
1. Introduction

This experiment helps you to study and compare the performance of a three-phase induction motor driven from a voltage source variable frequency supply ($V/f$) and with a rotor flux oriented controllers (RFOC). With $V/f$ control, the voltage to frequency ratio of the supply is kept nearly constant. This method is based on the steady-state equivalent circuit of the motor. With RFOC, three-phase currents supplied to the motor are first resolved into two quadrature current sources which independently regulate the torque and rotor flux linkage of the motor. The quadrature currents, $i_d$ and $i_q$, are expressed in the synchronously rotating reference frame. The particular topics of interest in this experiment are the control characteristics for torque and flux of the motor under RFOC and comparison of the dynamic performance of the drive supplied from the $V/f$ supply.

2. Brief Theory

$V/f$ control

The steady-state torque-speed characteristic of an induction motor can be readily examined with the help of the per phase equivalent circuit indicated in figure 1. The supply voltage to each phase of the motor is sinusoidal at a frequency $f_1$ which is related to the base (50 Hz) frequency by $\lambda f_0$ so that

$$\lambda = \frac{f_1}{f_0}$$

At frequency $f_1$, the circuit reactances are: $\lambda X_1$, $\lambda X_2$, and $\lambda X_m$ - which are the stator, rotor and magnetizing reactances, all referred to the stator at the stator frequency $f_1$.

The voltage that sets up the air-gap flux $\phi$ across the airgap, the airgap voltage, is given by
\[ e_t = N \frac{d\phi}{dt} \] ............................................................. (2)

or \[ E_t = 4.44K_sN_1\phi_mf_1 \] ........................................ (3)

Here the flux waveform has been assumed to be co-sinusoidal with a peak magnitude \( \phi_m \), \( K_s \) is the winding factor and \( N_1 \) is the number of stator turns/phase.

Note that the airgap voltage is the supply voltage/phase if the voltage drop across the series stator impedance is neglected.

It follows from above that the airgap flux remains approximately constant if the ratio of input voltage \( V_1 \) to input frequency \( f_1 \) ie \( V_1/f_1 \) is kept constant.

From the equivalent circuit,

\[ E_t = I_2 \left[ \frac{R_2}{s} + j\lambda X_2 \right] \] ........................................................  (4)

where slip, \( s = \frac{\omega_1 - \omega_m}{\omega_1} \) ................................................................. (5)

Thus \[ E_{ag} = I_2 \left[ \frac{R_2 f_1}{f_1 - f_r} + j \frac{f_1}{f_0} X_2 \right] \] .................................................. (6)

or \[ \phi_m \propto I_2 \left[ \frac{R_2}{f_1 - f_r} + j2\pi L_2 \right] \] .................................................. (7)

where \( f_r \) is the rotor speed in electrical cycles/sec and \( L_2 \) is the rotor inductance referred to stator.

Since the airgap flux is proportional to \( E_t/f_1 \), it follows that if \( \phi_m \) is kept constant, a given value of \( I_2 \) always occurs at the same slip frequency \( f_1 - f_r \). In other words if

\[ f_1' - f_r' = f_1'' - f_r'' = f_1''' - f_r''' = \cdots \]

then \( I_2 \) will be the same all cases, if \( \phi_m \) is kept constant.

It can also be shown that the developed torque of a 3-phase induction motor is given by

\[ T = \frac{3pl^2R_2}{2\pi(f_1 - f_r)} \] Nm .................................................. (8)

where \( p \) is the number of pole pairs.

Thus, under the condition of constant flux, a given torque \( T \) also occurs at a given slip \( f_1 - f_r \) frequency. The required terminal voltage to keep the flux \( \phi_m \) constant is obtained as
\[ V_1 = E_1 + I_1 R_1 + j \lambda X_1 I_1 \] .................................................... (9)

\[ = K \phi_m f_1 + I_1 R_1 + j 2 \pi f_1 L_1 I_1 \] .............................................. (10)

If \( R_1 \) and \( L_1 \) could be ignored, the required relationship would be \( V_1 \) proportional to \( f_1 \) as indicated in Figure 3(b). Note that the relative value of the second term is seen to increase in comparison with \( K \phi_m f_1 \) at low frequencies for which the first term is small. This is usually compensated at low frequencies as indicated in figure 3(a) and (b) for the rated current condition. This implies however that operation at light load at low frequency may cause over-fluxing of the machine and hence overheating.

It can also be shown that maximum torque occurs at \( \frac{R_2}{s} = \lambda X_2 \) and that

\[ T_{max} = \frac{3 p (K \phi_m)^2 f_0}{4 \pi X_2} \] ......................................................... (11)
which is independent of \( f_1 \). The family of \( T-\omega \) curves for various \( f_1 \) under constant flux would then look like the graphs of figure 4.

![Graph of \( T-\omega \) curves](image)

**Figure 4**

It can be observed from above analysis that:

A. the required supply frequency \( f_1 \) to develop maximum torque at start is given by

\[
f_1 = \frac{R_2}{2\pi L_2} \quad \text{.......................................................... (12)}
\]

B. the developed torque near synchronous speed is proportional to slip. Thus, if the slip \( s \) is clamped to a maximum value, the developed torque will be clamped too.

C. the required zero-frequency voltage boost to produce the rated flux in the air gap is \( I_{1\text{rated}} \times R_1 \) volts per phase.

It should be noted that the constant air-gap flux in \( V/f \) drives only remains constant in the steady-state, not in the transient state. As a result, the dynamics of IM drives under the \( V/f \) scheme, also called a Scalar control scheme, must be rather slow otherwise over-current and unregulated rotor flux, and hence torque, will occur.

In order to overcome the above problems, Vector control schemes are used. In this scheme, the rotor flux of the machine is maintained constant even during fast acceleration and deceleration, by supplying the motor with tightly regulated quadrature currents in the synchronously rotating reference frame. One of these currents, \( i_d \), controls the rotor flux only while the other current, \( i_q \), controls only the developed torque. In this way, the induction motor can be made to develop the characteristics of the DC motor. The underlying theory of rotor flux oriented control and how flux transients are eliminated in the transient modes of operation are covered in the lecture notes. A brief qualitative, but conceptual, description is included below.

**Rotor Flux Oriented Control**

In RFOC, motor currents \( i_a, i_b \) and \( i_c \) are resolved into their component values in the synchronously rotating \( d- \) and \( q- \) axes by using the position information of the synchronously rotating field. The translation of the torque demand (or speed error) into the controllable current \( i_q \)
is via a factor \( \frac{\hat{L}_r}{R_m} \) which is dependent on certain parameters of the motor and the rotor flux, as is also shown in figure 1. The relationship between the desired rotor flux and the controllable current \( i_d \) is dependent on the same parameters. These parameters must be accurately known for the RFOC scheme to work satisfactorily. Furthermore, the time delay between a change in rotor flux reference and the actual rotor flux also affects the accuracy of the torque and rotor flux control loops.

Figure 5. Indirect rotor flux oriented vector control scheme

Note that the amplitude of the rotor flux linkage vector, \( \hat{\lambda}_r = L_m i_{ds} \) in the steady-state, is obtained by measuring the stator currents and transforming them into \( i_{ds} \) using the angular information \( \theta_i \). The angle \( \theta_i \), which is also the angle of the synchronously rotating frame, is obtained by integrating the sum of the rotor speed and the slip speed. The accuracy of determining \( \theta_i \) is crucial and therefore the angular speed \( \omega_m \) must be sensed using a highly accurate speed or position sensor mounted on the motor shaft. The 12-bit optical encoder E in Figure 5 is used for this purpose.

The rotor flux reference is normally set to +1 pu for operation below the base speed which normally occurs when the stator supply frequency is 50Hz, regardless of the direction of rotation. When the motor is to be driven above the base speed, the rotor flux reference is reduced as a hyperbolic function of speed so as to drive the motor with constant power. This is necessary because of the limited DC-link and motor voltage ratings.

3. Equipment

The equipment required for the experiment are:

| The three-phase IGBT inverter | One digital three-phase meter |

Experiment 4 - IM with V/f and RFOC drives  
ELEC4613 – Electric Drive Systems  
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4.0 Experiment

The experimental set-up is indicated in Figure 6. The inverter is supplied from the 415V, 50 Hz AC mains via an isolator switch and an auto-transformer. The three-phase inverter includes a diode-bridge rectifier and an LC filter which supplies the smooth DC-link voltage to the inverter. The inverter is controlled from the DSP board resident inside the PC. The DSP user interface provides cursor adjustments for frequency for the \( V/f \) inverter and the \( i_d, i_q \) and speed references for the RFOC drive. These references, their actual values, and rotor flux and torque may also be displayed on the CRO and in the cockpit windows as desired.

A DC generator is used for applying load to the induction motor. The DC generator, and hence the induction motor, is loaded by connecting a (wall mounted) load resistor bank across it at high speed and a bench-top rheostat at low speed. The load torque in Nm applied to the induction motor is found by dividing the DC generator input power (obtained by multiplying the DC generator output voltage and current and adding to it the \( I^2R_s \) loss of the generator) by the shaft speed in rad/sec.

Caution! Before switching on the AC supply to the auto-transformer via isolator SW at any time, care must be taken so that the auto-transformer adjustment is initially at minimum or zero.
Before start, your laboratory supervisor will initialize the DSP board and run the appropriate programs for the two controllers.

Adjust the autotransformer slowly to 415V to create the rated DC link voltage for the inverter. If you have to switch off power to the inverter using the isolator for any reason, you must observe the precaution highlighted above.

4.2 Operation with V/f controller

4.2.1 After the inverter has been powered up, set the voltage boost to 0% using the cursor and gradually raise the output frequency to 50 Hz (for operation at rated speed). Record and plot in your logbook, the variation of speed with inverter frequency, as you reach 50Hz.

4.2.2 With the machine running at 50 Hz, use the DC generator to load the induction motor by adjusting the resistive load bank. For each load, record and plot in your logbook, the motor developed torque, speed and the amplitude of the stator flux linkage ($\hat{\phi}$) for several load settings using the DSP operator interface. Also record and plot in your logbook, the readings of motor RMS phase voltage, current, and the input power of the AC motor for each load.

**DO NOT EXCEED THE RATED CURRENT OF ANY OF THE TWO MACHINES. NOTE DOWN THESE VALUE IN YOUR RECORDS**

4.2.3 Repeat 4.2.2 for inverter output frequencies of 20 and 10 Hz. When operating at 20 and 10 Hz, you may have to replace the wall mounted load by the low-resistance rheostats for adequate loading via the DC generator. Experimental data for these frequencies should be plotted in your logbook using the same torque-speed axes range as for 4.2.2.

4.2.4 Set the inverter output frequency to 10 Hz. Repeat 4.2.2 for voltage boost levels to 10%, and 30%. Observe the effect of boosting the input voltage on the motor torque, speed, current and stator flux linkage at 10 Hz. Experimental data for these frequencies should be plotted in your logbook using same torque-speed axes range as for 4.2.2.

**Turn-off the AC supply to the variac, adjust it to zero, open the circuit breaker on the variac and then change the stator resistances of each phase of the machine. Your lab demonstrator must check the new connection before you switch AC power ON to the variac.**

4.2.5 For 20 Hz, repeat 4.2.2 with a 3.4Ω resistor added to each stator phase and the boost levels of 0% and 30%. This can be done easily by removing the short circuiting links across all three resistances. Experimental data for these frequencies should be plotted in your logbook using same torque-speed axes range as for 4.2.2.

4.2.6 Dynamic Operation under V/f controller

4.2.7 Turn down and switch OFF the autotransformer and remove the added stator resistances. Connect the DC generator to the wall mounted resistor bank for loading. Set the voltage boost to 0%. Set the CRO time base to 200msec/div and set it to Single Trigger mode. Run the motor at 10Hz. Using the numeric data entry, increase the supply frequency abruptly to 50 Hz. This should accelerate the motor to full speed. Observe and print the transient responses of motor current and stator flux while the motor accelerates.
4.2.8 Decelerate the motor from 50Hz to 10Hz and print the transient responses of motor current and stator flux while the motor decelerates. Adjust the autotransformer to minimum and switch it off.

4.3 *Operation with RFOC:*

During this part the lab demonstrator will run a fully tuned RFOC drive. Ask your lab demonstrator to setup the RFOC drive, load and the DSP program for RFOC. After the inverter has been powered up, the RFOC drive will be started with a speed reference. The drive is now operated with the RFOC controller of figure 5.

**Steady-state**

4.3.1 Set the $i_d$ reference of 4.2A for the rated rotor flux. Set a speed reference of 750 rev/min (= 25 Hz input frequency). Load the motor by the DC generator gradually and record the variation of speed with load. Also record variations in torque and rotor flux.

**Dynamic**

4.3.2 Connect DAC1 output to External trigger input of CRO. Connect the four signals DAC2 (*speed*), DAC3($\lambda_{rd}$), DAC4(*torque*) and $i_a$ from the inverter to the CRO.

4.3.3 Set the speed reference to 300 rev/min (=10 Hz). Allow the motor to accelerate and decelerate to and from 1500 rev/min (= 50 Hz). Also make sure that the peak current during acceleration and deceleration does not exceed 12A.

Record and print the speed, torque, stator current and rotor flux waveforms on the CRO.

4.3.4 Repeat 4.3.3 for operation with speed reversal to and from 1000 rev/min.

4.3.5 Set the CRO in the XY recorder mode (ask the lab supervisor for help). Connect the torque and motor speed signals to the X and Y inputs, respectively, of the CRO. Adjust the gains of channels X and Y of the CRO so that you get the display covering a significant square area of the CRO screen. Identify the quadrants of operation of the drive as it accelerates and decelerates in both directions with and without load. Record two XY plots and clearly identify operating quadrants with torque and speed.

Adjust the auto-transformer to zero and turn off the AC supply.

5. **Report**

1. At the end of the laboratory, produce your logbook with all plots of experimental data (your own drawing or from the CRO) to your lab demonstrator. He will mark the logbook according to the data presented in the logbook and your answers to any question that he may ask.

2. If you are assigned to write your lab report on this experiment, you should note the following:

Your lab report on this experiment should include brief theory, main objectives of the experiment and what you expected to learn from the experiment. You should indicate the formulae you used and sample calculations you performed. Your explanation of the experimental data and what you actually found and learned through the experiment, compared to what you actually expected should be included. Highlighting of any differences
from the expected results, if any, and your own explanations for these would be highly regarded. You are also expected to make some conclusions on the experimental data you obtained and the machine/drive behaviour.

You are also expected to include in your lab report your answers to the following:

**V/f drive**

5.1 Calculate and plot the motor torque-speed characteristics from the DC machine voltage, current and speed data, for all the frequency settings that were used and for each of the operating conditions. For ease of comparison, $T-\omega$ graphs for a given frequency of operation, with and without voltage boost or with and without added stator resistances should be plotted on a single graph paper with full frequency and torque ranges.

5.2 Calculate the required zero frequency voltage boost for the motor that will result in rated flux operation at rated current.

5.3 What should be the starting frequency for maximum acceleration at start?

5.4 Comment on the variable frequency performance (torque-speed characteristics) of the V-f drive at low speed with and without the voltage boost and the added stator resistance.

5.5 From the torque-speed characteristics of the motor for all the frequencies you have used, find the slip $s$ of the motor for the rated load of 2 Nm for each frequency of operation. Comment on the variation of this slip with frequency. In particular, comment on the variation of this slip with frequency when the motor is operated above the base speed (which is for 50 Hz).

5.6 Comment on the observed waveforms of motor currents for the various operating frequencies, voltage boost and stator resistance.

**RFOC drive**

5.7 Discuss your observations of experimental data from sections 4.3.1. Were there any variations in $i_d$ while $i_q$ was changed? Comment on the amplitudes of these variations relative to the rated value of $i_d$.

5.8 Comment on the transients in rotor flux while the motor is accelerated and decelerated under RFOC. Compare how the rotor flux changes during acceleration and deceleration the motor is operated with RFOC and V/f controls.

5.9 Comment on the acceleration times of the two schemes to top speed.
6. Machine parameters

Collect from your laboratory demonstrator the parameters of the induction and the DC machines. For the IM, the parameters are for 50Hz.

50 Hz parameters of the 415V, 3-phase induction motor used in this experiment are:

\[ R_1 = 3.257 \Omega; \quad L_s = 589.9 \text{ mH}; \quad R_2 = 3.392 \Omega; \quad L_r = 589.9 \text{ mH}; \quad L_m = 569.5 \text{ mH} \]

Rated speed, \( N = 1450 \text{ rev/min} \),

\( I_{\text{rated}} = 8.8A, 3.73 \text{ kW} \).

Parameters of the DC machine are:

\[ V_{\text{rated}} = 180V; \quad R_a = 1.54 \Omega; \quad I_{a \text{ rated}} = 21.6A, \quad N_{\text{rated}} = 1750 \text{ rev/min}, \quad 5 \text{ HP}. \]