THE EXTENT AND DEVELOPMENT OF
MACHINE - ELECTRONICS

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1. INTRODUCTORY REMARKS.

Rotating electrical machines have a relatively long history compared to some other branches of electrical engineering. For the duration of this historical development schemes have been devised to change the relationship between torque delivered by, and mechanical speed of, a particular machine. The relationship between these two mechanical variables of the machine, being determined by the electrical parameters of the machine, the parameters of the supply and the type of machine, is of a predestined form for a specific machine operating from one of the normally available supplies. The motivation for the above mentioned search has been the fact that the requirements of the driven loads will not always match the predestined relationship between torque and speed. Practical execution of the theoretical schemes suggested to achieve this end did not always follow so easily, and the eventual widespread practical application of the solutions to the problem was in many instances prevented by the intricate combination of economics, reliability, efficiency, power factor, speed range, regulation, simplicity, ease of control and maintenance, power-to-weight ratio, obsolescence and the many other factors determining the practical future of a solution to a problem in engineering practice.

During this development it is interesting to note the interest stimulated by every new device showing promise for the control of electrical machines. The enthusiasm with which the search for changing the torque-speed relationship has always been persecuted may be experienced even in 1896 in the work of Görges (1) where he reports on the first observations concerning the Görges-phenomenon, observing that under some conditions the machine will operate stably at approximately half-speed.
The methods of achieving this much sought after result by using power-electronics forms the basis of this study. Apart from these solutions, however, the years have presented a rich array of methods to change the torque-speed relationship. An interesting and comprehensive survey has been presented by Laithwaite (2), indicating the extent of the demand for simple variable speed drives.

Due to the previous developments, the machine-electronics covers an extensive field at present, and whether conducting study or research, it is wise to attempt to obtain a survey of the possibilities as they developed in the past, and are feasible today. Chapter 2 aims at presenting a very brief, partly systematic, survey of electronic regulation and control of direct voltage and alternating voltage electrical machines. In Chapter 3 the historical development of the various electronic means for effecting control of the machines are analysed, and extended by treating the development of the control schemes themselves. It may perhaps be stated that this type of investigation is a tool too lightly neglected by most engineering investigators. As will be pointed out in the conclusion, certain development patterns occur each time, and by taking these skillfully into account one is enabled to give meaningful direction to work in this field over longer periods.
2. MACHINE-ELECTRONICS

2.0. Synopsis

2.1. Definitions of power-electronics and machine-electronics

2.2. Review of possibilities for classification of the systems

2.3. Brief indication of a classification system

2.4. Machine-electronic systems in relation to other electromechanical variable speed drives

2.5. Review of machine-electronic systems

2.0. Synopsis

Before investigating all the different methods to control electrical machines it is advisable to build up a framework in which to conduct this study. Therefore it will first be attempted to formulate definitions for power electronics and machine-electronics, and after having placed this against a background of other types of variable speed drives, machine electronics will be considered in more detail.

2.1. Definitions of power electronics and machine electronics

Under normal conditions the accent in an electric system may fall on the information processing aspect or on the power processing aspect, quite apart from the power levels involved. In the electronic systems used in combination with electrical machines, these two functions are both present. It will be postulated here that that part of the system in which the accent is on information processing be called the information-electronics and the other part of the system correspondingly the power electronics. It will be realized that it is not in all practical systems possible to distinguish between these two functions explicitly, especially in the case of micromotors with electronic commutators (52), yet it remains advisable to make the distinction with a view to the classification system being developed.

The word "machine-electronics" in itself is misleading, since as such it merely means electronics used with a machine, not necessarily an electrical machine, and it is specifically intended to indicate
a system consisting of an electronic part and a rotating electromechanical transducer or rotating electrical machine. The use of this word is only justified since it forms a handy acronym for something that may be specified as a "power-electronic_rotating_electromechanical" transducer system.

From the preceding it is clear that a machine-electronic system consists of two subsystems - the electronics and the rotating electrical machine. Such a system is used instead of a singular electrical machine in order to be able to establish a torque-speed relationship differing from the predestined form for the machine when connected to a "normal" supply. It may be remarked that mostly the information-electronics is left out of the analysis of the system, and the subsystem electronics (see fig. 2.1) becomes the power electronics. In fig. 2.1 the dotted line marks that part of the system most commonly referred to, and being studied as machine-electronics. Since a mutual influence exists between the components of the system, the subject of machine-electronics does not merely combine the "classical" knowledge of power electronics and electrical machines.

As definitions may therefore be considered:

**Power-electronics**

concerns itself with the study of that part of an electronic system in which the accent falls on the processing of power necessary at the output rather than on information. The definition is not coupled to a certain absolute level of power, but is relative.

**Machine-electronics**

concerns itself with the study of systems consisting of power-electronics in conjunction with rotating electromechanical transducers (or rotating electrical machines). Practising of this branch of electrical engineering has as its objective the alteration of the "traditional" torque-speed relationship of a specific type of machine.
2.2. Review of the possibilities for classification of the systems

A systematic classification of machine-electronics may employ a number of approaches to the subject. Some of the most obvious alternatives are given below:

a. Classification according to the type of energy supply needed to excite the system.

b. Classification according to the different types of power-electronic circuits used as adjustors in the system.

c. Classification according to the parameters in the theoretical torque-speed relationship which are subject to changes due to

![Diagram of Electronic Rotating Electromechanical Transducer System](image)

Fig. 2.1 Electronic-rotating-electromechanical-transducer-system.
the presence of the power electronics.

d. Classification according to the type of electrical machine chosen as output unit for the system.
e. Classification according to the fundamental power relations in the system. This approach will be used here.

2.3. Brief indication of a classification system for machine-electronic systems.

It is possible to employ various different approaches to classify the different types of machine-electronic systems. One of the possibilities is to use the power relation in the whole electrical system. This approach will be used here.

Before considering these power relations it is necessary to make certain agreements regarding the electrical machines. The stator and rotor carry windings of m-phases and 2-p poles. Circular rotating magnetic fields of angular velocity of $\omega_s/p$ and $\omega_r/p$ with respect to the stator and rotor bodies are set up when these windings carry m-phase symmetrical current systems of frequency $f_s$ and $f_r$ on the stator and rotor respectively. To be able to obtain a d.c. machine in this configuration, the frequency changer must be inserted between the direct current supply and the stator windings (see for instance reference (68)).

A certain amount of power is fed into the power electronics, passes from the power electronics to the airgap of the electrical machine, and under the assumption of negligible power-electronic and stator loss (this is not essential to the argument, however) this power is split up in the rotor into two components - mechanical power delivered to the load, and a remaining amount of power that manifests itself as rotor losses unless fed back to the supply system.

If constant load torque be assumed, and the mechanical speed of the machine changes, the mechanical power will also change. In some types of machine-electronic systems the power electronics are used to change the stator frequency, and therefore the amount of power fed across the airgap in such a case. This makes it possible (in principle) to deliver a similar torque at two different mechanical speeds without changing the losses in the machine-electronic system, as the speed of
rotation of the magnetic field in the airgap has been adjusted. This class of systems comprise all machines where the stator frequency is changed by the power-electronics, such as semiconductor-commutator motors ("Stromrichtermaschinen") frequency-changers feeding squirrel-cage and synchronous machines etc. These group-I systems constitute one section.

The relation between mechanical speed of the machine and torque delivered may not only be changed by changing the supply frequency as indicated above, but amongst other things by influencing the induced current in the rotor or adjusting the mean applied stator voltage. In the case of either of these methods, however, the amount of power for the fundamental frequency of a specific electromagnetic torque in the airgap remains constant, to a first approximation, so that the system suffers from heavy rotor losses at low speeds unless the rotor power is recuperated. It follows immediately that induction motors with electronic rotor control and stator voltage switching will fall in this class - group-II systems.

The remaining types of machine-electronic systems all comprise conventional d.c. machines (with mechanical commutator) with armature voltage control or field control by electronic chopper or mutator circuits. Strictly speaking it will probably be better to consider these systems in a class of their own. In terms of the agreements made concerning the machine configurations (See second paragraph of this section, 2.3) the power electronics is located in series with the mechanical frequency changer in the stator for armature-voltage control or in the case of a field-chopper in the rotor circuit. The torque-speed relationship of the transducer without the mechanical frequency changer is a vertical line in the torque-speed plane (in this case the line is located at zero speed), and the function of the power electronics in this case is to change the maximum torque. The adaptation of the amount of power crossing the air-gap is the responsibility of the mechanical frequency changer, not of the power electronics. When the definition of group III systems is the following: Group III systems are those systems in which the power electronics do not have the function of changing the amount
of power fed across the air-gap of the machine, but changing the maximum amount of torque that may be delivered at a specific speed, all armature voltage-controlled, field controlled mechanical commutator machines fall into this class.

2.4. Machine-electronic systems in relation to other electromechanical variable speed drives

A machine-electronic system is but one of the possible solutions to the controlled or regulated variable speed drive problem. Although only these types of systems will be discussed in the present case, it is advisable to see the problem against the general background. This is always important, as the merits of such a controlled or regulated variable speed drive is influenced to a large extent by the electrical, mechanical and economical characteristics obtainable with other electrical drives.

It has been remarked previously (section 2.2) that a traditional way to classify electrical drives is by the supply system needed, i.e. alternating or direct voltage. Many past workers have used this as a starting point (2). In order to keep contact with past practice this approach may be found in fig. 2.2. In order to be able to select drives with a specific machine type, the classification by machine type referred to previously, has been introduced in an indirect way. From an inspection of the possible variations it is apparent that at present only the variable pole-pitch have no exact static (electronic) equivalent, while it is also evident that machine electronics form a relatively small fraction of all the possibilities.

2.5. Review of machine-electronic systems

In this brief review of machine-electronic systems attention will only be drawn to the different possibilities existing for regulating the machines, and not on the characteristics obtained - this will carry much too far for an introductory review.
2.5.1. Frequency regulation of induction and synchronous machines: Group-I systems

The regulation or control of induction and synchronous machines over a wide frequency range requires an adjustment of the amplitude of the output voltage of the inverter in order to prevent saturation of the magnetic circuits of the electrical machine. Of these converters or inverters a wide variety may be found in practice. It is worth pointing out the main types to be found:

First divide the circuits into two classes, depending on the nature of the commutation employed to reduce the current through the electronic switches in the converter to zero. Two cases will be considered.

(i) Natural commutation: The current through the switch becomes zero as a consequence of the circuit voltages always present in the circuit.
(ii) Forced commutation: The current through the switch becomes zero as a consequence of a voltage introduced at a certain time into the circuit. This voltage may be in parallel (fig.2.3 (i)) or in series (fig.2.3 (j)) with the conducting element.

In practice it is found that circuits employing natural commutation have a series configuration (example: all supply-synchronous converters or mutators) and most circuits with forced commutation use the parallel configuration (example: d.c. choppers of the high-low type or parallel inverters).

In each of these two classes different systems may be distinguished, depending on how the voltage-adjustment is carried out. It is important to distinguish between all these arts, as each will influence the machine in a characteristic way.

Forced commutation converters:

The normal alternating voltage supply is first converted by a rectifier, and when necessary passed through an intermediary filter circuit with inductance and/or capacitance. The direct voltage is then again converted to the necessary m-phase, variable frequency output by the forced-commutated inverter.
GROUP-I SYSTEMS. Frequency regulation of induction and synchronous machines.

FIG 2.3
Regulation of the output voltage with frequency (approximately proportional to frequency) may be obtained by including an autotransformer or induction regulator in either the input or the output circuit (fig. 2.3a). This technique will keep the form of the output voltage constant and change the amplitude of the peak voltage. Correspondingly the different harmonic frequencies remain constant in relation to the fundamental harmonic. It is also possible to adjust the intermediary direct voltage by using a controlled mutator as first stage (fig. 2.3b). The same considerations as previously mentioned apply for the voltage harmonics at the output (assuming that the filtering is effective).

When the output voltage is composed of a series of pulses, as indicated in fig. 2.3c, it is possible to obtain regulation of the output voltage by pulse-width modulation or pulse-frequency modulation. The amplitude of the pulses remains constant. Consequently the frequency spectrum relative to the fundamental output voltage will change drastically with frequency. On the other hand it is possible to obtain good simulation of any desired current waveform by employing two-level current control, with the desired waveform as the input.

**Natural commutation converters**

This type of converter (fig. 2.3d) may actually also be seen as a subsynchronous mutator. By triggering either of the antiparallel branches for equal periods an output voltage with positive or negative mean value may be obtained. Changing this triggering period changes the output frequency.

In the simplest system the elements in the mutator are gated "on" during the conduction period, the input or output voltage being regulated by means of autotransformers or induction regulators. However, when employing a delay of the triggering angle of each individual element to regulate the output voltage, a current control similar to that possible in fig. 2.3c may be used.

Difference amongst converter circuits may further be found in the ways in which the power switches are arranged in the forced-commutation part.
Basically most of these complicated arrangements may be broken down into a number of the centre-tapped circuits (fig.2.3e and g) or of the bridge-type circuits (fig.2.3f and h). Actual commutation circuits to obtain the desired voltages are responsible for the enormous variety of inverter circuits found in practice. This is important to the extent that these details often affect the circuit economy and reliability.

2.5.2. Stator and rotor regulation of induction machines: Group-II systems

Basically the stator and rotor regulation systems may be divided according to the frequency of operation of the switches used to influence the torque-speed characteristic. In both stator and rotor circuits the following switching modes will be distinguished:
(i) Switching frequency much higher than the stator/rotor frequency
(ii) Switching frequency equal to the stator/rotor frequency
(iii) Switching frequency much lower than the stator/rotor frequency.

It is not usual to choose the switching frequency different from the stator/rotor frequency, but of the same order. In such a case the beat frequencies will affect the machine-behaviour adversely.

Systems with a stator switching frequency much higher than the rotor or stator frequency have forced commutation. In order to avoid using 2m antiparallel switching circuits for an m-phase machine, a bridge-rectifier circuit is inserted between the stator windings and the star point, or the slipring voltage is first fed to a rectifier (fig. 2.4a(i) and fig. 2.4d(ii)). The output of this rectifier is then shorted by a forced commutation or d.v."chopper" circuit. Analogous to the previous example of such a pulse system in the inverter category, the stator voltage/rotor current may be regulated by a pulse width modulation, a pulse frequency modulation, or a bang-bang regulation of current. In none of these cases will the harmonic components be constant.
GROUP-II SYSTEMS. Stator and rotor regulation of induction machines.
Switching frequency equal to the stator/rotor frequency. In this case one may distinguish between two methods of conduction-angle control, each with its own merits. The angle of stator/rotor current extinction may be regulated, or the angle of current ignition may be regulated (fig. 2.4a(ii) and fig. 2.4d(i)). In both cases of extinction control the basic circuit configuration is the same as for the high-frequency control. The differences in commutation will be pointed out subsequently. The antiparallel configuration of the valves for the ignition angle control is indicated in both fig. 2.4b and 2.4c. A rectifier with switching of its output as in a and d cannot be employed, as the possibility exists that current flow will extend beyond 180°.

Switching frequency much lower than the stator/rotor frequency, operates with natural commutation, as the ignition angle control in the previous case. For both cases the circuit configurations may be chosen identical (fig. 2.4b(ii) and fig. 2.4c(ii)). This extremely simple method of regulation functions by changing the on-off ratio of the switches per switching cycle, i.e. t₁/T. The natural commutation has as a consequence that the regulation is not continuous, but proceeds in discrete steps determined by the fundamental frequency.

Systems feeding back the rotor power to the supply mostly operates at rotor frequency, with a rectifier in the rotor circuit. It is possible that frequencies equal to the supply frequency may be superposed by the mutator (fig. 2.4e).

Further diversity in systems for stator/rotor control of induction machines at a frequency much higher than, or equal to, the stator/rotor frequency may be found due to the forced commutation methods employed. Some systems, especially those for extinction angle control, employ a d.v. forced-commutator chopper at the output of a rectifier or mutator circuit. (fig. 2.4f). With parallel commutation this will give rise to short-circuit currents through the diodes, and it is essential to employ series-commutation.
GROUP-III SYSTEMS. Regulation of d.v. machines by electronic converters.

FIG 2.5
Legend to fig. 2.3, 2.4 and 2.5.

\[ f_1 \] : supply frequency  
\[ f_2 \] : variable frequency  
\[ V \] : voltage adjustor, such as autotransformer or induction regulator  
\[ v \] : instantaneous value of voltage  
\[ C,L \] : Filter circuit in d.c. intermediary circuit of converter  
\[ E \] : Direct voltage source. May be zero when converter control is applied to the field winding of machine  
\[ e_{1'} \] : Out of phase series commutation voltages  
\[ e_2 \]  
\[ IM \] : Induction machine  
\[ SM \] : Synchronous machine  
\[ Z \] : complex impedance  
\[ T,\tau \] : period of a switching cycle  
\[ \beta \] : fractional duty cycle  
\[ \alpha \] : variable angle of conduction delay in mutator control
On the other hand other systems (current regulation) employ an impedance in parallel to the chopper, with a large inductor to decouple the chopper from the rectifier, and keep the current constant. In these cases a chopper with parallel forced commutation may be used (fig. 2.4g). Further differences that may be found in the arrangement of the rest of the commutating circuits will not be treated (circuit details for obtaining correct charge polarity and voltage on the commutating capacitor etc.).

2.5.3. Electronic control of d.v. machines: Group-III systems

As indicated in fig. 2.5 a, b, the armature voltage or field voltage of the machine may be regulated by an electronic converter. This converter may be a mutator or a high-low d.v. chopper. A third possibility may be found by combining a and b, obtaining a series machine regulated by either of these means. This type of control is extremely important for all traction purposes.

Regulation by mutator employs a circuit with natural (series) commutation. The circuit configuration may be of an m-phase neutral point form, or of m-phase bridge form (fig. 2.5d). A freewheel-diode may be included in the output, and control of the output voltage is obtained by adjustment of the current ignition angle in each branch (fig. 2.5d(i)). This will adjust the mean output voltage from positive through zero to negative values. The output current is unidirectional, indicating that the direction of power flow can change through the mutator. It is one of the important advantages of these types of circuits when employed in electronic armature and series control that recuperative braking is possible.

Regulation by d.v. high-low chopper uses a circuit with forced commutation - mostly of the parallel type, as no parallel discharge path to the thyristor to be commutated exists. The system may incorporate an m-phase rectifier and intermediary L-C circuit as shown in fig. 2.5e. The methods of control possible are analogous to all the previously discussed pulse-systems: pulse-width modulation, pulse-frequency modulation, and a combination by using a two-level current control. Recuperative braking is not possible with this system: power flow is confined to one direction.
When recuperative braking of the d.v. machine is desired, a low-high chopper as indicated in fig. 2.5f must be added to the system. The rectifier circuit must become a mutator in order to absorb the reversed power flow.

With a d.v. source available (for instance lead batteries in traction vehicles) the system becomes simpler, the rectifier/mutator and the filter circuit being unnecessary. In this form it is a machine-electronic system that is widely applied at present in traction vehicles.
3. THE DEVELOPMENT OF THE DIFFERENT SWITCHING DEVICES, CIRCUITS AND CONTROL METHODS

3.0. General remarks
3.1. The development of the different switching devices
3.2. Circuits for the electronic control and regulation of electrical power
3.3. The development of machine-electronics

3.0. General remarks

The oldest known switch used in the control of electrical machines is the mechanical commutator. Subsequently the gaseous valves showed promise for generating the switching functions necessary to control machines. These devices had some disadvantages and at a time it appeared that the mechanical metallic rectifier (a modified commutator!) was the future promise. Almost simultaneously it was succeeded by a device developing in parallel - the transductor or magnetic amplifier. The era of the semiconductor switches then dawned - an era from which we, being still concerned in its development, are able to derive but limited historical perspective. Numerous works have been published and circuit configurations and methods of regulating electrical machines electronically worked out or suggested in the past. It has therefore become extremely difficult to ascertain the origin of most of the circuits and methods of control employed at present in machine electronics. The aim of this historical introduction is to present the knowledge acquired on these matters in an attempt to clear up some of these aspects.

3.1. The development of the different switching devices
3.1.1. Switches and machines

Regulation and control of electrical machines concerns the processing of power by electronic means. It is evident that necessity for reasonable power efficiency dictates that the flow of power must be regulated by a switching device. In the ideal case such a device should have zero voltage drop during conduction and infinite voltage...
drop during blocking. Two stable states, depending on direction of current flow and corresponding with the above, are already sufficient for conversion of alternating current to direct current. As soon as time control is possible, i.e. when it is possible to change from either of these states to the other at a chosen time, actual control of power flow becomes possible between systems. From chapter 2 and from the previous remarks it may therefore be gathered that for true efficient control only non-linear devices are to be taken into consideration.

It has already been pointed out that the first switching device used in rotating electrical machines was the mechanical commutator. It may be said that this development, through many forms, took place during the nineteenth century. This is evident when one compares the commutators employed by Page in the years 1840 in his electrical imitation of steam engines to the rotating commutators used subsequently in direct voltage machines by Siemens, Edison and others. Although interesting from a historical and educational point of view, this development will not be traced here.

The first static non-linear device discovered was the crystal detector by Braun in 1874 in Strasbourg (3), (4). Much later, after 1920, this was extensively used in the radio field, but was never developed to power levels applicable to electrical machines. The selenium rectifier of Presser (1925), (5), and the cuprous oxide rectifier of Grondahl (1926), (6), were used in the power field with good results. Facilities for time control did not exist with these devices, however. As far as a controllable electronic switching device is concerned, the grid controlled mercury-arc rectifier was the only predecessor of the present-day controllable semiconductor switching devices. Therefore the development of this device will now be considered.

3.1.2. Development of the gaseous switching elements

Although the practical development of these devices did not come into being before nearly a third of the twentieth century was past, it is interesting to note that the physical principles underlying the behaviour of mercury-arc rectifiers had apparently been recognised in 1882 by Jemin and Meneuvrier (7). They gave an account
Fig. 3.1. First proposal for controlling a mercury-arc discharge by Cooper-Hewitt (1903).

1 - 3 Mercury discharge tube
4 Capacitor plates functioning as control grid
9 -16 Alternating current circuit
17 Discharge gap for controlling the moment of firing.

of the property of an electric arc established between mercury and carbon electrodes, mentioning that the current will flow in one direction only. In 1889 Fleming investigated the property of unidirectional conductivity of the electric arc in air, while between 1894 en 1898 Sahulka described the results of identical investigations pertaining to atmospheric arcs between mercury and iron or carbon electrodes (7).

All these experiments were conducted under atmospheric conditions. In the years 1890-1892 Arons made the first vapour lamps by enclosing the arc in an evacuated vessel. Apparently a rectifier based on the unidirectional conduction principle of the mercury arc emerged around 1900 when Cooper-Hewitt took up the manufacture of these lamps on a commercial scale for lighting purposes. During further investigations of his lamps the idea of building a convertor for alternating current to direct current cropped up. This conversion equipment was apparently first demonstrated at the turn of the year 1902-1903 (9) (10) (See app.2) in public, and aroused conside-
Fig. 3.2 Glass bulb mercury-arc rectifier unit of Cooper-Hewitt (pre-1906).

Fig. 3.3 Patent of Cooper-Hewitt for the first metal mercury-arc rectifier filed in 1908.
rable interest. It is noteworthy that this equipment was built with a three-phase rectifier at a line voltage of approximately 190 V. The main interest was at first still concerned with the lighting characteristics of these lamps (10 and discussions thereto). In the U.S.A. the name of Steinmetz was already concerned with this type of convertor equipment in 1904 (11) and one has the impression that for the next few years these ideas at first only gradually gained field. From an inspection of fig. 3.2 it may be seen that the mercury-arc converters were still fabricated from glass. It was soon realised that in order to increase the power output, and therefore the cooling capacity, the vessel should be constructed from metal. The first proposition was made by Cooper-Hewitt (1908), a patent being granted in 1911 (fig.3.3). The construction of Schäfer was more practical (12), and especially on the Continent of Europe it was adopted almost universally. Fig. 3.4 gives an impression of the different metal construction practices followed after 1920 by most manufacturers, and fig.3.5 an impression of the detailed construction of a water-cooled mercury-arc rectifier. One may state that the stage was then set for a gradual application of the mercury-arc rectifier as a converting device in the high-power field, reaching general application in all types of service probably after 1925 and continuing to the present time.

In 1903 Cooper-Hewitt already indicated the possibility to control the current arc in a mercury rectifier by means of a "grid" between anode and cathode, and even mentioned the possibility to apply impulses to these "grids" (see fig. 3.1), but the development of the controlled rectifier did not follow immediately. As indicated in fig.3.1 the principle needed a high voltage-impulse. It may be considered well known that in the years after 1910 the thermionic triode of de Forest stimulated electronic work enormously, and an intensive study commenced on attempts to influence the plasma-discharge of gaseous tubes by a grid, and build a vapour triode. Although the outcome was not a device suited for linear amplification as might have been hoped, the presence of a grid delaying the moment of arc-ignition supplied the missing time control to arrive at an efficient control of power flow. In 1914 Langmuir in the U.S.A. indicated clearly the
control of the current by a grid in a hot-cathode thyratron, employing a steady grid potential of variable magnitude. In subsequent years other techniques for grid control, including phase control by an a.c. potential on the grid, were developed.

It was not before 1928 that the first practical mercury-arc controlled rectifier was put to practical power control application (13). Shortly afterwards the application of control grids to steel tank mercury-arc rectifiers was undertaken by Brown-Boveri, Siemens-Schuckertwerke and the Allgemeine Elektrizitäts Gesellschaft almost simultaneously. When the Second World Power Conference was held in Berlin in 1930 these three firms staged comprehensive displays of the new technique in their laboratories (7). Thus, 48 years after the first principles appear to have been realised, the controlled mercury-arc rectifier was ready for large-scale practical application.

The mercury-arc tubes of the controlled and rectifier variety had some severe shortcomings. The cooling and fragility of the large glass bulbs soon caused problems, so that the steel tank rectifiers were necessary. The maximum attainable voltage was limited to an order of 10 kV, and the current per anode to a few thousand amperes. Development of larger hot-cathode thyratrons (see fig. 3.7) for higher voltages and higher currents introduced the problem of a limited lifetime of a few thousand hours (813). Although some problems concerning "arcing back" in mercury vapour vessels were solved, and in later years the vacuum-pumps for maintaining the vacuum in steel units became unnecessary, these problems have not yet been solved satisfactorily even up to the present. As with all electronic elements, the mercury-arc tubes eventually found restriction in engineering applications as dictated by their characteristics.

The name "thyratron" was reserved and suggested by the General Electric Company in the U.S.A. (8upa) for hot-cathode and mercury-pool cathode gaseous discharge tubes, yet with the years it became mostly applicable only to hot-cathode elements.
Fig. 3.5 Cross section of a practical, water cooled mercury-arc valve, (trigger anode not shown).

W: Cooling vessel  T: Cooled anode connectors
D: Top cover  K: Metal skin of vessel
F: Protective cover of anode  isolated from cathode
M: Cathode

3.1.3. The mechanical metallic rectifier and the magnetic amplifier

Strictly speaking these devices will probably not be classed as electronic, but both came into accelerated development at a time when the disadvantages of the true electronic control and converting elements became obvious.

The idea of closing mechanical contacts synchronous with an alternating voltage supply to obtain rectification dates from the same time as the mercury-arc converters of Cooper-Hewitt. In 1901 a mechanical rectifier was suggested by Koch (14). Although serious consideration
Fig. 3.6
Cut-away view of a typical metal mercury arc rectifier. (AEG, 1930).

Fig. 3.7
Example of three hot-cathode power thyatrons
0.5A, 5000V
200A, 15000V
1000A, 15000V
(AEG, post 1930).
was given to this type of converter in the next two decades (see for instance (15)), the greater promise of the static devices overshadowed its capabilities. When the lower efficiency, fragility and large volume of the mercury-arc devices became only too apparent, the mechanical metallic rectifier received an increasing amount of attention. Much development work along these lines was done by Koppelmann (16), being one of the main exponents of this technique (see figures 3.10 and 3.11).

When one examines the efficiency and the small volume of the contact rectifier units as compared to other converting techniques (see fig. 3.12) the enormous advantage is evident. The voltage limitation, mechanical wear and dependence on atmospheric conditions (the same objections raised to mechanical commutators on electrical machines) limited the application of these converters. Interesting variants, such as the "Rollenstromrichter" (BE') of fig. 3.11 (b), (c) were developed through the years, and until recently contact rectifiers were manufactured for rectifying large currents at voltages of the order of 300 V.

The transductor or magnetic amplifier did not present itself so much as a converter (although these applications may be found), but as a control element bridging the gap between the vapour discharge tubes and the present semiconductor elements. In conjunction with rectifiers (Selenium, Germanium and Silicon) it was successfully used in converters (controlled bridges). At the time of the Second World War the principles underlying the functioning of the transductor had been known for a long time, yet only during these and subsequent years did it come to full development. As the transductors are of a recent date, and may be considered well known, it will carry too far to trace their development at present. For more information see (B10).

3.1.4. The solid state switching elements

It is at present well known that early in the 1950's the junction transistor followed the pioneering work of Bardeen, Brattain and Shockley in semiconductor devices at the Bell Laboratories in the U.S.A. (17). Furthermore it is extremely interesting to note that in the very first comprehensive work to appear on the p-n junction
Fig. 3.8
Modern multi-anode controlled mercury arc rectifier valve rated for 1800A, 150kV.
(English Electric).

Fig. 3.9
Thyristor unit rated at 200A, 2 x 50kV.
In operation on the Gotland HVDC-link
transistor in 1951, Shockley and his coworkers mention the $p_1^-n_1^-p_2^-n_2$ structure with an electrode attached to the $p_2$-region (17) — a structure we know as a thyristor at present. Yet it appears that the importance of this device when used as a switch was not realised. Following the work of Shockley, Ebers developed the now famous two transistor analogue to indicate what type of characteristics might be expected from such a p-n-p-n device (20).

Although silicon p-n junction devices as power rectifiers gained an increasing importance in the subsequent years, the matter of a controlled silicon rectifier rested until 1956, when Moll and his associates at Bell saw the promise of the four layer structure (19). Yet the p-n-p-n switch was still not widely appreciated, and the actual initiative of building a high current switch and introducing it to the practical application field should probably be credited to York of the General Electric Company (20). He was aware of the work at Bell, and with his coworkers built the first high current version of the thyristor or p-n-p-n switch in 1957. This touched off a world-wide investigation that has continued to this day. Although it is difficult to judge history over so short a span of time (only ten years have elapsed since), it appears that if a birth date for the practically useful thyristor has to be named, it should be 1957-1958. Thus, ten years after the first work on useful semiconductor amplifiers and switches was done by Bardeen, Brattain and Shockley, the new device was ready to conquer the power field. It must be remarked that the invention of the thyristor came at an extremely opportune moment, due to the high degree of development already reached at that time in the field of transistor-logic and amplifying circuitry.

The thyristor stimulated study of multi-p-n junction semiconductor devices during the past ten years, and this has resulted in a family of switching devices of a remarkable degree of sophistication, yet at present still in their infancy.

* thyristor: acronym from thyratron and transistor.
Fig. 3.10 Schematic indicating the working principle of the contact-converter (Koppelmann).

At present the most promising, the "triac" or bilateral triode switch, appears to be due to workers at the General Electric Company again (21). Other promising devices include the bilateral diode switch("diac"), gate-turn-off-switches (G.T.O.'s), light activated thyristors (Lascrs) and some other four terminal devices. At present the thyristor is employed almost exclusively in machine electronics, and therefore the historical development of these other devices will not be discussed. It appears correct to state that the stage of development has now been reached where it is evident that in the near future gaseous and solid state devices will both be applied in their own fields. Recent developments in high-voltage d.c. transmission indicate this state of mind (22). Mercury-arc converters for higher voltages (>100 kV remain necessary. (fig. 3.8). Although thyristor converters are in operation up to 50 kV (fig. 3.9), they consist of many elements in series, in this way neutralising their advantage of lower forward voltage drop. Especially in the high electric field phenomena many problems still exist in both types of equipment.

3.2. Circuits for the electronic control and regulation of electrical power.

In considering power electronic circuits it is possible to distinguish between the following different types:

(i) Power electronic frequency changers (rectifiers and inverters).
Fig. 3.11(a) Example of a six-phase contact rectifier for 5000A and 300V, indicating some detail. Cam-drive for voltage control included in the dome on top. (Koppelmann, 1941).

(b) Mechanical rectifier of the rolling type (b): R,S,T, three-phase contacts.
1. Isolating segment. 2. Roll-contactor. 3. D.C. contacts.
(c): Practical unit (Calor-Emag-Ratingen).
(ii) D.c. to d.c. transforming circuits (electronic choppers).
(iii) Phase control circuits for adjusting output voltage

These circuits will be considered in this order.

3.2.1. Power electronic frequency-changers.

The role of power electronic frequency changers in machine-electronics is primary. Normally available supplies are of a fixed frequency. To obtain other frequencies from this single-frequency supply a non-linear device is incorporated in the system. The spectrum arising out of this may be used in all its components or in one only - depending on the application. As already pointed out, machine-electronic systems are energy processing, and therefore the losses in the non-linear element should be small, or zero if possible, in order to obtain a high efficiency. The ideal switch answers to this description.

When thinking about "high frequency" of operation and adverse operating conditions dependent on external influences, it becomes clear why electronic devices have always been sought. The development of these types of devices known today has been examined in 3.1, and some remarks about the historical development of the circuits using these will now be made.

Soon after the practical value of the mercury vapour tube as a rectifier was realised, investigations into its circuit implications started (see for instance: 23).

In the following years till 1930 most of the uncontrolled rectifier circuit configurations known today were developed. A classical analysis of rectification has been given by Dällenbach and Gerecke in 1924 (24). This is one of the first building blocks of the present mutator theory. Uncontrolled rectifying circuits will be considered known, however, and not discussed further.

Although actual practical controlled mercury-arc rectifier units were not developed before 1928, the first inverter dates from 1925. The term "inverter" is due to D.C. Prince of the General Electric Company in the U.S.A. (25). Interesting is the following comment of the editor of that journal at the head of the above-mentioned article:

"In the September, 1924, issue of this magazine, Mr Prince contributed
Fig. 3.12(a)
Comparison of a mechanical rectifier with other solutions to the problem. Power level: 30 MW at 300 V. The horizontal line indicates the division between characteristics for the equipment and the transformer.

1. Rotating synchronous converter with necessary transformer and chokes included.
3. Contact-rectifier with transformer included.

M. Fe. Weight of iron and steel components.
M. Cu. Weight of copper components.
P. Power loss.

Fig. 3.12(b)
Comparison of a sixphase contact rectifier with other solutions to the problem. Power level: 30 A at 30 V to 230 V variable.

3. Copper-oxide rectifier.
4. Contact rectifier.

M: weight.
V: Volume of the equipment.
P: Power loss.
an article dealing with the tube-rectifier and its characteristic wave­
forms. In the present contribution the author has taken the rectifier
 circuit and inverted it, turning in direct current at one end and
drawing out alternating current at the other.
The new apparatus, consisting of pliotron tubes, transformers, reactances
etc. is known as the "Inverter" and offers a means of converting direct
current into alternating current without the use of any rotating machines.
From this quotation the origin of the word "inverter" still in use today
is obvious, - it was meant to indicate a circuit doing the inverse of
what a rectifier does. The first experimental set-up of Prince, and re­
results obtained, has been reproduced in fig. 3.13 (a) and (b).
The switching elements used by Prince were vacuum tubes. Due to the fact
that he employed 15 kV as operating voltage, the voltage drop over the
tubes was not important. The problem of supplying reactive power to the
system was overcome by using a synchronous machine in the output. It
should be noted that the configuration of the switches in the above system
is already of the parallel type.
The parallel-configuration is sometimes referred to as the "Wagner-inver­
ter", yet it would probably be more truthful to refer to it as the
"Prince-inverter", since Wagner worked much later (27), and Prince
already introduced the parallel capacitor commutated inverter in 1928 (13)
as clearly indicated in fig. 3.15
The so-called series inverters are due to Fitzgerald and Henderson
(1929) and Sabbah (1929) (26).
Before Wagner, Sabbah (28) and Tompkins (29) also discussed the charac­
teristics of parallel and series inverters.
After the invention of the steel tank controlled mercury-arc rectifiers
in Europe at the beginning of the 1930's an enormous activity in the
field of inverters was initiated. This may be verified by consulting
the histograms of the appendix. These developments concerned many aspects
of the problems associated with inverters. It is probably worthwhile to
note two further interesting points regarding development of these cir­
cuits. The first inverter proposed by Prince needed a synchronous machine
in the output to furnish the reactive power. This was the case with
all inverters proposed afterwards - in absence of a machine they could
not handle reactive power. In 1932 Petersen (30) proposed the use of
two additional valves ($S_2$ and $S'_2$ fig. 3.16 (a)) in the parallel inverter.
Fig. 3.13(a) Original laboratory inverter equipment of Prince. (1925)

Fig. 3.13(b) An example of some results obtained by Prince. (1925)
S.M. Synchronous machine  \( P_1, P_2 \): "Pliotron" tubes

G Generator supplying direct voltage T: Inverter transformer

Fig. 3.14 The inverter circuit of Prince (25)

to handle reactive power. It is possible to extend this principle also to systems having more than one phase. Petersen still used an additional voltage \( E \) for commutation purposes. Prince (13) (26) apparently first employed commutation capacitors in order to obtain a self-contained inverter ("selbst-geführte Wechselrichter") (fig. 3.16 (b)). This may be regarded as another major advance in the art of inverters.

The use of the commutating capacitor had one unwanted effect – it discharged over the transformer winding, impairing commutation. Incorporation of the decoupling diodes \( D_1 \) and \( D_2 \) (fig. 3.16 (c)) eliminates this effect. As far as it is possible to ascertain at present, this solution is of a relatively recent date.

According to Ward (31) these diodes are due to B.Y. Umarov and were first described by Hamudhanov (32).

On the other hand these diodes were used quite independently by de Zeeuw in 1961 at the Technological University of Eindhoven (33).
Fig. 3.15 Original circuit diagrams of Prince (1928) indicating the development of a forced commutated parallel inverter.

(a) Rectifier circuit.
(b) Supply commutated inverter.
(c) Dc converter with forced commutation.

In the literature before 1940 Tröger drew inverter diagrams with mercury arc rectifiers in series with the commutation capacitors in a review essay (34). Unfortunately the references given by Tröger are inadequate to be able to deduce the origin and function, and therefore this question will most probably have to remain unsolved for the time being.

The frequency changing circuits developed in the period of the controlled mercury-arc rectifier were limited in their complication by the cost, speed and size of these valves. The thyristor is much smaller, faster and already cheaper, and has therefore started off a development of
R<sub>1</sub> = load resistance
L<sub>L</sub> = load inductance
E: commutation EMF

Fig. 3.16 (a) Proposed inverter circuit of Petersen (30) with "Petersen valves".

S<sub>1</sub>, S<sub>1'</sub>, S<sub>2</sub>, S<sub>2'</sub> gas tubes
T: inverter transformer
L: commutating inductance

R<sub>L</sub>, L, T: inverter transformer
S<sub>1</sub>, S<sub>2</sub>: controlled rectifiers
D<sub>1</sub>, D<sub>2</sub>: decoupling diodes
C: commutating capacitor

Fig. 3.16 (b),(c) Development of parallel-inverter with decoupling diodes (32)(33).
extremely complex circuits, with a corresponding increase in possibilities for application. To attempt to trace the historical development of these circuits involve much detail and may safely be left to the specialized student of these units. At present no comprehensive survey of these circuits exists in the literature, the existing works being of limited scope (see for instance (35)).

Another type of frequency changer that has known a remarkable development is the so-called cycloconverter. The terms "cyclo-conversion" and "cycloconverter" were invented by Rissik (7) in the years before 1935 (see fig. 3.17). The main disadvantage of this type of cycloconverter was the non-sinusoidal output voltage more or less resembling a trapezium. To eliminate this, the envelope cycloconverters were developed. The Löbl-cycloconverter was of a synchronous type, having a definite phase relationship between the two systems (36).

The Krämer-cycloconverter (7) was asynchronous, yet still had a fixed ratio of output to input frequency.

Credit for the development of a continuously variable grid-controlled cycloconverter goes to Schenkel and von Issendorff (37)(38). This type of circuit configuration is again used to great advantage in modern thyristor circuits.

3.2.2. D.c. to d.c. transforming circuits (electronic choppers).

An important art in the power electronics of today is that of the d.c. chopper circuits. These circuits may in principle be considered to be able to regulate the flow of electrical power between sources of direct voltage, and with current control they function as extremely efficient transformers of variable voltage, constant current into variable current, constant voltage. Although the art of applying forced commutation to a thyatron conducting direct current was understood before 1930, as introduced by Prince (13) and Hull (26), and treated explicitly by Tompkins (29), it appears that further practical application to obtain the above mentioned characteristics remained until recently (65).

Further comment on these applications will be made in section 3.3.
3.2.3. Phase control circuits for adjusting output voltage

The technique of adjusting the output voltage of a power electronic circuit by delaying the angle of ignition became possible after invention of the control grid in the thyratron and mercury-arc rectifier and the control anode in the ignitron.

Using the same type of "grid" control (an external plate) suggested by Cooper-Hewitt in 1903, Toulon illustrated the possibility of voltage control in 1922 (B11), later further investigated by Dunoyer and Toulon (39) in order to obtain a regulation of the mean direct voltage at the output of a mutator. This technique was applied with success in the later units having true "grids" between anode and cathode. In the contact-rectifier systems of Koppelmann adjustment of the amplitude of the rectified output voltage was achieved by the same technique. By changing the phase between the supply being rectified and the supply of the synchronous motor driving the cams (fig. 3.10), the actual "ignition" angle was variable. Ignitron systems and magnetic amplifier-semiconductor-diode-bridge systems employed the same technique of conduction angle control. Detail of the application of these ideas to the regulation and control of the d.v. machines will be discussed in section 3.3.

Regulation of alternating voltage and current by using electronic switches in an antiparallel configuration is due to Lenz (40), who published it in 1933 (fig. 3.27). This configuration and the previous found extensive application in the control of welding equipment (41).

3.3. The development of machine-electronics

3.3.1. Some initial attempts

Let it suffice at present to say that machine-electronics concerns the systems consisting of rotating electrical machines and power electronics. In this case power electronics is a loosely defined entity, indicating electronic circuits in which the main function
3-phase supply

Rectifier transformer

positive half controlled rectifier

negative half controlled rectifier

single phase a.c. system $R_L$, $L_L$

Fig. 3.17 Original cycloconverter circuit of Rissik, 1935 (7).

is not information processing, but supplying power to some or other system to be controlled. The level of this power is not defined, and may even be micro-watts. It will be realised that this present definition is intuitive rather than exact.

Ideas to use electronic elements to control, regulate or augment electrical machines appear to have been put into practice for the first time during the years immediately before and after 1920. It is possible that these contributions may not be characterised as machine-electronics as it is known today, yet it may be considered as the very beginning of the subject.
In the year 1917 Bolliger came upon the idea of a "high-voltage" d.c. machine (published 1921) in which the substantial part of the commutator action is executed by a mercury-arc rectifier. To quote Bolliger: "Der Kommutator arbeitet lediglich als ein bei leerlaufenden Phasen kontaktmachender Spannungsschaltapparat, ohne jede Stromwendung unter den Bürsten. Der Gleichrichter hingegen wirkt als ein durch die Betriebsphasenspannungen gesteuerter Stromwendeapparat,...." (42).

From the previous paragraph and from figures 3.18 and 3.19 it may be gathered that by connecting the valve in series with a mechanical switch he was able to obtain the characteristic of a controlled rectifier. This is the more remarkable, since at that stage the controlled mercury-arc rectifier still belonged to the future. The high voltages in the reverse direction, and the actual commutation were the responsibilities of the rectifier. This indicates that Bolliger had already fully realised the necessity for a static electronic commutator; but did not yet have the necessary circuit elements. His appropriate comment on his own work was: "Einen Anfang zu etwas dass noch nicht ist".

Van der Bijl described control systems for d.c. generator current and voltage in 1920 (15), attributing the origin of the ideas to Wold. In these systems a vacuum triode ("audion") was connected either in series or in parallel with the field winding of the generator, the essential control element.

In the years before 1930 Voorhoeve in the Netherlands investigated possibilities to control generator voltages by electronic means. Contrary to the work reported by v.d. Bijl, he employed vacuum diodes, the heating current being the variable (fig. 3.21). This is understandable, since at that time the grid controlled mercury-arc tube had not yet been made widely known by Langmuir and his associates.

Later work by the same group included the use of vacuum triodes, but was overshadowed by the fast developing control schemes with grid controlled mercury-arc rectifiers (43)(44).
After the invention of the controlled gaseous valves an increasing amount of attention was given to the study of machine-electronic systems. With reference to the histograms included in the appendix it is evident that there exists a definite shift in time between the research work devoted to power electronics and machine-electronics.
Fig. 3.19 Schematic arrangement of the experimental high-voltage d.c. machine of Bolliger.

St. machine stator  Gl. Mercury rectifier
Ro. machine rotor  Bz. Battery for rectifier ignition
Ko. machine commutator
Bb,Ba brush holders.

3.3.2. Machines with electronic commutators

Reference has already previously been made to the fact that the electronic switches may be used to perform the same function as mechanical switches in conjunction with an electrical machine.
One of the initial ideas that sprung from the availability of the controlled mercury-arc rectifier was to build an electronic commutator. This idea grew gradually. It is worth mentioning that in 1913 two steel-tank mercury-arc rectifiers were installed in a traction unit of the Pennsylvania Railroad in the U.S.A. This unit, with four motors of 200 h.p., 600 V completed approximately 20,000 km in normal traction service in the years before 1920 (B7). In this case two frequency conversion processes are to be observed, one of which is still mechanical. The first machine to use a true electronic commutator was the machine of Kern—a now famous example (46). In fact, Kern suggested various configurations, one being shown in fig. 3.22, the first locomotive being built with this system by Brown Boveri around 1930 being shown in fig. 3.23.

In the years before 1940 these types of machines were studied by many workers, and were originally primarily intended for traction purposes (47).

Although it was applied on the European continent and in the U.S.A. to a certain extent (48), the thyratron or controlled mercury-arc commutator motor never attained true widespread practical application, despite considerable enthusiasm (see for instance discussion of Alexanderson to Marti (47)).

![Fig.3.20 Schemes presented by van der Bijl.](image)

A: audion, G: d.c. generator, $R_1$: current resistance, $R_g$: grid resistor, FW field winding.
In some cases smaller motors were driven by vacuum-tube oscillators or by thyatron relaxation oscillators, but all these applications remained special solutions to a limited number of problems. The motors used were mostly of the synchronous type.

It is understandable that since the thyristor has come of age, the thyristor commutator motors have received renewed attention. The characteristics of this element bring applications previously not feasible into view for reconsideration. In most cases the modern technology tends toward a separate inverter and motor, and not towards using the motor windings as part of the inverter. This approach may change with time, however.

One of the ideas being worked out at present is the use of thyristor-frequency changers in conjunction with squirrel-cage

![Diagram](attachment:image.png)

**Fig. 3.21** Original schemes of Voorhoeve for controlling generator voltage.
induction machines for electric traction purposes (49)(50). This idea has been considered in the past, but rejected (51). The reason for the rejection of this proposal in 1940 was the enormous amount of equipment needed, it being impossible to transport it aboard an ordinary locomotive. Thyristors are relatively small in size and eliminate this problem, as has been illustrated by the present experiments. The main hazards besetting the application of this type of traction at present seem to be economics and reliability.

The interest in electronic commutators stimulated anew by the thyristor have apparently stimulated the use of transistors for the same function in small machines. This is the inevitable conclusion, as it was not before 1962 that this type of electronically commutated machine received serious attention (53), although switching transis-
3.3.3. Schemes for control of induction machines without changing the supply frequency

Compared to direct current machines wound rotor induction machines are relatively cheap and it is therefore interesting to investigate all possibilities to control them. Electronic regulation of the rotor current of these machines has only recently received some worthwhile attention, however.

This may be verified by examination of the appropriate histogram in the appendix, and may be ascribed to the high voltage drop over the previously available electronic devices, as well as to their cost and size.
The first work on electronic rotor control of induction machines concerned electronic Scherbius cascades. Due to the considerations mentioned in section 3.1 the application was only interesting for larger machines. In 1939 Stöhr (54)(55) apparently proposed the first electronic Scherbius cascade, indicated in fig. 3.24.

Subsequently Hölters (1943) (56) also investigated this type of system. To his system the rather unfortunate name of "Asynchronstromrichtermotor" was given. This name has since been used to indicate another type of system, i.e. that of a variable frequency inverter feeding an induction motor, the motor windings being part of the inverter.

The magnetic amplifier was, and still is, applied with good results to this type of control (2) but it is only during the last decade after the development of the thyristor, that this type of control has received increasing attention in the form of electronic switching of the rotor current, notably in Germany (See for instance (57)).

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**Fig. 3.24** Electronic Scherbius cascase of Stöhr.

**IM**: induction motor, **MR**: mercury-arc rectifier

**RT_1, RT_2**: Rectifier transformers  **CMR**: controlled mercury-arc rectifiers
Development of silicon rectifiers renewed the interest in systems consisting of wound-rotor induction machines and frequency converters in the rotor (58), while thyristors holds the promise of making this drive economic and compact — also for smaller machines. Although the idea of using antiparallel switches to regulate voltage has been existent for a long time (see section 3.2.3.) it does not seem to have been worked out further for stator control of induction machines. In the years after 1950 the idea of applying phase-control to rotor and stator circuits of induction machines by magnetic amplifiers found wide application (2, 66). Only after 1960 did interest arise in employing this type of control to advantage on the stator of squirrel cage motors (67). The appearance of the triac has made this type of drive an attractive proposition in the lower power range (< 10 kW).

3.3.4. Voltage regulation of direct voltage machines by mutators

Control of d.c. machines fed by three phase or single-phase a.c. systems drew attention after the introduction of the controlled

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F.T.: Field Transformer  
M.T.: Main Transformer  
MR: Mercury rectifier  
CMR: controlled mercury rectifier
L: switching inductor  
M: direct current motor

Fig.3.25 Original scheme for a.c. fed d.c. motor investigated by Schilling (60).
Electronic chopper circuits as discussed by Hull (1929) in relation to the parallel inverter (26).

mercury-arc rectifier in 1928. It was realised that this offers the possibility to regulate the main current in the motor (59), and was apparently first extensively investigated by Schilling (69) (See fig. 3.25). As is evident from the histograms, interest in this type of control increased steadily through the years. Later attention was devoted to constructing static Ward-Leonard drives in this way. (See for instance (43)). Semiconductor switches increased the possibilities, and it may be expected that the present popularity of this type of semiconductor controlled drive will still continue for a considerable time.
3.3.5. Electronic chopper control of direct voltage machines

Apparently the inventor of armature voltage control of d.v. machines by pulse modulation, the so-called series chopper - was Blaufuss in 1940 (61). The problem was to obtain a mechanical or electronic switch that could be operated reliably and fast enough to achieve this control. It took years before the idea of Blaufuss was taken up again. Gutenbaum did theoretical work on this type of problem (62)(63) but it is not clear whether a system was practically realised. The first practical realisation of this scheme by electronic means appears to be due to Jones (64) in the U.S.A. and to Abraham, Heumann and Koppelmann (65) in Germany, the two groups working independently, and employing thyristors as switches. It is interesting to note that the electronic chopper as employed by these groups was discussed in 1929 by Hull in relation to the parallel inverter (26). The original circuits discussed by Hull are shown in fig. 3.26. These types of power-electronic systems have since developed rapidly - especially with respect to the circuits improvements possible. Electronic choppers regulating series direct voltage machines is one of the most successful machine-electronics systems at present, finding widespread application for low loss control in traction circuits.

Fig.3.27 Antiparallel system investigated by Lenz (1933).
4. **AFTERTHOUGHTS**

Having been at pains to trace the development of a subject as good as possible, it is a natural tendency to attempt to put the knowledge to good account. In the present case this concerns the philosophical implications more than the direct technical effects. The former is less direct, and perhaps more important to stress at this point.

1. To state an important point a part of a discussion of Ludwig to Marti (47) is cited (1932):

"It has also been recognized for some time that rectifiers may be used instead of commutators in conjunction with rotating electrical machinery. However, it would be no more correct to state that the rectifier can be used to replace the commutator than it would be to state that a gasoline engine can be used to replace the horse. Both gasoline engine and horse may be used as a source of power for locomotion, but certainly no one would expect to hitch a gasoline engine to the shaft of a wagon for the purpose of pulling it. Similarly, the rectifier is not the exact counterpart of the commutator. Two differences exist: (1) the rectifier is a unidirectional switch, whereas the commutator and brush will pass current in either direction, and (2) the rectifier for practical reasons must have a comparatively small number of anodes or segments, whereas the commutator usually has a large number. The result is that when a rectifier is used in place of a commutator, as suggested by Mr. Marti, the utilization of the windings on the motor is not nearly so good as the utilization if a commutator is used. For this reason, one may question whether it would not be better practise to use a controlled rectifier merely as a frequency-changer without direct regard to the motor, and to use with it some type of motor in which the utilization of copper is considerably better. Certainly with this poor utilization, the requirements of the controlled rectifier as to size, cost, and reliability seem to be much greater than can be met at the present time".

Although these comments refer to the mercury-arc controlled and uncontrolled rectifiers of more than a quarter of a century ago,
they suit the present situation concerning the application of thyristors equally well. It is wise to evaluate the total situation when applying a new electronic device, and not to concentrate on one or two undesirable characteristics of the existing solutions to the problem. The previous attempts at developing traction units with electronic commutators were unsuccessful due to insufficient reliability, economical factors and space required. Although the present semiconductor switching elements also have insufficient reliability as a drawback, the total situation may change to a large extent, as the size and weight of the new elements inspire application in all types of vehicles. This may in the end prove to give the necessary economic impetus to inspire the necessary development of extremely reliable commutators. Due to the restricted application of the mercury-arc rectifiers, (only large locomotives) this factor was absent in the 1930's.

2. Despite all the drawbacks normally claimed for the mechanical commutator and conventional d.c. machine, it has every time proved to be still more reliable and more economical than any electronic counterpart. A well-designed mechanical commutator is a very efficient piece of engineering equipment.

3. New switching devices seldom tend to replace existing ones in all functions, but rather have a supplementary nature. The question of total replacement is more often than not a sort of fashion.

4. The present development of new devices may be observed to differ from the previous patterns (mercury-tubes, vacuum tubes, selenium rectifiers etc.) in scale and accelerated rate of growth. This is an observation that is reflected in almost every other contemporary field of human knowledge.

5. The same observations as regards 4 may be held for the development of circuits and commutation methods. For the types of control applied to electrical machines a point of saturation is apparently being approached.
Some interesting parallels:

a. It is only natural to expect that the development of control methods to electrical machines, when a new device is introduced, will in some respects follow a parallel course to the previous historical development. One may for instance observe clearly at present that after an attempt to apply the thyristor everywhere, the applications are now slowly concentrating on the areas where the abilities of the semiconductor based circuits overlap the shortcomings of the previous solutions. This type of parallel is more evident than the following examples.

b. In 1903 Cooper-Hewitt clearly indicated the possibility to control the discharge in a mercury-arc tube, yet devices of this type did not come into practical operation before a quarter of a century had elapsed (1928,Prince). It is remarkable that exactly the same line followed with the thyristor. At the start of semiconductor technology the thyristor structure was clearly pointed out by Shockley (1951), but it found its way into the power field nearly a decade later.

c. Around 1920 Bolliger conducted his research on a combination of electronic switches and a mechanical commutator. The present work that has been taken up in England in this field of thyristor-assisted mechanical commutation (Bates 1966) (69) is strongly reminiscent of the work of Bolliger.

d. Observing the contact rectifiers of Koppelmann and the present semiconductor units, one parallel is conspicuous. Semiconductor units compare just as favourably with the volume and weight of mercury-arc equipment as the contact rectifiers. The contact-voltage drop and current capacity of the system of Koppelmann is as low as technically possible at room temperature. As the current-carrying capacity of silicon thyristors have been increased to the order of the fundamental maximum, (70) and the forward voltage drop during conduction mastered equally well (72), it is not to be expected that the volume of this type of equipment will decrease much in the future.
There are semiconductor elements having a lower voltage drop during conduction, such as superconducting tunnel junctions. It is reasonable to expect that what may be gained in this respect will be lost by the increased volume of the cooling equipment. The presently available voltage ratings may be expected to increase with a factor of 2 in the future. (5 kV)(71). This will then exceed the rating of the contact-rectifier by an order of magnitude.

In conclusion it is fitting to devote some attention to the problem of a turn-off power switch. Appearance of such a switch will have an important influence on machine-electronics. During development and existence of the mercury-arc tubes the investigation of a switch-off action by electrical grid control received as intensive attention as the development of a gate-turn-off thyristor. In both instances the results were very restricted. The history of these attempts have taught that control of discharges by an electrical field, after the discharge has set in, is not promising. Control by a high magnetic field is more promising, but unfortunately this is unpractical in the large volume mercury-arc devices. The semiconductor tablets have a volume at least $10^5$ times smaller than the active volume of the gaseous devices for the same rating, so that the magnetic approach appears more practicable. Recently important advances have been made in this technique (73), and it is not impossible that in the near future some modifications in the present commutation techniques may be expected.
Table 1. Schematic representation of various devices employed in power conversion.
**LEGEND TO TABLE 1.**

4. Ignitron.
5. High voltage controlled mercury-arc rectifier.
6. Contact rectifier (Koch 1901, Koppelmann 1941).
7. Selenium rectifier (Presser 1925).
8. Copper-oxide rectifier (Grondahl 1926).
11. Triac (Gentry, Scace, Flowers 1964).

<table>
<thead>
<tr>
<th>a</th>
<th>a.a.</th>
<th>t.a.</th>
<th>c.a.</th>
<th>g</th>
<th>c</th>
<th>v.d.</th>
<th>v.d.g.</th>
</tr>
</thead>
<tbody>
<tr>
<td>anode</td>
<td>auxiliary anode</td>
<td>trigger anode</td>
<td>control anode</td>
<td>control grid</td>
<td>cathode</td>
<td>voltage divider</td>
<td>voltage dividing grid</td>
</tr>
<tr>
<td>m.c.</td>
<td>m</td>
<td>metal</td>
<td>metal</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

m.c. metal carrier m metal
London. Unser Londoner Korrespondent erzählt uns unter dem 10. Januar:


Die Erscheinung beruht darauf, daß die Lampen Strom entladen, als der Strom der Lampen getrennt wird, und die Lampen werden auf diese Weise in eine elektromechanische Anordnung gebracht, indem die Lampen durch den Generator getrennt werden, indem der Generator nicht durch die Quecksilberdampfelektrode fließt. Der Generator muß also von der zweiten Klemme getrennt werden, damit der Strom für den Generator nicht durch die Quecksilberdampfelektrode fließt. Der Generator muß auch von der zweiten Klemme getrennt werden, damit der Strom für den Generator nicht durch die Quecksilberdampfelektrode fließt. Der Generator muß auch von der zweiten Klemme getrennt werden, damit der Strom für den Generator nicht durch die Quecksilberdampfelektrode fließt.
In Fig. 23 ist die Wirkungsweise des Apparates graphisch dargestellt; die Kurven 1, 2, 3 stellen die Momentanwerte der Schenkelspannung dar. Kurve 4 gibt den Verlauf der verkehrten Spannung zwischen 2 und 3 a a a entsprechend den drei Spannungen zwischen der unteren und einer der oberen Elektroden, und erkennt man hieraus deutlich ihre ventilartige Wirkung. Bei niedriger Periodenzahl tritt dies auch sichtbar in die Erscheinung, indem sich ein abwechselnd von einer der drie Elektroden zum Quecksilber übergehender Dampfstrahl bemerkbar macht. Die Quecksilbertemperatur selbst führt eine roterrore Bewegung aus, deren Winkelgeschwindigkeit sich mit der Polwechselzahl ändert. Schließlich sind noch drei Kurven, den Verlauf der Gleichstromspannung, Stromstärke und Leistung darstellend, in Fig. 23 enthalten. Diese Kurven lassen erkennen, daß der effektive Mittelwert der erzeugten Gleichstromspannung gleich der Schenkelspannung der Dreiecksmethode ist und im vorliegenden Falle 110 V beträcht.

Zu seinen Versuchen benutzte Hewitt eine Röhre von etwa 175 mm Durchmesser und 220 mm Länge, welche eine Leistung von etwa 8 KW umzusetzen und 300 16-kerzige Glühlampen zu speisen vermochte. Das Gewicht einer solchen Röhre beträgt etwa 1,4 kg. Die Röhre erwärmt sich bald nach ihrer Inbetriebsetzung auf eine konstant bleibende Temperatur, welche von der Größe der Belastung gänzlich unabhängig ist, da der Spannungsabfall zwischen oberen und unteren Elektroden einen konstanten Wert von 14 V besitzt. Neue Versuche zeigten, daß sich die Größe dieses Spannungsfalles bis auf 6 V herabdrücken läßt. Der Wirkungsgrad der Gleichrichter ist von der Größe der verwendeten Spannung abhängig und wurde bei 1800 V zu 59%, bei 600 V zu 55% bestimmt. Was die Höhe der Betriebsspannung anbelangt, so läßt sich diese ohne weiteres auf 3000 und höchst wahrscheinlich weiter bis auf 10000 V steigern.

Ein Verwendungsgebiet, für welches sich die vorliegende Erfindung ihrer großen Einfachheit halber ganz besonders eignen dürfte, wäre das Aufladen von Sammlerbatterien aus Drehstromnetzen, da hierbei eine konstante Gleichstromspannung nicht erforderlich ist.

Beim Verwendung der Drehstromnetze, z. B. Sechsphasenstrom, zum Betrieb einer solchen Röhre verwendet werden könnten, so bisher die Zahl der Phasen ist, desto mehr nähert sich natürlich der erzeugte pflügende Gleichstrom einem Strom konstanter Spannung.
HISTOGRAMS

Note: These histograms have been compiled from data obtained from a selected bibliography compiled on machine-electronics and related subjects (74). The most important selection criteria were that the contributions should treat theoretical and/or experimental study of problems associated with power-electronics, machine-electronics and closely related subjects.

Literature on power-electronics and all types of machine-electronics systems

<table>
<thead>
<tr>
<th>Time (five year periods)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1921-25</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Literature on power-electronic frequency changers

<table>
<thead>
<tr>
<th>Time (five year periods)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1941-25</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Literature concerning systems with frequency regulation of a.v. machines

Literature concerning rotor regulation of induction machines

Literature concerning systems with voltage control of machines (chiefly mutator and chopper control)

Literature on semiconductor power switching elements

A_3

1921-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65

time (five year periods)

A_4

1921-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65

time (five year periods)

A_5

1921-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65

time (five year periods)

A_6

1921-25 26-30 31-35 36-40 41-45 46-50 51-55 56-60 61-65

time (five year periods)
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