D.C.–d.c. converters

Rectifiers convert alternating current (a.c.) into direct current (d.c.). Conversely, inverters convert direct to alternating current.

With converters that convert from a.c. to a.c. or from d.c. to d.c. it is possible to change voltage, frequency, phase number, or polarity.

Circuits that can function as rectifiers or inverters, according to the way in which they are controlled, are often referred to simply as 'converters'.

With the exception of rectifiers, which can operate in an uncontrolled mode, all converters embody controllable valves.

A.C.–a.c. and D.C.–d.c. CONVERTERS

This group includes the following subgroups:

Direct a.c. converters (direct frequency changers, cycloconverters)

* As often in continental usage, and in accordance with the *IEC International Electrotechnical Vocabulary*, Chapter 551, the term 'valve' is applied generally in this book to the class of rectifying and switching devices which includes solid-state diodes and thyristors as well as vacuum, gas, or vapour-filled tubes.

Indirect a.c. converters (d.c.–link frequency changers)
D.C. regulators (d.c. choppers)
A.C. regulators

The direct frequency changer converts alternating current of one voltage, frequency, and phase number into a different voltage, frequency, and phase number directly, without a means of energy storage. The output frequency is usually lower than the input frequency.

The d.c.–link frequency changer serves basically the same purpose as the direct frequency changer, but includes in addition a means of energy storage in a direct current or direct voltage intermediate circuit. The output frequency is consequently independent of the input frequency.

In both d.c.–link and direct frequency changers energy can be translated in either direction. The d.c.–link frequency changer feeding a synchronous machine constitutes the so-called converter motor; connected in the rotor circuit of an asynchronous machine it forms a subsynchronous converter

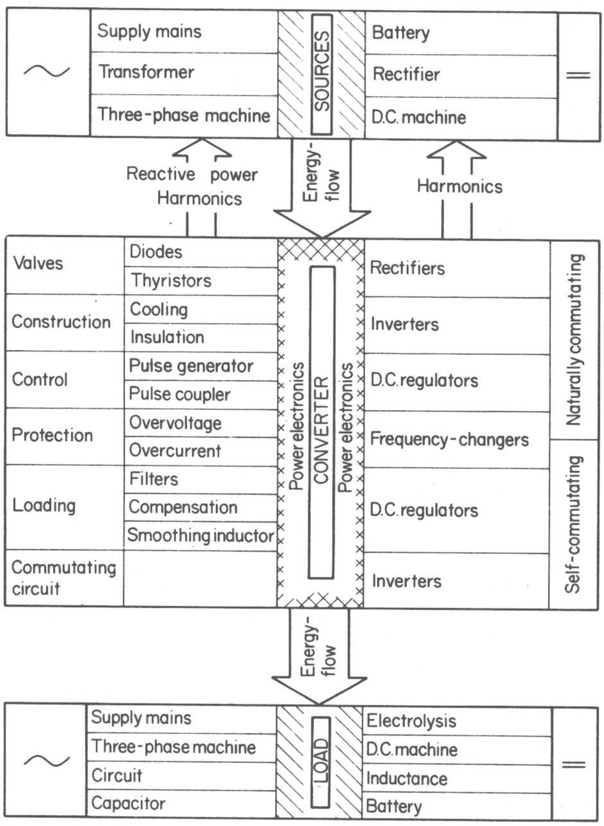

Figure 1. Diagrammatic presentation of the role of converters in energy conversion and control. The converters lie in the path of energy flowing between the source and the load. On the left are listed the components and the problem areas, on the right the classification of converter systems

cascade (the static Kraemer system), and in electricity supply systems it is used for high-voltage d.c. transmission.

The d.c. regulator facilitates the variation of d.c. voltage, without any intermediate circuit, but normally by dint of a forced commutation circuit (or valves with a turn-off facility).

The a.c. regulator affords a variation of a.c. voltage, at an unchanged frequency, again without an intermediate circuit.

The two regulators are not always counted as 'converters' but may be regarded as a distinct group. Figures 1 and 2 illustrate the classification of converters in terms of power flow, components, and grouping.

INTERNAL OPERATION OF CONVERTERS

Converter circuits are assemblies of converter valves, which function as controlled switching devices. The required conversion and control of voltage

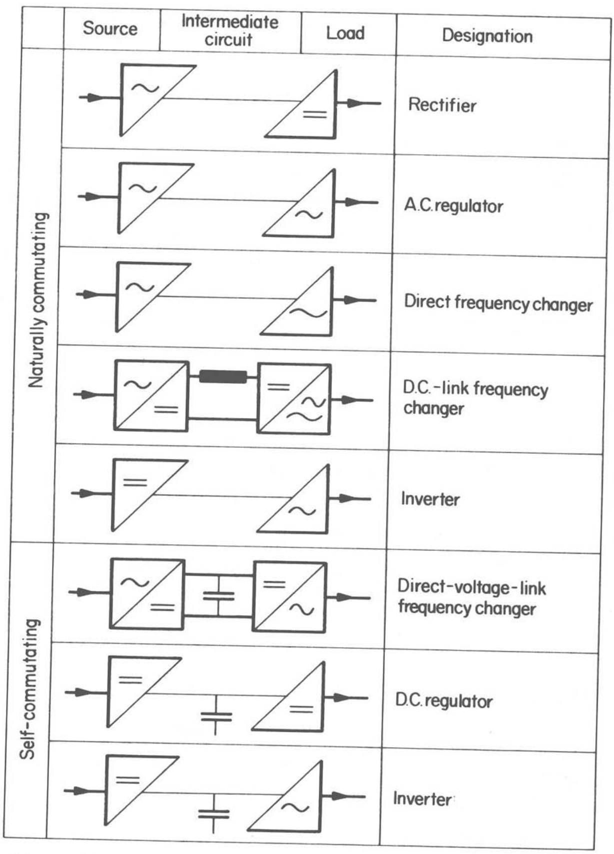

Figure 2. Systematic classification and simplified symbols of converter types. Converter circuits fall into two main groups: converters with natural (external) commutation and converters with forced commutation (self-commutating)