Direct Flux Control – A Sensorless Control Method of PMSM for all Speeds – Basics and Constraints

Muller, T, Thiemann, P, See, CH, Ghani, A & Bati, A

Original citation & hyperlink:
Muller, T, Thiemann, P, See, CH, Ghani, A & Bati, A 2017, 'Direct Flux Control – A Sensorless Control Method of PMSM for all Speeds – Basics and Constraints' *Electronics Letters*, vol 53, no. 16, pp. 1110-1111
https://dx.doi.org/10.1049/el.2017.1772

DOI 10.1049/el.2017.1772
ISSN 0013-5194
ESSN 1350-911X

Publisher: IEEE

Direct Flux Control – A Sensorless Control Method of PMSM for all Speeds – Basics and Constraints

T. Müller, C. See, A. Ghani, A. Bati, P. Thiemann

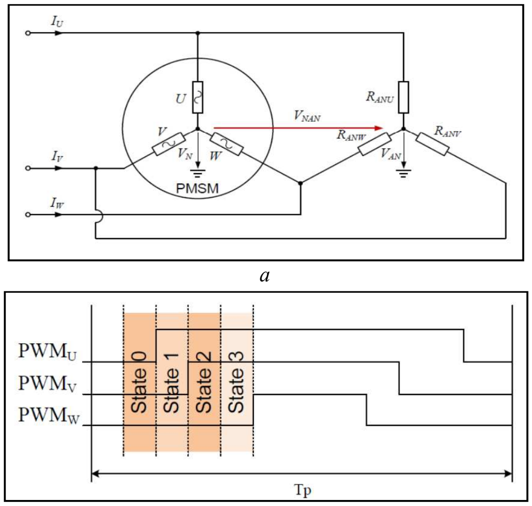
This paper discusses the limitations of sensorless control of permanent magnet synchronous machines and proposes a viable solution. The main concept of sensorless control of drives relies on additional information given by the machine during its normal operation. This information provided by the machine is essentially the Back Electro Motive Force and the variance of the stator inductivity, which are dependent on the rotor position. Several approaches and methods have discussed these problems and in most cases, they are not avoidable and that some methods work better on certain speeds of the drives. This paper presents the Direct Flux Control method to combat the above problems at all speeds. The flux linkage signal which contains the necessary information about the rotor position, can be measured between the neutral point of a permanent magnet synchronous machine and an artificial one. The mathematical derivation and the observations from the experiments show that this signal contains a second and a forth harmonic, which can be used to calculate the rotor position. Furthermore, the limitations of implementing Direct Flux Control are also addressed.

Introduction: Permanent Magnet Synchronous Machines (PMSM) have been used widely in all kind of industrial applications. Its high power density, accurate positioning and high dynamic performance made PMSMs as one of the most advantageous drives. Example applications are drives in E-cars, actuator or even pumps. During the last three decades, more and more computational power has become available which opened the doors for more complex on-line operating of such drives systems. Accordingly, sensorless control of PMSM became a more relevant aspect of research investigation in terms of optimization, reliability and cost efficiency. The core problem the machine itself brings to the table is that it needs information about the current rotor position of the magnetic field. This information is needed to actually commutate the current in a PMSM. Traditionally, a resolver is used to overcome this problem. However, the problems associated with such a mounted device are obvious. These include additional cost and space for the sensor itself, which reduces the reliability and increases the maintenance cost of a drive system [1].

Methodology of Sensorless Control: As stated above, a core problem of PMSM is the necessity of an additional mounted device, usually a resolver. The basic idea of sensorless control for PMSM is to replace such an additional mounted device by either an additional, easier, cost efficient measurement or by using an already available measurement. Such measurement could be the current measurement, which is standard in nowadays drive systems. However, the machine essentially delivers two parameters about the rotor position. The first one is the B-EMF (Back-Electro Motive Force), which is the induced voltage caused by the rotating magnetic field around the stationary stator. The second one is the variance of the stator inductivities. This inductivity is dependent on the current and the magnetic path, which can change during one electrical period if the rotor of the PMSM has asymmetries in its construction.

One of the well-known methods which is based on inductivity variance is the INFORM method (Indirect Flux detection by Online Reactance Measurement), as described in [2]. In this method the INFORM cycle is measured during the PWM cycle of the system. This is done via current measurement and especially requires for high speed PMSM with a high amount of pole pairs to make it very powerful microcontroller environment. The information INFORM receives out of this measurement is the current slope of the current ripple. This ripple mirrors the actual inductivity distribution in a PMSM and can be used to find the exact position of the rotor. In [3] a summary can be found about very common excitation methods for high frequency which also includes the zero-voltage/current sequence. As stated above, all these methods use the inductivity variance to find the rotor position. In contrast, methods based on BEMF were proposed in [4]. It uses additional algorithms to estimate and predict the rotor position. The fundamental problem of all these methods is that they cannot work at low speeds and standstill because the BEMF is either close to zero or not available at these speeds. To overcome this problem, [5] adopted the approach by adjusting the rotor to a certain position and then starting the movement of the drive from that known point. However, this does not solve the problems at low speeds. Moreover, typical application of sensorless control including observer based control is proposed in [6]; nonetheless problem remains the same rather it creates further problems such as stability.

To offer an alternative solution to the above problem, a novel sensors control of PMSM with Direct Flux Control (DFC) was proposed in this paper. This method works independently of the speed. The DFC signal is based on variance of the stator inductivity in a PMSM. To measure the DFC signal, the machine itself has to have an accessible neutral point. In addition, there is an artificial neutral point which is necessary as shown in Fig. 1a. As can be seen the neutral point consists of three resistors.



a

b

Fig. 1 *Complete measurement scheme for acquiring DFC signals*
a Setup with artificially created and neutral point of a PMSM
b Measurement timing in one PWM cycle T_P

To acquire the DFC signal, the voltage V_{NAN} has to be measured during the PWM cycle as depicted in Fig. 1b. Each of the state 0-3 needs to be measured a short time after switching the state. The measured information can be summed up as inductivity distribution of the stator and can be found in [7]. The result of this for the phase U is in (1), whereby u is the resulting voltage, V_{NANn} the according state, V_{DC} the DC-link voltage and $L_{U,V,W}$ the corresponding phase inductivity.

$$\frac{u}{V_{DC}} = \frac{V_{NAN1} - V_{NAN0}}{V_{DC}} = \frac{1}{L_U}\left(\frac{1}{L_U} + \frac{1}{L_V} + \frac{1}{L_W}\right)^{-1} \qquad (1)$$

The phase inductances L_U, L_V and L_W can be described as (2) as stated in [3]:

$$L_n = \frac{1}{3}\left[\left(L_d + L_q\right) + \left(L_d - L_q\right)\cos\left(2\alpha + n\frac{2\pi}{3}\right)\right] \quad n = 0,1,2 \qquad (2)$$

In equation (2), the parameter n corresponds to the phase inductance, whereby 0 is the phase u, 2 is the phase w and α the rotor position. By substituting (2) in (1), (3) can be established as follows:

$$\begin{aligned}\frac{u}{V_{DC}} = {} & \frac{\left[L_d + L_q\right]^2 - 0.25\left[L_d - L_q\right]^2 - \left[L_d - L_q\right]\left[L_d + L_q\right]\cos(2\alpha)}{3\left[L_d + L_q\right]^2 - 0.75\left[L_d - L_q\right]^2} \\ & + \frac{0.5\left[L_d - L_q\right]^2\cos(4\alpha)}{3\left[L_d + L_q\right]^2 - 0.75\left[L_d - L_q\right]^2} - \frac{1}{3} \end{aligned} \qquad (3)$$

where the inductance L_d and L_q are the corresponding inductivities in the synchronous frame. Whereas L_d mirrors the inductivity in flux direction and L_q the inductivity perpendicular to the flux direction.

From (3) it can be concluded that DFC does not work properly for SM-PMSM (Surface Mounted), or in general for PMSM, if L_d and L_q are equal, because the signal disappears as in (4).

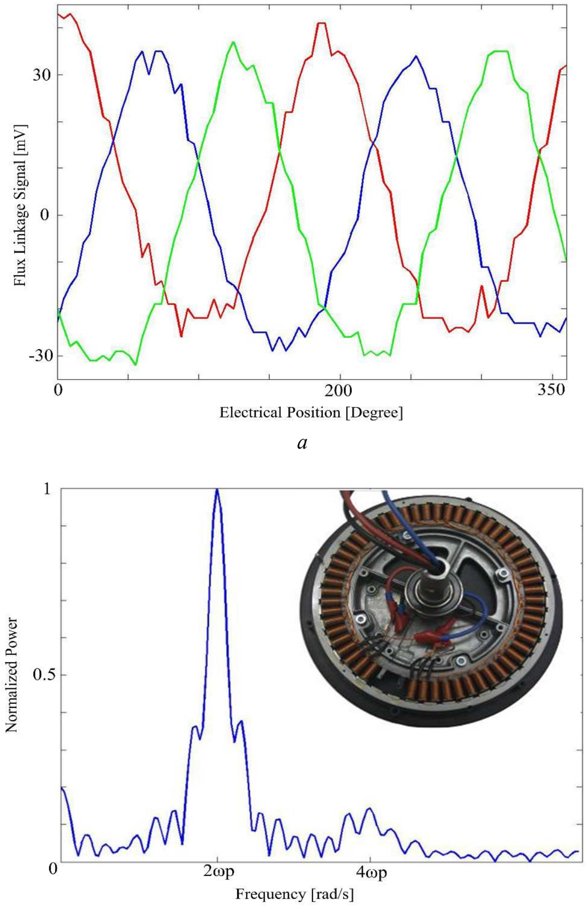
$$\frac{u}{V_{DC}}=\frac{\left[L_d+L_q\right]^2-0.25\left[0\right]^2-\left[0\right]\left[L_d+L_q\right]\cos\left(2\alpha\right)}{3\left[L_d+L_q\right]^2-0.75\left[0\right]^2}$$
$$+\frac{0.5\left[0\right]^2\cos\left(4\alpha\right)}{3\left[L_d+L_q\right]^2-0.75\left[0\right]^2}-\frac{1}{3}=\frac{\left[L_d+L_q\right]^2}{3\left[L_d+L_q\right]^2}-\frac{1}{3}=0 \tag{4}$$

Moreover, the DFC signal becomes better if the condition in (5) is met.

$$\left|\frac{L_d+L_q}{L_d-L_q}\right|>>0.5 \tag{5}$$

This elaborates that DFC can work with salient ($L_d > L_q$) and non-salient pole ($L_d < L_q$) PMSM and the signal can be influenced positively and optimized by choosing a properly magnetic path at design [8].

Experimental Setup and Results: To proof the result of (3), experimental tests have been done on a TriCore environment with a PXROS operating system. The switching frequency has been set to 2 KHz with a DC-link voltage of 24V. The PMSM (Caddy motor) is a surface mounted PMSM with 54 slots, 40 poles and $L_q > L_d$.



a

b

Fig. 2 *DFC Test with experimental results for Emotion PMSM*
a. Flux linkage Signals of phase u, v and w
b. Spectrum of flux linkage signal of phase u in Fig. 2*a* and used PMSM

Fig. 2a depicts the result of the calculations of the DFC signal for all three phases u, v and w. The signal acquired with a DC link voltage of 24V reaches from 30mV to -30mV on one electrical rotation. It can be noticed that the shape of this signal is almost sinusoidal and can be used for the commutation of the PMSM. There is also some noise, which is to be expected by this kind of measurement. However, by simplifying (3), a short form can be derived as shown in (6):

$$\frac{u}{V_{DC}}=\frac{k_1}{k_4}-\frac{k_2\cos\left(2\alpha\right)}{k_4}+\frac{k_3\cos\left(4\alpha\right)}{k_4}-\frac{1}{3} \tag{6}$$

where the constants k_1 - k_4 are the coefficients of the four main parts in (3). The result of the FFT of the signal in Fig. 2a is shown in Fig. 2b. It can be noticed, the FFT essentially shows three main parts, which are a DC offset, a second harmonic (which is the fundamental) and forth harmonic. This experimental result validates (6) and confirms the correctness of the mathematical derivation and the predicted FFT signal.

Conclusion: The major problem of sensorless control of permanent magnet synchronous machines is discussed in this article. The machine itself provides only two information about its actual and current rotor position. While methods based on BEMF usually fails at low speeds, whereas high frequency methods usually fails at high speeds. As Direct Flux Control is independent from the current speed of the permanent magnet synchronous drives and hence works at all speeds. As demonstrated, the extracted signal includes the fundamental and a fourth harmonic. The absolute distance in amplitude of these shapes, which has been shown, depends on the machine parameters and the variance of the stator inductivity. While DFC can work at all speeds, the method itself has some constraints regarding the permanent magnet synchronous machine where it is applied. The first constraint is that the machine needs an accessible neutral point, to measure the flux linkage signal. The second constraint is that the machine needs a certain variance in its inductivities L_d and L_q. It has been proven that the DFC signal disappears in case of symmetric inductivities. As an advantage the method itself can essentially run for all other types of machines, either salient or non-salient. The future work on DFC will investigate the stability during operating and the influence of stator currents on the flux linkage signals, which are not considered presently.

Affiliation

T. Mueller and *P. Thiemann* are with Electrical Machines and Power Electronics laboratory, South Westphalia University of Applied Sciences, Soest, Germany (email: mueller.tobias@fh-swf.de)

C. H. See and *A. Bati* are with School of Engineering, University of Bolton, Deane Road, Bolton, UK

A Ghani is with the School of Computing, Electronics and Mathematics, Coventry University, Coventry, UK

References

1. M. Pacas, “Sensorless drives in industrial applications,” IEEE Industrial Electronics Magazine, vol. 5, no. 2, pp. 16–23, Jun. 2011

2. E. Robeischl and M.Schroedl, “Optimized INFORM Measurement Sequence for Sensorless PM Synchronous Motor Drives with Respect to Minimum Current Distortion”, IEEE Transactions on Industry Applications, vol.40, no.2, pp.591-598, 2004

3. F.Briz and M. Degner, “A Review of High-Frequency Methods,” IEEE Industrial Electronics Magazine, vol.5, no.2, p. 24-35, 2011

4.F. Yan, L. Zhang, M. Cheng, KT. Chau, “Sensorless SVPWM-FADTC of a new flux-modulated permanent-magnet wheel motor based on a wide-speed sliding mode observer”, IEEE Transaction on Industrial Electronics, vol.62, no.5, p. 3143-3151, 2015

5. Z. Wang, K. Lu, F. Blaabjerg, “A Simple Start-up Strategy Based on Current Regulation for Back-EMF-Based Sensorless Control of PMSM” IEEE Transaction on Power Electronics, Vol. 27, No. 8, p. 3817-3825, 2012

6. Z. Qiao, T. Shi, Y. Wang, Y. Yan, C. Xia, “New Sliding- Mode Observer for Position Sensorless Control of Permanent-Magnet Synchronous Motor” IEEE Transaction on Industrial Electronics, Vol. 60, No. 2, 2013

7. C. Mantala, T. Müller, P. Thiemann, R. Strothmann, E. Zhou, “PMSM Sensorless Control with Direct Flux Control for all Speeds”, SLED, USA, 2012

8. T. Müller, C. See, A. Ghani, P. Thiemann, “Simulation o PMSM in Maxwell 3D/Simplorer to improve and optimize Direct Flux Control“, ISIE, UK, Scotland, 2017