Method to determine the internal angle of a synchronous machine for establishment of the experimental torque-angle characteristic

Dorin Lucache[1], Alecsandru Simion[1], Leonard Livadaru[1]

[1] *„Gh.Asachi" Technical University of Iasi, Faculty of Electrical Engineering, 53 D.Mangeron Blvd., Iasi, ROMANIA – 700050, +40-232-278680, Fax: +40-232-237627, lukake@tuiasi.ro*

Abstract- The paper describes the experimental determination of the internal angle of a permanent-magnet synchronous electrical machine with axial air gap, using the results of the usual measurements of voltages, currents and torque in transient load operation. The particular propriety of the used test-bench is pointed out, as well the necessary improvements to reduce the method limitations.

I. Introduction

The most usual characteristics for the synchronous electrical machines are the angular ones. In the case of the theoretical characteristics validation, we need to get the experimental values of the internal angle in order to trace the experimental angular characteristics. But it is known that the classic ways to determine the internal angle of a synchronous machine are not very facile and precises. We propose to calculate the internal-angle, starting from the directly obtained acquired data of voltage, current and torque.

If one considers that the angular speed is

$$\Omega = \Omega_0 + d\Omega \qquad (1)$$

where Ω_0 is the synchronous speed, than a relative internal-angle θ* results by integrating the previous equation:

$$\theta^* = \frac{1}{T}\int_0^T d\Omega dt = \frac{1}{T}\int_0^T (\Omega - \Omega_0)dt \qquad (2)$$

We called "relative internal-angle" because of the dependence on the integration reference. The used data acquisition program, LabView, is also suited to the calculation program.

II. Getting the angular characteristics

A. Experimental setup

The test bench that has been used to get the experimental angular characteristics of a disk-type synchronous motor is presented in Figure 1 and is composed mainly by an inverter-fed asynchronous loading-motor and a numeric acquisition system.

The loading-motor and his proper inverter are parts from a specialized system produced by *hps – System Technik*, Germany.

The values of currents and voltages on each phase are obtained by means of Hall-type LEM modules, the rotary speed is acquired by means of an encoder and the torque information comes from a tensometric-marks bridge that is placed under the load machine.

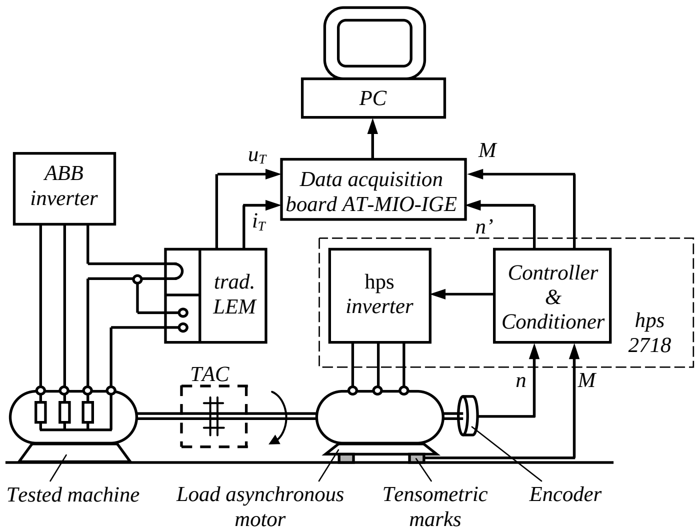

Figure 1. Experimental setup

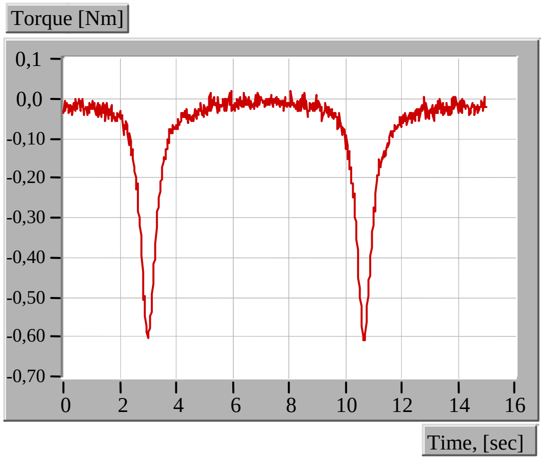

Figure 2. Time variation of the torque emphasizing the synchronism falling

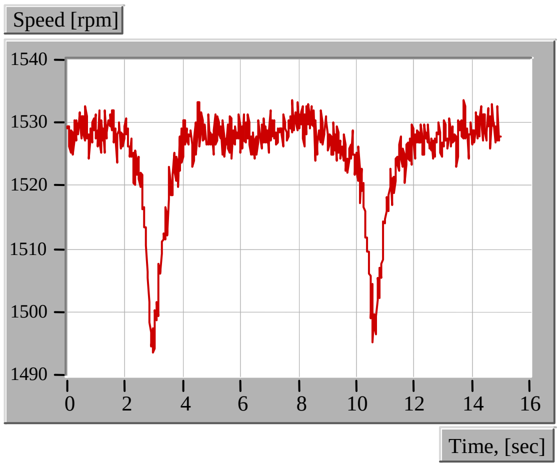

Figure 3. Speed-time variation during synchronism falling

A PWM inverter that allows steps of 0.1 Hz in the frequency control feeds the tested synchronous disk-rotor machine. The main advantage of this testing system is that allows slowly falling out of the synchronism, especially because the *hps* – controller modulate the loading torque. This behaviour is caught in the Figures 2 and 3.

B. Getting the internal angle

In the first instance we need to extract the exact synchronous speed Ω_0. As shown in the explanatory diagram shown in Figure 4, the *Mean* function and the integration block that applies the Simpson method was used. Figure 5 presents the obtained time-evolution of a variable that is proportional to the internal angle. The characteristic seems to have a near-periodical evolution and contains as many maxim values as falling out events can be counted during the measured interval.
The Figures 6, 8 and 10 show the dependence of the torque and current with the relative internal-angle for the entire measurement. One notices that, even though not very precise, it seems to be a repetition of the same cycle.
Unfortunately, the values of the relative internal angle (that appear in the Y-axis of the Figure 5 and in the X-axis in the next figures) have no practically signification because of the complete aleatory integration references. But some reference points can be deduced in a logic way.
After the synchronism falling, when the rotor regains its stability, the moment will correspond to the zero value of the internal angle. When the tested synchronous machine is loaded, the internal angle will increase. So it can be interpreted that the minimum-points from the characteristic to correspond to the moments when the internal angle is zero, (as for example the marked points O_1 and O_2 in Figure 5). On the other hand, the maximum-points can be interpreted that correspond to the synchronism falling. As

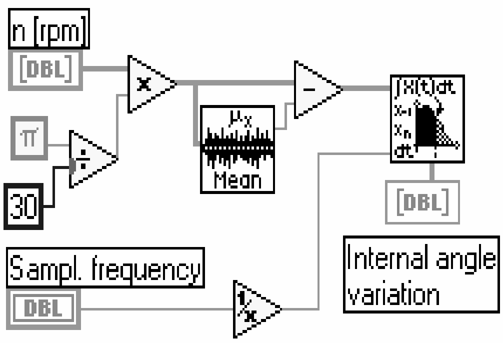

Figure 4. The LabView speed integration diagram

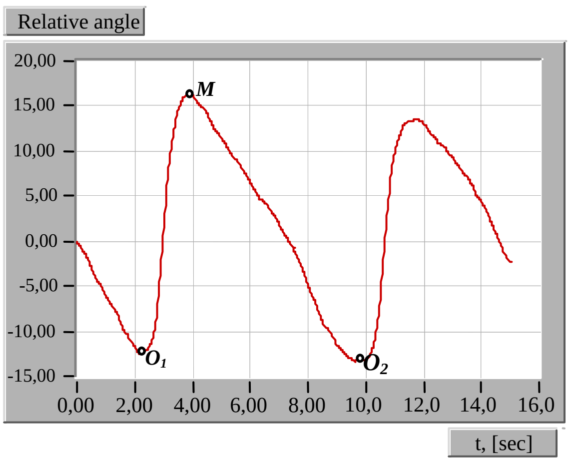

Figure 5. Result of speed integration

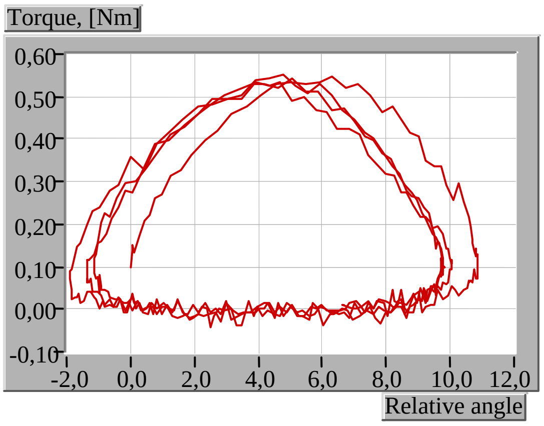

Figure 6. Torque evolution with the relative internal angle in the motoring regime

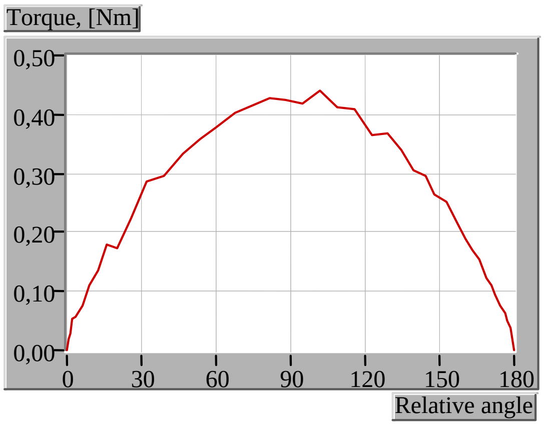

Figure 7. Torque - angle characteristic for the motoring regime

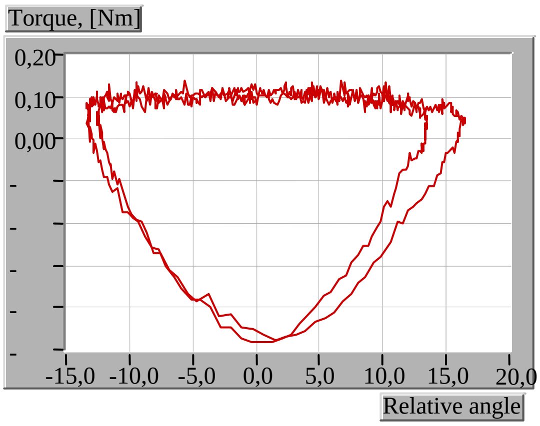

Figure 8. Torque evolution with the relative internal angle in the breaking regime

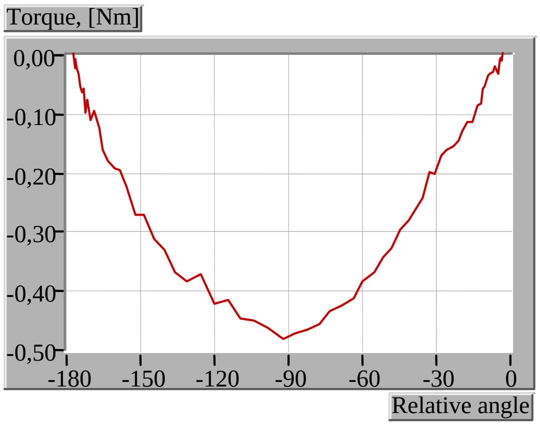

Figure 9. Torque- angle characteristic for the breaking regime

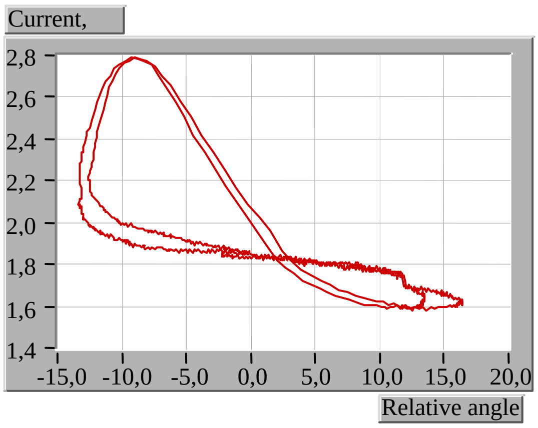

Figure 10. Current evolution depending on the relative internal angle in the breaking regime

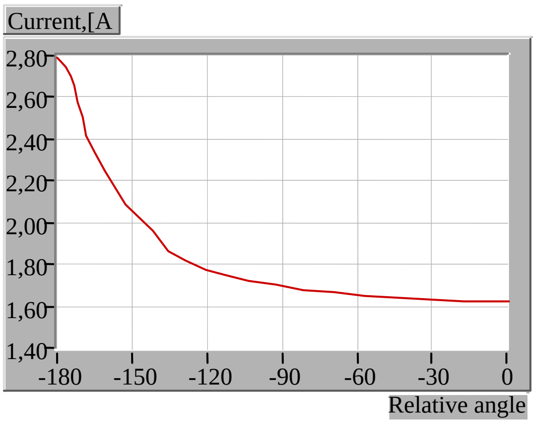

Figure 11. Approximation of the current angle characteristic

consequence, for the increasing slope between the points O_1 and M, for example, the internal angle will perform an excursion from 0 to 180 degree.
The decreasing slope will correspond to a transient process, which is characterised by oscillations because during this period, the two coupled-machines are practically not in contact up to the moment of the new synchronisation between the stator field and rotor of the tested motor.
From the data arrays, only the variable values that correspond to the interval between a maximum and a

minimum (the points O_1 and M) have been extracted and their dependence with the relative internal angle was represented. In Figures 7 and 9 one presents the obtained experimental torque – angle characteristics both in motoring and breaking regime. To get the desired values in the X-axis, the points of the beginning and the end (the marked points O_1 and M that correspond to the 0 and 180 degree values of the internal angle) were fixed and than, by means of simple arithmetic operations, the framing of the internal angle in this limits was forced.

C. Method limitations and improvements

One notes that, for the absolute values of the internal angle greater than 90 degree, both torque characteristics have a derivation from the expected path. This appears due to the system dynamic torque that cannot be neglected when important speed variations occur. In opposition, when the internal angle is up to 90 degree, the speed variations are low (depending on the testing conditions) and the obtained characteristic can be considered close from the real one.

Our test-bench allowed us getting with reasonable accuracy only the torque angular characteristic. Unfortunately, as we see in Figure 11, the getting of the current-angle characteristic is not so simple and precise without improving the test-bench performances. The problems we have met are due to the delay that appears between the electric variable (current for example) and the mechanical variables (as torque). Due to the system inertia, the response of the tensometric bridge has a variable delay, which is practically impossible to be determined. A possibility to eliminate this delay is the use of a direct torque transducer, which is usually placed between the two motors, test and load machines, replacing the used elastic coupling.

It must be pointed out again that the controller modulation over the loading torque is essential. Replacing the ensemble asynchronous motor – inverter with a DC machine to play the role of the load machine, the impossibility to get a slow process was demonstrated and, as consequence, the difficulty to point out the moment of the synchronism falling.

III. Conclusions

A method that allows with reasonable accuracy the determination of the torque angle characteristics is proposed. This requires only performing the usual data acquisitions during a slow synchronism falling regime and then using a calculation program. Such type of operating regime is possible to be obtained in a test-bench that uses for loading an asynchronous motor fed by a controlled inverter that is able to modulate the loading torque. The method is simple and useful for quick determination of the angular characteristic shape, but for a better accuracy it must be improved. A proper type and place for the torque transducer is recommended in order to eliminate the delays between electric and mechanical variables and so to get correctly angular characteristics for variables as current, power, etc.

References

[1] D.Lucache, Al.Simion, S.Calugareanu, V.Horga, “Design of a disk-type permanent-magnet synchronous machine for magnetic bearing applications”, *4th International Symposium on Advanced Electromechanical Motion Systems ELECTROMOTION 2001*, June 19-20, 2001, Bologna, Italy, ISBN 88-900615-0-2, vol.2, pp. 403-407

[2] J.J.Graham, A.Hamilton, C.L.Halsal, “Rotor angle measurement on a synchronous machine operating under transient load conditions”, *UPEC*, Jully 1987, pp.102-105

[3] Vaithianathan Venkatasubramanian, Rajesh G. Kavasseri, “Direct Computation of Generator Internal Dynamic States from Terminal Measurements”, *Proceedings of the Proceedings of the 37th Annual Hawaii International Conference on System Sciences* (HICSS'04) - Track 2 - Volume 2, 2004, ISBN:0-7695-2056-1, Pp. 20060.1

[4] M. J. Corley and R. D. Lorenz, "Rotor Position and Velocity Estimation for a Salient-Pole Permanent Magnet Synchronous Machine at Standstill and High Speeds", *IEEE Transactions on Industry Applications*, Volume 34, Number 4, July/August, pp.784-789, 1998

[5] Yamano, Noguchi, Kondoh "Position Sensorless Speed Control Method of Saliency-type PM Motor including Low Speed Region", *Technical Meeting on Semiconductor Power Converter*, IEEE Japan, SPC-97-13, pp. 75-82, 1997

[6] Magnetic pole position estimating method and control apparatus for synchronous motor, US Patent Issued on October 5, 2004