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# Sensorless Starting of Wound Rotor Synchronous Machines

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**Abstract** – The sensorless operation of wound rotor synchronous machines (WRSM) must meet several requirements. The most important to be mentioned is how to insure starting at full load and then operating at low speed in the presence of magnetic saturation. This work presents a solution for high power machines by combining a method of rotor location by high frequency injection and then starting it with a Phase Locked Loop (PLL) type solution. It should be noted that the location of the rotor leaves an indeterminacy of  $\pi$  on the electrical position that needs to be resolved. Initial experimental tests for rotor location confirm simulations and show how the scheduling of the two methods can solve the problem.

## INTRODUCTION

Wound rotor synchronous machines (WRSM) are synchronous machines (SM), in which the rotor flux is generated by an electric winding. WRSMs have certain characteristics that meet the needs of large industrial applications such as compressors or rolling mills very well. When using vector control, position information is required, which can be obtained using a sensor (resolver, optical encoder, etc.). The absence of this sensor reduces costs and can increase the reliability of the entire drive system. Sensorless controls are currently the subject of many studies [3], [4], [5], [6]. From start-up to nominal speed or higher, it is very often necessary to use several types of observers to benefit from the best performance depending on the speed. The first problem is the start-up and the acceleration which is the subject of our contribution. As soon as the machine has started and the electromotive forces become high, it is easier to rebuild the position. Many methods have already proven their worth.

First, the current trend is to use a method of injecting a high frequency signal to locate the rotor[x]. Conventional approaches for permanent magnet synchronous machines (PMSM) inject high frequency signal (HFSI) into the stator dq axes and by measuring currents in the same reference dq, the position is reconstructed [2], [8], [4]. Unlike PMSMs, WRSMs theoretically allow the rotor winding to be used as an injector of the HFSI and it is even possible to imagine the following solutions [7]:

- stator injection and stator measurement
- injection into the rotor and measurement on the stator
- injection into the stator and measurement in the rotor.

The most intuitive approach of the methods mentioned above is to emulate a resolver using the rotor as the transmitter and the stator as the receiver of the HF signal. However, if a rotating diode rectifier is used for rotor excitation, injecting a signal into the rotor can become difficult. If the stator is used as the transmitter and receiver of the HFSI, the rotor winding acts as a damping winding for the HFSI and the magnitude required for observation may therefore no longer be sufficiently present. In this article, we discuss the case of stator injection and stator current measurement when the machine is equipped with a diode rectifier.

In this context it is well known that the position is known with an indeterminate electric  $\pi$  angle. Several solutions exist to overcome this indeterminacy and here we propose a new method to address this problem.

The result of this procedure is used to initialize the machine start as well as a PLL procedure to

ensure the machine start up. We will analyze the benefits using the two methods in a specific sequencing on position estimation.

**MACHINE MODELING**

In this case we can establish two types of models, first of all a low-frequency model such as the Park type reflecting the traditional operation of the machine and a high-frequency model allowing to analyze the propagation of the injected high-frequency signal.



Fig. 1a WRSM in high power application

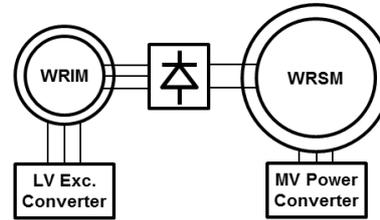


Fig. 1b WRSM Structure

Parameters of machine:  
 P=13.8 kW; Van=6.6 kV, Ian=1200 A,  
 Fn=60 Hz, rated speed=1800 rpm, two pole pairs

This type of machine (Figure 1a, 1b) actually consists of 2 machines running at the same speed (Figure 1.b). First of all, an wounded-rotor induction machine (WRIM), acting like a “rotating transformer”, is supplied by a three-phase VSI or by a thyristor converter; the rotor, seen as the secondary side of the rotating transformer, feeds a rotating diode bridge which, in turn, allows finally to energize the main machine (MP). This “brushless exciter” structure is mandatory in Oil & Gas application, in which the brushes and the related sparks are forbidden due to safety reasons.

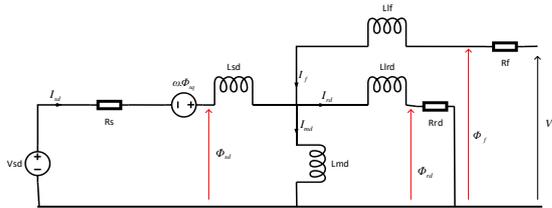


Fig. 2a: Electric model on the d axis

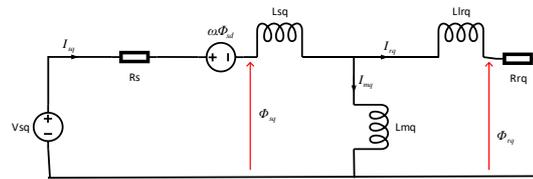


Fig.2b:Electric model on the q axis

Thus, by assuming an unsaturated functioning, the Park model can be written. This is how Park's model can be written.

$$\begin{cases}
 V_{sd} = R_s \cdot I_{sd} + \frac{d}{dt} \cdot \Phi_{sd} - \omega \cdot \Phi_{sq} \\
 V_{sq} = R_s \cdot I_{sq} + \frac{d}{dt} \cdot \Phi_{sq} + \omega \cdot \Phi_{sd} \\
 V_f = R_f \cdot I_f + \frac{d}{dt} \cdot \Phi_f \\
 0 = -R_{rd} \cdot I_{rd} + \frac{d}{dt} \cdot \Phi_{rd} \\
 0 = -R_{rq} \cdot I_{rq} + \frac{d}{dt} \cdot \Phi_{rq}
 \end{cases}
 \quad \text{with} \quad
 \begin{bmatrix}
 \Phi_{sd} \\
 \Phi_{sq} \\
 \Phi_f \\
 \Phi_{rd} \\
 \Phi_{rq}
 \end{bmatrix}
 =
 \begin{bmatrix}
 L_{sd} + L_{md} & 0 & L_{md} & -L_{md} & 0 \\
 0 & L_{sq} + L_{mq} & 0 & 0 & -L_{mq} \\
 L_{md} & 0 & L_f + L_{md} & -L_{md} & 0 \\
 L_{md} & 0 & L_{md} & -(L_{rd} + L_{md}) & 0 \\
 0 & L_{mq} & 0 & 0 & -(L_{rq} + L_{mq})
 \end{bmatrix}
 \cdot
 \begin{bmatrix}
 I_{sd} \\
 I_{sq} \\
 I_f \\
 I_{rd} \\
 I_{rq}
 \end{bmatrix}
 \quad (1)$$

With  $T_{em} = p \cdot (\Phi_{sd} \cdot I_{sq} - \Phi_{sq} \cdot I_{sd})$  (2)

For high frequency the equivalent dq circuit of the machine can be summarized as follows [1].

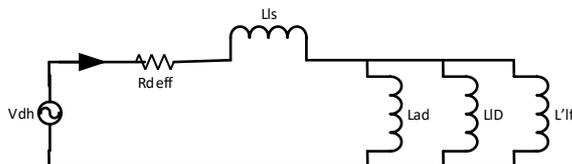


Figure 3 a: Equivalent circuit on the d-axis for HF operation

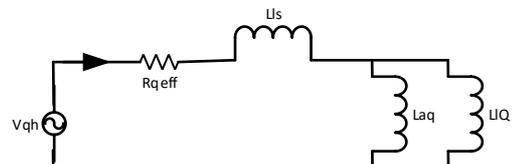


Figure 3 b: Equivalent circuit of q-axis for HF operation

These model show new values such as effective resistances  $R_{d\text{eff}}, R_{q\text{eff}}$ , effective inductances  $L_{d\text{eff}}, L_{q\text{eff}}$  and leakage inductances  $L_{\sigma d}, L_{\sigma q}, L'_{ij}$  which play an important role because of their low value compared to magnetizing inductances. In addition, saturation plays a major role, in particular by also reducing the value of magnetizing inductances. The parameters of these models are linked to the parameters of the low frequency model and also depend on the saturation state of the machine.

**SENSORLESS CONTROL OF THE MACHINE**

Sensorless operation is compatible with vector control and consists of replacing the position measurement with a device that reconstructs the position from some measurements on the dq axis and after digital signal processing, fig. 4.

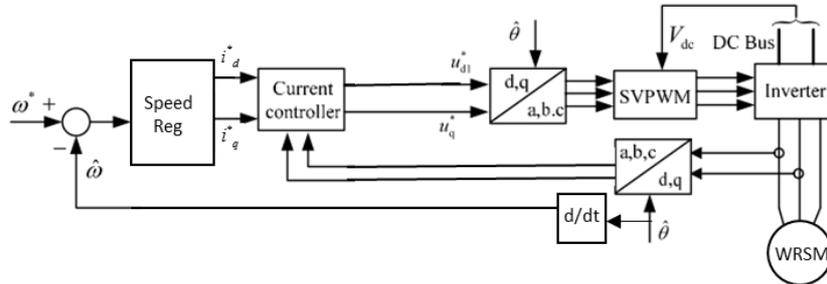


Figure 4: Control diagram without position sensor

Note that the estimated speed is obtained from the estimated position either by direct filtering or by a looped device. For machines with smooth poles the current in the d-axis is imposed at zero. On the other hand, for machines with salient poles an additional torque component can be obtained by imposing a negative  $i_d$  current in relation to the torque level in order to operate in Maximum Torque per Amp MTPA [11].

**HIGH FREQUENCY INJECTION**

Injection-based methods have been known for many years [10]. In our case, the injection is done on the d-axis in order to limit the impact on the machine's torque. The signal demodulation is performed using a specific processing illustrated in Figure 6 and uses a PI controller to cancel the DC component that contains information on the position deviation. This method can be used in stationary state to locate the rotor or at low speed. In the latter case, it is important to properly design the filters so that the rotation speed does not disturb the operation.

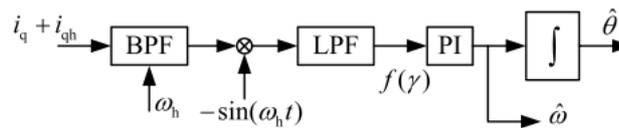


Figure 6: Position extraction by demodulation

The position estimation converges towards a point of equilibrium with a phenomenon of polarity which results in an indeterminacy of the position of a value equal to  $\pi$  electric. It should be noted that the response time varies with the actual position, reflecting non-linear behavior.

It should be noted that this method operates in a closed loop with a bandwidth defined by the regulator.

**USING THE ATAN2 FUNCTION**

Another method is to measure the current components on the  $\alpha$  and  $\beta$  axes and estimate the position using an ATAN2 function, Figure 7. This method operates in an open loop and is very sensitive to noise.

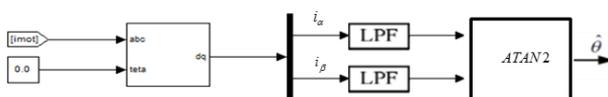


Figure 7a: Position extraction with ATAN2 function

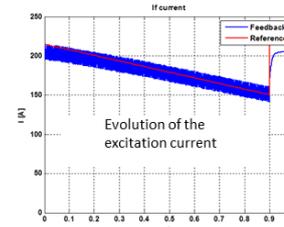


Figure 7b: Evolution of the excitation current

While applying the HFSI voltage, a controlled variation of the excitation current is also given. It is possible to apply a voltage step to the excitation circuit, or switch off the exciter, or control a descending ramp. The Figures 8 illustrate the reconstruction of the stationary position with the 2 methods, with different initial mechanical condition  $\Theta_m(0)$ . Note that the machine has 2 pairs of poles. The curves show that the procedure based on the ATAN2 function ensures the location of the rotor independently of the initial conditions while the closed loop method using a PI controller without procedure correction shows an indeterminacy of the location of the rotor.

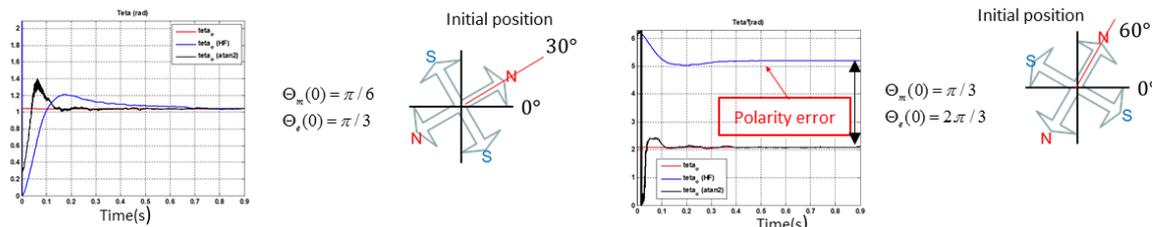


Figure 8a: Initial condition on the mechanical position  $\Theta_m(0) = \pi / 6$

Figure 8b: Initial condition on the mechanical position  $\Theta_m(0) = \pi / 3$

**HYBRID METHOD FOR INITIAL POSITION DETECTION**

The experimental results show that the ATAN2 (open loop) calculation is affected by noise, which results in an uncertainty band of some electrical degrees. On the contrary, the HFSI method provides a clean measure, although affected by a possible polarity error. This suggests to combine the methods: the ATAN2 method is used only to understand the polarity and, in case, add  $\pi$  to the position calculated by the HF method.

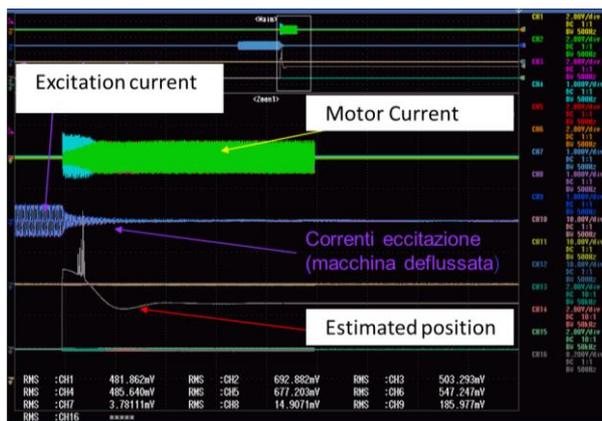


Figure 9: Experimental results - excitation current cut-off.

The validation tests (see figure 9) have been carried out by applying the proposed method on the aforementioned machine, and comparing the results with the measurement of an absolute encoder. A maximum deviation of  $\pm 2$  mechanical degrees has been recorded. In any case, after each test, the machine has been correctly started without any problem.

The result of the hybrid detection method can thus be used as a good point for starting the machine without the absolute encoder, and for initializing the PLL in case of full sensorless application.

**OBSERVATION WITH PLL**

The construction of PLL-based observers is an interesting method that can work as soon as the speed is different from zero.

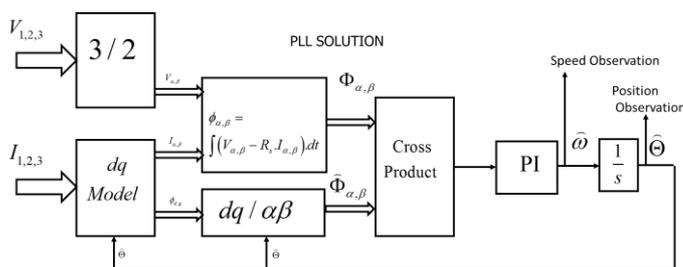


Figure 10 : Position observation with PLL

The idea of this solution is to converge flux on the axes  $\alpha$  and  $\beta$  calculated with 2 different models. The convergence of these two quantities implies that the estimated position converges towards the real position of the machine recovering the initial error of rotor position. Convergence is provided by a PI regulator, Fig. 10. This loop is a non-linear system and the convergence dynamics of the error is a function of the speed, so it is important to adapt the gain of the PI controller according to speed.

### SIMULATION RESULTS

The experimental device we wish to test in simulation includes an incremental encoder to determine the rotational speed. In the following tests, we propose to compare the performance obtained using this sensor with the one obtained from the observer.

In addition, we try to evaluate the robustness of our procedure by injecting an initial position error of  $3^\circ$  mechanical or  $6^\circ$  electrical. The PLL method is evaluated during a start without load and then for a loaded start (parabolic evolution according  $T_r=36632 \times (\omega/1800)^2$ ). The reference speeds is first low (21.6 rpm) and then higher (432 rpm).

#### NO LOAD – SPEED REFERENCE =21.6 rpm

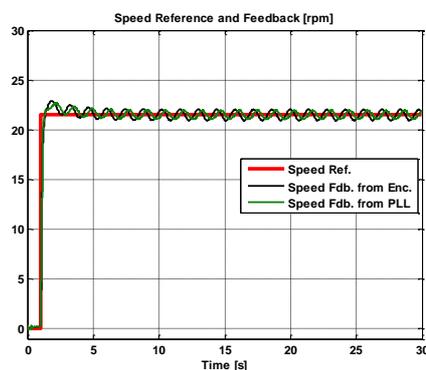


Figure 11 a: Initial position error  $0^\circ$

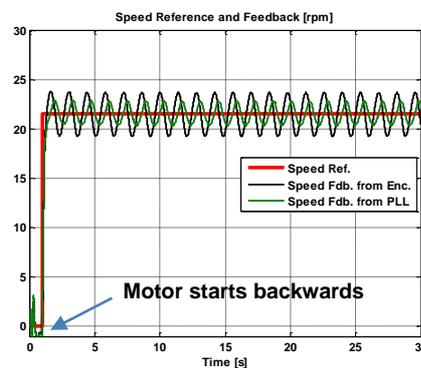


Figure 11 b: Initial position error  $3^\circ$  mechanical

Figures 11 show the use of the speed output of the PLL gives lower speed oscillations than for operation with the incremental sensor, especially when the initial position error is large. It should be noted that at low reference speed the possibility of a reverse start exists when the position error is not zero.

#### NO LOAD – SPEED REFERENCE =432 rpm

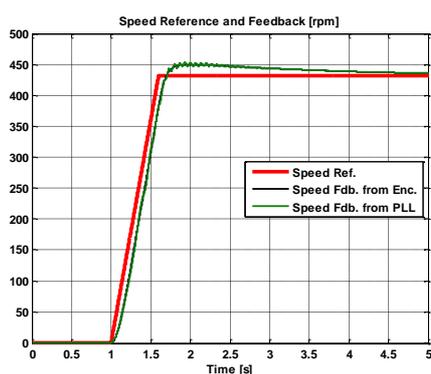


Figure 12 a: Initial position error  $0^\circ$

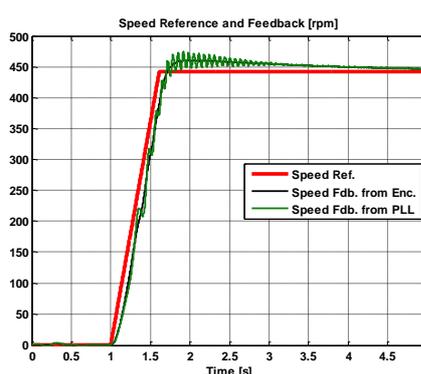


Figure 12 b : Initial position error  $3^\circ$  mechanical

We notice in Figures 12 that for higher reference speeds the risk of starting in the opposite direction disappears.

#### WITH LOAD – SPEED REFERENCE =2160 rpm

The target speed profile consists of a ramp from zero to 2160 rpm in 3s. In steady state the torque is 52750 Nm, corresponding to a power of 11.9 MW.

For a start with quadratic load (Figures 13) we find that the PLL-based observer works correctly

even in the presence of an initial position error. The incremental encoder does not bring any additional advantage.

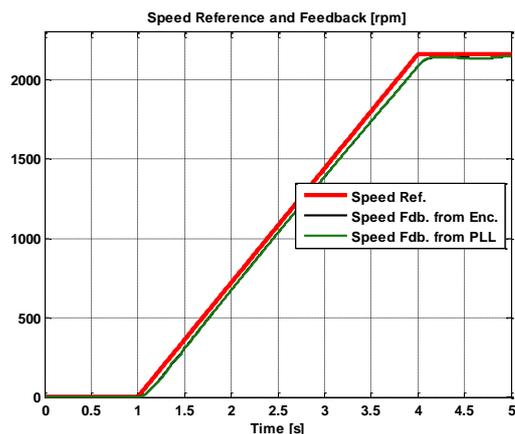


Figure 13a: Initial position error  $0^\circ$

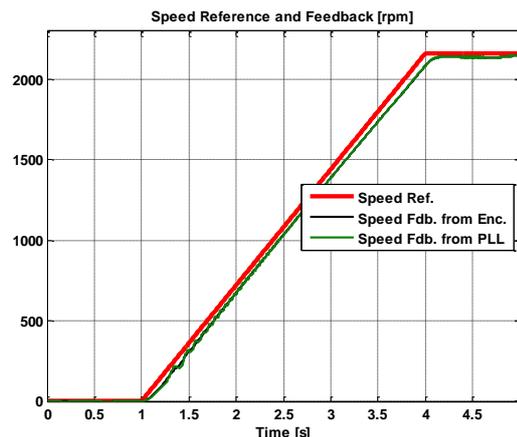


Figure 13b: Initial position error  $3^\circ$  mechanical

## CONCLUSION

In this work we have shown that it is necessary to know the position of the rotor well to ensure a correct start of the WRSM machine, especially when the load is high. The solution we have studied is satisfactory and based on 3 specific steps in succession. First of all, a localization of the rotor by injecting a high frequency signal into the stator, which makes it possible to know the position with an indeterminacy of  $\pi$ . Then by acting on the excitation current we lift this indeterminacy and the position of the rotor is then known but the mechanical accuracy is not high. Combining the HF and arctangent-type methods, experimental results have been proven that it is possible to get a good accuracy and speed. The result obtained can be used as an initial condition for a closed-loop observation procedure based on PLL. This procedure gives satisfactory results and the incremental speed encoder is no longer necessary.

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