Appendix B: The induction machine per-phase model

The induction machine model is shown in figure 1. The induction machine is represented as an equivalent circuit. This is a model of one phase of the machine. Each of the electrical components in this equivalent circuit represents a particular characteristic of the real induction machine, as listed below.

\( R_S \) represents the resistance of the stator windings.

\( X_S \) represents the leakage reactance of the stator windings.

\( R' \) represents the resistance of the rotor windings, referred to the stator side of the machine.

\( X' \) represents the leakage reactance of the rotor windings, referred to the stator side of the machine.

\( R_M \) is used to represent the energy losses that occur in the steel of the induction machine, due to eddy currents and hysteresis.

\( X_M \) is the magnetising reactance of the induction machine and the current that flows in it is the current necessary to set up the flux.

There is another term used in the equivalent circuit that is extremely important. This is the term ‘s’ that is combined with the \( R'/S \) term. It is known as the slip. Slip is a measure of the difference in speed between the rotation of the flux, \( \omega_s \) and the physical rotation of the rotor, \( \omega_r \). The difference is normalised by dividing by \( \omega_s \). Slip is calculated as:

\[
S = \frac{\omega_s - \omega_r}{\omega_s}
\]

\( V_S \) is the voltage across the stator phase winding.

\( P \) is the power input to the induction machine.

\( T \) is the torque produced by the induction machine.

To verify that the equivalent circuit is a good representation of an induction machine it is necessary to do a comparison between model and system. To allow us to model the system accurately it is necessary to obtain values for the equivalent circuit model parameters. In other words, values for \( R_S, X_S, R', X', R_M, \) and \( X_M \) need to be found. To find values for these parameters various tests can be done on the induction machine.

Finding \( R_S \)

To obtain \( R_S \) we need to find the resistance of a stator phase winding. This can be done by connecting a DC voltage across a stator phase winding and measuring the current flow. \( R_S \) is then determined simply from Ohm’s law.

The determination of \( R_S \) has already been done for you and is found to be 0.095 ohms per phase.

Finding \( R', X' \) and \( X_S \)

To establish the parameter values for \( R', X' \) and \( X_S \) a standstill test is conducted. The standstill test, as its name implies, is conducted with a rotor speed of zero. With a stationary rotor, the slip for the induction machine is one, hence the \( R'/S \) term in the equivalent circuit reduces to just \( R' \). If it is assumed that the values of \( R_M \) and \( X_M \) are large compared to \( R' + j X' \), then \( R_M \) and \( X_M \) can be ignored. This results in the simplified equivalent circuit shown in figure 2.

**Warning:** A locked rotor results in a very low impedance as measured at the induction machine terminals. This means very large currents may flow in the induction machine if the applied voltage is not reduced. You must reduce the stator voltage to an appropriate level for the standstill test.
Two equations can be written to describe the circuit of figure 2. Ohm's law:

\[ V_S = IZ \]
\[ V_S = I[(R_S + R'_R) + j(X_S + X'_R)] \]

and an equation relating input power to circuit parameters:

\[ P = I^2 (R_S + R'_R) \]

Hence, if readings of \( P, I \) and \( V_S \) are taken when the rotor is stationary, the terms \( R'_R \) and \( X_S + X'_R \) may be determined by manipulation of the above equations.

Unfortunately it is difficult to split the terms \( X_S \) and \( X'_R \). It is possible by applying a voltage to the rotor with the stator left open-circuit. However, this is not practical with the experimental set-up here. As an approximation it is assumed \( X_S = X'_R \).

To discover the parameter values for \( R_M \) and \( X_M \) a synchronous test is conducted. The synchronous test involves running the motor to synchronous speed, when this happens the slip for the motor is zero. Hence the \( R'_S/J \) term in the equivalent circuit is infinite. If it is now assumed that \( R_S + jX_S \) is much smaller than \( R_M || jX_M \), the equivalent circuit may be further reduced to that of figure 3. By measuring real power in, current and voltage for this circuit values for \( X_M \) and \( R_M \) may be calculated.