# Modelling and Control of a Synchronous Transversal Flux Motor

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*Abstract*— **This work presents a study of the synchronous transversal flux machine with Ne-Fe-B permanent magnet, aiming at its speed control. A dynamic model is presented, with all its parameters identified for the prototype built by *Weg Indústrias S.A. - Motores*. Two possibilities of current waveform were considered and the resultant torque analyzed. A speed control scheme was proposed.**

*Keywords*— **Transversal flux, synchromous motor, permanent magnet, torque control, speed control.**

## I. Introduction

As mentioned in [4], the introduction of new high energy density permanent magnets has led to a number of machine concepts for high air-gap flux densities. The restrictions imposed by the cross-section of the stator teeth to the increase of the air-gap flux limits the force density. An increase in tooth width reduces the space available for the armature slots resulting in higher current densities and higher losses. In other words, the interaction in designing the electrical and the magnetic circuit of the armature prevents higher force densities in an optimum configuration.

The answer for this limiting compromise would be, according to the authors in [4], a transversal configuration for the flux, instead of the standard longitudinal magnetic circuit. This would lead to a permanent magnet synchronous motor with high efficiency at low speed. There are many application for this type of motor as, for instance, direct driven wind-energy generators, naval propellers, high torque servo motors with low winding losses, etc.

Andrade *et al.*, [1] have presented an interesting study of the transversal flux machine, where the Synchronous Transversal Flux Machine - STFM, as proposed in [4] and [5], is modelled with respect to its magnetic properties, using finite elements. Following the studies of [1], a prototype of the motor was constructed by *Weg Indústrias S.A. - Motores*, in Brazil, under the supervision of two of the authors of the present work. Figure 1 shows: the cover part of the stator of the motor (up); the rotor (center) of this prototype; and a scheme of its magnetic circuit where the transversal flux characteristic is shown (down). There, it can be seen that the motor flux is transversal rather than radial. Also, the stator current flows outside and inside the rotor, thus ameliorating the ratio torque *versus* current density. The rotor is made of four independent magnetic phases, and has Nd-Fe-B permanent magnets mounted on its surface.

The mentioned papers do not study or propose any dynamic model for the STFM. Their main concern is with the motor project.

In the present work, the main concern is twofold: i) to extract from the magnetic model of the motor, a substantially simpler dynamic model, suitable for control purposes, *i.e.*, analytical and with lumped parameters; ii) to propose a basic scheme of torque control for the motor, aiming at the prototyping and development of the controller. In other words, this work presents a preliminary study of the dynamic behavior of a synchronous transversal flux motor - STFM aiming at the achievement of its model and proposition of a scheme of controlling its torque.

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## II. Dynamical model of the STFM

The STFM we are considering, shown in Figure 1, is made of 4 phases, magnetically independent, which present induced e.m.f. of phase displacement of $\pi/4$ electrical rad. This configuration, according to [1] produces a resultant torque (the sum of the four phase torques) which has less ripple than each individual phase torque. Andrade *et al.* show also, that the induced e.m.f. by each magnet presents a three stage behavior, due to the fact that the pole arc is smaller than the pole pitch. The induced e.m.f. of the magnet is a function of the flux density in the air-gap, the rotor speed and the number of coils of the stator windings. In the specific case of the STFM, the stator winding has an internal and an external winding, connected in series (see [1]). Therefore, the induced e.m.f. by each magnet, $e$, can be written as:

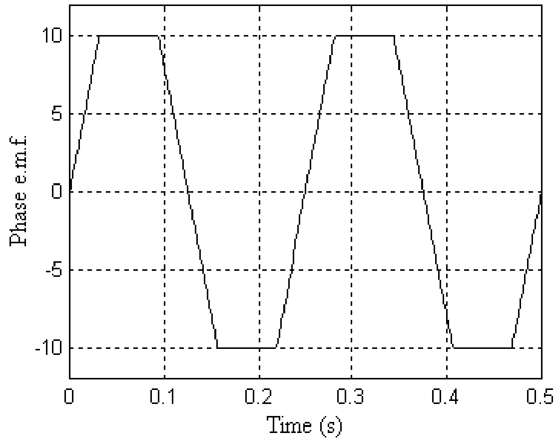
$$e = -m\frac{d\varphi}{dt} = -m\,\frac{d\varphi}{d\theta}\,\frac{d\theta}{dt} = -m\,\omega\,\frac{d\varphi}{d\theta}, \qquad (1)$$

where $m$, is the sum of the number of internal plus external stator windings, $\omega$, is the rotor speed (in electrical rad/s), $\varphi$, is the flux interlacing the pole magnetic circuit and $\theta$, is the rotor position.

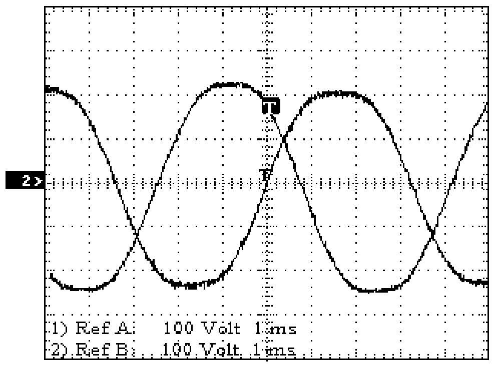
This implies that the e.m.f. per phase is the sum of the induced e.m.f per pole pair, written as:

$$E_f = -N_p\,m\,\omega\,\frac{d\varphi}{d\theta}. \qquad (2)$$


Fig. 1. The synchronous trasversal flux motor: the stator cover (up); the motor rotor (middle); the magnetic circuit (down)




**a) ideal trapezoidal shape**




**b) real shape of the e.m.f.**

Fig. 2. Trapezoidal shape of the per phase induced e.m.f.

where $N_p$, is number of pole pairs and $\omega = d\theta/dt$, is the rotor speed.

It is worth mentioning that $d\varphi/d\theta$ has the three stage mentioned above, as a consequence of the pole arc and pitch geometry. This leads to a phase e.m.f with a trapezoidal shape, as in Figure 2, where in a) we have the ideal shape and, in b) the real measured shape, obtained from the motor operating as a generator. Notice also, that the amplitude and frequency of the induced e.m.f. will depend on the rotor speed.

The per phase active power of the motor is given as:

$$P_f = E_f i_f = -N_p m\omega \frac{d\varphi}{d\theta} i_f. \tag{3}$$

Therefor, the per phase torque of the motor is:

$$T_f = P_f \,/\, \omega = -N_p \, m \, \frac{d\varphi}{d\theta} \, i_f. \tag{4}$$

Given that $N_p$ and $m$ are constant project parameters and that the trapezoidal shape of $d\varphi/d\theta$ is also issue of

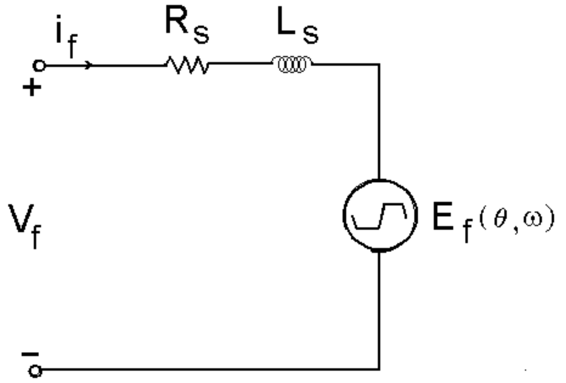



Fig. 3. Basic per phase equivalent circuit of the STFM

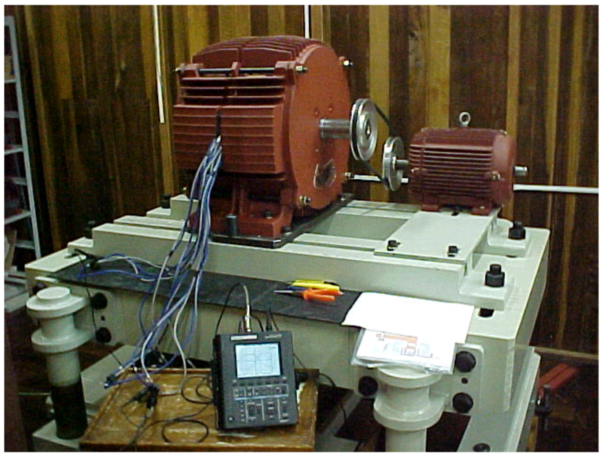


Fig. 4. Test platform of the STFM

the motor construction, the torque imposition is made by the control of the stator phase current $i_f$.

Let us now define the total instantaneous and the average electromagnetic torque, $T_t$ and $T_m$, as:

$$\begin{aligned} T_t &= T_{f1} + T_{f2} + T_{f3} + T_{f4} \\ T_m &= \frac{1}{T}\int_0^T T_t\, dt = k_f\, I_{fm} \end{aligned} \tag{5}$$

where $T_{fi}$, $i = 1,..,4$, corresponds to the torque produced by phase $i$, $T$, is the electrical time period, $k_f$ is a constant, $I_{fm}$, corresponds to the phase current amplitude (assuming that all phase currents have the same amplitude and frequency and have a phase displacement of $\pi/4$ rad). Another assumption made here is that the phase currents are in phase with the respective induced e.m.f. and their shape is trapezoidal. This will be discussed in Section III. See Figure 5 a) for an example.

In order to build an electrical model of the motor some hypothesis are made:
1. The equivalent phase inductance is constant, since the rotor of a surface magnet presents no considerable saliency.
2. The e.m.f. is proportional to the rotational frequency and has trapezoidal waveform.

In connection with this, see observations made by T. M. Jahns about the trapezoidal PMAC machine in [2], Chapter 6.

The motor phase circuit is given by Fig. 3. The motor test platform is shown in Fig. 4.

The corresponding electrical equation of a phase of the motor is

$$V_f = R_s i_f + L_s \frac{di_f}{dt} + E_f(\theta, \omega). \tag{6}$$

As mentioned before, the ideal waveform of the induced e.m.f., $E_f(\omega)$ is trapezoidal with frequency $\omega$ and with amplitude $k_f\omega$. A mathematical description of $E_f(\omega)$, for a given time period $T$ is given as:

$$E_f(\theta,\omega) = \begin{cases} c_1\theta \ , \ 0 \leqslant \theta(t) \leqslant \theta_1 \\ c_2 \ , \ \theta_1 < \theta(t) \leqslant \theta_2 \\ c_2 - c_1\theta \ , \ \theta_2 < \theta(t) \leqslant \theta_3 \\ -c_2 \ , \ \theta_3 < \theta(t) \leqslant \theta_4 \\ -c_2 + c_1\theta \ , \ t_4 < \theta(t) \leqslant \theta_5 \end{cases} \tag{7}$$

$$\text{with} \quad \begin{array}{lll} c_1 = k_f\omega 4/\pi & c_2 = k_f\omega & \\ \theta_1 = 2\pi/8 & \theta_2 = 6\pi/8 & \theta_3 = 10\pi/8 \\ \theta_4 = 14\pi/8 & \theta_5 = 2\pi & \theta(t) = \int \omega(t)\, dt \end{array}$$

Considering this to be the model of phase 1, the other phases would have the same model with an angular displacement of $\pi/4$ rad.

### A. The parameters of the prototype machine

The synchronous transversal flux prototype machine built by *Weg Indústrias S.A. - Motores* has the following design parameters:

Rated power: 10 KW
Rated phase voltage, $V_f^n$ : 220 V
Rated phase current, $I_f^n$ : 17.3 A
No. of pole pairs $N_p$: 45
Rated speed, $\omega^n$ : 20.94 rad/s
Rated torque, $\tau^n$ : 477.55 Nm
Magnet: Nd-Fe-B

The following electrical parameters have been calculated as the average values of the phase parameters obtained by circuit measurements and experimental tests of the motor functioning as a generator (see Fig. 4) , under different voltage and speed operating conditions:

Stator resistance $R_s$ : 0.444 $\Omega$ (*, **)
Stator inductance, $L_s$ : 0.385 $H$ (*)
e.m.f. coef., $k_f$ : 10.48

(*) - The measurements were made at $26,2\ ^\circ C$.
(**) - The resistance mean value was corrected considering an operating temperature of $100\ ^\circ C$.
The resistances were measured with a Kelvin bridge. The inductances were measured with an Induction bridge.

**Note:** The test platform is shown in Fig. 4.

## III. The control of the Synchronous Transversal Flux Motor

The problem of controlling the STFM is that of imposing torque instantaneously by controlling the phase currents $I_f$, of each of the four phases of the motor. The most appealing strategy is one similar to what is made for the trapezoidal PMAC motors [2]. In other words, the torque control via the phase currents $I_f$. This can be achieved by means of an inverter.

The use of permanent magnets allows generating substantial air-gap magnetic flux without external excitation. Therefore, the efficiency characteristics of permanent magnet synchronous machines, in general, are quite good. This leads to machine designs of with very high values of power density an torque-to-inertia ratios [6]. In the case of transversal flux synchronous machines, these features are improved in the sense of even larger torques at, specially, lower speeds. This fact stems from two characteristics of the machine: 1.) high armature current with reasonable current and flux densities; 2.) large number of poles.

On the other hand, there is a particular requirement for both, PMAC and STFM, which is the synchronization of the excitation waveforms with the rotational speed. This fact implies in accompanying power electronics and the need for suitable control strategies. This problem is even more crucial in the case of STFM due to the high number of poles (90 poles in the prototype we are considering here).

### *A. The excitation current waveform*

Standard PMSM can be either trapezoidal or sinusoidal [3]. The main difference between them is the excitation waveform, sinusoidal or trapezoidal. In this work, it has been considered both types of excitation. This is shown in Figure 5 with a simulated example, supposing constant speed and induced e.m.f. The trapezoidal current wave form is shown in a) whereas the sinusoidal form is in b).

The mathematical description of the trapezoidal form of one of the phase currents, $i_f\left(\theta\left(t\right)\right)$, in phase with the phase voltage, for one period of time $T$, is as follows:

$$i_f\left(\theta(t)\right) = \begin{cases} c_{i1}\theta\ ,\ 0 \leqslant \theta\left(t\right) \leqslant \theta_1 \\ c_{i2}\ ,\ \theta_1 < \theta\left(t\right) \leqslant \theta_2 \\ c_{i2} - c_{i1}\theta\ ,\ \theta_2 < \theta\left(t\right) \leqslant \theta_3 \\ -c_{i2}\ ,\ \theta_3 < \theta\left(t\right) \leqslant \theta_4 \\ -c_{i2} + c_{i1}\theta\ ,\ \theta_4 < \theta\left(t\right) \leqslant \theta_5 \end{cases} \tag{8}$$

$$\text{with} \quad \begin{array}{ll} c_{i1} = 8I_{fm}/\pi & c_{i2} = I_{fm} \\ \theta_1 = \pi/8 & \theta_2 = 7\pi/8 \\ \theta_3 = 9\pi/8 & \theta_4 = 15\pi/8 \\ \theta_5 = 2\pi & \theta\left(t\right) = \int \omega\left(t\right) dt \end{array}$$

where $I_{fm}$ is the maximum value of the phase current. In the case of the sinusoidal current wave form, in phase with the phase voltage, its mathematical description is simply

$$i_f\left(\theta(t)\right) = I_{fm} \sin\theta(t). \tag{9}$$

Once more, $I_{fm}$ is the current maximum value (amplitude).

Notice that the correspondent equations to the other phase currents, either trapezoidal or sinusoidal, have the same shape of those in Eqs. (8) and (9), with an angular displacement of $\pi/4$ among them.

The correspondent phase voltage forms, necessary to obtain current forms given in (8) and (9) are given by Eq. (6).

The total torque produced (sum of all four phases), as defined in Eq. (5), is shown in Fig. 5 c), where $\tau_1$ is the produced torque for a trapezoidal current waveform and $\tau_2$, corresponds to the sinusoidal waveform. Notice that with trapezoidal currents there is less torque ripple and a larger average resultant torque.

Furthermore, we have considered the eventual displacement of the excitation waveform and the rotor position. This is shown in Figure 6. In this case, the phase displacement between phase currents and e.m.f. is 20 degrees. The resultant torques in both cases present a greater amount of ripple and the resultant average torque values are smaller than the case shown in Fig. 5. The resultant torque, with sinusoidal waveform, is even worse, as it can be seen from c). It is worth noticing that these simulation examples are qualitative. They are not supposed to correspond exactly to the prototype STFM.

**Note:** It has been observed, in the case of phase displacement between current and induced e.m.f., that the larger the displacement is, the smaller is the average torque (with more ripple). For larger enough displacements, it gets negative (resistent). There is also a symmetry: for displacements of $+\delta$ or - $\delta$, the resultant average torque is the same. As a conclusion we would affirm that the better excitation current waveform is trapezoidal, as proposed in [1].

### *B. Speed control of the STFM*

The speed control proposed for the STFM is conceived as a cascaded structure, where the internal loop generates the electromagnetic torque whereas the external loop controls the motor speed through the torque control. This scheme is shown in Figure 7.

In order to impose the STFM torque:
i) the absolute rotor position measurement is needed;
ii) the phase currents measurements are also necessary.

Condition i) stems from the fact that phase currents and induced e.m.f. must be in phase. Condition ii) comes from the fact that the torques per phase as in

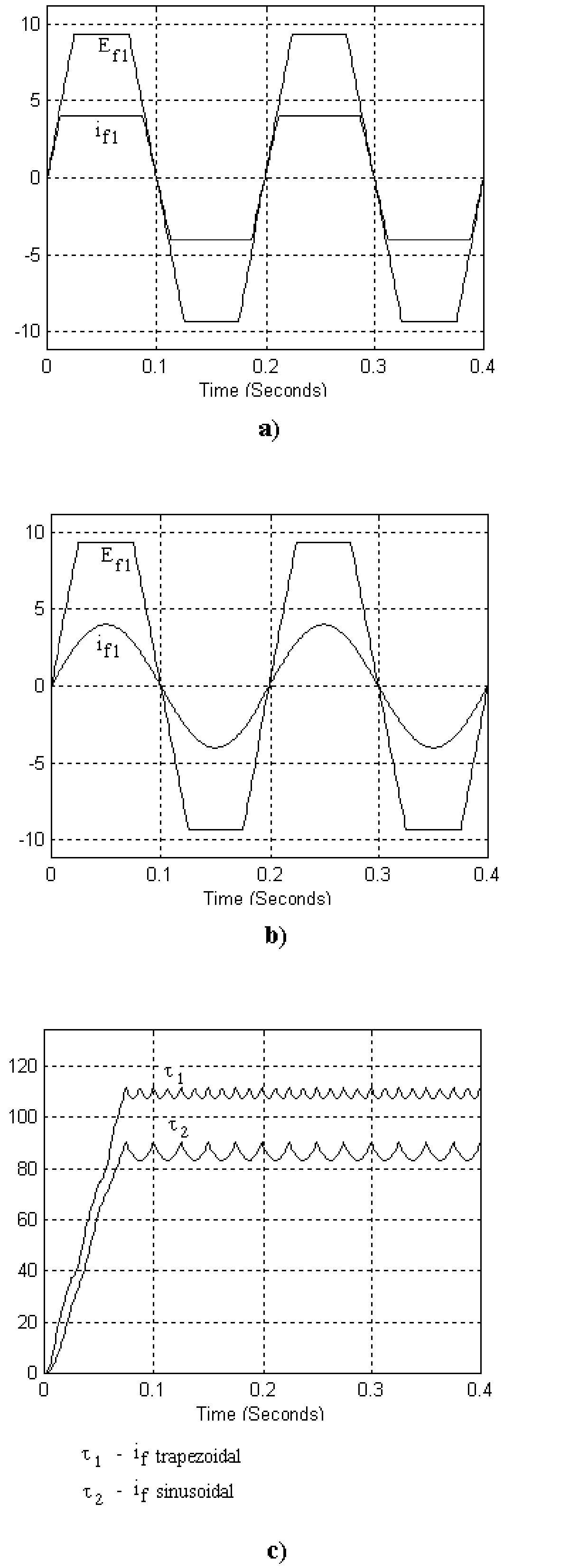



Fig. 5. a) Trapezoidal current waveform; b) sinusoidal current waveform; c) correspondent resultant torques

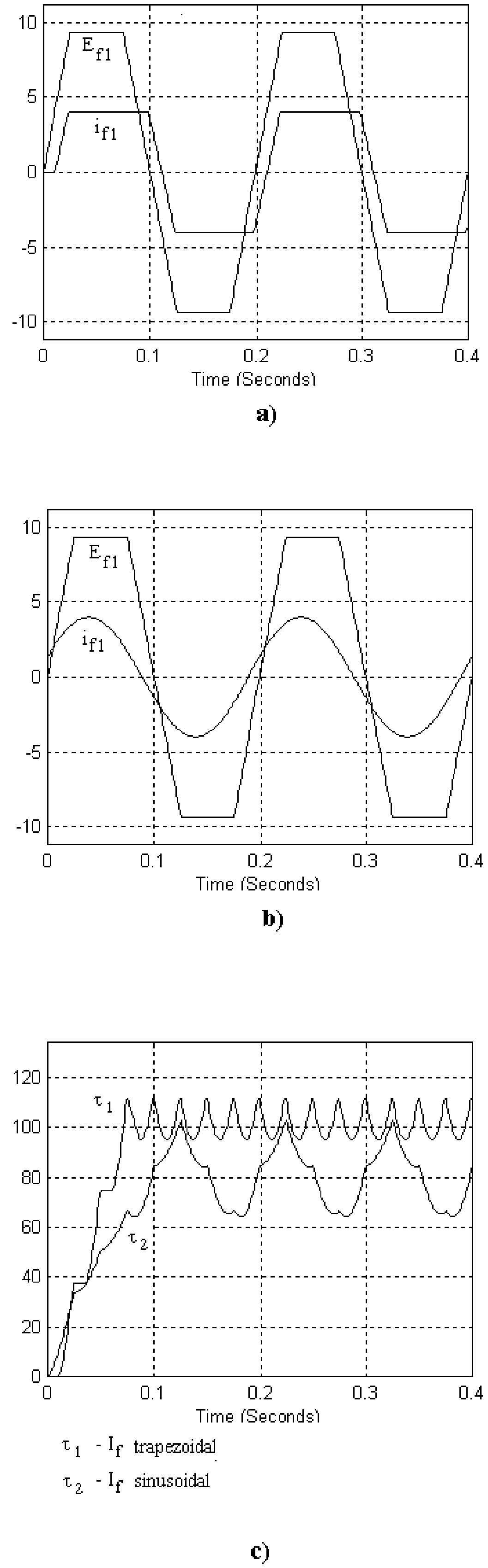



Fig. 6. a) trapezoidal current waveform with phase displacement of 20 degrees; b) sinusoidal current waveform with phase displacement of 20 degrees; c) correspondent resultant torques

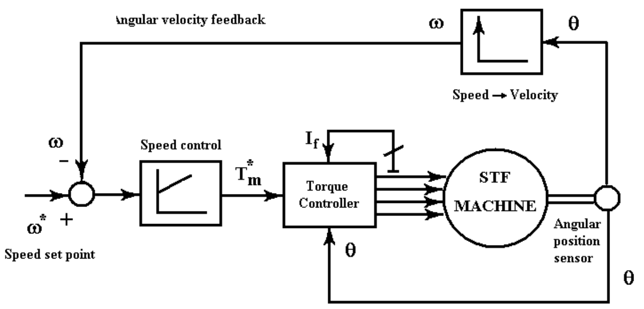



Fig. 7. Cascaded control of the speed of the Synchronous Transversal Flux Machine

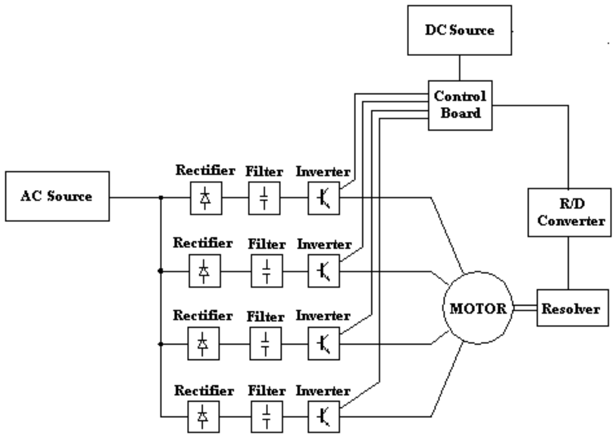



Fig. 8. The STFM fed by a four phase inverter

(4), is proportional to the product of e.m.f. and the phase current.

Therefor, the control scheme proposed has a three level structure:

1. A speed loop generates, through a PI control with a given speed set-point $\omega^*$, the torque reference $T_m^*$.
2. A second loop generates, through a PI control, the phase current set-point, $I_f^*$. The set-point are derived from Eqs. (5) and (6).
3. A third loop generates the phase voltage references, $V_f^*$, from the phase current error, which are to be obtained through a PWM of each of the four inverters feeding the STFM phases.

### *C. The four phase inverter*

The hardware scheme for the STFM is shown in Fig. 8. As it can be seen, there are four separate rectifiers, filters and single phase inverters which feed the independent four phases of the motor. Despite being magnetically and electrically independent, the four phases fed voltages must be controlled in a synchronized way.

Figure 9 shows a picture of the hardware built by *Grameyer Ltda.*

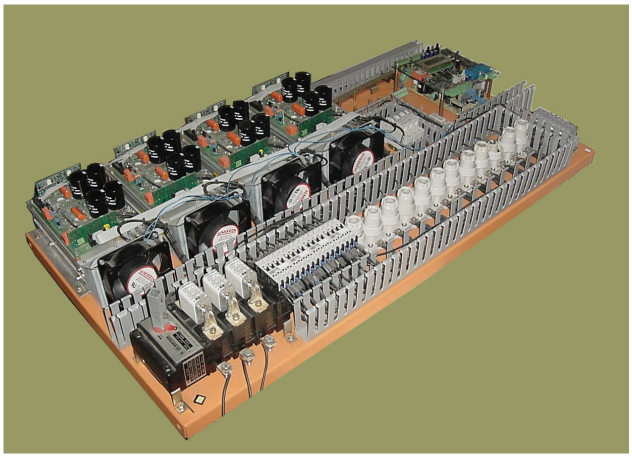


Fig. 9. The four phase inverter

## IV. Final comments

A study of the synchronous transversal flux has been presented and its dynamical model has been obtained. Aspects concerning the motor resultant torque subject to two types of current waveforms (trapezoidal or sinusoidal) have been analyzed, as well as phase displacement between current and induced e.m.f. Furthermore, as a first effort on building a driver to control the motor torque and speed, a control scheme has been proposed.

Following this work, a four phase inverter is being built by *Grameyer Equipamentos Eletrônicos Ltda.* to perform the control of the motor speed. It is the authors belief that the rotor position acquisition is one of the crucial points of the motor control, due to its large number of poles. Implementation aspects are currently being studied as, for instance, the current control by the inverter and alternative control strategies aiming at minimizing torque ripple.

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