Real time dq0 analysis of FOC systems

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Abstract— **Currently designers measure direct-quadrature-zero (dq0) with custom built embedded control software and additional hardware using FPGA for Field Oriented Control (FOC). This is a complex and expensive task. It requires access to probing points on the controller board which can be challenging [3].**
This paper talks about how motor designers can measure dq0 components and resultant drive vector for sensor and sensorless systems. Combined Clarke and Park transforms are applied to correlate with the controller circuit behavior. Designers can visualize optimal torque generated for the given electrical input using D and Q components. This also gives an indication of the efficiency of the motor. With oscilloscope's cursors feature, dq0 can be seen as a rotating frame at the sample rate.
For sensorless systems, angle is computed precisely using filtered electrical signals. The dq0 signals are used to refine the controller algorithms. Phasor diagram representation shows stator and rotor vectors simultaneously.

I. INTRODUCTION

The behavior of three-phase AC and DC machines can be modelled by the rotating voltage and current equations as below, where R, S and T are three phase AC signals, Vg is the corresponding gain and 'ω' is 2 * π * f, where 'f' is the nominal frequency [11].

$$V_R = Vg * \cos(\omega t) \quad (1)$$
$$V_S = Vg * \cos(\omega t - 2*\pi/3) \quad (2)$$
$$V_T = Vg * \cos(\omega t - 4\pi*/3) \quad (3)$$

The R-S-T AC signals are 120 degrees out of phase. dq0 rotates the reference frames to convert AC time-varying signals to DC time-invariant signals [9]. This allows simplified calculations on the DC signals before performing the inverse transform to recover the actual three-phase AC results [12]. 3-Phase R-S-T waveforms are converted to dq0 waveforms using the combined Clarke and Park transform [9]. For R-phase to d-axis alignment the following matrix formula is applied [10,13].

$$\begin{bmatrix} d(t) \\ q(t) \\ 0(t) \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ \sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} R(t) \\ s(t) \\ T(t) \end{bmatrix} \quad (4)$$

Where R, S and T can be taken as $I_{R,S,T}(t)$ or $V_{RN,SN,TN}(t)$. t is sample time and starts from 0 to the acquired duration. θ is the electrical angle determined from Quadrature Encoder Interface (QEI) output of the motor.
dq0 is the rotating frame of reference, which represents the system with respect to the position of rotor. At any point of time, d axis is along the south to north axis of the rotor and represents the rotor flux direction. q axis is 90 degrees ahead of d axis. Since perpendicular magnetic flux from stator and rotor produce torque, it is desirable to have stator and rotor flux at 90 degrees angle, i.e., it is desirable to have the stator flux, or resultant stator current along the q axis. d represents rotor flux axis and q represents torque axis. In Field Oriented Control (FOC), the goal is to control the d-q values to achieve the requested torque. By controlling d and q independently, it's possible to achieve Maximum Torque Per Ampere ratio (MPTA). [1,7]

II. FIELD ORIENTED CONTROL

FOC is the recommended control technique for the motors today compared to trapezoidal or sinusoidal commutation methods. In this approach, the 3-Phase R-S-T waveforms are converted to dq0. The Clarke transform converts the three-phase axis system to 2 axis system of α and β. Park transform converts the stationary α and β axes to the rotating d and q axes [1]. This gives the resultant current as a sum of two DC waveforms, called as d and q components. q component shows the portion of current translating into torque. So, the part of the current along the d-axis is not translated into usable mechanical energy.
In the control block the d and q components are compared with the desired d ref and q ref components as shown in Fig. 1. d ref value is zero for a permanent magnet rotor and q ref is the desired torque from the motor. The error value is set to the PI controllers as shown in Fig. 1. This will adjust the motor current so that the motor operates in steady state for a varying load.
The output of the PI controllers with the Inverse Park transform are given as inputs to the Space Vector PWM (SVPWM) block to get the 3-Phase PWM signals which are fed to the motor [2,3]. The SVM block has the inverter sub section which consists of 6 half bridge MOSFETS used to switch between 8 different sectors to generate the 3-Phase PWM signals. The reference vector magnitude (Vref), the resultant of α and β is used for modulating the inverter output. The objective of SVM technique is to generate 3-Phase PWM signals whose resultant is equivalent to reference voltage vector Vref [4,5].

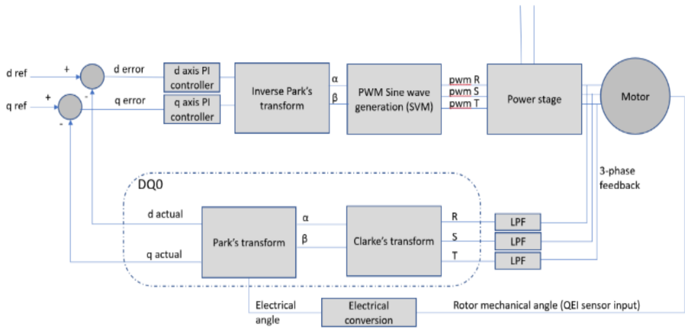

Fig. 1. Field Oriented Control system (FOC) for BLDC motors

III. ENCODER THETA INTEGRATION

Rotor angular position from sensor data that is using QEI encoder with index pulse output is integrated with the dq0 measurement. This mechanical angle is converted to electrical angle θ using Pulses Per Rotation (PPR) as in (5). Index pulse (Z) rise edge is considered as 0-degree position of the rotor magnet, where d-axis gets aligned with R-axis. The incremental angle (5) added to offset angle (phase difference between Z and the reference voltage or current waveform) will be used as θ in the matrix equation as in (4).

Incremental Angle(theta) in degrees is,

$$angle = \frac{360}{(4*PPR)} \tag{5}$$

The resultant vector is computed as,

$$R(t) = \sqrt{d(t)^2 + q(t)^2} \tag{6}$$

This resultant vector as shown in Fig. 2 is equivalent to Vref in the FOC systems.

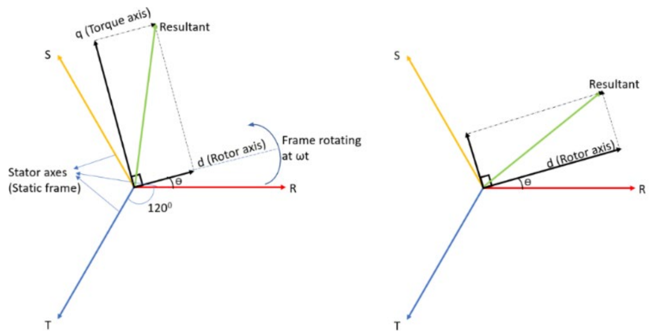

Fig. 2a. Motor with high torque (q >> d)
Fig. 2b. Motor with low torque (d > q)

Low value of q compared to d as shown in Fig. 2b can also happen when the encoder position is not aligned precisely with flux of phase A. Oscilloscope software provides a provision to enter electrical offset angle to compensate the offset from sensor mounting or filter application. The software low pass filters (LPF) are applied on 3-Phase waveforms to mitigate the effects of high frequency distortion, voltage spikes, high frequency ripple from switching converters and EMI pickup in the signal path. Fig. 3 shows the phasor diagram with and without LPF application. The offset angle and LPF can be used for sensorless system to get dq frame properly aligned.

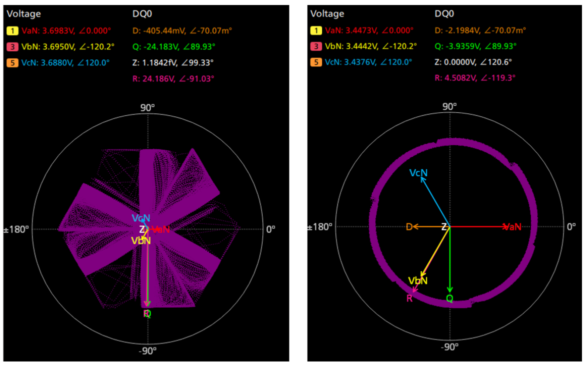

Fig. 3a. Phasor diagram without filtering
Fig. 3b. Phasor diagram with filtering

The software computes the resultant drive vector (6), by computing the hypotenuse vector from d and q as shown in Fig. 4. This helps to know what drive current is and identify if there are any places where waveform is not ideal. R starts at 0 degrees and will be aligned with QEI index Z pulse. The resultant circle in purple color as shown in Fig. 4 indicates motor's rotation stability and shows distortions if any. This gets the dynamic drive profile and helps to correlate with Vref in the d-q plane [4]. Note that D, Q and Z vectors are instantaneous, and represent the time point where oscilloscope cursor A is placed.

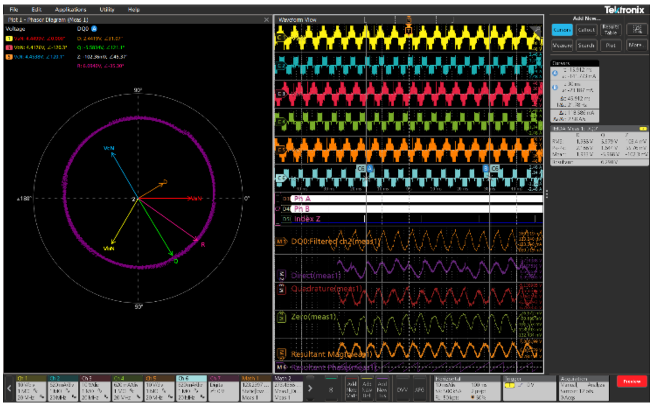

Fig. 4. Resultant Drive Plot and the dq0 transformed waveforms

IV. CONCLUSIONS AND FUTURE WORK

The scope based dq0 plot helps to relate how well the motor is spinning by looking at the graphical Resultant plot. Motor designers can observe the uniformness of the motor rotation, ripple and harmonic components which are essential in applications like electric vehicles [6]. The higher value of q vector compared to the d vector symbolizes higher value of torque. Since R-S-T AC waveforms are converted to dq0 DC waveforms, it is easier to analyze the motor behavior. Simultaneous representation of R-S-T and dq0 values help designers correlate to resultant value which can be similar to Vref which is fed to the SVM block.

In future, the constellation diagram of the SVM switching states can be shown and calculation of theta can be extended using resolver, sine-cosine encoder, and hall sensor.

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