Motor Performance Measurement Without a Dyno

A Portable Dynamometer

R. Gene Smiley Nov 2018

ABSTRACT

There are many scenarios where a quick, accurate validation of motor performance is valuable – R&D, vendor qualification, production, integration, commissioning, troubleshooting, or post-repair. Traditional methods for generating motor performance curves involve extensive time, effort, and resources for connection of the test motor to a loading device – which requires not only an alignment procedure but also significant infrastructure and resource to install, operate and maintain the loading system. In the subject approach, none of the loading system infrastructure or resources are necessary. The results are quickly available after just a few uncoupled motor starts, including documentation of motor losses; in full compliance with IEEE and other standards; and the procedure is self-calibrating.

INTRODUCTION

The core idea of starting an uncoupled motor against only its own inertia, is of course not new. Historical efforts have resulted in many publications from universities and even a few functional but short-lived commercial products. By and large, these commercial efforts suffered from a weakness of the "whole product" value proposition – i.e., the combination of initial price, required operator training, traceability, validation, calibration and maintenance was inconsistent with industrial customer needs.

The resources required to perform the procedures described herein, consist of three main components. First, facilities to safely start and run a motor, even if at reduced or ramped voltage. Second, instrumentation and data collection equipment to properly record high-resolution current, voltage and rotor speed during a motor start. And third, a data analysis tool to convert raw data into the desired calibrated results in a format convenient for reporting and archiving in the end user's information environment. The first two of these are readily available as existing or easily-procured commercial tools from multiple suppliers. The focus of the work described herein is on the third core component, with special emphasis on compliance with industrial standards, results validation, commercial maintainability, and convenience for the end user.

BASIC PHYSICS BEHIND THE METHOD

To begin, recognize that saying that an uncoupled motor is "unloaded" is not correct. During a start, the load on an uncoupled motor contains inertia, friction and windage. Inertia is the physical mass property that resists speed change. Friction and windage are speed-dependent mechanical losses from shaft-attached cooling fans, air circulation in the air gap and stator cooling system, and bearings.

During startup, rotor inertia is the main "load" that resists speed change, requiring external (electrical) energy to change operation from any speed to a higher speed. As the motor speed increases, the internal friction and windage load increases. If there's no speed change, there's no *inertial* load, only friction and windage - hence the descriptive "full-speed, no-load" operating condition for an uncoupled motor.

A rotor has no kinetic energy at rest, and a fixed amount of kinetic energy at full speed. Power is a measure of the *rate* of energy delivery to the motor, required to overcome losses due to internal electrical and mechanical losses plus change the speed of the rotating inertia. Power input can be measured, and if the losses are known, can be integrated to obtain rotor kinetic energy; and since speed is measured, the rotor inertia can be calculated directly. Fig 0 shows the difference in torque-vs-speed results from a 500 HP induction motor comparing a transient start across the line, and a steady-state ramp from zero to full speed [3]. The three primary differences of note are:

1. Significant dynamic torque ripple at line frequency, during the across the line start;
2. Breakdown torque is somewhat higher for the steady-state case; and
3. Overshoot and torque oscillation about the final operating point (full speed, no-load) during the transient start.

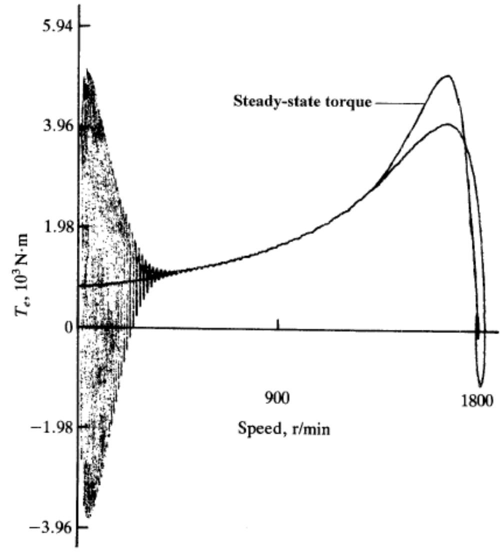


Fig 0. Steady-state vs across the line torque vs speed result, 500HP/460V/4P induction motor [3]

Temperature change affects winding resistance (thus also current, torque and watts), friction and windage. The effect of temperature on inductance is usually ignored but could be included as required. If the motor start is fast enough, the effect of change in resistance can be ignored in these tests. In any case, winding resistance can be measured before and after a test to give a good indication as to the validity of a temperature change assumption. Note that IEEE 112 procedure [1] recommends a preliminary step of running an uncoupled motor at no load for sufficient time to reach stable temperature – which may be 30 min or more.

Testing at different voltages is necessary to separate and document the various energy loss mechanisms described above. The procedure for their separation is well-understood, built into the post-processing software, and described in the IEEE standards mentioned below.

COMPLIANCE WITH STANDARDS

IEEE-112 [1] contains published procedures for obtaining performance characteristics of polyphase induction motors using various test methods, including an inertial acceleration test. IEEE-114 has similar procedures for single-phase induction motors. These and BLDC motors also must of course obey basic and immutable laws of physics. The methods used in the proposed procedure and data processing, including documentation of all mechanical and electrical losses in the motor, are in full compliance with methods described therein.

LIMITATIONS

Because this is a transient test method (IEEE-112 refers to it as an ‘acceleration’ method), the basic idea is to achieve a test condition where the motor’s behavior in a controllable situation, is measured with some precision. Most of the limitations arise from ignoring basic laws of physics, especially in situations other than simple across-the-line starts. When a drive or soft-start is in front of the motor, unless care is taken with ramp rates, current limits and so on, we can end up testing the behavior of the (drive + motor) system instead of just the motor. A pre-test planning tool based on motor nameplate data with some reasonable assumptions based on experience, is described in the last example. Limitations and errors arise also from lack of attention during setup; as will be seen in the example below, if the measurements are valid, and the motor is behaving properly, the results will be seen as self-calibrating.

With minor modifications, this procedure works on:

- Induction, brushed & brushless DC, and PMAC motors
- Across-the-line or soft starts
- Power supplies that are variable-voltage constant-Hz (variable transformers), or constant V/Hz (VFDs)

DESCRIPTION OF THE METHOD

The actual work process is quite simple.

a) Position the test motor on a pad, uncoupled.
b) Measure winding resistance with a suitable instrument.
c) Connect power leads and test equipment (voltage clamps, CTs, and small speed encoder).
d) Obtain nameplate data and enter into the recording system.
e) Run the motor under no load at any convenient voltage. Validate the test setup and sensor connections, including correct phase sequencing, CT polarity, etc. If desired, confirm the observed amps and volts against a separate (calibrated) meter, as a reality check on the setup. Stop the motor.
f) Start the uncoupled motor at reduced voltage, run at no load for a few seconds, and cut the power. The starting voltage can be across-the line, or ramped. If ramped, start at reduced voltage then ramp to full voltage *after* NL full speed is reached. Record current, voltage, and speed at high resolution during the full cycle.
g) Repeat (f) at two or more additional voltages. If the starting voltage is ramped, this step can be skipped.
h) Run a post-processing software application, using the recorded data from the multiple starts, as input.

EXAMPLE

The following results are from a test performed on an industrial 250HP/460V/3600RPM induction motor. (Note that comparable-resolution results are obtainable for 3P PMAC and DC motors, with a slightly-modified procedure.) The motor and test equipment are arranged as in Fig. 1. The motor is started 5 times, resulting in 5 speed-vs-time traces as in Fig 2.

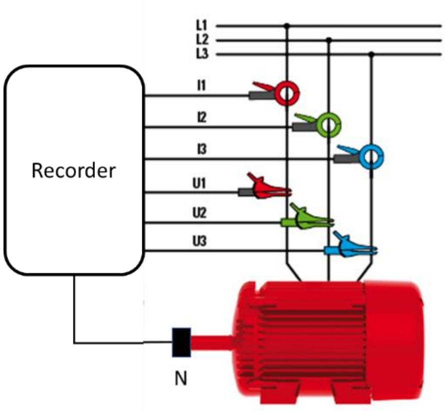


Fig 1 – Arrangement of DUT and equipment

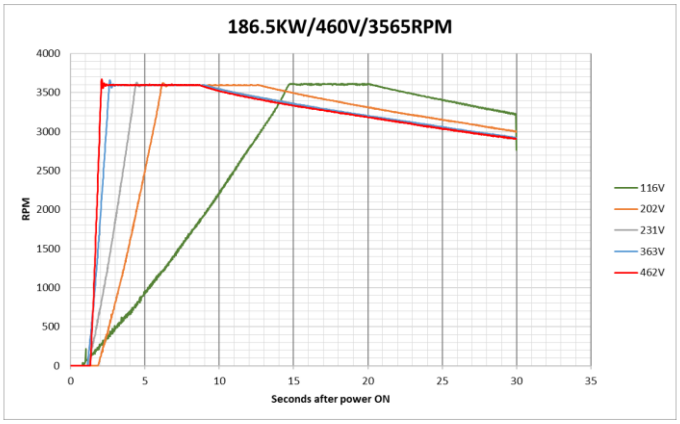


Fig 2 – Speed-vs-time for starts at 5 different line voltages

After all starts are recorded, the processing can begin. The first step is to transform the speed-vs-time data from Fig 2, into the form shown in Fig 3. The parameters enabling this transform [4] reveal a unique element of the nonlinear behavior of this induction motor's behavior; the close overlay of the graphs indicates both that it's performing as expected, and that the data is consistent.

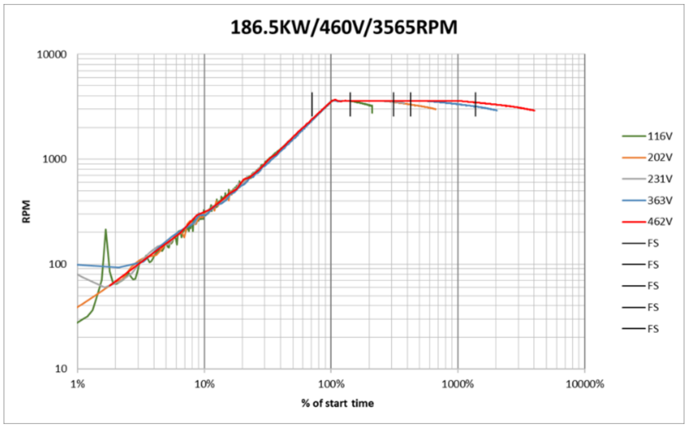
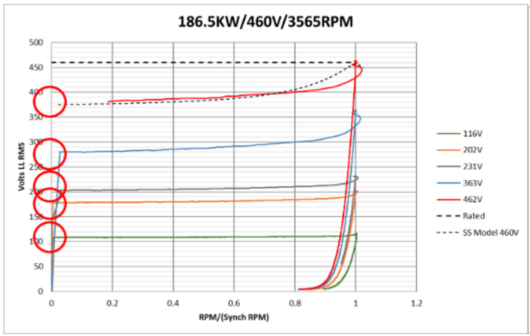
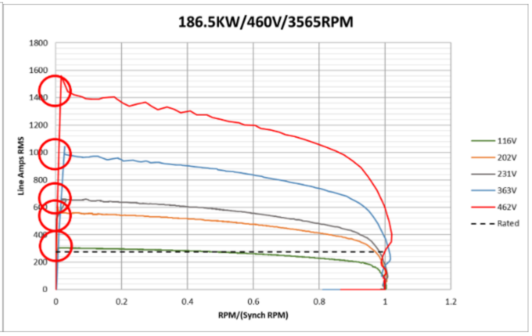


Fig 3 – Speed-vs-time startup consistency, independent of line voltage

Next, because voltage and current waveforms were measured, the real-time power in Watts can be easily calculated using a well-established method that appears in all commercial wattmeters, along with average RMS LL Volts and phase current. Graphing these results vs speed, as shown in Fig 4a-c, and locating the 0-speed intercepts (circles in Figs 4a-c), yields locked-rotor values for voltage, current, and input power. We can also easily extract the no-load voltage, current, input watts and speed from the measurements, from the period of operation between reaching full speed, and power off. From the speed-vs-time curves, we can also easily calculate the average acceleration, simply by dividing full speed by the start time, which varies with line voltage. We note also that differentiation of the speed-vs-time data, provides an acceleration-vs-time result that can be analyzed for locked-rotor acceleration in a manner similar to Fig 4. Finally, real-time air gap torque can also be calculated and analyzed similarly as Fig 4, to obtain locked rotor and no-load torques.





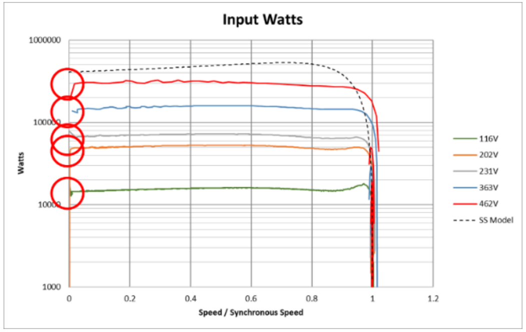


Fig 4a – Avg LL Volts RMS vs speed during start Fig 4b – Avg Amps RMS vs speed during start

Fig 4c – Avg input Watts RMS vs speed during start

Graphing the locked rotor current, input power, torque, and acceleration vs locked rotor voltage in log-log as in Fig 5, yields an interesting result from which we can extract a correlating non-linear characteristic of motor behavior, as well as another indicator of consistency of both the measured results and motor behavior: the slope of these lines, which in a healthy motor are all equal (except for line current, which is ½ of the slope of the other results), is a characteristic parameter of the motor that correlates with a parameter used in the transform that caused all the start curves to overlap as in Fig 3.

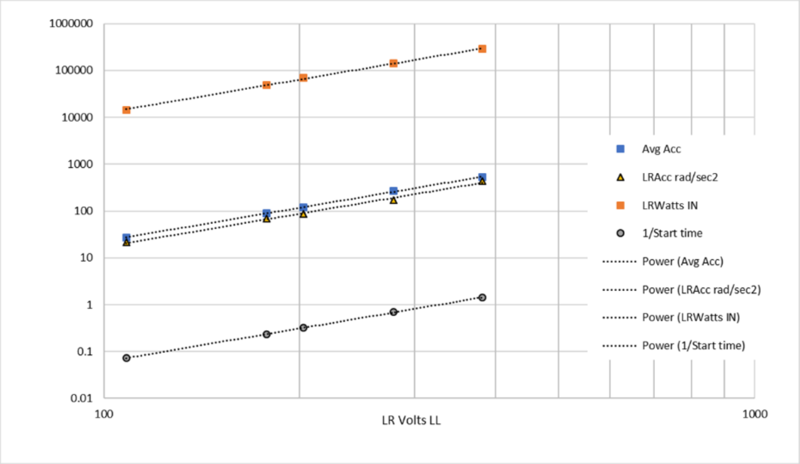


Fig 5 – Acceleration, power torque and input watts vs locked rotor (dashed lines are linear curve fits)

We have measured speed, so we obtain acceleration vs time by a simple differentiation, as mentioned earlier. Now if we know the inertia, we can get the mechanical output torque, by a simple multiplication. Fortunately, there is a way to obtain the inertia from the data we have collected. IEEE-112 describes the method for enumerating losses (i^2R, friction & windage, & core loss) based on no-load input watts. We follow this procedure, and then integrate (input Watts – losses) vs time, to obtain energy. After the losses have been removed, the energy that is left, is simply rotor kinetic energy. Since we know the speed, a simple calculation yields an inertia-vs-time result as in Fig 6. Again, the fact that all these results, from motor starts at different voltages, yield the same result, validate our estimate of inertia, which is of course invariant. In this case, the inertia for our 250HP motor is seen to be equal to 1.2 Kg-m^2.

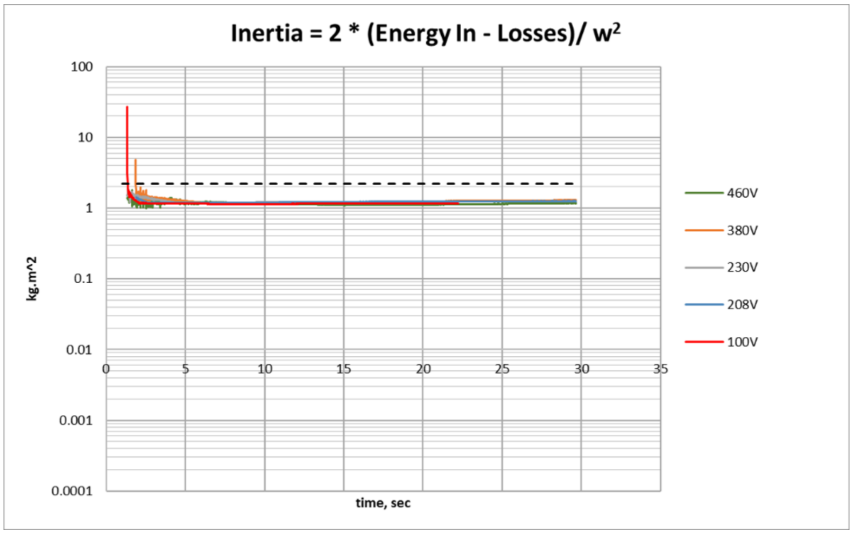


Fig 6 - Inertia vs time, calculated for each motor start

With the foregoing results, we are now ready to produce the final, originally-sought result: torque-vs-speed plots. Correcting the results from each run to rated voltage, and superimposing the results, gives the result shown in Fig 7. Again, the consistent overlay of the results from multiple tests, reinforces the validity of the results, and ensures that the motor is operating as expected.

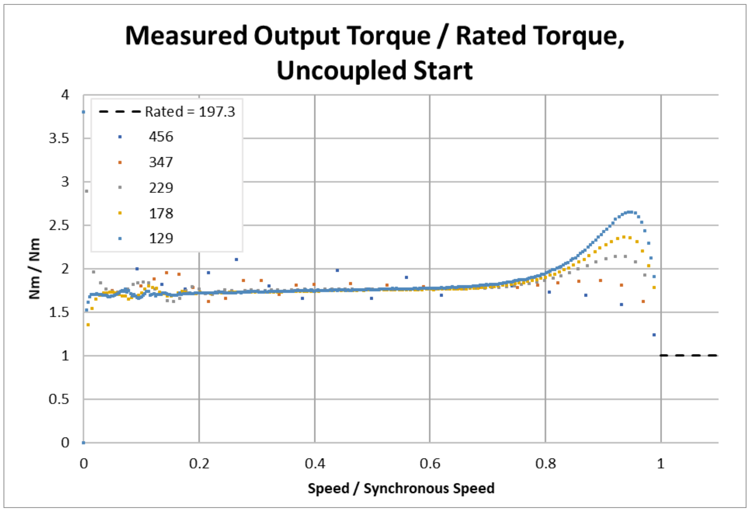


Fig 7 – Torque-vs-speed results from motor starts at multiple line voltages, corrected to rated voltage and divided by rated torque.

Conclusion

A method has been demonstrated for obtaining motor performance curves using uncoupled motor starts. In addition to providing the required numerical performance values, the technique is new in that it provides consistency metrics ensuring data validity, verification that the motor is operating as expected and according to laws of physics.

Future Work

The methods described herein are covered under US patent. It forms the basis of a commercial tool that is presently undergoing certification trials under NRC regulations for use in the US nuclear power generation industry. Recent satisfactory results in trials on PMAC motors more familiar to the vehicle industry, are expected to result in additional publications in the very near future.

References

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