A NEW INVERTER WITH LOADCOMMUTATION FOR RELUCTANCE MACHINES

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1. INTRODUCTION

If one compares the advantages and disadvantages of synchronous machines, then one finds the reluctance machine as the simplest, most inexpensive and most robust type of machine. Initially the disadvantages of the low power factor the high noise and the large weight for each unit of power faced these advantages. Since the efficiency of a reluctance machine depends strongly on the relation of the magnetic conductivenesses in the longitudinal field and transverse field direction of the rotor, one aims at a magnetically strongly asymmetrical structure of the active components by constructional measures, in order to work against the disadvantages mentioned. In the passed years reluctance machines with changing magnetic conductance both in the rotor and in the stator i.e. with double saliency were introduced. To it belong the Switched Reluctance Machine (SRM) and also the transverse flux machine (electrically excited TFE) (fig. 1). The two versions of this type of reluctance machines differ in system-oriented regard by the following features:

- with a switched reluctance machine a fixed connection exists between the bipolar number and the phase number of the machine; in another hand with the transverse flux machines this dependency is removed by one for direction of rotation transversal flux guidance. This independence of the bipolar number from the phase number enables depending upon machine variable any enlargement to the bipolar number, whose optimum can be deduced from a field analysis. This type of machine permits a very fast modification of the torque, because they are operating generally with relatively high supply frequencies (some 100 to approx. 1000 Hz). In order to be able, become to use the dynamic characteristics fully to the static inverter and its regulation high request placed. At the same time the desire exists to keep the costs of the static inverter and the reactive power requirement of the machine as small as possible. Aim of this current work in the Institute for Electrical Power Engineering is to execute the comparison of well-known and again-developed versions of static inverter circuits for such machines as well as their evaluation under technical-economic criteria. The theoretical results are to be supported by experimental investigations at a test stand. Aim thereby is to be indicated a new static inverter version as improved characteristics (smaller losses, higher utilisation of machine) and tested on a laboratory scale.

2. A NEW STATIC INVERTER CIRCUIT FOR RELUCTANCE AND TRANSVERSE FLUX MACHINES

The reluctance machines of conventional design are laid out for small performances and high revolution speed, against what the transverse flux machines for middle until larger performances and torques are conceivable [1]. Over suitable static inverter circuits for reluctance machines an extensive literature exists [2]. For example Krishnan and Materu tried, the static inverter expenditure of the reluctance machines of smaller performances in [3], [4], [5] to minimise.

Specially with because of their high utilisation [1] particularly attractive transverse flux machines (here four-phase fig. 1a) today the classical static inverter (fig. 2) with altogether four valves (2 IGBT ' s and 2 diodes) per phase is used [6]. A substantial advantage of this circuit is the possibility of heading for each phase of the machine independently. This permits an optimisation of the points of switching time and the current flow duration. These advantages can be achieved through the new concept of the commutation converter also with fewer complex circuits. (fig. 3)

The new circuit is characterised by the parallel connection of two phases. Thus the valve number can somewhat be reduced and the valve current by a freewheeling (scored line) of the stator current ($I_2(t)$, $I_4(t)$) during the commutation of phase 2 (1) to phase 4 (3) be reduced. The commutation runs to a large extent load commutated, i.e. the rotative induced voltages U_{rot2}, U_{rot4} drive, if S41, S42 get switch off initiating the commutation from $I_4(t)$ to $I_2(t)$, the free-wheel current into the subsequent phase. The magnetic energy of the energised phase is passed on without the DC voltage intermediate circuit to load directly into the following phase, which brings basic advantages with itself. The valves and the intermediate circuit are relieved by the commutation reactive power, whereby the losses act. Because of the magnetic flux in the subsequent phase is removed immediately after the beginning and thus in former times as during the circuit according to fig. 2, are also in the torque gain to be expected.

Is the natural commutation over, so that $I_2(t)$ is equal $I_4(t)$, S21/S22 will be switched on further current feeding into the coil, and $I_2(t)$ achieved its final value. If the current becomes excessive, either both switches in the mode of "changing steps" are opened or only one in the so called "single steps". The current $I_4(t)$ fades away faster with changing steps than with single steps, because inductance L_2 unloads itself in the first case against the intermediate circuit voltage, in second case it is switched into the freewheeling mode, which leads to small current rate of change, because the backlash voltage in this state is smaller than the DC voltage. Since this case entails with otherwise same conditions a smaller switching frequency appears so that the losses are reduced. Therefore only the single steps mode is further pursued.

3.SET UP A MACHINE MODEL

Based on the voltage equation (l) for the machine string a mathematical model was developed:

$$U = I_2 \cdot R_2 + \frac{d\psi_2(I_2 \cdot \varepsilon)}{dt}$$

$$\text{with} \quad \psi_2(I_2,\varepsilon) = L(I_2,\varepsilon) \cdot I_2(t) \qquad (1)$$

With neglect of the saturation influences the voltage equation of the electrically excited reluctance machine for a string can to be written as following:

$$U(t) = I_2(t) \cdot R_2 + \frac{d}{dt}\left(L_2(\varepsilon) \cdot I_2(t)\right) \qquad (2)$$

$$U(t) = I_2(t) \cdot R_2 + L_2(\varepsilon) \cdot \frac{dI_2(t)}{dt} + I_2(t) \cdot \frac{dL_2(\varepsilon)}{d\varepsilon} \cdot \omega_{el}$$

with $d\varepsilon = \omega_{el} \cdot dt$ (3)

$$U(t) = U_{R_2}(t) + U_{L_2}(t) + U_{rot_2}(t) \qquad (4)$$

The rotative induced voltage, which can be derived together with the current I_2, which results in internal power P_{i2}, from which the internal moment $M_{i1}(t)$ of a pole, is strongly dependent on the function $L_2(\varepsilon)$:

$$M_{i_2} = \frac{1}{2} \cdot \frac{U_{rot_2} \cdot I_2}{\omega_{el}} = \frac{1}{2} \cdot \frac{dL_2(\varepsilon)}{d\varepsilon} \cdot I_2^2(t) \qquad (5)$$

This function is specified to the machine. It was therefore determined for the available 30 kW machines instrumentally. The result of measurement shows fig. 5. One detected that $L_2(\varepsilon)$ within a range from 1 mH $\leq L_2 \leq$ 2,5 mH over a pole partition varies. The inductance differences in the phases ($\Delta L_1 > \Delta L_2$) are conditioned design and can become balanced by appropriate coil circuit diagram.

4. SIMULATION RESULTS

For the simulation of the time processes of a phase $L_2(\varepsilon)$ according to fig. 5 was linearlised and by a triangle function approximated. Fig. 6 shows the pertinent simulation result for phase two. The rotation voltage U_{rot2} results after equation 3 to

$$U_{rot_2} = I_2 \cdot E\&_2(\varepsilon) \qquad (6)$$

One detected that their zero crossover coincides with one from $E\&(\varepsilon)$. The here not represented internal power

$$P_{i_2} = \frac{1}{2} \cdot I_2 \cdot U_{rot_2} = \frac{1}{2} \cdot \frac{dL_2(\varepsilon)}{d\varepsilon} \cdot \varpi_{el} \cdot I_2^2 \qquad (7)$$

has predominantly positive proportions. Those by available negative proportions lead to unwanted brake torques. The latters can be influenced by adjustment of the preignition time Δt_v (fig. 6). The optimal preignition results, if applies

$$\overline{P}_{i_2} = \frac{1}{\tau_p / \varpi_{el}} \int_0^{\tau_p/\varpi_{el}} P_{i_2}(t) \cdot dt = P_{i_2\,max} \qquad (8)$$

Since τ_p constructionally is fixed, for the current guide duration Θ_2 of the stator current I_2 always, because of the finite commutation time, $\Theta_2 \leq \tau_p/2\omega_{el}$ is allowed and $E\&_2(\varepsilon)$ current- and geometry-dependently fluctuates, $\Delta t_{v\,opt}$ must be determined for each operating point instrumentation and in a database stored. That controller was developed therefore together with the static inverter power circuit.

Fig. 7 shows in comparison with fig. 6 a simulation result with supply the same transverse flux machine led across the new inverter named commutation inverter according to fig. 3 with double revolution speed and half phase current I_2. Clearly to detect is the other current curve shape. Those is to be due in substantial to the principle-conditioned parallel connection of both machine phases. The arising relatively large current overlap between I_2, I_4 is characteristic for this circuit. It is one follows of the freewheeling current, which flows during the time period of the separation the machine from the DC voltage intermediate circuit through openning all four semiconductor switches (fig. 3). The back supply of the stored magnetic energy into the intermediate circuit does not take place, because by parallel connection to the coil of two phases over the two freewheeling diodes (D2, D4). A side-changing free-wheel circuit exists, which is meaningful also from physical point of view, because the magnetic energy during operation in the machine is kept widely. Theoretically however a reversal current can also flow over the four main branch diode (D21, D22, D41, D42) in this phase. They serve also as protection diodes against overvoltage during misguided control. They cann't also be omitted, because during the "single step" the free-wheel circuit for current control when pulsing over them is closed (example fig. 3).

5.COMPARISON OF RESULTS OF MEASUREMENT

The simulation results show the differences based on the operation modes of the two circuits. Cause of more exact inquiries of conditions in the test stand with 30 kW-water-cooled TFE machine was structured, which became to operate for better comparison alternatively with the classical and new static inverter. The first results of measurement are to be introduced and discussed in following. The fig. 8 shows the time processes for a stationary operating point with supply of the machine over that classical static inverters and two different preignition angle. In the first case (a) $L_2(t)$ and $I_2(t)$ cut themselves in zero crossover; the preignition angle is zero. In this case the internal moment cann't be after equation 5 equal to the maximum, because by the factor $\dot{L}_2 \geq 0$ one does not cut out max. area on the current-time-curve I_2^2 (t). Like measurements resulted is this first by $\omega_{el\,\bullet\,\Delta tv2} = 90°$. With this angle $\dot{L}_2 = 0$ meets with the current maximum I_2 =120 A. The reason for the higher moment, which is situated according to fig. 10 with M = 210 Nm, is the current waste of I_2, slower in the comparison to the rise.

From the time-curve of U_2 the pulse phase $U_2 = 0$ / U_2 = 400 V is exactly to detect. The larger surface of voltage correspond as expected with the positive and negative current modification of I_2.

The fig. 9 shows the same machine variables U_2, I_2, L_2 with supply with the new commutation static inverter according to fig. 3. One detected similar time curves as in fig. 8. An important difference is situated however in the optimal preignition angle $\omega_{el\,\Delta tv2} = 45°$. This is only half as large as during the classical static inverter supply over a two-quadrant-controller (fig. 2). The reason for it is situated in the load commutated stator current without substantial integration of the DC intermediate circuit. This leads like fig. 10 shows, to an up to 6% increase of the effective torque with otherwise same conditions.

Since, as is to be still proven in further measurement results, also the efficiency of the new static inverter will be better and two freewheel diodes can be saved, the new circuit concept promises advantages in relation to the state of the technology. The investigations in addition are not final however yet. In particular still circuit supplements are examined, which cause by bringing in a commutation or a symmetry induction coil fast fading away of the tail of the stator current. They have as a goal to reduce the shaded square represented in fig. 9 further in order to eliminate thereby possible brake torques.

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6.REFERENCES

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APPENDIX

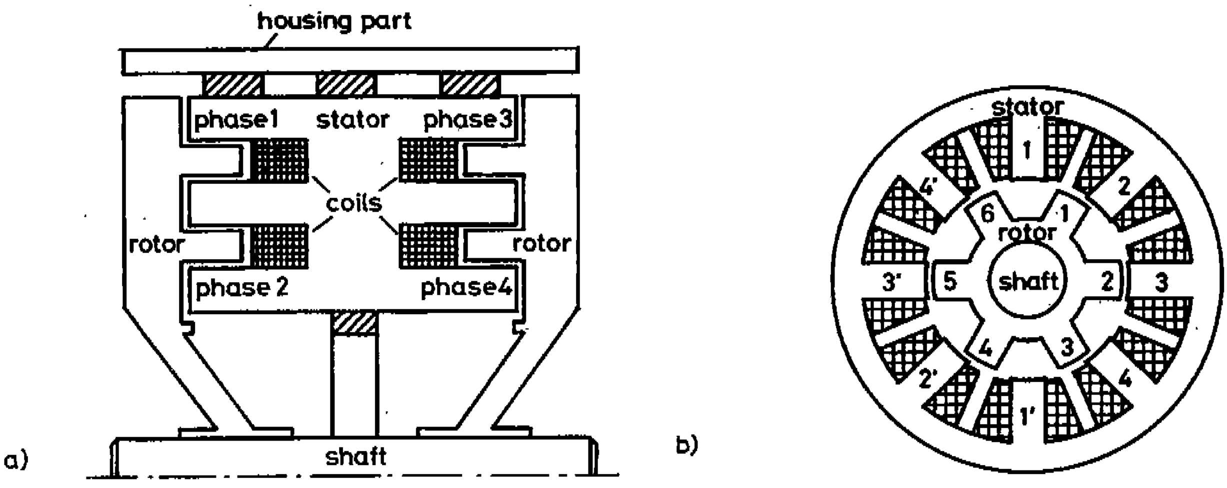


Fig. 1 Schematic diagrams of a
a) Transverse Flux Machine (electrically excited TFE)
b) Switched Reluctance Motor (SRM)

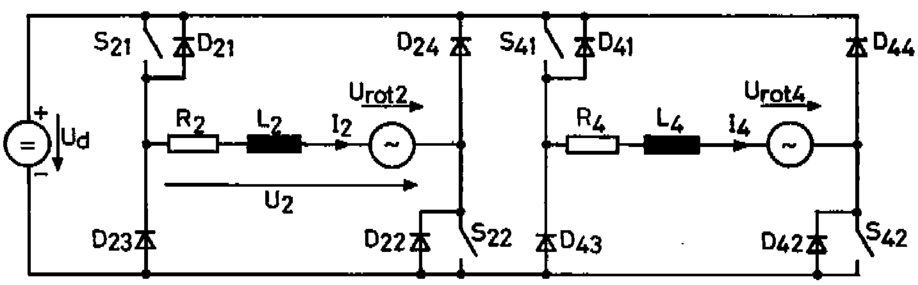


Fig. 2 Classic inverter for feeding TFE-machines

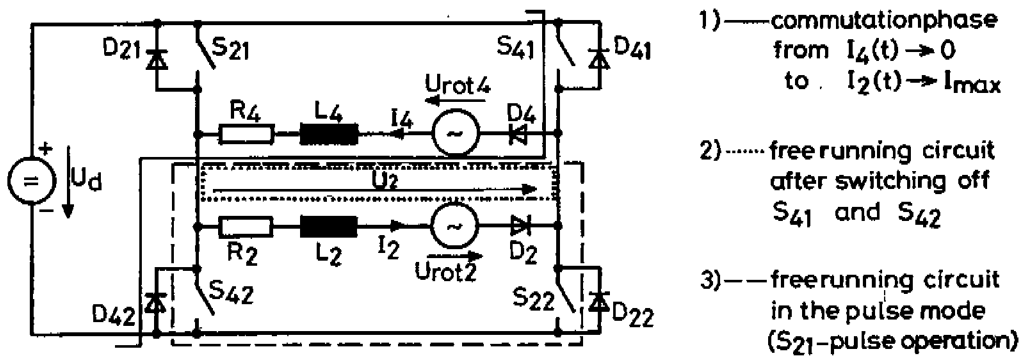


Fig. 3 Circuit diagram of the new Commutation Converter

the instantaneous values and parameters

$U(t)$	: voltage
U_d	: supply voltage
$I_2(t)$	: coil current
$\psi_2(t)$	: magnetic concatenation flux
ω_{el}	: electrical angular speed
ω_m	: mechanical angular speed
ε (t)	: electrical angles

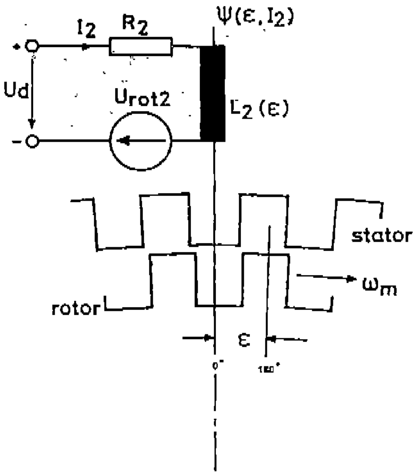


Fig. 4 Alternate circuit diagram of a strand of the TFE phase

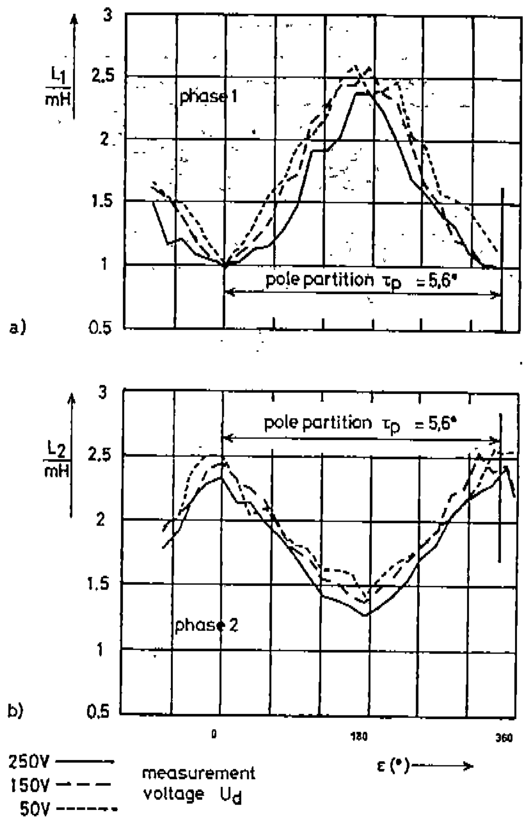


Fig. 5 Measured Function L(ε) (compare Fig. 4)

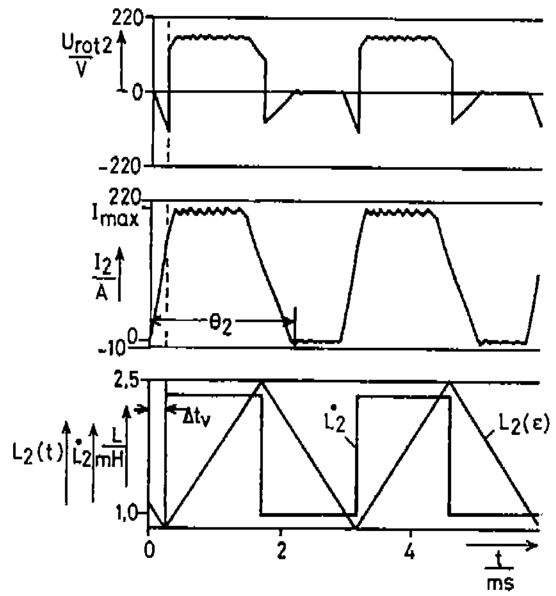
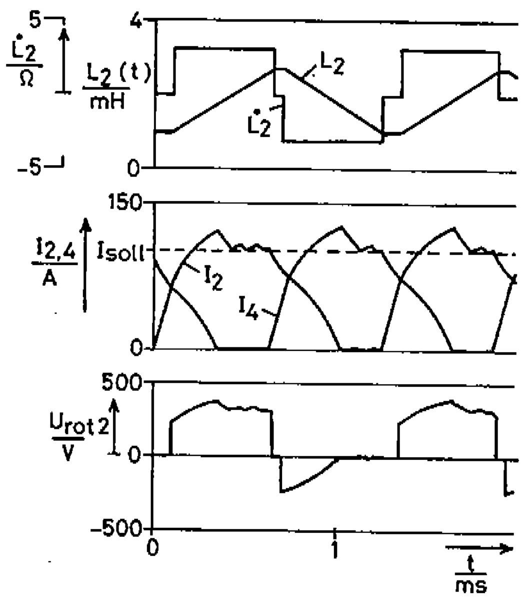


Fig. 6 Simulation results of the electrical values of a machine string which is feeding by the classic converter (Fig. 2)



a) from phase 1 b) from phase 2

Fig. 7 Simulation results of the electrical values of a machine string which is feeding by the commutation converter

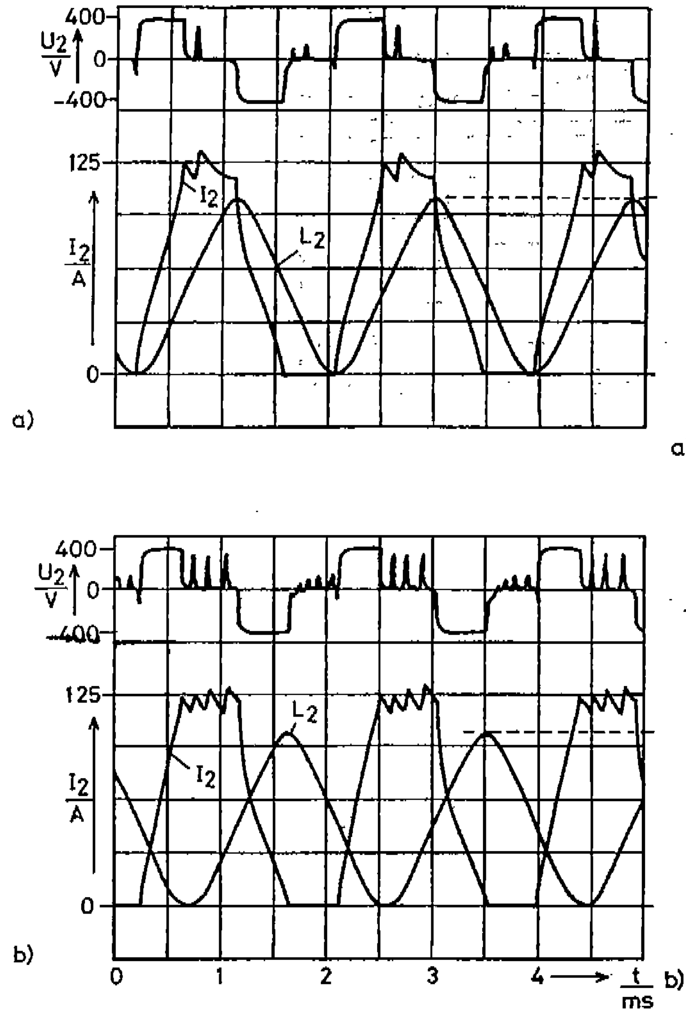


Fig. 8 Measured curves U_2, I_2, L_2 of the TFE feeding

by classic converter, n=500 min^{-1}

a) without preignition

b) with optimal preignition

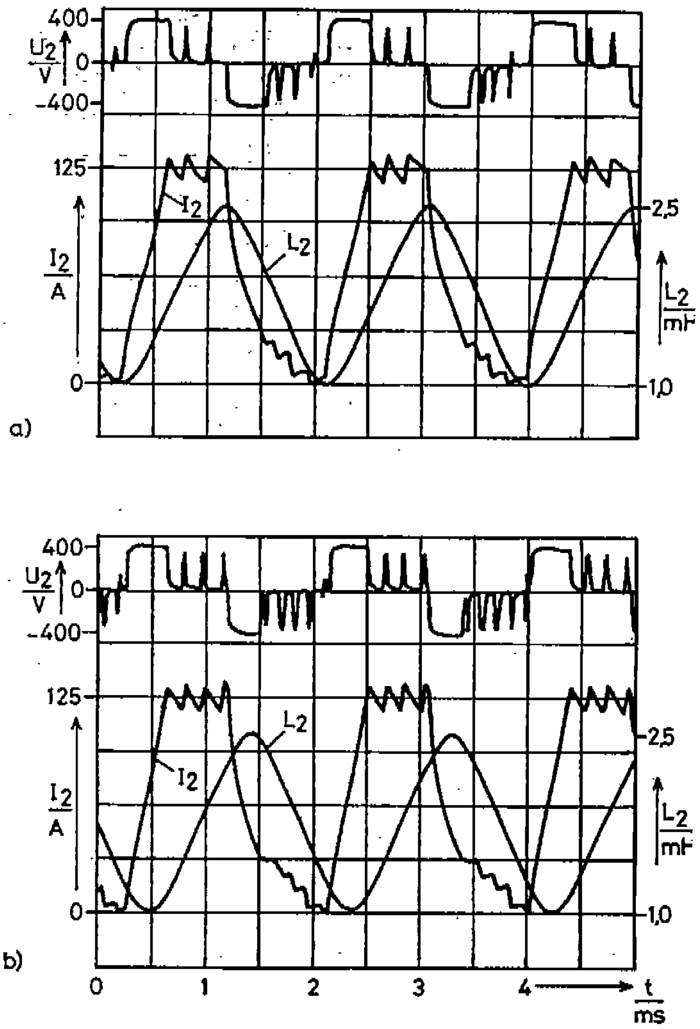


Fig. 9 Measured curves U_2, I_2, L_2 of the TFE feeding

by new converter, n=500 min^{-1}

a) without preignition

b) with optimal preignition

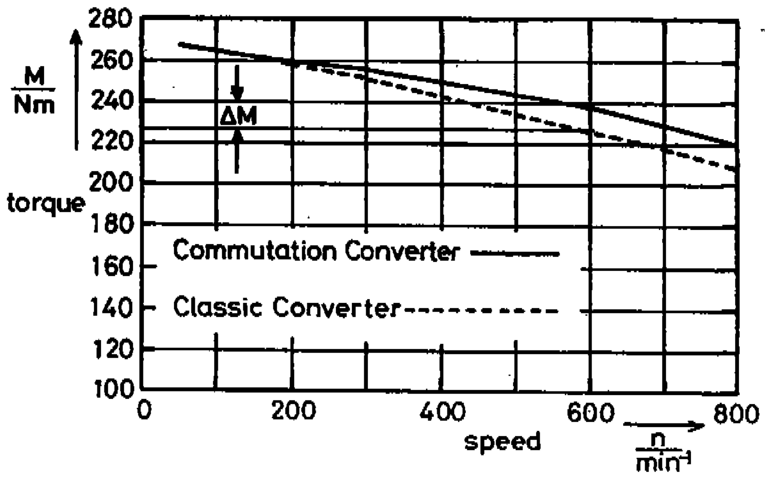


Fig. 10 Comparison of the torque-speed-function feeding the TFE by classic (fig. 2) and commutation (fig. 3) converter