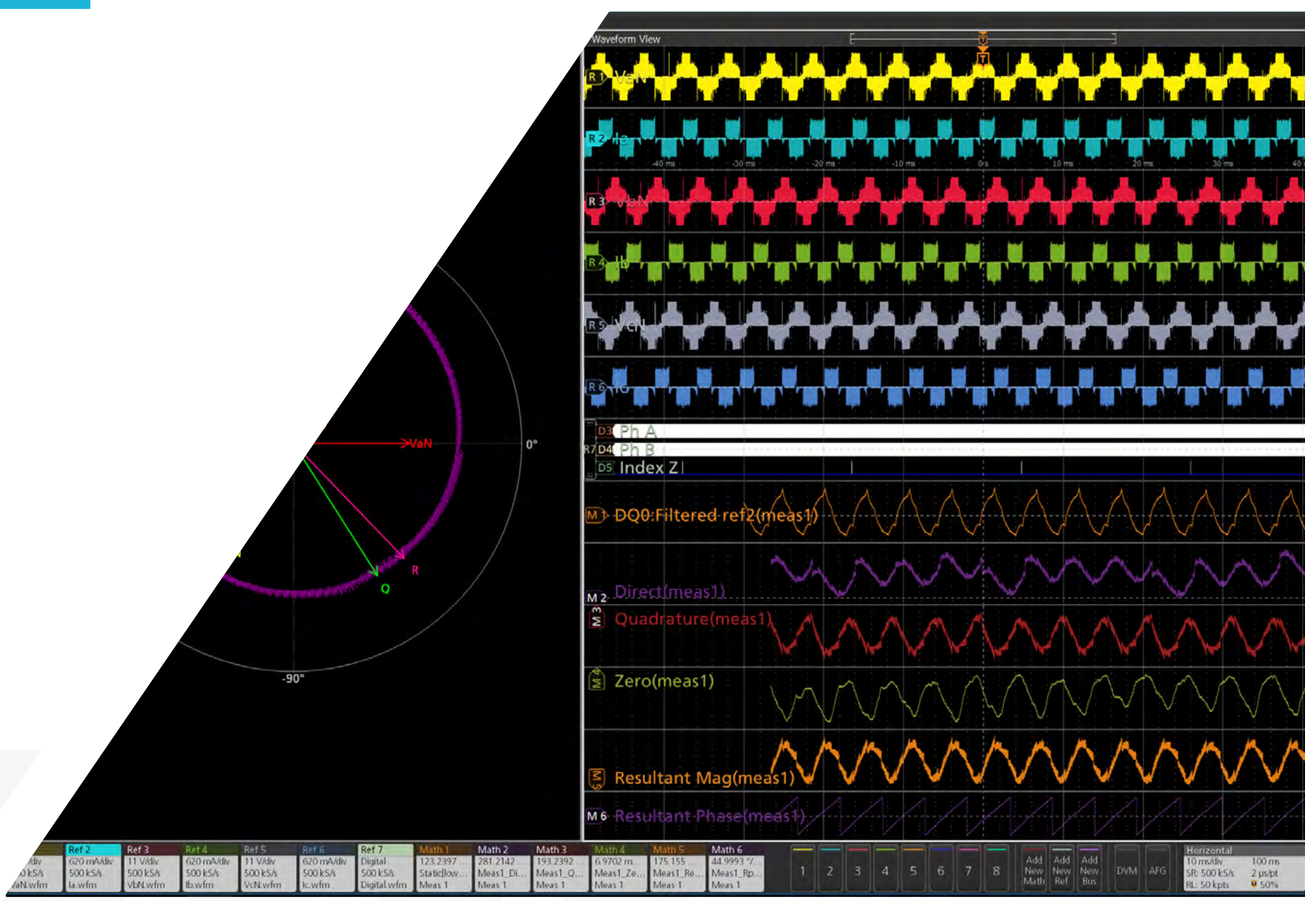
DQ0 Analysis of Motor Control Systems Using an Oscilloscope

WHITE PAPER



Direct quadrature zero (dq0) parameters are important variables in field-oriented control algorithms. These key parameters typically exist deep within the control systems, but during design optimization and debugging it is advantageous to make these parameters available for measurement in real time, and to correlate their values with other measurements such as torque output.

Previously, motor drive and inverter designers who needed to correlate dq0 parameters with torque used custom built software and hardware to measure these parameters. This custom approach introduces significant complexity and expense.

Tektronix has developed an alternative method for measuring dq0 components and the resultant drive vector for rotary sensor-based and sensorless systems. This technique is supported as an option in the Inverters, Motors and Drivers Analysis package (Option IMDA-DQ0) on 5 or 6 Series MSO oscilloscopes. It uses signal processing to compute d, q and 0 control parameters based on real-time measurements of drive system outputs. This enables motor designers to visualize the optimal torque generated for a given electrical input.

Vector Drives / Field-Oriented Control

Advanced drives for synchronous and AC induction motors usually employ vector drive techniques. Vector drives provide smoother operation, quicker acceleration, and superior torque control than simpler scalar drives. Vector drives use field-oriented control (FOC) and while they are versatile and efficient, they are also significantly more complex than scalar drives. **Figure 1** shows the PWM output waveforms generatred by a field-oriented control system.

A simplified block diagram of a field-oriented control system is shown in **Figure 2**. Within the control system, Clarke and Park transformations are used to convert the 3-phase voltages being applied to a motor to orthogonal D and Q vectors. These simplified vectors can easily be scaled and integrated to maintain a desired speed and torque. Reverse transforms may then be used to create the drive signals for pulse width modulation within the inverter.

Note that the control system also measures the position of the rotor. This may be done by using sensors such as hall sensors, resolvers, or a quadrature encoder interface

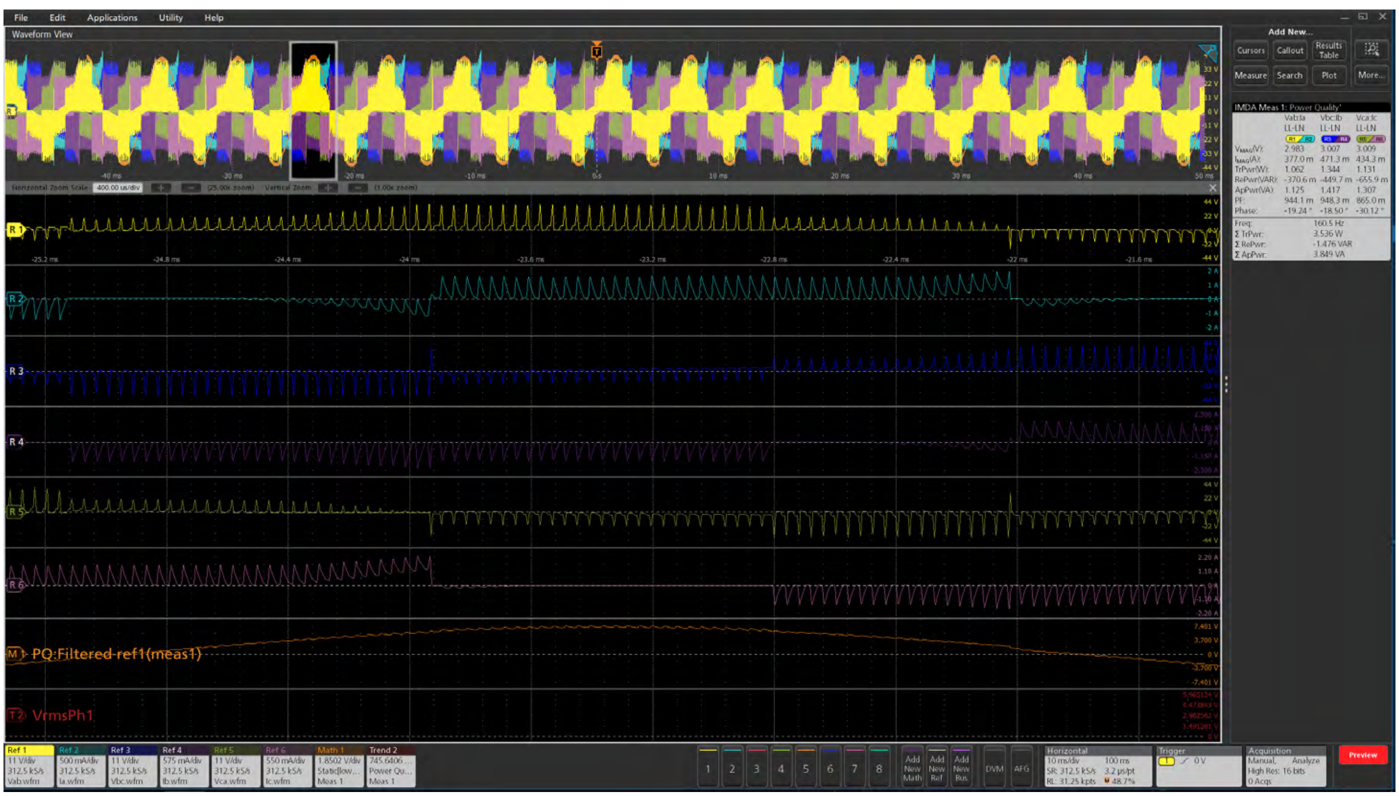


Figure 1. Vector or field-oriented control uses complex PWM waveforms.

(QEI). Sensorless systems are also used in which the control system uses the back-emf of the motor to determine rotor position.

As **Figure 1** suggests, the D and Q values typically reside deep within a digital signal processing block, such as an FPGA, and may not be available for direct measurement. The IMDA-DQO software can expose these key parameters based on the sampled 3-phase output voltage or current, along with the angular position of the rotor. This allows engineers to see the effects of control system adjustments and view signal relationships quickly and easily.

DQO Measurement Theory

As noted above, the IMDA-DQO software, running on an oscilloscope uses sampled voltage or current and angular position information to compute d, q and 0 in real time. This section explains the theory behind these measurements.

Three-phase AC and DC machines can be modelled by rotating voltage and current equations. Equations 1 through 3 show V_R, V_S, and V_T as three-phase voltage functions of time, V_G is the corresponding gain, and 'ω' is 2 * π * f, where 'f' is the nominal frequency.

$$v_R = v_G \cos(\omega t) \qquad \text{Equation 1}$$

$$v_s = v_G \cos\left(\omega t - \frac{2\pi}{3}\right) \qquad \text{Equation 2}$$

$$v_T = v_G \cos\left(\omega t - \frac{4\pi}{3}\right) \qquad \text{Equation 3}$$

When properly connected, the oscilloscope can measure each of these instantaneous voltage values throughout an acquisition – typically on the order of 10 complete cycles, depending on the sample rate and available record length. Low pass filters may be applied to mitigate the effects of high-frequency distortion, voltage spikes, switching noise and EMI.

The oscilloscope can also measure the angular position of the rotor, using the output of a Hall effect transducer, QEI or resolver.

Given the voltage or current vectors, along with rotor angle, one can find d, q and 0. For conversion from voltage or current vectors to d-axis alignment the matrix equation (Equation 4) can be applied to convert from the 3-phase vector to a dq0 vector.

$$\begin{pmatrix} d(t) \\ q(t) \\ 0(t) \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos(\Theta) & \cos\left(\Theta - \frac{2\pi}{3}\right) & \cos\left(\Theta + \frac{2\pi}{3}\right) \\ \sin(\Theta) & -\sin\left(\Theta - \frac{2\pi}{3}\right) & -\sin\left(\Theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} R(t) \\ S(t) \\ T(t) \end{pmatrix} \qquad \text{Equation 4}$$

- *R, S,* and *T* can represent either $I_{R,S,T}(t)$ or $V_{RN,SN,TN}(t)$.
- *t* is the sample time and goes from 0 to the acquired duration.
- θ is the electrical angle determined from Hall effect sensor, Quadrature Encoder Interface (QEI) or resolver on the output of the motor. An offset angle relative to the reference voltage or current may be used for sensorless systems.
- The resulting DQ0 is the rotating frame of reference, which represents the system with respect to the position of the rotor.

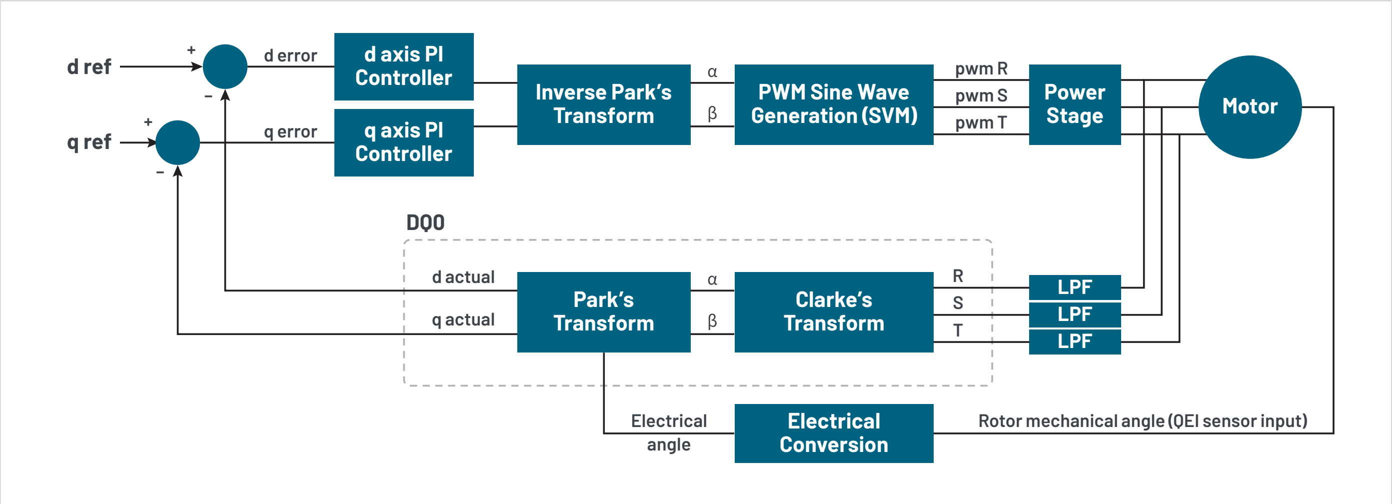


Figure 2. A simplified block diagram of a field-oriented control system showing how d and q are used to simplify the feedback in a 3-phase PWM motor drive.

Making Oscilloscope Measurements

Within the Inverters, Motors and Drives Analysis package for the 5 and 6 Series B MSOs, key electrical measurements are grouped under Electrical Analysis. Within the Electrical Analysis group is the Tektronix patented Direct Quadrature Zero (DQ0) measurement.

Figure 3 shows an example of the source setup for DQ0 measurements. In addition to selecting the sources and wiring, one can also specify a low pass filter that can be applied to all sources, or only to the edge qualifier. As noted above, this is useful for reducing noise due to EMI pickup and switching noise.

In this example, a QEI encoder is used. For sensorless systems, it is possible to use the back-emf method with an offset angle and filtered electrical signals.

In field-oriented control, the goal is to control the D and Q values to achieve the requested torque. By controlling D and Q independently, one can achieve the Maximum Torque Per Ampere ratio (MTPA). **Figure 4** shows a phasor diagram available on the oscilloscope, with D and Q vectors overlaid on the 3-phase voltage vectors.

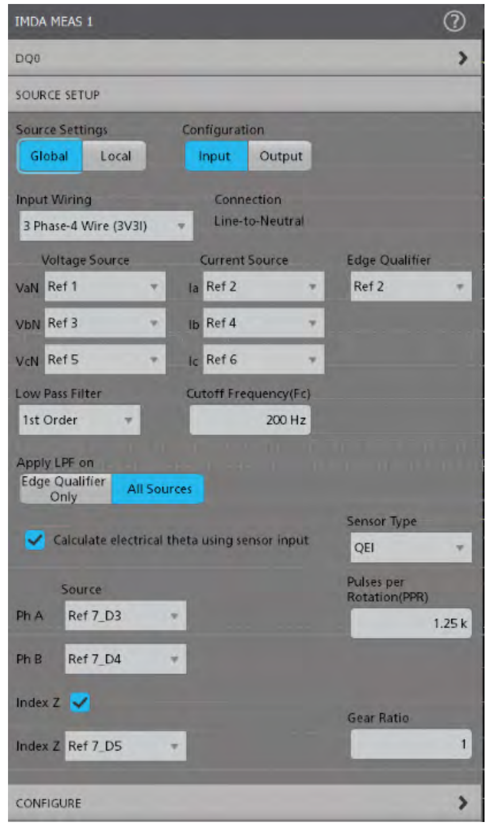


Figure 3. Configuring the oscilloscope for DQ0 measurements on a system using a quadrature encoder interface (QEI).

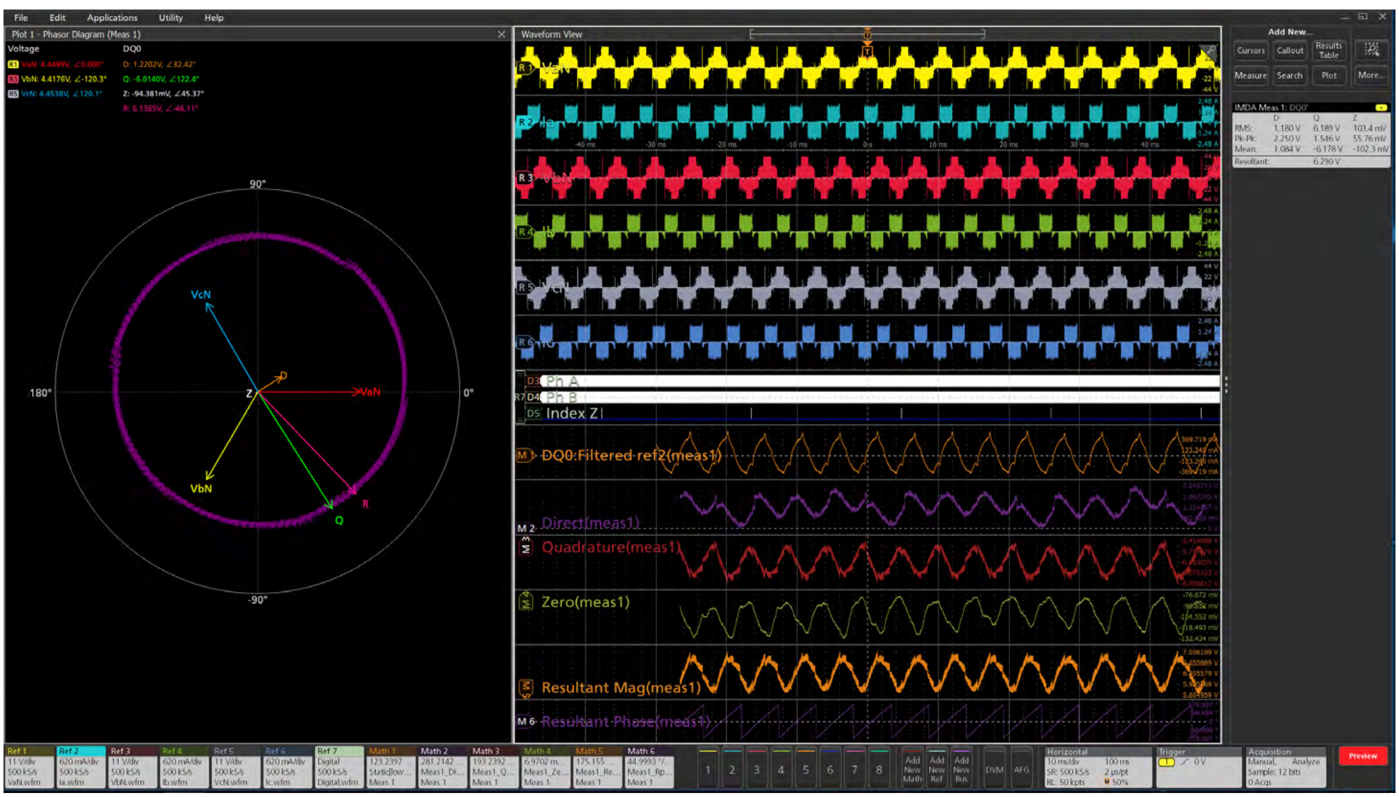


Figure 4. DQ0 Phasor plot showing D vector, Q vector and the resultant vector (R) with motor speed and direction feedback provided by a quadrature encoder sensor.

At any point in time, the d-axis is along the south to north axis of the rotor and represents the rotor flux direction. The q-axis is 90 degrees ahead of the d-axis. D represents the rotor flux axis and Q represents the torque axis. Since perpendicular magnetic flux from the stator and rotor produce torque, it is desirable to have the stator and rotor flux at a 90 degree angle relative to one another. That is, it is desirable to have the stator flux or resultant stator current along the q-axis.

Traditionally, D and Q have been viewed as constant values, whereas with this approach, one can visualize the ripple on D and Q, using the time domain math waveforms (as shown in **Figure 4**). This is another indicator of the input stability.

In addition to D and Q, the analysis software also shows the resultant vector (R). R is calculated by computing the hypotenuse of the D and Q vectors at each sample point of D and Q. The R vector starts at 0 degrees. In this example, this is determined by the QEI index pulse (Z). The incremental angle is computed by the QEI based on the encoder's pulses per revolution (PPR). By observing the R vector rotation one can see whether the control system is driving the motor smoothly. One can also observe the number of commutations — note the six distortion points in the R vector plot in **Figure 4**, corresponding to six commutation steps.

Time plots of D, Q, 0 and R are shown in the lower right of **Figure 4**. Using the oscilloscope's cursors feature, these values can be seen simultaneously as measurements in time and as a rotating frame on the phasor diagram.

Conclusion

D, Q, 0, and R are key variables in field-oriented control systems that are common in vector motor drives. Even so, they can be difficult to observe in real time. The new technique described in this paper, allows engineers to expose these variables and correlate them with electrical and mechanical parameters on their oscilloscope. This provides valuable insight as a drive system or inverter is being brought up and optimized.

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