AN INTELLIGENT PREDICTIVE CONTROL OF DTC SCHEME OF CONTROL FOR PMSM

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ABSTRACT

This paper presents a sensor-less analytical technique for surface-mounted permanent– magnet synchronous machines by using direct torque control (PDTC). This is proficient to work with at a wide range of speeds. At zero and very low speeds of working conditions, the recognition of the rotor position is carried out by employing test voltage signals in order to identify the machine saliency created by the stator magnetic saturation. Then, the adequate signals that include the corresponding information of the position of the rotor are digitally performed by a quadrature phase-locked-loop tracking observer arrangement. The speed of the machine at middle and high speeds, the rotor angular position is expected with a closed-loop sliding-mode observer technique is regulate on stator flux which uses reconstructed and maintained the required stator voltages and deliberate stator currents. Then, a steady changeover between two algorithms is proposed for coupling both expected values of the position of the rotor. This strategy has no extra hardware and no requirement of special current transducers, or supplementary connections are essential in checking with a conventional standard drive with an encoder. Experimental output results in a wide speed range confirm high performance of the implemented encoder-less PDTC technique.

Index Terms: Permanent-Magnet (PM) Machines Magnetic Anisotropy, Sensor-Less Control, Predictive Control, and Torque Control

I. INTRODUCTION

The direct torque control (DTC) method that was first developed for induction machines (IMs) has also been performed on interior permanent-magnet (PM) synchronous machines with surface-mounted PM synchronous machines (SMPMSMs). The main inspiration to use this control proposal is to demonstrate excellent dynamic response concerning the progress of the electromagnetic torque. Additionally, the DTC can be implemented easily while it does not require a pulse width modulation technique (PWM) neither does it require transformation to the coordinates of the rotating frame. However, when the traditional DTC is proposed in a digital format, it tends to produce large torque ripple, and the operating frequency is changeable due to the stable bandwidth of the hysteresis controller arrangements. In order to conquer these shortcomings, analytical DTC (PDTC) methods for PM-synchronous machines have been implemented.

These analytical algorithms compute the “on” time of two pre-selected active voltage space vectors (AVSVs) produced from a two-level voltage source inverter (VSI), which enhances the torque one step in advance progress; subsequently, the trajectory waveforms of the stator flux is taken into consideration in order to choose the best one, so that the operating frequency can be lesser than that used on the digital accomplishment of the traditional DTC. As an extension of the PDTC technique is proposed in, an encoder-less PDTC arrangement, it has the capable to work with in a wide range of speeds with determined zero speed, is implemented in this project.

A large number of published projects concerning encoder-less control strategies for PM synchronous machines have established that anaccurate encoder-less operation at the speeds are middle and high that can be generated by using the fundamental-wave model arrangement of the machine.

For this cause, voltage controlled model, Kalman filter, or position observers have been included, and freshly, they have been proposed even on PDTC technique but without the ability to function at very low and zero speeds operations, since fundamental-wave representations have their restrictions at zero stator frequency.

The produced voltage is equals zero, which causes the machine is an unobservable condition. Thus, as it has been frequently verified, in these cases of modes, the assessment of the rotor position can be gladly achieved by addition of high-frequency (HF) carrier signal arrangements, by programming customized PWMs, by maintaining associations of the machine in order to get the third harmonic constituent or by monitoring the air-gap flux, it called indirect flux recognition by online reactance measurement (INFORM). Currently, these techniques have a obvious inclination on field-oriented proscribed machines, because the development is moderately simple in this control arrangement. In difference, injection of High Frequency carrier signals on DTC or PDTC approaches is not appropriate encoder-less approach, since the separate output values from the hysteresis compensators or operating tables are changed directly to firing signals; furthermore, the PDTC design does not having a PWM, which raises the complexity of injecting HF carrier signals, or the INFORM approach. Consequently, in this project, the technique of employing test voltage signals (TVSs) is implemented.

This recognition strategy has technical affinities to the INFORM approach, but they are in their basic knowledge distant different; in addition, the offset that delivers the adequate rotor position signals not available with different control strategies as the ones projected for the INFORM technique arrangement.

On the other hand, the recognition methodology presented and was testes and verified on a PDTC scheme proposal for synchronous reluctance machines (SynRMs), and there is only work at very low and zero speeds has been delivered. In this paper, the implemented encoder-less PDTC method for SMPMSMs is experimentally tested and verified in a very wide range of speed.

II. MODEL OF THE MACHINE

The SMPMSM is normally careful to have a symmetrical rotor, except a small amount of geometrical irregularity is usually present owing to the semi-insertion values of the magnets into the rotor iron.

As a consequence, the direct axis inductance *LD* is lower than the inductance maintained in quadrature axis *LQ* generating the stator inductance to be work with the rotor position; consequently, allowing for a three-phase SMPMSM, the stator self-inductances are given as

$$I_U = I_o' - \Delta l \cos 2\gamma$$

$$I_V = I_o' - \Delta l \cos(2\gamma + \frac{2\pi}{3})$$

$$I_W = I_o' - \Delta l \cos(2\gamma - \frac{2\pi}{3})$$

Then the Saturation-auditioned saliencies are not constant to the rotor and will be pretentious by load

$$I_o' = \frac{1}{3}[l_q\,(M) + l_d$$

$$\Delta l = \frac{1}{3}[l_q\ (M) + l_d$$

The implemented sensor-less PDTC approach has been designed on stator ($\alpha-\beta$) reference frame considerations. In this reference structure, the SMPMSM voltage equations can be given

$$\text{as}\mu_\alpha = Ri_\alpha + \frac{d}{dt}[L_o - L_1 \cos 2\gamma]i_\alpha - \frac{d}{dt}[L_1 \sin 2\gamma]i_\beta - \omega\psi\ \text{PMsin}\quad \gamma$$

$$\mu_\beta = Ri_\beta + \frac{d}{dt}[L_o - L_1 \cos 2\gamma]i_\beta - \frac{d}{dt}[L_1 \sin 2\gamma]i_\alpha - \omega\psi\ \text{PMsin}\quad \gamma$$

Here$L0$ = (3⁄2) l_ 0 and $L1$ = (3⁄2) Δl.

The electromagnetic torque is determined by using below

$$\text{M}=\frac{3}{2}p(\psi_a\ i_\beta - \psi_b\ Ri_\alpha$$

And the mechanical equation is represented as

$$\text{J}=\frac{d}{dt}\Omega = M - M_L\ \Omega\ = \frac{\omega}{P} = \frac{1}{P}\frac{d}{dt}\gamma$$

III.PDTC

3.1 Torque Control

The PDTC algorithm determines the operating conditions immediately of two pre-selected AVSVs technique, which are developed from a two-level Voltage Source Inverter in order to achieve the require torque demand one step in progress.

The VSI produces six AVSVs definite as $u1$, $u6$ and two zero voltage space vectors (ZVSVs) specified as $u0$ and $u7$ (see Fig. 1). As an instance, by pretentious that the stator flux space vector Ψ is positioned in sector 1 of the $\alpha-\beta$ scheme plane (sect. 1, Fig. 1), for positive revolution, $u2$ is preferred in order to enhance its amplitude. Equally, the reduced value of Ψ is produced by offering$u3$. In standard working approach, one AVSP and one ZVSV are functional during the control cycle operation (see Fig. 2). In dynamic conditions, it is not operated from the AVSP to ZVSP, and a single state remains maintained the whole control cycle operation process.

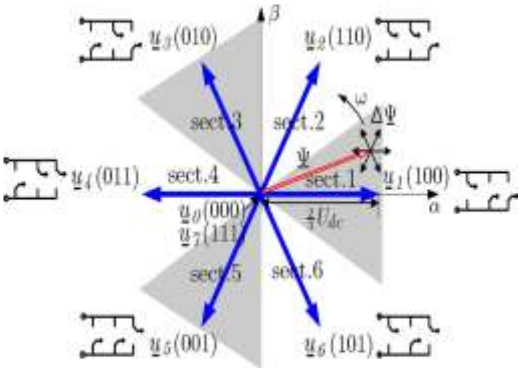


Fig. 1. Six avsvs and Two Zvsvs Generated by The Eight Possible Switching States of A Two-Level VSI, The Six Sectors, and Flux Variation.

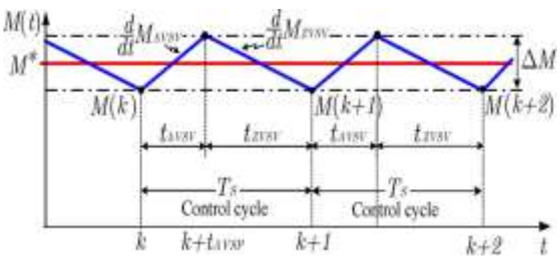


Fig. 2Torque Performance of The PDTC (Steady State).

By estimating a linear shape of the torque through the control operated cycle *TS*, in which an AVSP is useful during the time *T*avsp and a zvsp is employed during the remaining control cycle process, the amplitude of the torque at (*k* + 2) can be given asas

$$M(K+2)=M(K+1)\frac{d}{dt}M_{AVSV}(K+1).t_{AVSV}(K+1)+\frac{d}{dt}M_{ZVSV}(K+1).$$

$$T_S - t_{AVSV}(K+1) - M^* - \Delta M(K+1)$$

Recording to the same circuit, the virtual hysteresis loop width Δ*M* of the torque at (*k* + 1) can be deliberated as

$$\Delta M(K+1)=\frac{\frac{d}{dt}M_{AVSV}(K+1).M_{ZVSV}(K+1)}{\frac{d}{dt}M_{AVSV}(K+1)-M_{ZVSV}(K+1)}T_S$$

The analytical value of the torque derivatives function *dM*AVSV*/dt*and *dM*ZVSV*/dt*is calculated by (6) to develop the *T*avsp yields.

$$t_{AVSV}(K+1)=\frac{M^* - M(K+1) - M^* - \frac{1}{2}\Delta M(K+1) - \frac{d}{dt}M_{ZVSV}(K+1).T_S}{\frac{d}{dt}M_{AVSV}(K+1) - \frac{d}{dt}M_{ZVSV}(K+1).T_S}$$

And the “off” time can be determined as given below

$$T_{ZVSV} = T_S - t_{AVSV}(K+1)$$

3.2 Flux Control

The magnitude of the stator flux must be analyzed for the two pre-selected AVSVs considerations in order to select the most excellent one, so that the AVSV that tends to less flux divergence (from its required referenced value) at the end of the subsequently control cycle will be employed to the machine. The alternation of the flux magnitude between no-load and required rated-load criteria’s is not huge; but, its correction is used to maintain the actual torque increases the efficiency and reliability of the system.

IV. ESTIMATION OF THE ROTOR POSITION AT LOW SPEED

4.1 Algorithm for Low Speeds

This method to approximate the rotor angular position low speed of operation implemented in this operation is comparable to the developed one. But with some manipulations are used, because the SMPMSM generates lower saliency ratio over than a SynRMs.

It includes the addition of an AVSV, which performs like as TVS. This TVS is directly mitigated by an equal and different opposite voltage signal considerations (OVS) in order to neutralize current harmonics.

In this mode, one TVS and its equivalent OVS are employed in each three control cycle operations with phase sequence (*u*1, *u*4), (*u*3, *u*6), and (*u*5, *u*2) within the standard commutation procedure for PDTC, whereas a ZVSV is functional to the machine as it is illustrated in Fig. 3.

Since a linear analogy of the rotor position can be presented in each three consecutive control cycles, it is not essential to introduce the TVS in each operating cycle. Conversely, when the TVS is employed, times Ttvs and *T*ovs throughout which the TVS and the OVS are employed and they must be differentiate from the *TS* in order to get a correct forecast of the machine variable parameters.

If the AVSV *u*1(100) is employed to the machine throughout a very small time, then the stator resistance result can be insignificant, and since the research analysis is controlled at low speeds, the back EMF can also be reduced. Consequently, after the equivalent calculations, the below arrangement is produced

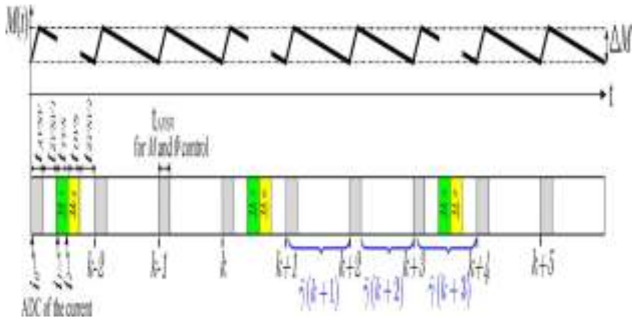
$$\frac{d}{dt}I_{U,U\_1} = \frac{1}{g}[2 \quad - \frac{1}{l_o'}\Delta l \cos 2\gamma]$$

$$-\frac{d}{dt}I_{W,U\_1} = \frac{1}{g}[1 + \frac{1}{I_o'}\Delta l \cos(2\gamma - \frac{2\pi}{3})]$$

$$-\frac{d}{dt}I_{V,U\_1} = \frac{1}{g}[1 + \frac{1}{I_o'}\Delta l \cos(2\gamma + \frac{2\pi}{3})]$$

Individually$g = 3I_o'[1 - (\frac{\Delta l}{I_o'})2] / U_{dc}$

*U*DC denotes the voltage of the dc link. The figure of (10) gives the significant a rotor position signal space vector consideration p_*r*as$P_r = \frac{3}{2}[P_U + aP_V + a2P_W] = P_\alpha + jP_\beta$



Here *a* = *ej* (2/3) *π*. Phase component parameters *pU*, *pV*, and *pW*of the *p_ r* as defined in (12) are introduced in (10) to obtain

$$P_{U,\_U1} = -g\frac{d}{dt}I_{U,U\_1} + 2$$

$$P_{V,\_U1} = -g\frac{d}{dt}I_{W,U\_1} - 1$$

$$P_{W,\_U1} = -g\frac{d}{dt}I_{V,U\_1} - 1$$

The phase component devices for the two TVS *u*3(010) and *u*5(001) can be determined by a similar process explained earlier. The offsets that show in (13) are mitigated. A superscript "_" has been specified to the adequate orthogonal parameters *p_ α* and *p_ β*, in order to point out that these signals are not nevertheless good adequate to be used on an accurate sensor-less operation.

4.2 Acquisition of Rotor Position Signals

The current derivative equations are digitally estimated by considering two successive current measurements and determining the slope. The current measurement devices are considered in two strategic required points; the first sampled stator current value is considered as 4 *μ*s after selection of the TVS in order to permit for some time up to the HF components vanished. The second sampled verification value is taken 3 *μ*s before the TVS is switched "off" (see Fig. 4).

To accomplish the current measurement in accurate at any instant of time, a field-programmable gate array (FPGA) is included as an interrupter block and where an "exceptional" modulator with the competence to generate five singular operating states at each control cycle has been developed.

The first operating state is for analytical flux and torque control (*T*avsp). Then, the second operating state employs a ZVSP1.When a TVS is injected an extra required time, then, the modulator produces three operating states much over than that of TVS, OVS, and a second ZVSP2 .These final three operating states are only necessary in each three control modes of operations, and when they are not important, then, switching times *T*tvs, *T*ovs, and *t*ZVSP2 are set equal to zero, and consequently, these working states can be concealed.

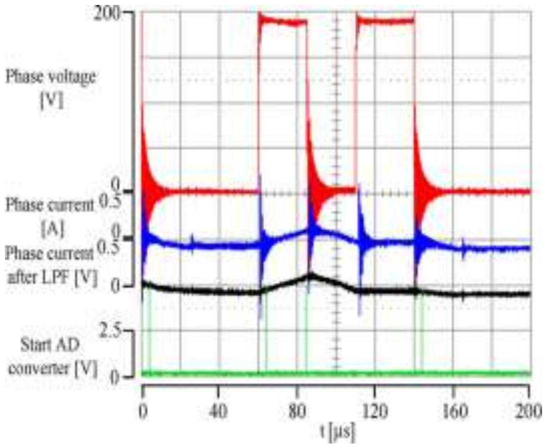


Fig. 4. Experimental Output Waveforms. (From Top) Phase Voltage, Phase Current, Phase Current After LPF, and Signal To Start The Analog-To-Digital Converter.

The operating state of the first ZVSP1 ($u0$ or $u7$) based on the preceding AVSP, although the second ZVSP2 is position as $u7$ in order to continue the sampling frequency is very less. The short period of time throughout which the TVS is induced has been set taking into selection the following considerations are taken into account: First, in order to reduce low current harmonics, it is attractive that the TVS and the OVS remains maintain a minimum of time (usually between 5 and 50 μs) which is based on the length and on the quantity of the inductances of the synchronous machine. Second, the width of the TVS must be adequately long in order to achieve enough position-based signals. In this significant case, the time period of the TVS was theoretically manipulates to *T*tvs = 25 μs. Conversely, since hardware requirements some clock cycles to position and to carry out the conversion technique, it is done after 2 μs more. As an output result, the time $t2-1$ between the two switching standards of the current is only of $t2-1$ = 17 μs.

4.3 Signal Conditioning

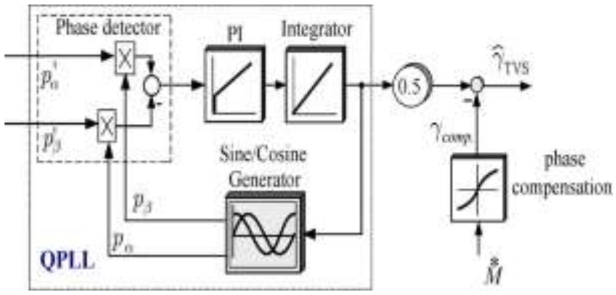


Fig. 5. Block Diagram of the Digital Signal Conditioning.

As it has been established in [36], a suitable signal controlling can be proficient well by use of a quadrature phase locked loop (QPLL) technique [see Fig. 5]. The PI controller parameters are preferred by assuming a negotiation between the required bandwidth and the required dynamic of the system are widely implemented.

Conversely, in this project, since an SMPMSM is preferred, the TVS injection method produces a saliency position only; therefore, a phase correction have to be introduced on the QPLL to restrain the shift of the saturation saliency owing to load variations, and the compensation angle is represents as γcomp. It was experimentally produced through a sensored self-commissioning procedure.

The correction technique of the saturation phase shift generates precise assessment of the rotor angular position, and for a correct accomplishment of the PDTC, the calculation of the predictable angular position is essential, and it is expressed as

$$\gamma^{\wedge}_{TVS}(K+1) = 3\gamma^{\wedge}(K) - 3\gamma^{\wedge}(K-1) + 3\gamma^{\wedge}(K-2)$$

A linear deterioration of the order 100 has been proposed in order to neutralize even more the error on the predictable angular arrangement of the rotor.

V. CONCLUSION

A digitally proposed wide-speed-range sensor-less procedure to approximation the rotor angular position a analytical-torque-monitored SMPMSM has been presented. The recognition of rotor arrangement at very low speeds of process is depended on the magnetic rotor anisotropy that the machine produces; next, a hybrid algorithm is selected to reach sensor-less action with a wide range of speeds with zero speed.

The implemented method to approximation the rotor position does not require special current transducers or supplementary connections in association with a regular drive with an encoder.

Negative belongings due to saturation procedure have been productively minimized, so that a constant sensor-less operation even in transients is experimentally tested and verified. The error of the predictable arrangement was within a assortment of 0–5 electrical degrees.

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