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Inverter-fed AC Machines

H. Kleinrath

This paper presents a review of the state of engineering, of present-day problems and of the future development in the field of inverter-fed AC machines.

Der Aufsatz gibt einen Überblick über den Stand der Technik, über aktuelle Probleme und die zukünftige Entwicklung im Bereich der umrichter gespeisten Wechselstrom-maschinen.

L'article présente une vue d'ensemble de l'état de la technique, des problèmes principaux actuels et du développement futur dans le domaine des machines à courant alternatif alimentées par convertisseurs

State of Engineering

The present development in the field of electrical drives with variable speed is comparable to the development in the early years of our century by means of AC machines with a rotating commutator. This technique has opened a wide range of possibilities both for inventions and for inventors; a lot of different solutions have been found — but only a limited number of them staid alive. As the older colleagues know very well, mainly the rotor-fed AC shunt-wound motor (in German: "Schrage-Motor") has been applied until recent times mostly for spinning-machines. Another drive which still exists today is the single-phase series-connected AC motor as a standard drive for electrical traction. A third drive of manifold application was the series-connected 3-phase motor, mainly for heavy drives of fans in electrical power stations.

This introduction and comparison should draw the reader's attention to the fact that practical requirements use to be very rigorous, the challenge lying as well in the costs as in the demand for simplicity, for reliability and for low maintenance. Therefore it is to be expected that in the new field of variable-speed drives by means of power electronics, too, only solutions will

survive over a long time which fulfill these requirements. Figure 1 shows three standardized drives using an asynchronous machine, where the variable speed is realized by variation of its *primary frequency*.

The first one (fig. 1a) is the current-source inverter in its preferred version with auto-sequential commutation. The preference for this type of inverter is well founded on its simplicity and its possibility to conduct the energy flow into both directions with just one group of thyristors in the primary part.

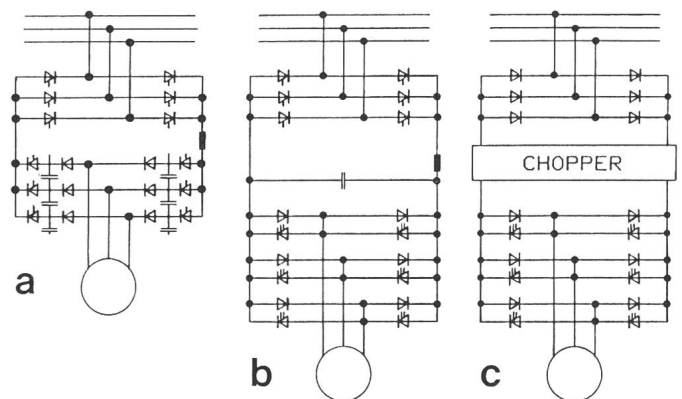
The second drive (fig. 1b) shows the voltage-source inverter, without details concerning the commutation in its inverter section. According to the mode of firing the inverter the DC voltage in the medium circuit can be constant or has to be variable. If the DC voltage is kept constant, the voltage at the outlet has to be controlled both in frequency and amplitude by means of PWM (pulse width modulation).

The third version with a chopper series-connected with the rectifier (fig. 1c) is used in order to avoid a poor power factor in the primary grid. Instead of the rectifiers at the inlet of the chopper a DC source might be used.

In figure 2 the characteristic waveforms of the current and the voltage in the motor winding are plotted for the

Fig. 1
Variable-speed drives of asynchronous machines by varying the primary frequency

- a Current-source inverter
- b Voltage-source inverter
- c Chopper inverter
- $n = (1-s)f/p$
- n speed (revolutions)
- s slip
- f primary motor frequency
- p pair of poles of the motor



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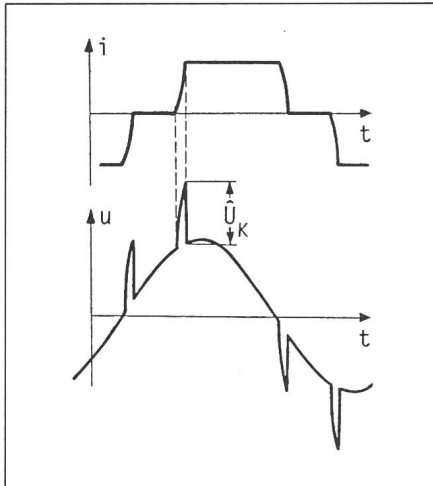


Fig. 2 Motor-current and motor-voltage waveform in a circuit with current-source inverter (fig. 1a)

U_K Commutation peak voltage

current-source inverter, calculated on the basis of an ideal smooth current in the medium circuit. Figure 3 shows the waveforms of the current, the voltage and the torque in the case of a voltage-source inverter fired in a 180° mode.

With the drive shown in figure 4 variable speed will be realized by *changing the slip* of the asynchronous machine. If a diode-bridge is used in the left part of the inverter, only subsynchronous operation is possible, whereas a thyristor-bridge allows both subsynchronous and supersynchronous speed. The waveform of the rotor current has been calculated for the special case of operation with a slip of exactly $1/6$. The unusual waveform is caused by the fact that the 5. harmonic is strongly suppressed at this slip; therefore as a matter of fact no significant increase of the pulsating torque occurs at the slip $s = 1/6$.

The drive consisting of a current-source inverter and a synchronous machine shown in figure 5 has the advantage not to need forced commutation

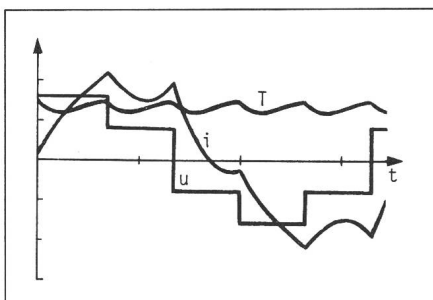


Fig. 3 Voltage, current and torque in a motor fed by a voltage-source inverter (fig. 1b)

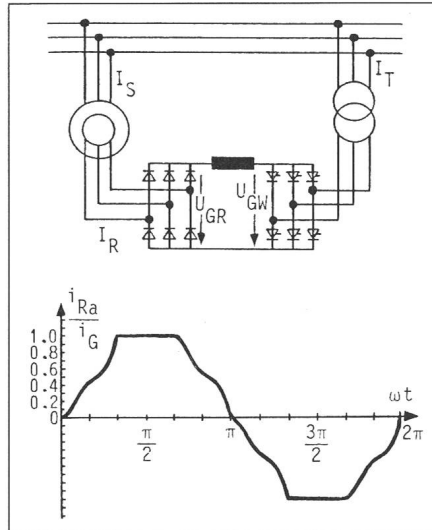


Fig. 4 Circuit and rated rotor-current in case of variable speed by means of slip-changing

$s = 1/6$

I_R rotor current

I_S stator current

I_T transformer current

i_{Ra} rotor phase current

i_G medium circuit DC current

U_{GR}, U_{GW} medium circuit DC voltages

in the inverter under normal operating conditions. However, the start-up procedure requires an additional equipment.

Especially for heavy drives with low speed the synchronous machine fed by

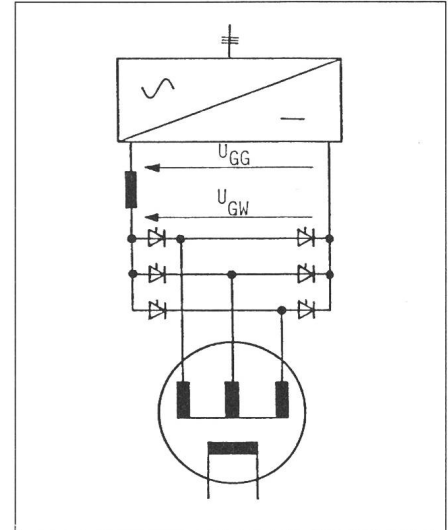
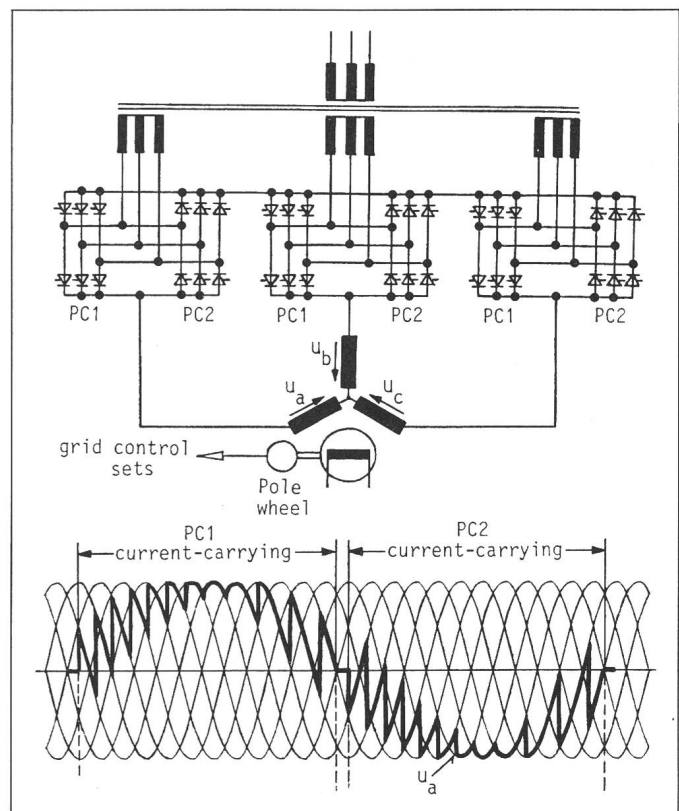


Fig. 5 Synchronous machine fed by a current-source inverter

a cycloconverter as shown in figure 6 is a well established solution. Such drives are usually operated with frequencies of some 5 Hz and sizes of 5 to 6 MW.

Of course the list of drives which are to be qualified as standard solutions might be continued arbitrarily. It seems reasonable to stop it here with regard to the expectation suggested at the beginning of this paper. Nevertheless, whoever would want to include any further solution may do it freely.

Fig. 6 Cycloconverter-fed synchronous machine
PC Partial Converter



Modified circuits

Series-manufactured motor or special design

Standardized inverter or special development

Simplified cheap drives

Optimal system for electric traction fed from a single-phase source

Optimization of PWM strategies

Operation of inverter-fed ASM with field-weakening

Better understanding of the behaviour under failure conditions

Present-day Problems

An overview of selected items of problems which are under discussion today is given in table I.

Figure 7 shows two examples of modifications of well-established drives. Figure 7a is a variant of the cascade of an asynchronous machine with a converter in its slipring circuit. By splitting the machine into two units with wound rotors and connecting the rotor windings within the rotating part a drive can be built without sliprings and brushes. It should be pointed out that the lowest possible number of effective poles of this arrangement is 4 because the synchronous speed corresponds to the sum of the poles of both machines. Another disadvantage is the poor power factor. It can be improved by means of capacitors in parallel with the rotor winding. Such a drive may be of special interest in the case of explosion-proof conditions.

Figure 7b shows another possibility of a machine without sliprings, the so-called self-cascade asynchronous motor (b).

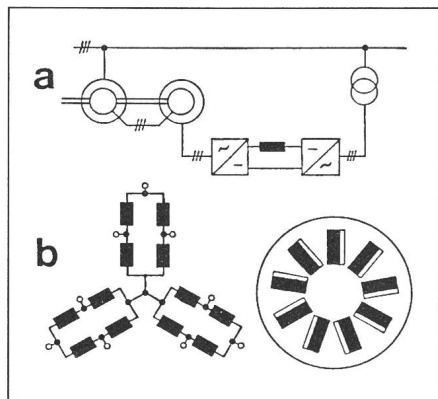


Fig. 7 Asynchronous cascade with converter-fed slipring circuit (a) and self-cascade asynchronous motor (b)

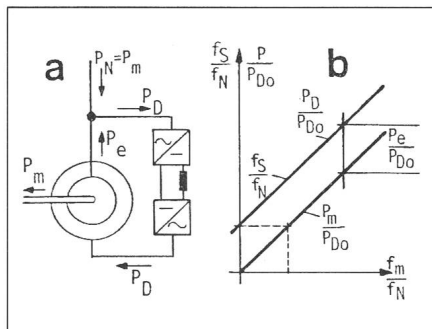


Fig. 8 Schematic diagram and characteristics of a double-fed asynchronous machine

f_m, f_N, f_s mechanical, network and stator frequencies

$P_D (P_{Do})$ air gap power (at synchronous speed)

P_e, P_m, P_N electrical, mechanical and network power

has two different numbers of poles, the wound rotor has a couple of short-circuited parts, which respond selectively to the corresponding harmonics of the rotating field.

A special type of a double fed asynchronous machine is shown in figure 8. The wound rotor of the asynchronous machine is directly connected to the grid, thus exciting a magnetic field which is rotating against the rotor with synchronous speed f/p (f = frequency of the source). The stator is fed by a frequency converter with variable frequencies. From the diagram figure 8b the behaviour of this drive and its special properties can be derived, assuming operation with constant torque. Since the torque T is proportional

$$T \sim P_D / f_s$$

the mechanical power at the shaft can be determined by application of the basic formulas

$$P_m = \left(1 - \frac{f_R}{f_s}\right) \cdot P_D = \frac{P_D}{f_s} (f_s - f_R) \sim T \cdot f_m$$

and for the electric power flowing over the sliprings

$$P_{el} = \frac{f_R}{f_s} \cdot P_D \sim T \cdot f_R = \text{const.}$$

Looking for the dependency of P_m and P_D on the rotational frequency f_m , figure 8b shows that the electrical power which has to pass the sliprings is only a small portion of the mechanical power if the drive is operated at a high ratio f_s/f_N .

Thus just small sliprings are required. The main advantage of this drive is the fact that there is no need

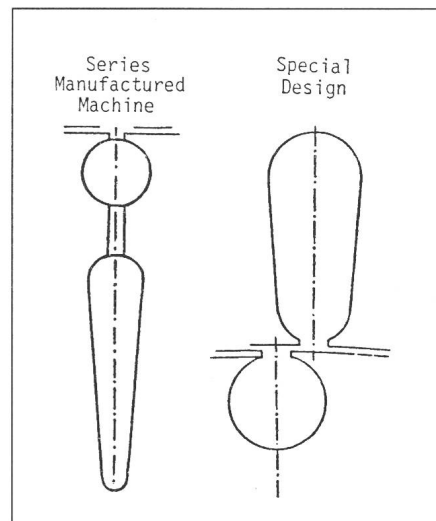


Fig. 9 Comparison of losses of a standard-type motor and a specially designed one

P_r	45 kW	45 kW
f	50 Hz	75 Hz
n_r	1475 rpm	1480 rpm

Losses at 300 rpm, rated torque

Due to basic harmonic	2155 W	2105 W
Due to higher harmonics	785 W	335 W
Total	2950 W	2470 W

for forced commutation.

Obviously there are considerable advantages if a series-manufactured motor can be used also for a variable-speed drive. However, it is well known, that due to higher harmonics as well in the currents as in the voltages additional losses occur especially in the cage of the rotor. These losses can be reduced by a specially designed rotor with as little eddy current effects as possible. Figure 9 gives an idea of the advantage of such a special design. The cage of the series-manufactured machine is made of aluminium and its slots are skewed by one slot-pitch, the special motor has an unskewed cage of copper. Since the gain of these relatively expensive measures is only a reduction of the total losses of 16%, the example makes it understandable that the use of series-manufactured machines is to be preferred. For large machines, however, a special design may be worthwhile—except for machines to be operated temporarily direct fed from a grid.

Standardized inverters are also on the market, although rather for small sizes.

An open problem is a variable-speed drive for small output competitive with classical solutions like a DC

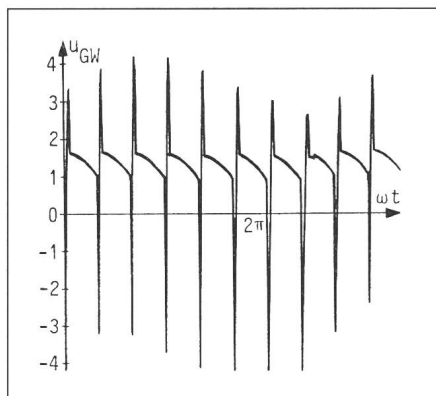


Fig. 10 Voltage in the medium circuit of a current-source inverter fed from a single-phase system

machine or a gearbox. Perhaps a simplified electronic equipment could overcome the break-even point and thus open a wide field of applications.

A special problem occurs in Germany, Switzerland and Austria because of the single-phase supply system for railways with a frequency of $16\frac{2}{3}$ Hz. The low frequency of the pulsating power-flow in a single-phase system causes an extremely high demand for storing capacity in a converter for a three-phase AC motor. To demonstrate this effect figure 10 shows the voltages in the medium circuit of a current-source inverter, figure 11 the voltage, the current and the torque of the AC motor. The strong variation of the peak values gives rise to additional oscillations in the mechanical system. While several different systems as well relating to the power circuit as to the

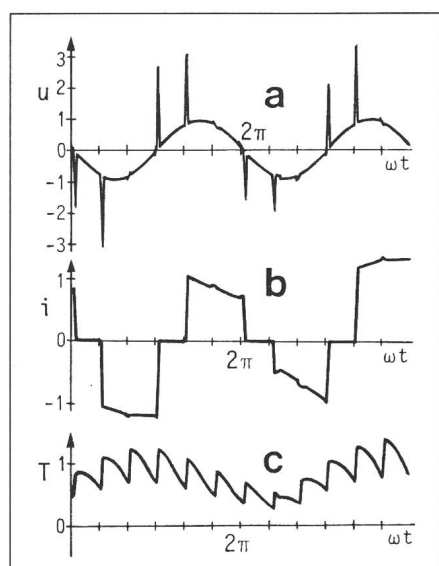


Fig. 11 Phase voltage and current and torque of an AC motor fed by a current-source inverter from a single-phase system

control strategy compete each other, it is not clear at present, which system will win this competition. A lot of expensive research and development is done in this field in the industries.

As to the optimization of PWM strategies¹⁾ a lot of papers of ICEM 84 deal with this problem. One aspect to be mentioned here is that several strategies which were estimated as being too complicated may become more attractive since microprocessors are very cheap today.

Future Development

Table II gives a schedule of selected items concerning the future development—selected of course from a personal point of view without any pretention to completeness. With regard to the increased application of microprocessors one can state that the future has already begun. For instance the field-oriented control of asynchronous machines is realized by means of simulation networks using digital data processing. Advantages of the new digital technique are to be expected whenever a wide range of different operating conditions must be managed—for instance the above mentioned operation of an asynchronous machine in the field weakening range. Another application could be the realization of pretentious strategies for PWM.

Hand in hand with the development of powerful transistors for high currents their application within power electronic equipment is increasing. For instance electronic switches already exist which are able to switch a current of some 100 A on or off with a frequency of up to 100 kHz. A network which takes away the switching losses from the main transistor makes this possible. By scanning the current of an asynchronous machine with such a high frequency and switching it on and off from the source, it is possible to follow up a reference sine wave with very high accuracy. Thus a simple control system can be used and at the same time losses in the machine due to higher harmonics as well as torque ripples do not occur.

Avoiding transformers is also a goal of the development, because they are heavy, expensive and voluminous devices.

If it became possible to manufacture a variable-speed drive with low cost, a

Future Development

Table II

Forced application of microprocessors
Inverters with GTOs or transistors
Inverters without transformers
Low-cost drives
Reducing the disturbances in the supply system
Reducing the magnetic noise
Improved safety under failure conditions

wide field of applications could be opened up. What I have in mind is a combination of a power electronic arrangement together with a special adapted machine and a simple control system, all coordinated not with the goal of highest technical quality but of lowest possible costs. Perhaps this will remain a fiction, however, the goal is tempting and several but as far as I know industrial firms are looking for such a drive.

The reduction of disturbances of the supply network becomes the more necessary with an increasing portion of users including power electronic elements. Besides the deterioration of the voltage waveform disturbance of communication networks and of data-processing networks have to be avoided.

Since higher harmonics cause additional magnetic noise in AC machines we have to take care for those effects. In principle the precalculation of the magnetic forces is well known but due to the broader spectrum of excitations it becomes more difficult to avoid resonances between electromagnetic excitations and mechanical natural frequencies.

It is easy to demonstrate how a well-known arrangement could be improved with respect to its safety under failure conditions. Usually the rectifier in the circuit of figure 4 consists of diodes. In the case of a breakdown in the supply system heavy currents occur both in the stator and in the rotor windings of the machine thus overloading the diodes and the thyristors of the whole inverter. By replacing the diodes by thyristors the duration of these high currents can be shortened drastically by blocking the thyristors in the case of a breakdown or other failure conditions. As soon as the current goes through zero it can no more arise. Thereafter the currents in the stator winding are reduced to the magnetizing values which are slowly fading away.

¹⁾ PWM Peak Width Modulation