

Case Study of Motor Starting and Acceleration Analysis

Kush Jain¹, Prakhar Kumar Vaish², Vishal Mehtre³

Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be University) College of Engineering,
Pune, India

ABSTRACT: This paper offers a comprehensive case study on the starting and acceleration characteristics of three-phase induction motors through two complementary investigations. The initial study entails laboratory testing of a 3 HP, 440 V motor utilizing Direct-On-Line (DOL) and auto-transformer starting at different load levels, and cable lengths, with results checked against ETAP Power Station simulations. The second study uses ETAP to look at three 200 HP motors that were started at the same time using DOL, auto-transformer, and Variable Frequency Drive (VFD) methods. It focuses on bus voltage sag, inrush current, acceleration time, and motor slip characteristics. The auto-transformer method cuts inrush current by about 58% compared to DOL in both studies. The VFD starting method, on the other hand, limits the peak current to near full-load levels and gives the smoothest acceleration profile. Capacitor compensation at motor terminals has been shown to be a good way to support voltage in installations with long cables. The results, when looked at together, give useful advice on how to choose starting methods for motors of different sizes and power system setups.

KEYWORDS: Induction motor, motor starting, DOL starter, auto-transformer, VFD, ETAP simulation, voltage sag, locked rotor current, and capacitor compensation are all important terms.

I. INTRODUCTION

Induction motors are the most important parts of industrial electrical systems. They are the best choice for loads ranging from small fans to large compressors and conveyor drives because they are easy to use, strong, and not too expensive to buy or run. They are not like DC machines.

can be plugged directly into the AC grid without a rectifier front-end, which makes the system simpler and less expensive to install. A well-known limit, though, shows up when the power is turned on. When the supply is first connected, the rotor is not moving, so the motor acts like a short-circuited transformer. secondary, and the locked-rotor current (LRC) that comes out of it can be many times the full-load current (FLC) on the nameplate.

Engineers use starting devices that either lower the initial terminal voltage or control the motor current directly to keep these effects within acceptable limits. The choice depends on the acceptable voltage drop, the needed starting torque, and the project's cost limit. This paper discusses both small-motor laboratory Experimentation and large-motor ETAP simulation, contrasting DOL, auto-transformer, and VFD starting techniques across various system configurations.

II. BACKGROUND ON MOTOR STARTING

When the supply switch closes while an induction motor is not running, the air-gap flux builds up quickly, and the rotor bars get a large voltage. The rotor current is high and lags behind the flux by almost 90 degrees because the rotor circuit resistance is low compared to its reactance at the supply frequency.

So, the overall input power factor is bad during the first few cycles of starting, usually between 0.10 and 0.20. As the rotor speeds up, the slip, rotor reactance, and current strength all go down. Because of this, the supply voltage starts to go back up. The amount of time it takes to recover depends on the load inertia and the difference between the motor torque and the load torque at each operating point. Industry standards, including NEMA MG-1, recommend that terminal voltage during starting must remain at or above 80 percent of rated voltage to guarantee adequate accelerating

torque for a standard design-B motor. A 35 percent reduction in terminal voltage reduces starting torque by roughly 57 percent, because torque varies with the square of the applied voltage.

III. CLASSIFICATION OF STARTING METHODS

A. Full-Voltage Starting (DOL)

The DOL method of starting a motor applies the rated voltage to the motor stator at the instant the motor is energized. DOL starting requires only a main contactor and a thermal overload relay, making it one of the most cost-effective starting methods. A DOL starting method is acceptable if the driven machine can withstand the mechanical shock of a rapid application of torque and if the supply system can absorb the voltage drop without causing disruption to other loads. For small motors that are fed by strong supply systems, DOL is usually the preferred starting method.

B. Reduced-Voltage Starting (Conventional)

If the DOL method produces too much of a voltage disturbance, then the motor will first start at a lower voltage than normal until it reaches a suitable speed and then switched to normal operating voltage. The trade-off with this method is reducing the amount of available starting torque, which is proportional to the square of the amount of reduced voltage. Table 1 shows common traditional reduced-voltage starter configurations.

Table 1. Types of Traditional Induction Motor Starters

Starter Type	Description
None (DOL)	Motor terminals connected directly to full supply voltage without any intermediate device.
Auto-Transformer	A tapped transformer supplies reduced voltage to the motor during start-up; full voltage applied after acceleration.
Stator Resistor	A fixed resistor placed in series with the stator circuit to reduce the initial terminal voltage.
Stator Reactor	A reactor inserted in series with the stator; effective at higher power levels than resistor starters.
Capacitor (Bus)	Shunt capacitor bank installed on the supply bus to supply reactive power and support bus voltage.
Capacitor (Terminal)	Shunt capacitor placed directly at motor terminals to compensate reactive current drawn through the feeder.
Rotor Resistor	External resistance connected into the rotor circuit of a slip-ring motor to limit inrush current.
Star-Delta	Stator windings connected in star during starting; switched to delta at near-full speed for normal operation.

There are several limitations that apply to traditional starters, including: the start of a motor causes torque pulsations that occur at the moment of voltage changeover; due to extended starting times, the windings experience a rise in temperature above normal levels; and efficiency at partial loads is less than with electronic control methods.

C. Electronic Soft Starters

In order to control the voltage supplied to the motor windings, a solid-state soft starter has two pairs of thyristors connected in back-to-back fashion for each supply phase. The firing angle of these thyristors can be altered to allow for a gradual increase of the terminal voltage to the motor winding or stator during acceleration. This prevents the abrupt current surge and torque peaks that commonly occur with conventional starters. A summary of the primary control methods used by different soft-start designs can be found in Table 2.

Table2. Categories of Solid-State Soft Starters

Soft Starter Type	Controlled Parameter
Current Limit	Clamps inrush current below a pre-set threshold using thyristor firing angle adjustment.
Current Control	Continuously regulates current magnitude throughout the entire run-up period.
Voltage Control	Gradually ramps the terminal voltage from a low starting value up to full supply level.
Torque Control	Shapes the torque profile during acceleration to minimise mechanical jolt on the driven load.

Soft starters provide benefits such as smooth torque delivery, controllable inrush current, and the potential of recovering energy at light loads through a reduction in voltage. However, soft starters also produce low-order harmonics (e.g., the fifth harmonic) which can cause issues; additionally, their efficiency tends to decrease as load values increase. Because of these factors combined with the fact that most small motors have short duty cycles, energy savings are often not enough to offset the cost of the capital investment; therefore, most facilities still utilize conventional starters for lower power applications.

D. Variable Frequency Drive (VFD) Starting

With a variable frequency drive, you can vary the supply voltage and frequency to the motor. This allows the motor to accelerate from zero speed to normal operating speed in a fully controlled manner. As a result, the air-gap flux can be maintained approximately constant during the entire acceleration period, which will yield rated torque at very low inrush current conditions. The peak current drawn from the electrical supply during starting will be very close to that of the full-load current of the motor; therefore, voltage sag will virtually not affect the supply bus. The VFD also provides the necessary ability to precisely control speed during continuous run operation, making it an ideal solution for critical process applications. The two main disadvantages of VFDs are that they have a higher initial cost than conventional methods and they produce harmonic currents that enter the supply network.

A-I Part A: 3 HP Motor

The three-phase squirrel cage induction motor, rated 3 HP, 440 V, 4.5 A and 50 Hz, found to be under similar conditions as in the laboratory by using the following standard tests to extract equivalent-circuit parameters:

- The no-load test is to establish core losses and magnetising reactance.
- The blocked-rotor test is to establish leakage reactance and referred rotor resistance.

Measurements from the no-load test were used to determine the load at 75% of rated load and 100% of rated load to calculate efficiency and running slip. All equivalent-circuit parameters from the tests were compared to manufacturer's catalogue values in Table 3.

Table3. Comparison of Standard and Measured Motor Parameters (3 HP Motor)

Parameter	Standard Value	Measured Value
Stator Resistance (Rs)	4.37 Ω	10.5 Ω
Power Factor (75% load)	0.84	0.39
Power Factor (100% load)	0.84	0.71
Efficiency (75% load)	77.96%	55%
Efficiency (100% load)	80.91%	59%

The measured stator resistance of 10.5 ohms is much greater than the value of 4.37 ohms found in the catalogue. The power factor and efficiency figures at both loading levels also are much lower than catalogue values. Accordingly, the discrepancies from the catalogue values suggest that the motor was not in factory-new condition at the time of the tests, accounting for some of the discrepancies described in Section VI regarding the differences between the simulation predictions and the recorded values.

ETAP Power Station is software designed for simulating electrical power systems. The laboratory power supply diagram shows a 0.44 kV utility bus supplying a variable-length cable to the motor bus with the 3 HP induction motor as an electrical load.

B-II Part B: 200 HP Motor System

A. System Description

Preparing a second separate simulation study included comparing the three different types of starting methods (including VFD start) to determine their performance characteristics on a larger Industrial electrical supply system. The simulated electrical network performed in ETAP demonstrated the operating characteristics of a typical low voltage supply system of an industrial facility, with an example of a utility supply to a step-down transformer to a low-voltage bus to three different (identical) induction motors of 200 HP, where one of the three will be started using one of the methods.

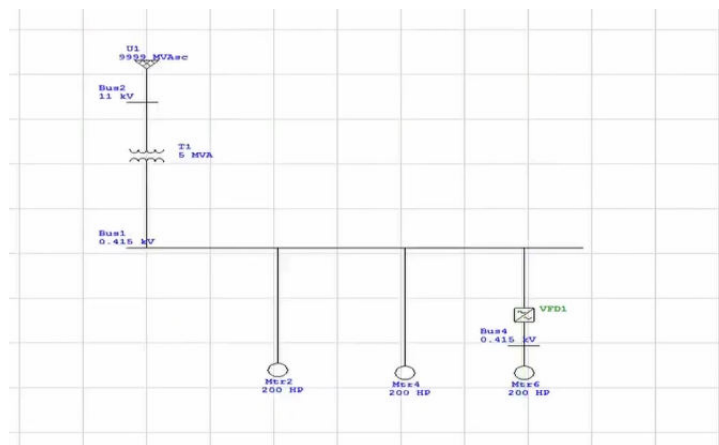


Fig: Motor acceleration analysis Etap

The three induction motors within this simulation were started at the same time providing the most extreme scenario for performance comparisons of the different start methods by creating the same supply conditions at the motors to allow for easy performance comparisons on a side-by-side basis. Key System Components are detailed in Table 7 and Motor Specifications are detailed in Table 8.

Table7. Key System Components — 200 HP Motor Study

Component	Type	Rating	Voltage Level
U1	Utility Source	3500 MVA	11 kV
T1	Step-down Transformer	5 MVA	11 kV / 0.416 kV
Bus 1	HV Busbar	—	11 kV
Bus 2	LV Main Busbar	—	0.416 kV
Bus 4	VFD Output Busbar	—	0.415 kV

Table8. Motor Specifications — 200 HP Motor Study

Motor ID	Type	Rating (HP)	Voltage (kV)	Starting Method	Supply Bus
Mtr2	Squirrel Cage IM	200	0.416	Direct Online (DOL)	Bus 2
Mtr4	Squirrel Cage IM	200	0.416	Auto-Transformer	Bus 2
Mtr6	Squirrel Cage IM	200	0.416	Variable Freq. Drive	Bus 4 (via VFD1)

B. VFD Configuration

Motor Mtr6 utilized a Variable Frequency Drive (VFD1) rated at 200 horsepower output, 149 executed kVA calculated automatically, 237.5 amperes full load current, and 87.36 percent power factor, to connect the motor to the power supply. The VFD was set-up to offer a constant voltage/Hz ratio of 800 during acceleration to maintain constant air-gap flux while increasing frequency. The frequency control scheme for this last simulation run (see Table 9).

Table9. VFD Frequency Control Schedule (Mtr6, Final Configuration)

Event Time (s)	Frequency (%)	V/Hz Ratio	Control Type	Notes
0	0	800	Ramp	Motor at standstill
1	50	800	Ramp	Motor accelerating
2	75	800	Ramp	Continued ramp-up
3	90	800	Ramp	Approaching rated speed
4	100	800	Ramp	Full speed reached

C. Simulation Setup

In ETAP 12.6.0, a motor startup simulation was conducted using an adaptive Newton-Raphson solution with a maximum of 99999 iterations and a convergence tolerance of 0.0001. The simulation was run for 20 seconds, with the motors starting at t=1.0 seconds; however, when the initial time step used was 0.001 seconds, this resulted in a calculation divergence since there are 3 motors starting simultaneously and there is an ill-conditioned system's parameter. This led to having to reduce the time step to 0.0001 seconds, allowing for the numerical instability to be resolved, and the simulation was able to be completed successfully.

VII. PART B: 200 HP MOTOR STUDY

A. Bus Voltage Profile

ETAP recorded voltage alerts for all motors started with a simultaneous start sequence. The auto-transformer motor (Mtr4) had a terminal voltage that was only 63.6% of nominal for 1.11 seconds. This is well below 80%, which NEMA design-B requires for a reliable start. Mtr6 had a terminal voltage that fell to 0.8% of nominal for 0.30 seconds at the point of start; this is a transient condition prior to stable operation from VFD. These alerts show the potential hazards of simultaneously starting multiple large motors on one bus with insufficient available supply capacity.

B. Motor Terminal Undervoltage Alerts

Table 10 presents the undervoltage alerts recorded by ETAP during the simultaneous starting sequence. The auto-transformer motor (Mtr4) experienced a terminal voltage of only 63.6 percent of nominal for a duration of 1.11 seconds, which is well below the 80 percent threshold required for reliable NEMA design-B starting. Mtr6 briefly fell to 0.8 percent of nominal for 0.30 seconds at the moment of starting, which reflects the transient condition before the

VFD establishes controlled operation. These alerts highlight the hazard of starting multiple large motors simultaneously on a single bus without adequate supply capacity.

Table10. Motor Undervoltage

Motor	Type	Alert	Condition	Rated (kV)	Operating (kV)	% Vn	Duration (s)
Mtr4	Motor	Voltage	Under Voltage	0.415	0.264	63.6%	1.11 s (from t=1s)
Mtr6	Motor	Voltage	Under Voltage	0.415	0.003	0.8%	0.30 s (from t=1s)
Mtr4	Motor	Voltage	Under Voltage	0.415	0.332	80.0%	0.68 s (from t=2.11s)
Mtr6	Motor	Voltage	Under Voltage	0.415	0.334	80.4%	0.03 (from t=1.3s)

A.Motor Terminal Current

The terminal current traces confirmed the predicted inrush current hierarchy for the three methods of starting the motors. Mtr2 (DOL) drew a peak inrush current of 650 to 700 amps, consistent with the expected 5 to 7 times full-load current for direct starting. This peak inrush current was maintained for about 1.5 to 2 seconds before decreasing as the motor accelerated. Mtr4 (from the auto transformer) had an average inrush current of 400 to 450 amps, approximately 36 to 40 percent less than the DOL peak inrush current. A second "bump" in the current trace was noted when the auto transformer was bypassed and the motor was switched to full supply voltage. Mtr6 (VFD) drew only 100 to 150 amps during the acceleration and would have been near its full-load current of about 237 amps. The ramp did not produce any transient currents because of the continuous control of the motor current by the VFD.

B.Motor Acceleration and Speed Profile

Mtr2 (DOL) achieved reached 100% rated speed after approximately 5-6 seconds. The speed profile of Mtr2 demonstrated a noticeably steep initial slope progressively flattening as the motor approached synchronous speed. Mtr4 (auto-transformer) took longer to reach full speed than Mtr2 and did so in 6-7 seconds due to lower starting torque. Mtr6 (VFD) was the fastest of the three motors to go from 0-100% rated speed, achieving this in approximately 4.5 seconds as the VFD frequency schedule was revised to reach 100% of frequency at t=4 seconds. Additionally, Mtr6 demonstrated the most continuous and smooth acceleration profile without any sudden increases/decreases in current and/or speed due to it being controlled by a VFD who continuously adjusts the frequency and voltage to output the necessary torque.

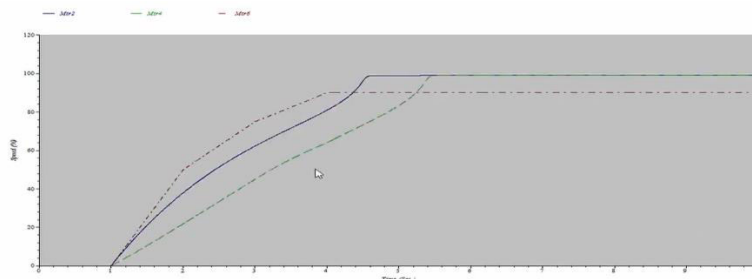


Fig.2. Acceleration Curve

E. Motor Slip Characteristic

Slip is the amount of deviation between the synchronous speed set by the power supply frequency and the actual rotor speed. Both the Mtr2 Motor Data and the Mtr4 Motor Data show that slip was initially 100 percent (i.e., the rotor is stopped) and decreased to steady-state value, which is near zero, as each motor reached full speed over a duration of

approximately 5 - 7 seconds. However, the Mtr6 Motor Data indicated that the difference in slip in relation to the instantaneous synchronous speed (the synchronous speed of the VFD is continuously increasing as the power supply frequency is increased) was almost immediately reduced to a very low level of less than 5 percent and remained at that value during the acceleration process. This is because the VFD controls the operating point of the motor, controlling the difference between the power supply frequency and the actual rotor speed so that the motor continues to operate with a very low slip and therefore low copper losses in the rotor during the acceleration process.

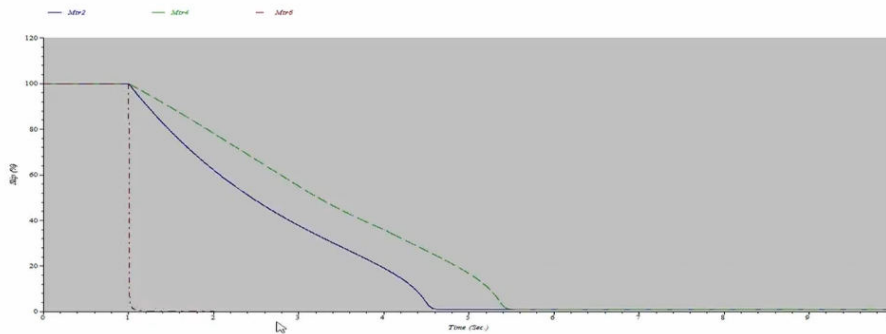


Fig.3. Motor Slip Curve

VIII. DISCUSSION

In summary, there are a number of criteria by which the various starting methods can be evaluated based on the results of the Three HP Data Acquisition Laboratory Study as well as the 200 HP ETAP Simulation Study. Table 11 provides a summary of all key performance indicators for the 200 HP study on each of the three starting methods.

Table11. Performance Comparison — DOL vs. Auto-Transformer vs. VFD Starting (200 HP Motors)

Parameter	DOL (Mtr2)	Auto-Transformer (Mtr4)	VFD (Mtr6)
Peak Inrush Current (A)	650–700	400–450	100–150
Bus Voltage Sag (% drop)	~2% at Bus 1	~2% at Bus 1	Minimal (<0.5%)
Motor Terminal Undervoltage	No alert	63.6% Vn (1.11 s)	~0.8% Vn (0.3 s, transient)
Time to Rated Speed (s)	5–6	6–7	~4.5
Steady-State Slip	Reaches near 0% by ~6 s	Reaches near 0% by ~7 s	Maintained near 0% via VFD
Acceleration Smoothness	Abrupt, step change	Step change at bypass	Smooth ramp throughout
Cost and Complexity	Lowest	Moderate	Highest

Due to the higher starting torque and simplicity of its circuit, direct-on-line (DOL) starting provides the maximum amount of voltage disturbance to the electrical supply (the electrical supply will experience the maximum amount of voltage dip). Therefore, the DOL starting method is ideal for the smaller type of motors connected to a strong (stiff) electrical supply, where the allowable voltage dip is not exceeded. An autotransformer starting method approximately reduces the amount of peak current draw anywhere from 40 to 58 per cent, depending on the tap ratio selected. However, this will also cause an increased time to achieve full speed and create a step transient at the moment of bypass changeover. In summary, the autotransformer starting method is an acceptable solution for medium-sized motors in industrial applications. VFD starting consumes the least amount of power during start and has the least

impact on the motor and the electrical supply system due to the drive's ability to limit continuous current. However, the initial cost of a VFD is greater than either the DOL or autotransformer starting methods and therefore may limit its application in places where VFDs need harmonic filtering to prevent harmonic distortion from adversely affecting sensitive loads on their electrical supply systems.

IX. CONCLUSION

Through laboratory experiments performed on a 3 HP motor, and the ETAP simulation of 3 HP and 200 HP motor systems, this paper has reviewed both DOL starting (Direct On-Line), Auto-Transformer starting and VFD (Variable Frequency Drive) starting for induction motors. The main conclusions can be summarised as follows:

- The highest inrush current occurs with DOL starting – approximately six (6.6) times the full-load current for the 3 HP motor, and 650 - 700 A for the 200 HP motor, both resulting in the deepest sag in the supply bus voltage at the time of starting.
- Auto-transformer starting will reduce the peak inrush current by approximately fifty-five to fifty-eight percent (55 – 58 percent) thereby, causing a considerable reduction in the disturbance of the supply. The trade-off is a longer run-up time, as less torque is available during the start process and also a transient event during the changeover moment.
- VFD starting limits the inrush current to near the full-load current throughout the acceleration process causing the smoothest profile of both torque and speed, and has the least impact on the bus voltage. Time to the rated speed was much shorter than either DOL or auto-transformer in the 200 HP study providing good electrical performance and mechanical gentleness.
- The starting time of the feeder cable has a significant effect; however, the feeder cable length does not affect the magnitude of the starting inrush current.

REFERENCES

- [1] J. H. Stout, "Capacitor Starting of Large Motors," IEEE Transactions on Industry Applications, vol. IA-14, no. 3, pp. 209–212, May/Jun. 1978.
- [2] A. J. Williams and M. S. Griffith, "Evaluating the Effects of Motor Starting on Industrial and Commercial Power Systems," IEEE Transactions on Industry Applications, vol. IA-14, no. 4, pp. 292–305, Jul./Aug. 1978.
- [3] J. A. Kay, R. H. Paes, J. G. Seggewiss, and R. G. Ellis, "Methods for the Control of Large Medium-Voltage Motors: Application Considerations and Guidelines," IEEE Transactions on Industry Applications, vol. 36, no. 6, pp. 1688–1696, Nov./Dec. 2000.
- [4] M. G. Solveson, "Soft-Started Induction Motor Modeling," IEEE Transactions on Industry Applications, vol. 42, no. 4, pp. 973–982, Jul./Aug. 2006.
- [5] A. J. Rezek, "Energy Conservation With Use of Soft Starter," in Proc. IEEE Industry Applications Society Annual Meeting, 2000, pp. 354–359.
- [6] F. Blaabjerg, "Can Soft Starters Help Save Energy," IEEE Industry Applications Magazine, pp. 56–66, Sep./Oct. 1997.
- [7] R. Parekh, AC Induction Motor Fundamentals, Application Note AN887. Chandler, AZ: Microchip Technology Inc.
- [8] V. Cohen, Induction Motor — Protection and Starting. Johannesburg, South Africa: Circuit Breaker Industries, Technical Note.
- [9] B. L. Theraja, Textbook of Electrical Engineering, Vol. II. New Delhi, India: S. Chand & Co., 2008.
- [10] Memories.ai, "Motor Acceleration Analysis: A Comparative Case Study of Starting Methods (200 HP ETAP Study)," shared analysis, Oct. 2023. [Online]. Available: <https://memories.ai/app/share/chat/b421ef66-c4b2-4e98-9d99-e7c6f54841a4>



INTERNATIONAL
STANDARD
SERIAL
NUMBER
INDIA



INTERNATIONAL JOURNAL OF INNOVATIVE RESEARCH

IN SCIENCE | ENGINEERING | TECHNOLOGY

 9940 572 462  6381 907 438  ijirset@gmail.com



www.ijirset.com

Scan to save the contact details