Modelling of a wound rotor salient pole synchronous machine and its converter in the constant power zone

Pr G. Friedrich
Université de Technologie de Compiègne (UTC)
Laboratoire d'électromécanique
BP 20 529
60 205 COMPIEGNE CEDEX
France
Email: guy.friedrich@utc.fr

Absract

The wound rotor salient pole synchronous machine (WRSM) is generally used in very high power applications associated with a cyclo-converter (low speed applications) or a current source inverter. Nevertheless, this machine allows high efficiency and high power factor operations in medium range power applications.

On other hand, efficiency optimization or avoiding the gear box need a flux varying operation. In the constant power zone, the maximum voltage, due to the embedded accumulators, is applied. Generally, the supplied voltage tends from a sinusoidal to a rectangular waveform. This technique allows the use of the maximum value of the DC bus, but the currents (stator and field) may be disturbed and therefore create, high torque ripple.

The proposed model of the WRSM and its associated converter allows a precise modeling of these phenomena.

Thanks to the retained approach and the used tools, (Matlab simulink) it is possible to integrate the model in a more complex system such as electric or hybrid vehicle

A comparison with the experimental results taken with a 12kW motor for electric cars allows the validation of the approach.

Introduction

The wound rotor synchronous machine (WRSM), compared with the induction, synchronous permanent magnet or even reluctance machines have not been often proposed and studied for the propulsion of electric or hybrid vehicles.

This type of machine is generally dedicated to high power applications such as locomotives, for example the french high speed train "TGV Atlantique[1,2]. In this case, the machine is supplied with a forced commutation current inverter and so, is not adapted to medium or low power systems such as electric vehicles.

Nevertheless, the WRSM thanks to its three control parameters, (stator current amplitude, torque angle and field current) allows an efficiency optimization [3,4,5,6] and therefore can reach permanent magnets machine performances[7].

On the other hand, in order to avoid a gear box, automotive applications generally need a wide "constant power" operation. In this type of application, the maximum voltage (due to the embedded batteries), is applied so as to reach the maximum voltage value. The voltage waveforms tends from PWM sinusoidal to rectangular waveforms. Under these conditions field and stator currents may be highly disturbed and generate high pulsating torques. A judicious machine design allows the reduction of these phenomena.

The article suggests a model of a wound rotor synchronous machine with its current controlled voltage converter. It allows a valid and efficient model under a sinusoidal, pseudo-sinusoidal, or rectangular supply.

Following a precise justification of the model, a comparison will be made between the simulated and experimental results.

Drive description

Regardless of the application, the basic structure of an electric drive remain the same and can be described in the figure 1:

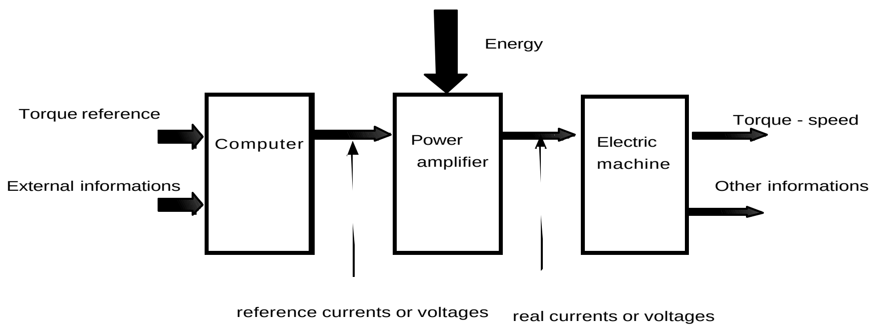


Figure 1: Basic structure

An optimal operation of the system needs an optimal operation of every part. A very elaborate calculation of the electric quantities has no use if the « amplifier » is not able to apply them to the system.

Electric Amplifier

Role of the 'amplifiers'

- amplitude of the stator current (Is),
- angle of the torque (δ),
- excitation current (If).

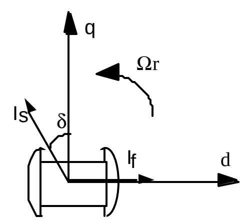


Figure 2: Controlled quantities

Depending on the amplitude of Is and the angle δ (from the calculator), three current reference signals is1, is2, is3 will be sent to the amplifiers. The reference field current is sent in the same way to an amplifier with the same structure.

Structure of the « amplifier »

Figure 3 shows the structure of the « amplifier ». It consists of a current controlled voltage source.

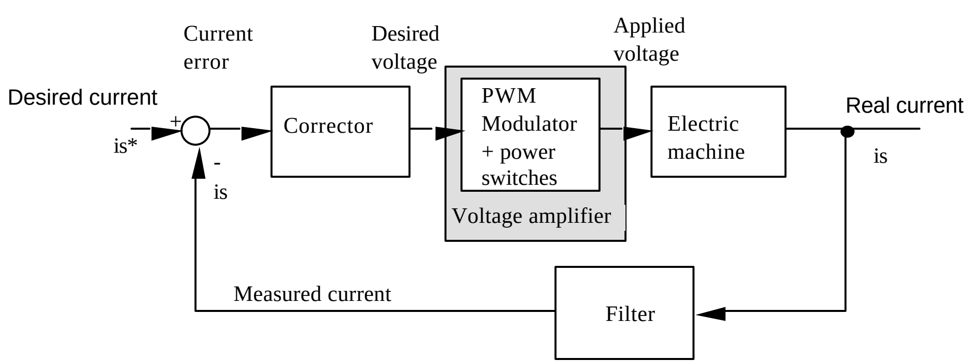


Figure 3: Structure of the amplifier

The role of the corrector is to generate a signal that corresponds to the desired voltage in order to minimize the error of the current.

The voltage reference signal is sent to a PWM modulator that controls the power switches, which is, in our case, a three-leg bridge.

The load of the voltage amplifier is constituted by the windings of the electric machine.

The strategy choice used by the PWM is difficult and has been treated in many publications. Nevertheless, the objective is still to obtain a voltage across the load that represents the « maximum of similarities » with the desired voltage and to reduce the switching frequency.

The most commonly used strategy is to compare the signal that has to be amplified with a triangular wave. The result of that comparison creates the command signal for the power switches. This strategy, called « natural sampling »[8 9] produces excellent results as long as the frequency of the triangular wave remains higher than one of the signal that to be amplified (about 10 times). Under these conditions, the fundamental of the generated wave is directly proportional to the reference signal as long as voltage of the DC bus is sufficient.

In the special case of a sinusoidal supply, the injected current remains sinusoidal as long as the voltage from the DC supply remains sufficient. The voltage limit is reached when the reference signal becomes too large. The converter will then apply the highest available voltage, thus creating an evolution from a sinusoidal to a rectangular waveform of the signal applied to the machine. Under these conditions, the error of the current reaches high values and a modelling of the operation becomes difficult [9].

The electric machine

Figure 4 shows such a machine and specifies the used notations:

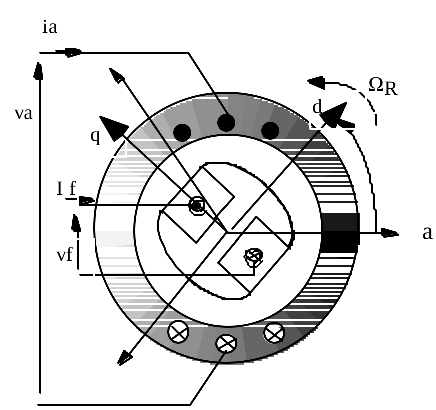


Figure 4: Synchronous machine with salient poles (WRSM)

Classically, the equations lie in the d,q coordinate system of the rotor and are expressed as follows (without saturation):

$$vd = Rs.id + \frac{dyd}{dt} - \omega r.\Psi q \tag{1}$$

$$vq = Rs.iq + \frac{dyq}{dt} + \omega r.\Psi d \tag{2}$$

$$vf = Rf.If + \frac{dyf}{dt} \tag{3}$$

The following magnetic equations define Ψd and Ψf:

$$\begin{bmatrix} yd \\ yf \end{bmatrix} = \begin{bmatrix} L_d & M_{af} \\ \frac{3}{2} M_{af} & L_f \end{bmatrix} * \begin{bmatrix} id \\ if \end{bmatrix} \tag{4}$$

$$\Psi q = Lq.iq \tag{5}$$

The machine’s torque is expressed as :

$$Tem = \frac{3}{2}\ p\ (\Psi d.iq - \Psi q.id) \tag{6}$$

The system becomes completely defined once it is completed with a simple mechanical equation :

$$T_{em} - T_r = J\ \frac{d\Omega_r}{dt} \qquad \text{(without friction)} \tag{7}$$

In the particular case of an sinusoidal supply and constant speed operation, all projected values of voltages or currents on the d q axis will be constant.

Proposed modelling

Modelling of the motor and amplifier

Figure 5 shows the principle used: The calculator produces the signals is1* and is2* which are sinusoidal in the case of a constant rotation. The voltages vs1, vs2, and vs3 are sinusoidal as well, as long as the available voltage is sufficient. If this is not the case, the applied voltages tend to be rectangular.

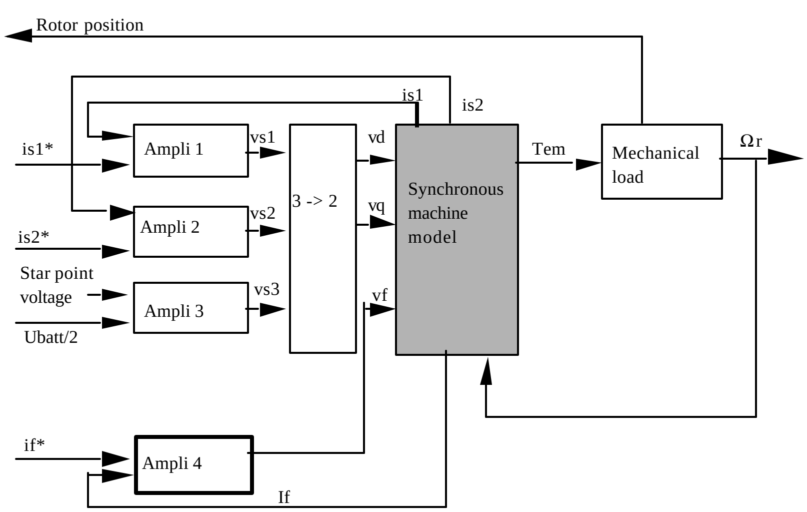


Figure 5 : Modelling of the machine and its converter

The machine is Y connected. In order to avoid a redundant command of the currents, two currents are imposed and the third amplifier controls the potential at the neutral point to the half of the DC supply.

Modelling of the amplifier

As long as the period of the chopping is sufficiently short in comparison to the system's time-constants, it can be considered that the voltage that is applied to the machine can be reduced to its average value that was established during one chopping period. Thus the phenomenon of the quasi-rectangular voltage is correctly modelled.

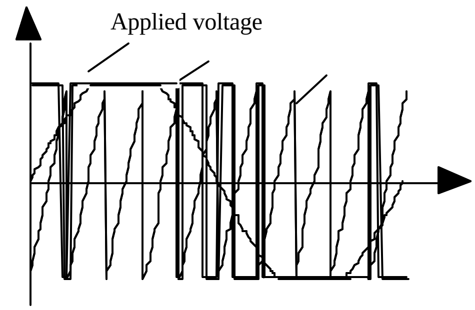
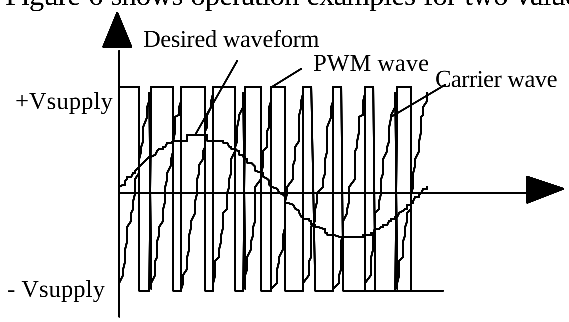


Figure 6 shows operation examples for two values of modulation depth



a b

Figure 6: Principle of the used modelling
a: sinusoidal waveform
b: quasi-rectangular waveform (insufficient voltage to assure the injection of the desired current)

As a result, the PWM and its power stage can be considered as a perfect voltage source, as long as the maximum available DC voltage has not been reached.

Figure 7 describes the suggested modelling:

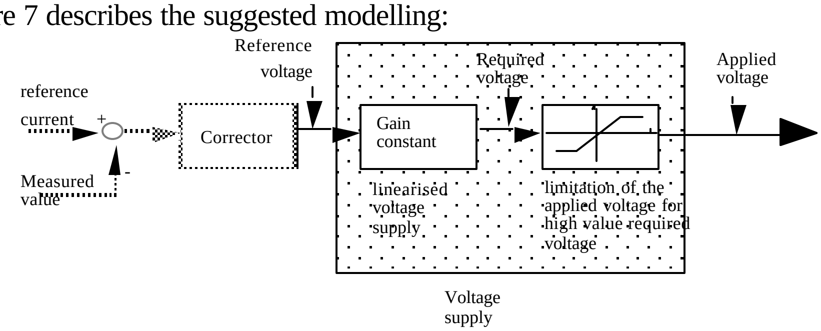


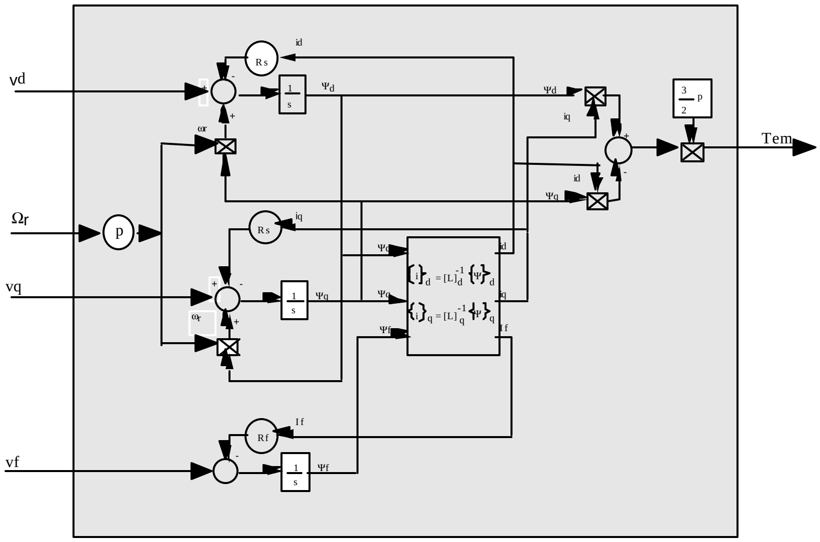
Figure 7: Model used for the amplifier

If the required voltage is realisable, it will be fully applied. In the opposite case, maximum voltage (limited by embedded accumulators) is applied.

The structure of the amplifier shown in figure 7 is reproduced in the three phases of the machine and the rotor circuit.

Modeling of the machine

The set of the equations 1 to 5 (the grey part of figure 5) can be represented in figure 8 :



with :

$$\{\Psi\}_d = \begin{Bmatrix} yd \\ yf \end{Bmatrix} \quad ; \{i\}_d = \begin{Bmatrix} id \\ if \end{Bmatrix} \quad ; [L]_d = \begin{bmatrix} L_d & M_{af} \\ \frac{3}{2} M_{af} & L_f \end{bmatrix}$$

$$\{\Psi\}_q = \Psi q \quad ; \{i\}_q = iq \quad ; [L]_q = Lq$$

Figure 8: Modelling of the synchronous machine

This model is independent of the applied waveforms and allows the evaluation of the influence of the different couplings which can disturb the functioning ; in particular under pseudo-sinusoidal or rectangular supplies.

Results

Results of the simulation

Different phenomena, which appear during pseudo-sinusoidal supply, can be shown with the used model. In order to show more clearly the interest of the proposed model, the regulation of the current in the induction circuit is deactivated: the permanent value (sinusoidal operating) of the field current is obtained by inserting a resistor in the field supply.

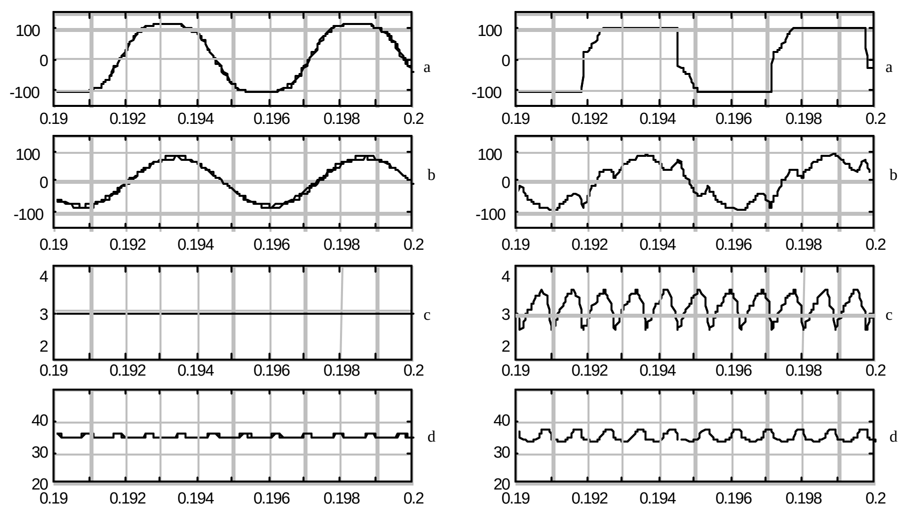


Figure 9 : Example of the functioning (C=35Nm - n=3500rpm)
(a) - Voltage across one stator phase (V)
(b) - Stator current (A)
(c) - Rotor current (A)
(d) - Resultant torque (Nm)

Figure 9 shows different waveforms. The left column corresponds to an operation where the voltage levels are sufficiently high to apply the desired voltages computed by the calculator. The right column corresponds to the same case but with the supply voltage reduced by 15% (batteries voltage drop).

A comparison of the figures shows clearly the perturbations which follow a reduction of the supply voltage. Figure 9 corresponds to the application of a quasi-rectangular voltage (pseudo-sinusoidal supply) within the limits of the allowed hypothesis. This results in the appearance of harmonics in the rotor current (9c) and stator current (9b) and thus generating a pulsation of the torque (9d).

This phenomenon can lead to very bad functioning if it is not taken into account during the design of the machine.

Experimental results

The experimental results were taken with a 12kW motor for an electric vehicle.

The testing bench does not allow an instantaneous measuring of the torque but it gives its average value. Nevertheless, figure 10 shows the recording of the rotor and stator current at the previously simulated operation.

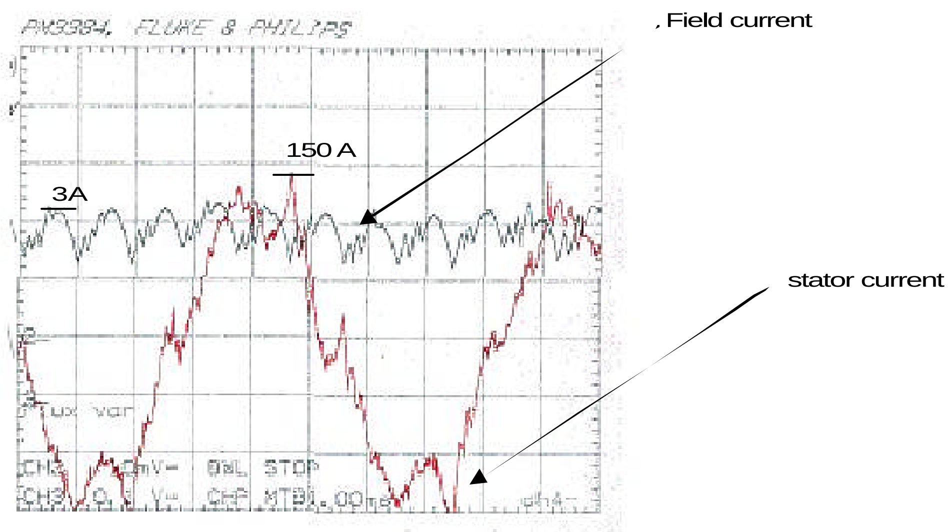


Figure 10: Experimental stator and field currents in a pseudo PWM supply

The recording in figure 10 shows clearly the phenomenon of the injection of harmonics (mainly the 6^{th}) into the rotor. The amplitude of the disturbances corresponds to the ones that were simulated. The average value of the torque corresponds precisely to the one simulated.

Conclusion

A method for the modelling of a synchronous machine with salient poles and its (PWM) converter is proposed.

It allows the operation to be accurately modelled under sinusoidal, pseudo-sinusoidal, or rectangular supply and thus, allows the study of the evolution of the operation under the changing from sinusoidal to rectangular supply.

Generally, the two supply modes are treated in a dissociated way: The sinusoidal mode is analysed in terms of complex functions and the rectangular mode in terms of a decomposition of the direct and reversed three-phase systems.

Compared to the classical method, this modelling has the following advantages:

- irrespective of whatever functioning mode, the use of only one model enables us to take into account the operation of the machine and its converter.
- the evaluation of the machine's performances under non-sinusoidal supply (pulsation of the torque, disturbances of the stator and rotor currents) are clearly shown
- it suggests a solution to the delicate problem of choosing the corrector gain for the current control loops.

Thanks to the retained approach and the used tools (MATLAB-SIMULINK) it is possible to integrate the model into a more complex system (electric or hybrid vehicle).

The comparison between the simulations and the experiments shows that it is perfectly justified to neglect the saturation. This was predictable because, by definition, the saturation has no influence in a constant power zone (operating at reduced field).

The modelling of the converter, although very simple (neglecting the phenomena due to the chopping) takes a correct care of the principal phenomena. The machine model may take into account the phenomena due to the pulse width modulation, but it would need a very long computation time for a low precision improvements as long as the commutation frequency of remains high with respect to the machine electric time constants.

The model can efficiently complete the classic models used for the synchronous machine with salient poles, particularly when the machine is integrated to a more complex system with a vector-based command structure and a power supply that cannot be regulated; i.e. storage batteries.

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