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AC Motors and Drive Architectures: From Electromechanical Starters to Solid-State Variable Frequency Control

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Abstract: This paper presents a comprehensive examination of alternating current (AC) induction motors, synchronous machines, and their associated control topologies, bridging classical electromagnetic theory with heavy-duty industrial field realities. Beginning with fundamental operating principles—governed by Faraday's Law of Induction, Lorentz Force mechanisms, and the critical role of high-permeability, laminated silicon steel cores in mitigating eddy currents, the discussion evaluates the inherent self-regulating torque-speed feedback loop and slip dynamics. A comparative analysis is drawn between asynchronous squirrel-cage machines and synchronous architectures across high-reliability environments, examining mechanical wear mechanisms in carbon brushes versus brushless configurations. Furthermore, the operational and economic evolution of motor starting and speed control methodologies is investigated, contrasting traditional electromechanical techniques (Direct-On-Line, Star-Delta, and Korndörfer autotransformer starters) with modern solid-state power electronics (SCR soft starters, cycloconverters, and IGBT-based Variable Frequency Drives). While Pulse Width Modulation (PWM) and DSP-driven Field-Oriented Control (FOC) deliver unmatched dynamic performance in precision robotics and process lines, their associated dielectric stresses (dV/dt transients), harmonic generation, and lifecycle cost trade-offs are critically analyzed against robust, low-cost electromechanical alternatives. Finally, practical operational insights on grounding integrity, active magnetic bearings, brushless excitation topologies, and universal motor dynamics are provided to guide field engineers and facility designers in selecting optimized, cost-effective drive solutions.

Keywords: Primary Terms: Induction motors, Squirrel-cage rotor, Synchronous motors, Rotating Magnetic Field (RMF), Slip dynamics, Motor starters. Power Electronics & Drives: Variable Frequency Drives (VFD), Insulated Gate Bipolar Transistors (IGBT), Silicon Controlled Rectifiers (SCR), Cycloconverters, Pulse Width Modulation (PWM), Field-Oriented Control (FOC), Digital Signal Processing (DSP). Electromechanical Starting & Control: Direct-On-Line (DOL), Star-Delta starter, Autotransformer starter, Korndörfer circuit, Inrush current reduction. Design & Machine Reliability: Relative magnetic permeability, Silicon steel laminations, Eddy current suppression, Harmonic distortion, dV/dt transients, Active Magnetic Bearings (AMB), Brushless generators, Universal motors.

INTRODUCTION

Induction Motor Functioning

Induction motors were invented by Nikola Tesla. Today, induction motors consume 50% of all electricity generated worldwide, and 90% of all motors used in industry are induction motors. Over 300 million induction motors are currently in use across the globe, with more than 30 million sold annually for industrial applications alone [Dood, K. J. *et al*., 1989].

CURRENT LANDSCAPE OF MOTORS

In an induction motor, the rotating magnetic field (RMF) rotates around the stator (the stationary part of the motor) at a synchronous speed determined by the supply frequency and the motor's pole count. It can be visualized as a physical magnet rotating around the stator.

The rotor (the rotating inner part) typically features a squirrel-cage design, consisting of conductive bars short-circuited at both ends by two end rings. As the RMF sweeps across a rotor bar, it induces a voltage and current in that bar according to Faraday's Law of Induction. Current flows down one bar, travels through the end ring, and returns along a parallel bar on the opposite side, completing a continuous circuit loop.

Inside the squirrel cage, the space between the bars is filled with stacked silicon steel laminations, each coated with a thin layer of electrical insulation. This tremendously increases the magnetic field strength generated by the current flowing through the rotor bars. Similarly, the stator is constructed from insulated silicon steel laminations to amplify the strength of the RMF.

To understand why laminations are insulated, consider placing a magnet on top of a sheet of paper with an iron nail suspended beneath it. The nail is held in place because magnetic flux easily passes through an electrical insulator like paper. However, if you insert paper in between a copper wire circuit, current flow stops completely because paper blocks electricity. In an electric motor, we want magnetic flux to flow freely through the iron core while keeping eddy currents confined within individual laminations.

For electrical conduction, the best materials are silver, copper, gold, and aluminum. But for

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magnetic conduction—known as relative magnetic permeability (μ_r)—iron is the best economically viable material. The relative permeability of air, paper, copper, and aluminum hovers around 1, whereas that of silicon steel can exceed 1,000 [Bowler, N. 2006].

I once energized a 24 V contactor coil without its iron core and touched the tip of a screwdriver to it; there was only a weak magnetic pull. However, once the iron core was inserted into the coil, the screwdriver was drawn in with tremendous force. This practical demonstration clearly shows how high magnetic permeability drastically increases the effectiveness of an electromagnetic device.

This current flow transforms the rotor bar into an electromagnet, generating a magnetic force (Lorentz Force: $F = BIL$) that pulls the rotor along in the direction of the RMF. However, if the rotor were to reach the exact speed of the RMF, there would no longer be any relative motion between the bars and the magnetic field. Without relative motion, no voltage or current is induced, the bar loses its magnetism, and the rotor falls behind the RMF.

As soon as the rotor slows down, relative motion resumes, current is induced once more, and the rotor accelerates. Consequently, the rotor can be envisioned as continuously trying to catch up with the RMF while perpetually falling behind creating an overall speed lag relative to the RMF, a difference known as **slip**.

An induction motor typically operates at around 95% of synchronous speed under load. Note that this is not a fixed 95%; depending on the applied load, it can vary dynamically anywhere from nearly 100% at no-load down to 95% or lower under heavy load.

Because of this variable slip, an uncompensated induction motor cannot be used for precision applications—such as a robot arm trying to grab a cup—because it lacks exact position control and will miss its target [Ferreira, F. *et al*., 2015].

The Self-Regulating Torque-Speed Loop

When a load changes, the motor automatically stabilizes its speed through an inherent negative feedback loop:

[Rotor Slows Down Slightly]
↓
[Relative Speed Difference (Slip) Increases]
↓
[Magnetic Field Lines Cut Rotor Bars Faster]
↓
[Induced EMF & Rotor Current Increase
(Faraday's Law)]
↓
[Electromagnetic Torque Increases
(Lorentz Force: $F = BIL$)]
↓
[Motor Accelerates Back Up to Equilibrium]

Motor Control, Durability, and Evolution

Concepts like *synchronism* and *induction* can sound intimidating at first, but their core mechanisms are straightforward.

When my 13-year-old son came home from school and asked my wife (who is also an electrical engineer), *"What does synchronous mean?"*, she asked him to mirror her as she stretched out her arms and raised them up in rhythm. She then said, *"You are now in synchronism with me."*

Synchronous vs. Induction Motors

In a synchronous motor, the rotor locks onto and rotates in exact synchronism with the stator's Rotating Magnetic Field (RMF). Traditionally, wound-rotor synchronous motors require carbon brushes and slip rings to supply DC excitation to the rotor coils, introducing a mechanical wear point that eventually degrades over time.

An induction motor (often called an asynchronous motor), on the other hand, derives its name from electromagnetic induction: the RMF induces current directly into the rotor bars without physical contact or external wiring.

Because standard induction motors have no brushes or slip rings, they are remarkably durable.

- Real-World Durability: At the Western Digital factory in Kuching (where I previously worked), an exceptionally well-

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built induction motor ran continuously for 31 years without failure.

- Failure Points: The only primary failure points in an induction motor are the shaft bearings and the insulating varnish coating the stator windings. If high-grade bearings and insulation are used, an induction motor can run reliably for decades. Conversely, no matter how well a brushed synchronous motor is constructed, its carbon brushes will inevitably wear out and require maintenance.

The Evolution of Motor Drives in Elevators and EVs

Historically, elevator control systems relied predominantly on DC motors because electronic control signals from early computer controllers had to be translated into variable power outputs. An elevator cabin cannot start or stop abruptly without passengers experiencing a harsh jerk at every floor, requiring smooth deceleration profiles via variable motor drives.

1. The SCR Era: The first power electronic device capable of using low-power control signals to switch high-power loads was the Silicon Controlled Rectifier (SCR). Because early SCR circuits were fundamentally designed for DC voltage control, lift motors initially relied on DC systems (such as Ward-Leonard generator sets or SCR-based DC phase controllers). Later, anti-parallel (back-to-back) SCR configurations were developed to control AC induction motors directly by ramping AC voltage.
2. The IGBT Revolution: Following the invention and commercialization of the Insulated Gate Bipolar Transistor (IGBT) by Dr. B. Jayant Baliga in the early 1980s, precise, high-frequency Pulse Width Modulation (PWM) control of AC induction motors became possible. As a result, modern elevators transitioned from DC drives to Variable Voltage Variable Frequency (VVVF) AC drives, delivering exceptionally smooth S-curve acceleration, precise floor leveling, and high energy efficiency [Bendre, A. *et al*., 2002].

Distinguishing VSD, VFD, and VVVF

In industrial engineering, terms like VSD, VFD, and VVVF are often used interchangeably, but VSD (Variable Speed Drive) is the broad umbrella term for *any* system—electronic, electrical, or mechanical—that alters the operating speed of driven machinery:

- AC Electronic Drives (VFD / VVVF): Electronic drives that control AC induction or permanent magnet motors by adjusting supply frequency and voltage simultaneously (V/f control).
- DC Electronic Drives: Solid-state drives that adjust armature voltage or field current to control a DC motor.
- Mechanical VSDs: Variator systems utilizing adjustable cone pulleys, traction drives, or belts to mechanically alter the speed ratio while the driving motor runs at a fixed RPM.
- Hydraulic VSDs: Hydrokinetic fluid couplings or variable-displacement pumps used in heavy mining, marine, and power plant applications to slip torque and modulate speed.

I once met a maintenance technician working in a 22-story building that housed high-profile executives. Although he knew that modern carbon brushes could last up to 20 years under normal conditions, he replaced them every single month. He knew that carbon brushes would eventually fail, and he refused to risk an executive getting trapped in a lift—a scenario that would cost him his job [Kirange, Y. K. *et al*.,].

Although the first modern electric vehicle (EV) was built with a traditional induction motor—initially invented by Nikola Tesla (Tesla, Inc. was named to honor the great scientist; it is not owned by his descendants)—the technology evolved toward Permanent Magnet Synchronous Motors (PMSMs), which do not require carbon brushes or slip rings.

PMSMs take advantage of both magnetic generation and high magnetic permeability:

1. The Neodymium Magnet ($\mu_r \approx 1.05$): Acts as the source of high-density magnetic flux ($B_r \approx$ 1.2–1.4 T) without needing an external power source or field current.
2. The Silicon Steel Laminations ($\mu_r > 1{,}000$): Surround the magnets to act as the high-permeability "highway" (low magnetic reluctance) that channels, concentrates, and directs that magnetic flux across the air gap toward the stator windings.

Think of the Neodymium magnet as a high-pressure water pump (the force creator), and the iron/silicon steel as the pipes (the high-permeability pathway). Without high-permeability iron, the magnet's field would simply spill out in all directions into the surrounding air instead of being focused directly into the motor coils!

However, researchers in Bengaluru developed advanced VFD firmware and wireless rotating

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transformer technology that continuously adjusts the applied stator frequency, forcing the rotor to maintain an exact, steady speed despite changing loads. This development may negate the need for expensive rare-earth elements used in the permanent magnet rotors of modern EVs.

In a typical large generator, a high current is initially generated as the DC-magnetized rotor sequentially passes the L1, L2, and L3 coils. In an induction motor located far away (for instance, 1000 km away from a population center), a magnetic north pole is generated sequentially in its L1, L2, and L3 coils. The induction motor stator coils thus become magnetized almost as soon as the corresponding coils in the distant generator are energized. In effect, the induction of current in the generator coils creates what Nikola Tesla termed a "whirlwind of magnetism" around the stator coils of the motor 1000 km away. Today, this sequential magnetization of the stator coils in an induction motor is known as a Rotating Magnetic Field (RMF).

As shown in Equation (8.1), as the generator's magnetic rotor passes a stator coil, it energizes the corresponding coil in the remote induction motor in approximately 0.003 seconds. Consequently, the magnetization of the motor's stator coils directly tracks the rotation of the generator's rotor.

The grid frequency is fixed at 60 Hz in North America and 50 Hz across most of the rest of the world, setting the required rotational speed for generator rotors. Motors and generators adhere to Equation (8.2) for synchronous speed. But because gas turbines naturally spin at higher speeds and cannot be easily throttled down to 50 Hz or 60 Hz, generators with fewer poles (higher numerator) are used to maintain the target grid frequency. Conversely, because hydroelectric turbines naturally turn much slower, generators with more poles (lower numerator) are used to achieve the required 50 Hz or 60 Hz output.
As shown in the calculation below, it takes only approximately 0.003 seconds for the induced current from a generator coil to magnetize the corresponding coil in a motor 1000 km away:

$$S = \frac{D}{t} \quad (8.1)$$

$$\text{or} \quad t = \frac{D}{S} \quad (8.1)$$

$$t = \frac{1000 \text{ km}}{300{,}000 \text{ km/s}} = 0.0033 \text{ s}$$

$$\eta_s = \frac{120f}{P} \quad (8.2)$$

$$f = \frac{\eta_s P}{120} \quad (8.2)$$

This calculation assumes the electromagnetic signal propagates near the speed of light, which closely approximates reality for bare overhead transmission lines. However, when insulation surrounds the conductors, the propagation speed decreases slightly due to the dielectric properties of the insulation material rather than heat buildup. Additionally, underground cables act as continuous longitudinal capacitors that charge and discharge twice every cycle, further slowing signal propagation and introducing capacitive reactive losses.

Induction motors can last up to sixty years if the varnish surrounding the copper coils and the two bearings supporting both ends of the rotor are of high quality. The most modern high-speed induction motors use Active Magnetic Bearings (AMBs). Here, the shaft is levitated in space by actively controlled electromagnets, leaving zero contact between the stator and rotor. These are called Ultra-High-Speed Magnetic Bearings. With no friction, magnetic bearings not only drastically increase lifespan but also enable operation in a vacuum at extremely high rotational speeds. Speeds of up to 500,000 RPM (revolutions per minute) have been achieved [Ferreira, F. J. *et al*., 2015; Dutta, D. *et al*., 2024].

Consider a single bar of a squirrel-cage rotor with respect to the Rotating Magnetic Field (RMF) in the stator. In slow motion, when someone switches on the three-phase induction motor, the RMF is activated. The RMF field lines cut through the stationary bar of the squirrel-cage rotor. By Fleming's right-hand rule for generators, a current is induced in this bar. This current flows to the end ring, travels halfway around it, moves down through the opposing bar to the second end ring, travels halfway around that ring as well, and

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returns to the first bar. Therefore, at any given moment, the electrons move in a closed rectangular circuit. This current generates its own magnetic field according to the right-hand rule.

This induced magnetic field interacts with the RMF to create a rotational force (via Fleming's left-hand rule), causing the rotor to turn and chase the speed of the RMF (synchronous speed). When the rotor lags far behind the RMF, it cuts through a greater number of field lines per unit of time, experiencing a rapidly changing magnetic flux density. This induces more current and generates stronger magnetism in the rotor bars. Conversely, as the rotor approaches the speed of the RMF, it cuts fewer lines per unit of time, reducing the induced current and magnetic field strength, causing the rotor to slow down.

An analogy is two cars traveling at the exact same speed: the passengers can talk to each other because the relative speed between the cars is zero. Similarly, if the rotor bar were to reach the exact speed of the RMF, it would experience no change in magnetic flux density. The induced current would drop to zero, and the bar would lose its magnetic field. Without these magnetic field lines, the magnetic force pulling the rotor disappears, causing the bar to lag behind. However, as it falls back, it experiences a changing field density once again, regaining current flow and its magnetic field. Re-establishing this magnetic force allows the bar to try to catch up with the RMF again. This continuous process of catching up and falling back ensures smooth continuous operation, with the lag adjusting whenever the motor's load changes.

Synchronous motors run at synchronous speed, meaning the rotor rotates at the exact same speed as the Rotating Magnetic Field (RMF) generated by the stator. In a grid-connected system, this stator RMF rotates in unison with the RMF of a power station generator—such as a steam turbine located 1,000 km away—because the generator's rotational speed dictates the grid frequency. An induction motor, by contrast, operates with a slight lag called *slip*, typically running at roughly 1% to 5% below synchronous speed under full load.

Traditional synchronous motors use carbon brushes to feed DC power into the rotor to energize its magnetic field. However, modern precision synchronous motors—such as Permanent Magnet Synchronous Motors (PMSMs)—eliminate brushes entirely by using high-strength permanent magnets in the rotor [Sain, C. *et al*., 2021].

By the mid-2010s, high-precision synchronous motors had largely taken over high-speed robotic arm applications. This shift became possible because engineers achieved precise digital control over the stator's Rotating Magnetic Field (RMF) using Digital Signal Processors (DSPs).

Historically, processing analog signals relied on complex calculus—such as double, triple, and contour integrals—making real-time motor control computationally prohibitive. Consequently, students who took telecommunication engineering during that era faced low pass rates.

DSP technology simplified this by sampling continuous analog signals into discrete digital data points at precise intervals. The higher the sampling rate along the time axis, the more accurately the digital system can reconstruct and control the signal.

For example, a music waveform consists of a continuous sequence of peaks and troughs. If that continuous wave is divided along the time and voltage axes, the signal can be quantified at each time interval by measuring the rectangular blocks it occupies. As these time intervals are made smaller—a process known as increasing the sampling rate—the digital representation becomes far more accurate, yielding clearer, more melodious music. This process of converting continuous signals into digital data is called Analog-to-Digital Conversion (ADC).

This advance in DSP algorithms—originally driven by telecommunications and mobile phone development—eventually revolutionized motor drives. By utilizing DSP-driven Vector Control (or Field-Oriented Control), controllers can dynamically modulate the RMF to position a synchronous motor with micro-millimeter precision [Sambhavi, Y. V., & Vijayapriya, R. *et al*., 2025].

Previously, robotic arms relied primarily on stepper motors or older hydraulic/servo systems. While stepper motors provide precise step-based movement, they lack the high torque density and efficiency needed for heavy-duty industrial tasks. Synchronous motors deliver immense power and speed, making high-torque industrial robotics feasible given an adequate power supply [Athani, V. V. 1997].

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Induction motors are unsuitable for high-precision robotic arms because of variable rotor slip. While an induction motor's lag might average around 5%, this slip fluctuates constantly based on mechanical load—ranging from near 0% under no load to much higher percentages under heavy stress. This load-dependent variance prevents the exact position control required in advanced manufacturing.

For example, in high-speed manufacturing environments—such as a Western Digital facility where robotic arms handle delicate computer hard disk platters—the robot must pick up platters and align them inside cassettes with clearances as tight as 0.5 mm. Because these operations happen faster than the human eye can track, even a minor fraction of a millimeter in position variance caused by motor slip would destroy the media. Synchronous motors ensure that the rotor follows the stator's RMF precisely, providing the zero-slip reliability required for extreme robotic precision.

$$\eta_s = \frac{120f}{P} \quad (8.2)$$

$$f = \frac{\eta_s P}{120} \quad (8.2)$$

The P in Equation (8.2) represents the number of poles in the motor. For the two-pole, delta-connected induction motor shown in Fig. 1.1, each phase is connected to one end of a coil, and the other end of that coil connects to another phase. Thus, two phases energize a single coil—a solenoid that produces one North (N) and one South (S) pole—which is why it is called a two-pole (two magnetic poles) motor.

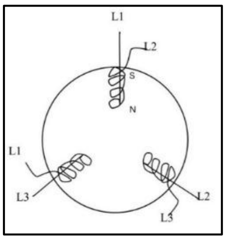

Fig. 1.1: Two-pole induction motor connection with two magnetic poles, N, S

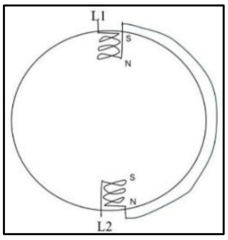

Fig. 1.2: Four-pole motor with four magnetic poles, N, S, S, N

For the four-pole motor shown in Fig. 1.2, the line wire $L1$ connects to the start of a clockwise-wound coil, which then connects in series to a bottom coil wound counterclockwise before reaching line $L2$. Consequently, each pair of phases generates two magnetic pairs—N, S and S, N—resulting in a four-pole motor.

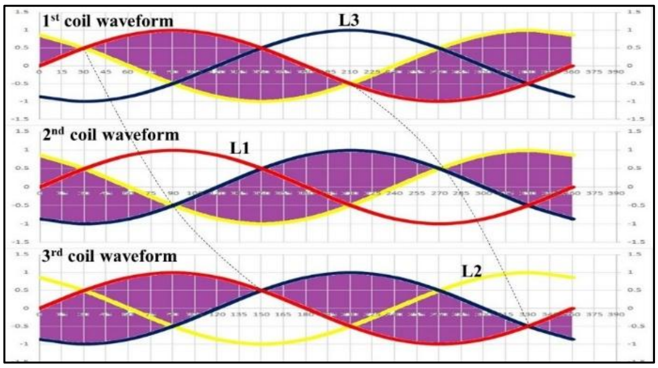

Fig. 1.3: Three-phase waveform going into a two-pole, three-phase induction motor

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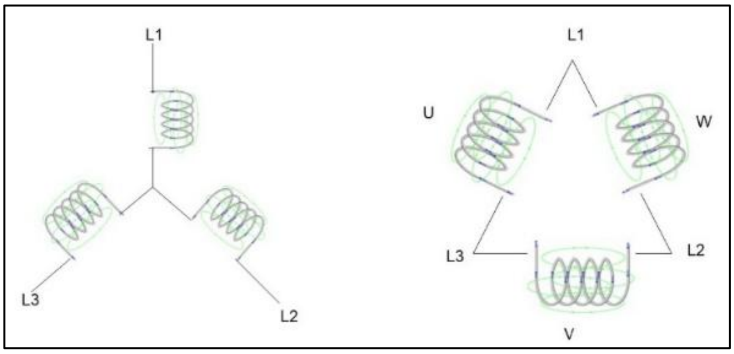

Fig. 1.4: Star-connected motor on the left, Delta-connected motor on the right

Fig. 1.3 shows the waveform generated for the two-pole, three-phase induction motor depicted in Fig. 1.1. Following the $L1, L2, L3$ sequence, the first coil is energized across $L1$ and $L2$, the second across $L2$ and $L3$, and the third across $L3$ and $L1$. A three-phase induction motor typically features six connection terminals: three top and three bottom. Installers can connect $L1, L2, L3$ across the top and bottom terminals to complete the circuit. This configuration is called a Delta connection, as illustrated on the right side of Fig. 1.4.

Another way to wire the motor in Delta is using the three jumper bars supplied with the motor. Place the three bars vertically to connect each top terminal to the terminal directly beneath it. With this arrangement, only three supply wires need to run from the starter or control panel to the motor terminals. As shown in Fig. 1.4 (right), each motor phase coil (U, V, W) sits directly between two line phases.

To wire the motor in a Star (Wye) configuration, use the three jumper bars horizontally to short-circuit the top three terminals together. Then, connect the three bottom terminals to the incoming supply lines $(L1, L2, L3)$. As shown in Fig. 1.4 (left), each coil sits between a phase line and a neutral point created by tying all three phases together.

Why do the three connected phases sum to 0 V? Examine Fig. 1.5: at 5 ms along the X-axis, the red and yellow waveforms are both at -0.5, while the blue waveform is at $+1.0$:

$$-0.5 + (-0.5) + 1.0 = 0 \text{ V}$$

At 15 ms, the red and yellow waveforms rise to $+0.5$ while the blue waveform drops to -1.0:

$$+0.5 + (+0.5) + (-1.0) = 0 \text{ V}$$

At any point in time along the X-axis, the instantaneous sum of the three phase voltages is always 0 V.

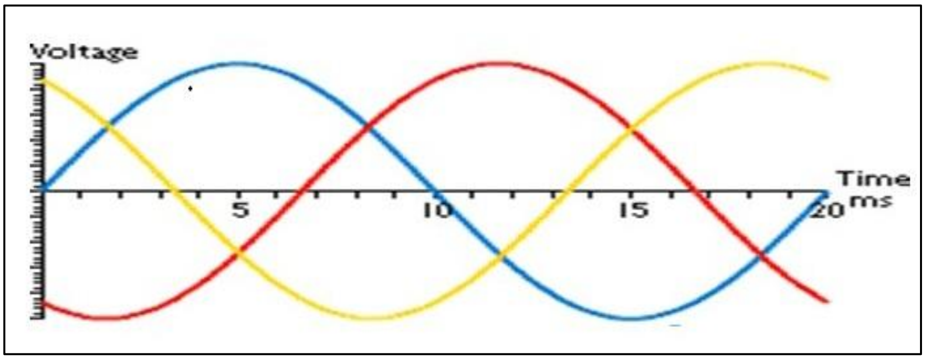

Fig. 1.5: Three-phase waveform going into a two-pole three-phase induction motor

Therefore, connecting the motor in Delta applies the full phase-to-phase voltage (Φ–Φ) across each coil—typically 208 V in the US and 415 V in the UK. Connecting the motor in Star subjects each coil to phase-to-neutral voltage (Φ–N)—typically 120 V in the US and 240 V in the UK. As a result, a motor wired in Delta delivers noticeably higher power and starting torque.

The line voltage (phase-to-phase voltage) across the three motor coils corresponds to the shaded region between phases shown in Fig. 1.3. The dashed lines indicate the three coils being energized sequentially around a three-phase, two-pole induction motor. While four-pole induction motors are the most common in practice, the two-pole motor is easier to conceptualize, and the same fundamental principles expand directly to a four-pole configuration.

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Looking at the purple-colored sections:

- Coil 1 collapses to 0 V at 30°
- Coil 2 collapses to 0 V at 90°
- Coil 3 collapses to 0 V at 150°

Thus, there is a 60° electrical offset ($90^\circ - 30^\circ = 60^\circ$) between Coil 1 and Coil 2 reaching zero voltage, and similarly 60° ($150^\circ - 90^\circ = 60^\circ$) between Coil 2 and Coil 3 reaching zero voltage.

Timing Calculations for Phase Offset

For a **60 Hz system** (standard in North America), 1 complete electrical cycle takes:

$$T = \frac{1}{60\ \text{Hz}} = 0.01667\ \text{s} = 16.67\ \text{ms}$$

The time delay corresponding to a 60° phase shift between sequential coil de-energizations is:

$$t_{60^\circ} = \frac{60^\circ}{360^\circ} \times 16.67\ \text{ms} = 2.78\ \text{ms}$$

For a **50 Hz system** (standard in Europe and Asia), 1 complete cycle takes:

$$T = \frac{1}{50\ \text{Hz}} = 0.020\ \text{s} = 20.0\ \text{ms}$$

The corresponding time delay for a 60° phase shift is:

$$t_{60^\circ} = \frac{60^\circ}{360^\circ} \times 20.0\ \text{ms} = 3.33\ \text{ms}$$

Four-Pole Motor Configuration & Speed

In a standard four-pole induction motor, each phase winding is divided into two separate coils (solenoids), as shown in Fig. 1.6.

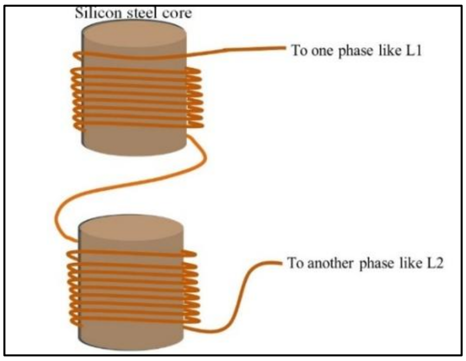

Fig. 1.6: Winding method

Each solenoid creates a North (N) and South (S) magnetic pole, yielding a total of four poles across the machine ($2 \times 2 = 4$). The total number of magnetic poles formed per phase defines the pole rating of the motor.

The synchronous speed (n_s) of a four-pole motor is calculated using:

$$n_s = \frac{120 \times f}{P}$$

Where f is the line frequency and P is the number of poles:

- **At 60 Hz:** $n_s = \frac{120\times60}{4} = 1800$ RPM
- **At 50 Hz:** $n_s = \frac{120\times50}{4} = 1500$ RPM

If each phase wire forms a clockwise coil and continues into a counterclockwise coil in series, four poles are generated: N and S on the clockwise winding, and S and N on the counterclockwise winding [UV, S. S., & Kishore, R. Y. N. 2025].

Rotor Current & The Variable Frequency Drive (VFD)

In a squirrel-cage rotor, induced currents reach maximum intensity in one rotor bar and gradually taper in adjacent bars. However, these localized currents all flow in the same longitudinal direction (e.g., left to right in Fig. 1.7).

The current travels to the end ring, loops down to the opposite side of the cage, and returns from right to left through the bottom bars to form a complete circulating loop. This circulating current generates a rotor magnetic field that interacts with

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the rotating magnetic field (RMF) produced by the stator.

Historically, a major limitation of induction motors was their fixed operational speed, which locked them to the grid frequency (minus a small slip factor of approximately 3–5%):

- 60 Hz (4-pole actual speed): $n_r = 1800 \times 0.95 = 1710$ RPM
- 50 Hz (4-pole actual speed): $n_r = 1500 \times 0.95 = 1425$ RPM

The commercial introduction of the Insulated Gate Bipolar Transistor (IGBT) in the 1980s revolutionized motor control. Microprocessor-controlled Variable Frequency Drives (VFDs) using IGBT switches synthesize custom AC waveforms, allowing induction motors to operate continuously from near zero RPM to speeds significantly higher than synchronous grid speed [12].

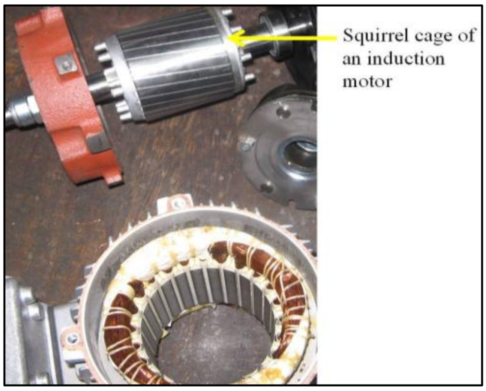

Fig. 1.7: Squirrel cage of an induction motor

Construction Features of the Squirrel-Cage Rotor

1. Skewed Rotor Bars

The rotor bars are arranged at a slight angle relative to the central shaft rather than parallel to it. This skewing serves two main purposes:

1. Noise Reduction: Reduces magnetic hum caused by slot harmonics.
2. Smooth Operation: Prevents "cogging" (magnetic locking between stator and rotor teeth) during startup.

2. Rotor Bar Materials

- Aluminum: Lightweight with lower inertia, making the motor easier to start up with lower inrush torque requirements.
- Copper: Higher electrical conductivity, yielding higher operating efficiency, lower thermal losses, and reduced energy consumption.

3. Laminated Steel Core

Laminated silicon steel sheets stacked within the rotor cage serve three essential engineering functions:

1. High Permeability: Iron provides a low-reluctance magnetic path ($\mu_r \approx 100$ to $10{,}000$) compared to air ($\mu_r = 1$), concentrating the magnetic flux generated by induced currents.
2. Mechanical Rigidity: The steel core provides structural strength to support high mechanical loads and torque production.
3. Eddy Current Suppression: Insulation (varnish) between thin laminations restricts eddy currents to small loops within individual sheets, preventing severe core overheating and efficiency losses [Baliga, B. J. 2015].

The Critical Role of Proper Grounding

Unchecked eddy currents and high-frequency noise induced in ungrounded motor frames can cause severe operational instability. Operating a three-phase motor with its frame Protective Earth (PE) line disconnected often leads to noticeable physical vibration and audible frame chatter ("tak-tak-tak" hammering) as stray capacitive charges and eddy currents seek an alternative return path.

In one test conducted by me on a 25 HP motor, disconnecting the earth ground wire caused the motor to vibrate violently with a loud, rhythmic "tak-tak-tak" chatter. Once the ground wire was reconnected, the frame potential stabilized, the vibration ceased immediately, and the motor returned to its normal, smooth operational hum ("tweeee"). Interestingly, this phenomenon is far less pronounced—and often imperceptible to the ear—on smaller machines, such as a 5 HP motor, due to their lower magnetic flux density and smaller frame capacitance.

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In industrial environments, weak ground connections often lead to mysterious intermittent line trips. Ground faults in auxiliary equipment (e.g., metallic desk lamps shorting internally) can cause nuisance tripping across plant distribution networks if junction splices are poorly insulated or improperly grounded. Always maintain proper physical spacing between conductor splices and use high-grade electrical tape to prevent insulation breakdown over time.

MOTOR STARTERS

The below WhatsApp conversation (with someone with zero knowledge of starters) is a good description of DOL (Direct On line) motor starter:

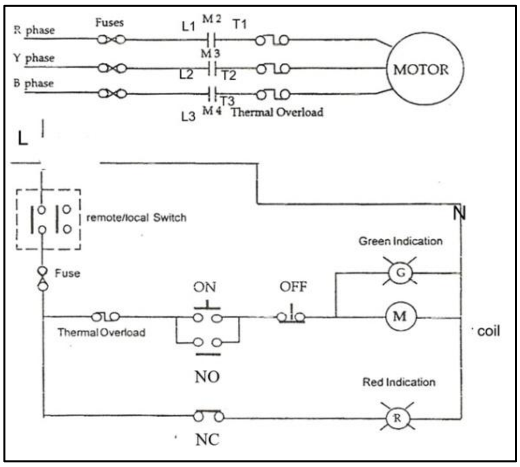

Fig. 1.8: DOL motor starter schematic

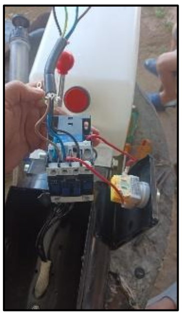

Fig. 1.9: wrongly connected DOL motor starter

Prashobh: Take a look at the schematic in Fig. 1.8. The critical part is that the ON (green) push-button switch is held closed by the NO (Normally Open) auxiliary contact. The wires running through the center of the contactor (L_1, L_2, L_3) are the main power lines. In this setup, line wire L connects to the NO auxiliary contact on the side of the contactor before routing through the main contactor alongside N, which then both connect to the motor terminals (L and N).

Former Student: But right now we don't have a 3-phase supply. How should I wire it if I'm using a single-phase supply?

Prashobh: You still use the L_1, L_2, and L_3 terminals, but you only route your single-phase live (L) and neutral (N) wires through them.

Prashobh: You see a lot of improperly wired circuits like this in the field (Fig. 1.9) where technicians take shortcuts because they don't understand how the auxiliary hold-in contact works. Since they don't grasp the primary purpose of the starter, they simply bypass it.

Prashobh: The main reason we use a DOL starter or contactor—instead of a standard manual switch—is that larger motors draw high current. Manual switching with a human finger is far too slow, causing electric arcing across the contacts and posing a major safety hazard. Because a human finger moves slowly, you press a push button to energize an electromagnetic coil, which snaps the contactor contacts shut extremely fast to minimize arcing.

Main Purpose of Motor Starters

This section covers common methods for starting AC induction motors that offer a cost-effective balance between performance and equipment protection.

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Primary Functions

The core purpose of a motor starter is to safely overcome **inertia**—the physical resistance of a stationary object to motion. Just like pushing a heavy cabinet, the energy required to break static friction and get it moving from a standstill is far greater than the energy needed to keep it sliding.

Without a motor starter, an AC induction motor started Direct-On-Line naturally draws an inrush current that spikes to **6 to 8 times** its rated full-load current. A motor starter limits this sudden surge to prevent:

- **Electrical stress** on the motor windings (risk of thermal overload, insulation breakdown, and coil burnout).
- **Mechanical stress** on the motor bearings, couplings, and rotor shaft caused by a sudden, harsh torque spike.

By using a reduced-voltage starter to temporarily cut the starting voltage by half ($0.5\,V$), the starting current drops proportionally ($0.5\,I$). Because electrical power absorbed by the motor scales as $P = V \times I$, halving both voltage and current drastically reduces the initial power draw to **25%** ($0.5 \times 0.5 = 0.25$) of full-voltage starting power:

$$P_{\text{start}} = V_{\text{reduced}} \times I_{\text{reduced}} = (0.5V) \times (0.5I) = 0.25\,P_{\text{full}}$$

This sudden power suppression protects the motor coils from burning out while eliminating mechanical jerks on the shaft bearings. In standard industrial practice, this reduced-voltage sequence typically lasts about **6 seconds** before transitioning to full line voltage.

Reduced Voltage Starting

Starter Hierarchy & Starting Smoothness

Going down the list from 1 to 7, motor starting becomes progressively smoother. For instance, if a DOL starter is used on a 10 HP motor, the motor will jerk violently upon starting. By contrast, advanced electronic starters (methods 6 and 7) accelerate the motor smoothly without any vibration.

1. **DOL (Direct-On-Line):** Used for small fractional motors below 1 HP (and up to 5 HP in standard industrial applications).
2. **Star-Delta:** Commonly used for medium-sized motors from 1 HP to 5 HP (and up to 25 HP).
3. **Autotransformer (Auto-Trans):** Used for larger motors up to 200 HP (and higher).
4. **Primary Resistance:** Used for large industrial drives (such as 3,600 HP cement mill motors) where heavy-duty resistor banks—often immersed in insulating oil or liquid tanks to dissipate extreme heat—are placed in series with the stator windings.
5. **Slip-Ring (Wound Rotor) Induction Motors:** Typically used for high-inertia loads ranging from 300 HP to over 10,000 HP, utilizing external rotor resistance to control torque and inrush current.
6. **Soft Starters (using SCRs / Silicon Controlled Rectifiers):** Solid-state reduced-voltage starters used extensively with AC induction motors to smoothly ramp starting voltage up and down.
7. **VFD (Variable Frequency Drive) / VSD / Inverters (using IGBTs):** Provide full control over motor speed, frequency, and torque. These drives range from small units up to massive 35 MW to 45 MW systems, such as the multi-megawatt Siemens Robicon VFDs used on main refrigerant compressor strings in Qatar's LNG liquefaction plants.

The Realities and Cost Trade-offs of VFDs

Despite their operational advantages, many industrial operators express regret after replacing traditional starters with VFDs due to high capital costs and poor repairability:

- **High Cost & Irreparability:** Standard motor starters are simple to maintain—replacing a failed contactor costs as little as US$37 on a unit with an initial cost around US$250. In contrast, industrial VFDs can cost upwards of US$10,000. When a VFD fails, it usually requires a full unit replacement or expensive specialized board-level repair.
- **Environmental Exposure:** Industry personnel often overlook that a VFD is essentially a full computer (similar to a laptop with heavy power electronics). In applications like oil palm mills, a US$10,000 VFD is often mounted inside an unprotected shed, exposing sensitive circuitry to extreme ambient heat, humidity, and dust. Spending an additional US$500 on a small enclosure with air conditioning would significantly extend its service life.
- **Alternative Speed Control:** While facility engineers often claim a US$10,000VFD is mandatory to adjust conveyor speeds and prevent boiler jams, cheaper alternatives exist. Mechanical gearboxes, multi-speed motors, or cycloconverters can achieve variable speed at

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a fraction of the cost. It must be noted that in oil palm mills, when a VFD fails, the cost is not just the US$10,000 for a VFD a production loss of even one day could easily cost much more than S10,000. And since these ABB or Siemens VFD are expansive, so local companies do not keep ready stock. They must be flown in with expensive freight charge and still it may take 3-7 days of loss production.

Cycloconverters: Direct AC-to-AC Frequency Conversion

A cycloconverter converts a fixed-frequency AC supply into a lower, variable-frequency AC supply directly—without converting it to DC first. They utilize thyristors (Silicon Controlled Rectifiers / SCRs), which operate as solid-state controlled switches.

Unlike complex VFDs, cycloconverters are simpler, robust, and significantly cheaper (often costing around US$200 for small-scale applications).

As illustrated in Fig. 1.10, a cycloconverter synthesizes a lower output frequency by combining complete cycles of the incoming utility AC supply. For example, taking four full cycles of the input waveform to synthesize a single cycle of the output waveform reduces the frequency to $\frac{1}{4}$ of the input frequency [CHATTOPADHYAY, A. K. 1997].

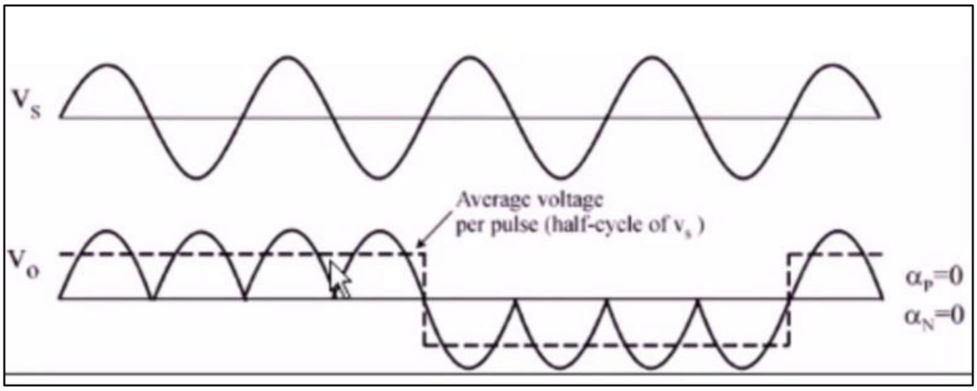

Fig. 1.10: Schematic and waveform synthesis of a single-phase cycloconverter

Frequency Formulas

On a 60 Hz utility grid, synthesized output frequencies can be:

$$f_{\text{out}} = \frac{60\text{ Hz}}{N} \quad \text{where } N = 1,2,3,4,\ldots$$

$$\text{For } N = 4: \quad f_{\text{out}} = \frac{60\text{ Hz}}{4} = 15\text{ Hz}$$

On a 50 Hz utility grid, synthesized output frequencies can be:

$$f_{\text{out}} = \frac{50\text{ Hz}}{N} \quad \text{where } N = 1,2,3,4,\ldots$$

$$\text{For } N = 4: \quad f_{\text{out}} = \frac{50\text{ Hz}}{4} = 12.5\text{ Hz}$$

DIRECT-ON-LINE STARTERS

Though this is the simplest starter, it is by far the most common method to start a motor. Fig. 1.11 is the schematic. It basically utilizes a three-phase contactor to send all three-phases to the motor. Why a contactor is used instead of a human hand operated switch is because the human hand is too slow. This is especially the case if the motor is very large. So, a human finger presses a start button and the contactor NO contact is used to hold this signal which sends current to the contactor coil. The contactor closes very fast, energizing the three phase wires going into the motor terminals. On the contactor is written L1, L2, L3 as the incoming phase cables and on the other side are U1, V1, W1 which are the names of the motor in-coming terminals. Because of the improvement in the technology of varnish and bearings today, up to 40 kw motors are today using DOL starters. Meaning the in-rush of current and mechanical jerking can be handled by the improved varnish and bearings.

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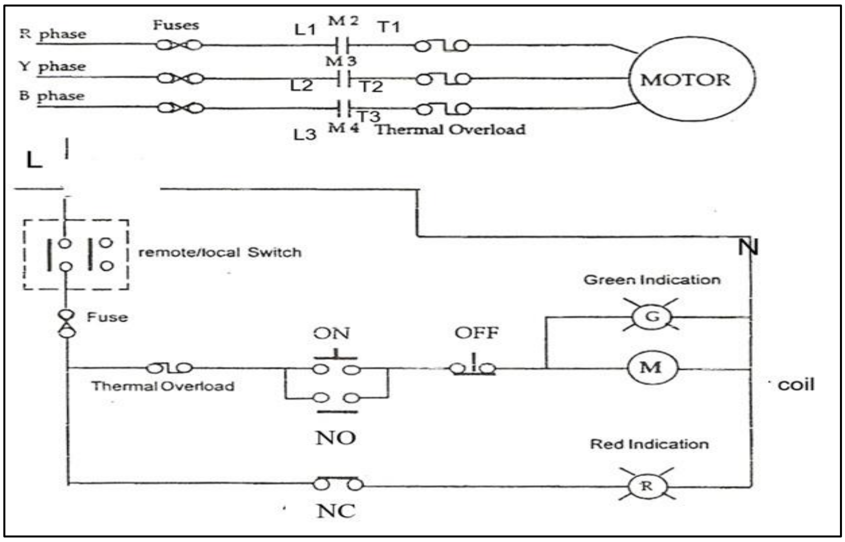

Fig. 1.11: The DOL starter

Although it is the simplest starter available, the Direct-On-Line (DOL) starter is by far the most common method for starting a motor (Fig. 1.11). It primarily utilizes a three-phase contactor to connect all three phases directly to the motor. A contactor is used instead of a manual switch because human operation is far too slow, especially for larger motors.

When an operator presses the start button, a Normally Open (NO) contact on the contactor latches the signal, energizing the contactor coil. The contactor then closes rapidly, energizing the three-phase power lines connected to the motor terminals. The incoming phase cables are connected to terminals L1, L2, and L3 on the contactor, while the outgoing side connects to the motor terminals labeled U1, V1, and W1.

Thanks to advancements in bearing design and wire varnish insulation, motors rated up to 40 kW can now safely use DOL starters, as modern components are capable of handling the resulting mechanical jerk and high inrush current.

STAR-DELTA STARTER

Before understanding how a Star-Delta motor starter operates, one must first understand the operation of an electrical contactor. Fig. 1.12 illustrates the operating schematic of a typical contactor. While physical contact arrangements and mechanical layouts vary by manufacturer, the underlying principle remains the same.

When the solenoid coil is de-energized, the Normally Closed (NC) contacts remain closed. Here, "normally" refers to the unenergized state. When voltage is applied to the solenoid, it becomes magnetized and pulls the upper armature, opening the NC contacts. Simultaneously, it draws the lower armature, causing the Normally Open (NO) contacts to close.

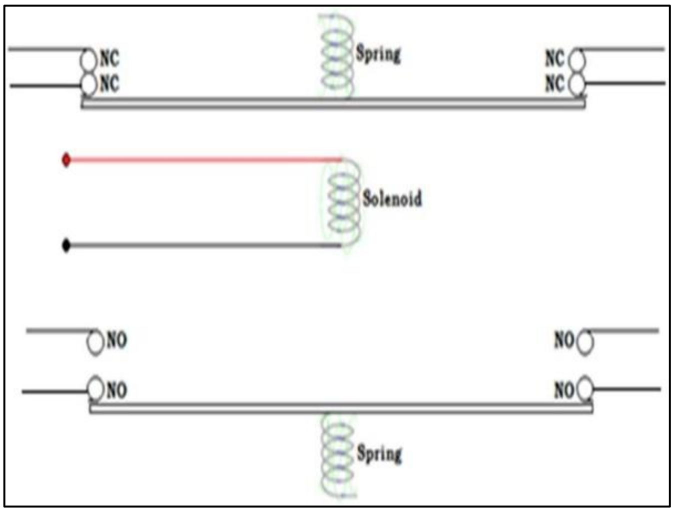

Fig. 1.12: Functional schematic of an electrical contactor

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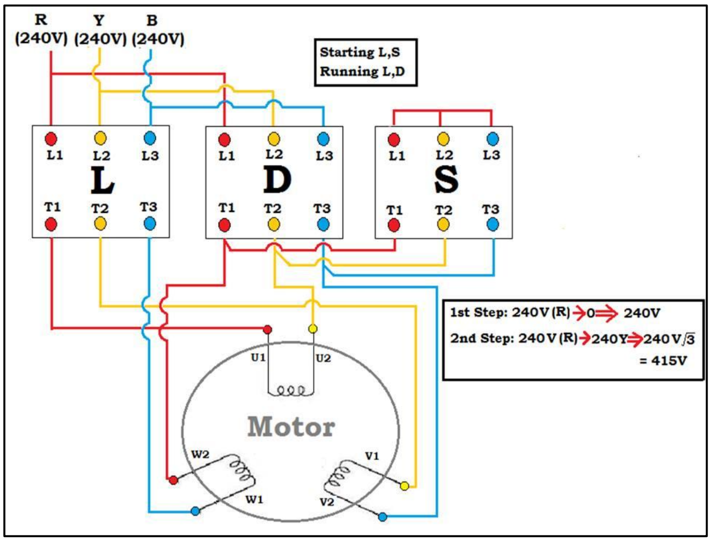

Fig. 1.13: Power Circuit of a Star-Delta Motor Starter

Fig. 1.13 is the power circuit schematic for a Star-Delta starter. The three contactors in the circuit are designated as Line (L), Delta (D), and Star (S). Although the contactors themselves are identical, their different designations dictate their specific wiring configurations.

During initial startup, contactors L and S close while D remains open. Looking at the U1–U2 winding of the motor, one side receives the phase voltage—120 V (or 240 V under the British/IEC standard)—from phase L1. The opposite terminal (U2) connects through the S contactor, where the three outgoing terminals are shorted together to form a star point (0 V). This applies a phase voltage of 120 V (240 V British) across the U1–U2 winding.

After approximately 6 seconds, contactor S opens and D closes. The U1 terminal continues to receive 120 V (240 V British) from phase L1, while terminal U2 now receives supply from phase L2. This applies full line-to-line voltage across the winding:

$$120\sqrt{3} \approx 208 \text{ V} \quad \left(\text{or } 240\sqrt{3} \approx 415 \text{ V in the British system}\right)$$

The other two motor windings (V1–V2 and W1–W2) undergo the exact same transition, initially experiencing phase voltage (120 V / 240 V) during start mode, followed by line voltage (208 V / 415 V) in delta run mode.

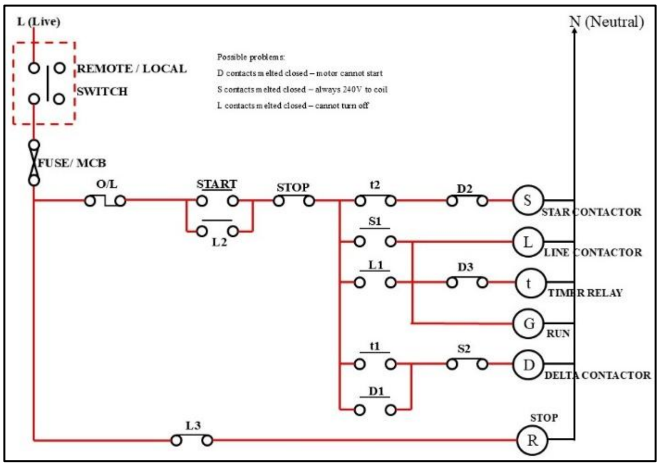

Fig. 1.14: shows the control circuit that accomplishes this sequence.

Fig. 1.14 is the control circuit for the Star Delta starter. When the Start button is pressed, power is supplied to the coil of the **Star (S)** contactor. Magnetization of the **S** coil closes contact **S1**, which in turn energizes three parallel branches feeding coils **L**, **t** (timer), and **G** (green indicator lamp).

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Energizing coil **L** closes contact **L1** (which serves as a holding contact for coil **L**) as well as contact **L2**, which latches the circuit so it remains energized after the operator releases the Start button.

Once timer coil **t** is energized, its internal timing mechanism initiates. After a 6-second delay, the Normally Closed contact **t2** opens to de-energize coil **S**. Simultaneously, the Normally Open contact **t1** closes momentarily, energizing coil **D**.

Because **t1** provides only a momentary signal (similar to a push button press), a holding circuit is required to keep coil **D** energized. Contact **D1** provides this self-holding function. Contacts **D2**, **D3**, and **S2** serve as an electrical interlocking system to prevent incorrect contactor sequencing—a critical safety measure, as these circuits can control motors up to 500 HP, where an improper sequence could cause severe damage or failure.

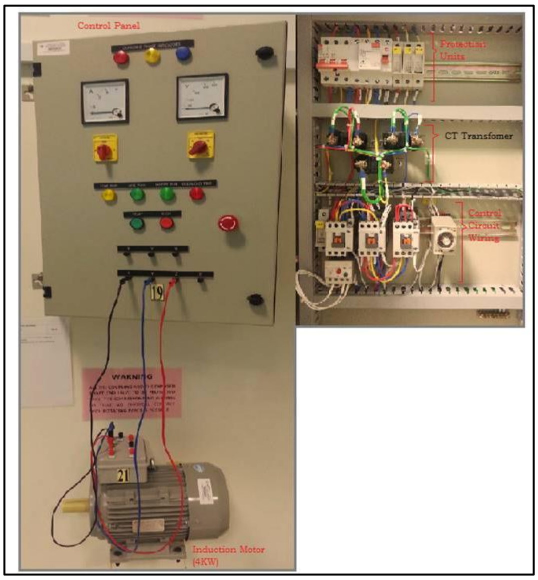

Fig. 1.15: Combined power and control circuit of a Star-Delta motor starter

AUTOTRAN STARTER

"Autotran" is short for autotransformer. This starter circuit utilizes an autotransformer—a transformer with a single continuous coil that uses its number of turns (N) to step down or split voltage. For example, if an autotran has 200 turns, scratching the varnish at the 100-turn point and soldering a wire there creates a tap. When energized with 120 V, the output voltage at that tapped wire will be 60 V.

For the autotransformer power circuit in Fig. 1.16, the three contactors are designated as **L** (Line), **T** (Transformer), and **S** (Star). Although these contactors are identical in hardware, their distinct functional roles require specific wiring connections. The circuit's operation can be best understood by analyzing a single phase (L1) and one motor coil.

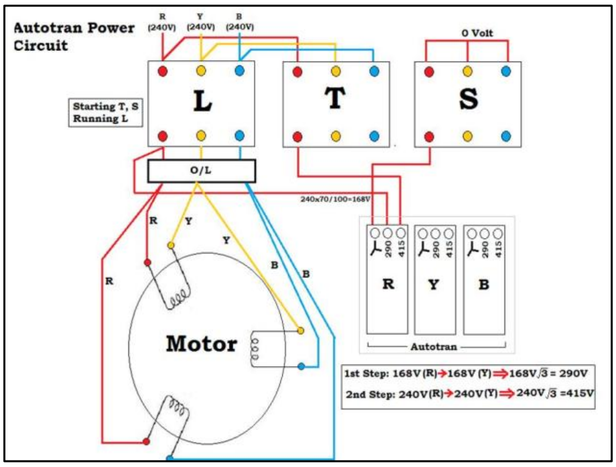

Fig. 1.16: Power circuit for an autotransformer motor starter

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Three separate autotransformers share a single core. Each is designed to reduce the initial line-to-neutral voltage of its respective phase (L_1, L_2, or L_3) to 70%. This gives:

$$\frac{70}{100} \times 120\ \text{V} = 84\ \text{V} \quad \left(\text{or } \frac{70}{100} \times 240\ \text{V} = 168\ \text{V in 240 V systems}\right)$$

In the second stage (after 6 seconds), the autotransformer is bypassed completely. The incoming phase lines connect directly to the motor windings in a Direct-on-Line (DOL) configuration.

To understand this process, consider a single autotransformer coil and motor winding. Initially, contactors **T** and **S** close to energize the autotransformer. Contactor **T** applies 120 V (240 V in UK systems) from phase L_1 to the top of the autotransformer coil, while contactor **S** connects to the bottom. At the other side of the **S** contactor, L_1, L_2, and L_3 are tied together to form a neutral star point (0 V) at the bottom of the coil.

Consequently, the tap joint at the 70% point delivers 84 V (168 V in UK systems). This 84 V from phase L_1 feeds one side of the motor winding, while an equivalent 84 V from phase L_2 feeds the opposite side via the second autotransformer. Having 84 V from L_1 on one terminal and 84 V from L_2 on the other produces a line-to-line voltage across the winding of:

$$84 \times \sqrt{3} \approx 145\ \text{V} \quad \left(168 \times \sqrt{3} \approx 290\ \text{V in UK systems}\right)$$

After 6 seconds, contactors **T** and **S** open, taking the autotransformer out of the circuit. Then, contactor **L** closes, applying full phase voltage (120 V L_1 and 120 V L_2, or 240 V on L_1 and 240 V on L_2 in UK systems) directly across the motor's winding terminals. This increases the voltage across the motor coil to:

$$120 \times \sqrt{3} \approx 208\ \text{V} \quad \left(240 \times \sqrt{3} \approx 415\ \text{V in UK systems}\right)$$

Thus, the motor winding initially experiences 145 V (290 V in UK systems**)** and steps up to 208 V (415 V UK) after 6 seconds. By comparison, a standard Star-Delta starter applies 120 V (240 V UK) initially before switching to 208 V (415 V UK).

However, the autotransformer starter provides a much smoother transition for the motor. For instance, a 10 HP motor can visibly jerk during a Star-Delta transition, whereas an autotransformer starter eliminates this visible movement.

Primary resistance starters offer an even smoother start than autotransformer starters, while a Variable Frequency Drive (VFD) provides the smoothest operation of all. However, specifying a VFD is often total overkill—its initial cost can be up to 40 times higher, and replacing a failed industrial unit can cost over US$6,500. By contrast, an autotransformer starter circuit can often be restored to service simply by replacing a US$30 contactor.

I have observed a university where the campus air-conditioning system was driven by a large VFD (costing much more than US$6,500). When the drive failed, the facility was left without cooling because the institution could not afford the replacement cost. A robust autotransformer starter could have easily solved this issue. Furthermore, modern AC motors are engineered with tougher insulation and heavy-duty bearings that readily handle starting current surges and mechanical stress.

The control circuit taps control power from phase L_1. The current passes through a miniature circuit breaker (MCB)—represented in the schematic by a fuse—and flows downstream to contact T_3 (an auxiliary contact on contactor T) and auxiliary contact L_5 on contactor L to illuminate the red indicator light (R). Current also flows to the overload (O/L) relay contacts. Power passing through the overload contacts flows through the normally closed (NC) Stop button and arrives at one terminal of the normally open (NO) Start button.

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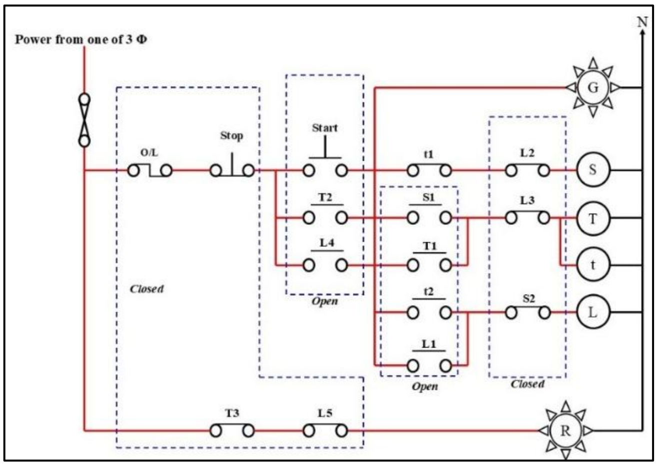

Fig. 1.17: Control circuit for an autotransformer motor starter

When the Start button is pressed, current flows through timer contact t_1 and contactor interlock L_2 to energize coil S (the star contactor). Energizing a contactor coil causes all of its associated auxiliary contacts to change state.

Consequently, contact S_1 closes, allowing current to flow through interlock L_3 to energize both contactor coil T and timer coil t (lowercase t represents the timer, while uppercase T represents the transformer contactor). Current can now also flow through T_2 and L_4, which form the holding (latching) circuit across the Start button.

The Start button is spring-returned, so it opens as soon as it is released. However, current continues to flow to the right branch of the circuit through the parallel paths provided by T_2 and L_4. Similarly, coil T remains energized via holding contact T_1.

After a 6-second delay, contact t_1 opens and t_2 closes. Note that t_1 and t_2 represent two sides of a single timer contact assembly. The spring-return movable contact touches t_1 when de-energized and switches to touch t_2 when energized.

Opening t_1 de-energizes coil S, causing contact S_1 to open. Opening S_1 in turn de-energizes coil T and timer coil t. Power now flows through t_2 and normally closed interlock S_2 to energize coil L. Auxiliary contact L_1 closes to latch power through this line even after the timer de-energizes.

When coil L energizes, interlock contacts L_2 and L_3 open, ensuring that contactors S and T, as well as timer coil t, remain completely isolated. From this point forward, only line contactor L remains closed while S and T stay open, applying full line voltage across each motor winding. The blue dotted boxes are included to help readers memorize different portions of the circuit.

Figure 1.18 shows the combined control and power circuit for the autotransformer starter.
While there is no strict theoretical upper limit to the power rating of a motor started by an autotransformer (or Korndörfer) starter, practical limits are imposed by operating voltage levels, equipment physical size, manufacturing standards, and competing technology.

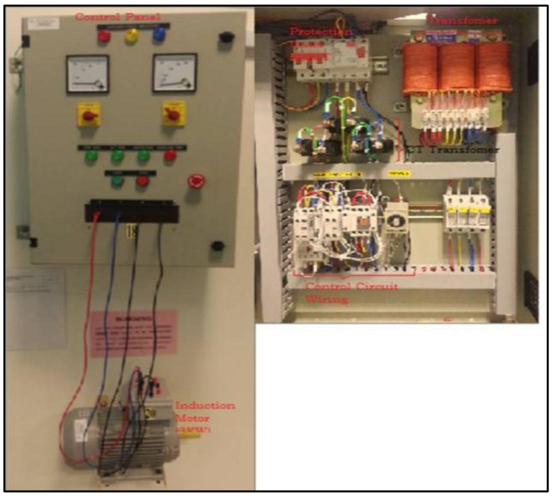

Fig. 1.18: Combined control and power circuit of an autotransformer motor starter

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Typical Upper Limits by Voltage Class

- Low-Voltage Applications (< 600 V):
  - Standard off-the-shelf industrial autotransformer starters typically top out around 700 kW to 1,200 kW (1,000 HP to 1,600 HP).
  - At low voltages, high horsepower requires extremely large conductor cross-sections and very heavy transformer magnetic cores, making larger low-voltage starters economically impractical compared to stepping up the system voltage.
- Medium-Voltage Applications (2.3 kV to 13.8 kV):
  - By utilizing the Korndörfer autotransformer circuit (which maintains a continuous closed transition to avoid damaging open-transition surges), custom starters are manufactured for motors rated from 5,000 kW to 10,000 kW + (approx. 7,000 HP to 13,000 HP).
  - These large starter units are employed in heavy industrial systems such as oil refinery gas compressors, mining ball mills, and major municipal water intake pumps.

Why Motors Are Rarely Started with Autotransformers Above ≈ 10 MW

- Voltage Transient Risk: At medium and high voltages, switching the central star point during the transition stage creates steep voltage transients ($\frac{dV}{dt}$) that can degrade stator winding insulation over time.
- Physical Size and Cost: An autotransformer rated for a 10 MW motor is a massive piece of electromagnetic equipment requiring extensive space and active cooling.
- Dominance of VFDs and Soft Starters: Above the 5 MW to 10 MW range, power electronics—such as solid-state soft starters and Medium-Voltage VFDs—become far more economical, offering precise torque control, near-zero line surge, and elimination of mechanical switching transients [Joshua, O. P. 2015].

Table 8.1: Power range of motor starters using Star Delta or Autotran

Parameter	Star-Delta (Y−Δ) Starter	Autotransformer Starter (Korndörfer)
Typical Practical Range (LV)	Up to 75 kW−150 kW (≈100−200 hp)	Up to 300 kW−500 kW (≈400−650 hp)
Medium-Voltage (MV) Feasibility	Extremely rare / Impractical	Standard practice: 1 MW to 15–25 MW+ (3.3 kV−13.8 kV)
Voltage Reduction	Fixed at 57.7% (1/3 of line voltage)	Flexible tap selection (50%, 65%, 80%)
Starting Torque (Tstart)	Fixed at 33% (1/3) of Direct-On-Line (DOL)	25% to 64% of DOL depending on selected tap
Transition Type	Usually Open transition (unless extra resistor contactors are added)	Closed transition (series reactor buffering)
Cabling Requirement	Requires 6 leads brought out from motor stator to starter panel	Standard 3 leads connected to the motor

VARIABLE FREQUENCY DRIVE (VFD)

A Variable Frequency Drive (VFD), also known as a Variable Speed Drive (VSD) or Inverter (a common misnomer, as inverting strictly means converting DC to AC—much like using "Xerox" for photocopying), is used to provide variable speed control for induction motors. It utilizes Insulated Gate Bipolar Transistors (IGBTs)—invented by Indian-American electrical engineer B. Jayant Baliga at the General Electric (GE) Research and Development Center—as high-speed switches to achieve this. The IGBT schematic is shown in Fig. 1.17 [Baliga, B. J. 2011].

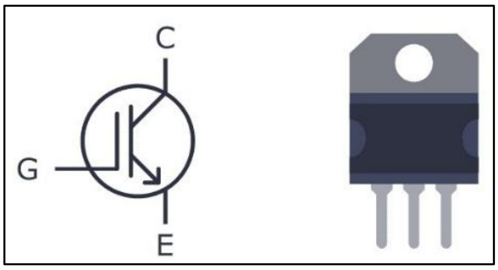

Fig. 1.19: Internal structure and schematic symbol of an Insulated Gate Bipolar Transistor (IGBT)

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Following the invention of the IGBT, the industry shifted toward VFDs, which directly control AC motor speeds. The early 1980s marked a dramatic surge in induction motor adoption, as their speed could finally be regulated efficiently. Prior to that, the primary limitation of induction motors was their fixed operating speed, dictated by the rotating magnetic field (RMF) of the line frequency supplied by the power utility:

$$N_s = \frac{120 \times f}{P}$$

(where $f = 50$ Hz or 60 Hz, yielding synchronous speeds such as 1500 RPM or 1800 RPM for a 4-pole motor).

Over my 14 years working at the Western Digital (WD) factory, I witnessed this transition from DC motors to induction motors firsthand. However, DC motors have evolved significantly since Joseph Henry's early prototypes in the 1830s—especially with modern carbon brushes that can last up to 20 years in lighter applications—the maintenance and wear associated with brushes remain the primary reason industry is moving to induction motors.

The main difference between a VFD and the former most popular motor drive, Soft starter, is the power electronics. VFD uses IGBT and Soft Starters use SCR or thyristors. Since SCR was the only way to use computers or electronic circuits to control high power, it was the main drive for high power motors. In fact, after my High School in 1980, I asked a person who just passed his EE degree what to study and he answered confidently, SCR because all control of big machines before 1982 used only SCR.

Because an SCR conducts in only one direction, two antiparallel SCRs are required to control both the positive and negative halves of an AC waveform. The primary advantages of IGBTs over SCRs in variable-frequency control include:

- High Switching Frequency: IGBTs can switch at tens of kilohertz (kHz), enabling high-resolution Pulse Width Modulation (PWM), whereas line-commutated SCR arrangements are typically constrained to the grid frequency (50–60 Hz) or low-frequency phase control.
- Full Gate Turn-Off Capability: SCRs latch on once triggered and only turn off when the load current naturally drops to zero (natural commutation). In contrast, an IGBT can be turned on and off instantaneously at the gate, making it ideal for high-speed, forced-switching applications.

Historically, large DC motors were preferred for elevators and traction applications because their speed and deceleration could be smoothly regulated using DC drives or Ward-Leonard systems, preventing passenger discomfort from sudden jerks during stopping. Before VFDs became economical, solid-state soft starters (utilizing SCRs) were widely used to ramp up AC induction motors smoothly and reduce mechanical shock. However, a soft starter only controls voltage during starting and stopping rather than continuously regulating operating speed. Consequently, virtually all modern elevators have transitioned to AC induction or permanent-magnet motors driven by Variable Frequency Drives (VFDs), which provide precise deceleration profiles, superior energy efficiency, and lower maintenance.

A maintenance manager in a 22-story building housing government offices for top state politicians told me he was terrified that a brush failure would eventually trap a politician in the lift, leading to his dismissal. Therefore, even though the DC motor brushes could easily last for years under normal conditions, he chose to replace them every month as a precaution.

This is precisely why industry transitioned so decisively to induction motors. Free of brushes and sliding contacts, a squirrel-cage motor experiences virtually no contact wear. The only critical points of failure remain the mechanical bearings (which industry leaders like SKF continue to refine) and the stator winding insulation, where Class H varnishes and advanced resins have largely eliminated premature thermal breakdown. At the WD facility, for example, a heavy-duty Baldor induction motor drawing 600 A per phase has operated virtually continuously since 1995—a clear testament to the unmatched longevity of AC machines pioneered by Nikola Tesla.

The latest high-speed induction motors eliminate mechanical bearings entirely by magnetically levitating the rotor shaft at both ends. Known as an Active Magnetic Bearing (AMB) system, this contactless technology enables rotational speeds exceeding 300,000 RPM with zero friction or mechanical wear.

After 1982 many engineers started to replace the Soft Starter and DC motor with a VFD and AC induction motors. The main reason is because the AC induction motors do not use carbon brush. Carbon brush will fail as it is continuously being

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scratched. But since carbon brush technology is about 150 years old, there are a few big and old companies which can produce carbon brushes that can last for up to 10 years of continuous operation like the Bodine brand DC motor at the Western Digital factory where I worked. But it must be noted that I once bought a carbon brush from a regular hardware store which drove a DC motor for only two weeks so there is a wide range in carbon brush quality. That former case was a disaster because I thought I was a good engineer saving the factory a lot of money by purchasing a US$0.6 bearing while Bodine was selling them for US$80 price. But since that carbon brush was installed in a factory machine and it stopped working suddenly after two weeks, the damaged hard disk platter that did not go through the process of that motor turning was worth US$800. This is why in a factory, only the most lasting motors and parts must be used.

After 1982, many engineers began replacing DC motors and drives with VFDs and AC induction motors. The primary motivation was that squirrel-cage induction motors have no carbon brushes to wear out. A carbon brush will inevitably degrade over time due to continuous friction and electrical arcing against the commutator. However, because carbon brush technology has matured over 150 years, reputable manufacturers produce brushes capable of lasting up to a decade in continuous operation, such as those in the Bodine DC motors at the Western Digital factory where I worked.

Quality, however, varies drastically across the market. I once bought a generic carbon brush from a local hardware store that lasted only two weeks in a production DC motor. It turned into an expensive lesson: I thought I was being a frugal engineer by buying a US$0.60 brush instead of Bodine's $80 brush. But when that cheap brush failed abruptly after two weeks**,** US$800 worth of hard disk platters that missed that critical process with that motor turning had to be discarded. That experience showed me why industrial environments must always use top-tier, high-reliability components, because the cost of lost production far exceeds the price of the parts themselves.

Because a PLC output is limited to milliamperes while a large motor can draw as much as 90 A, the high-power circuit is managed through an external relay or contactor (Fig. 1.20)—a contactor being simply a heavy-duty, higher-power version of a relay. Think of the system as two separate circuits: the 90 A motor is already wired directly to its dedicated power source, with a switch on that high power wire which is the contactor. The low-power PLC energizes the contactor's coil through an optoisolator (Fig. 1.21), snapping that switch closed to allow the 90 A to flow. In the latest installations, electromechanical contactors are often replaced by solid-state relays (SSRs) or power blocks to perform this switching electronically.

Referring to the relay in Fig. 1.20, the printed schematic on the clear plastic body identifies the pin numbers. On the relay base below, matching terminal numbers are molded into the plastic directly above each screw terminal. Proper wiring requires reading this schematic and the corresponding terminal numbers accurately—a routine necessity for electricians when dealing with fine labeling on industrial components. Because these markings are often too small to read comfortably, especially for aging eyes, I have relied on a handy tool for over 20 years: an intact lens salvaged from a pair of eyeglasses that was dropped and run over by a car. Unlike a conventional magnifying glass with a handle, which is bulky and prone to breakage, this standalone lens is compact, robust, and easily kept in a soft velvet earbud pouch in the pouch I hang on my belt which also holds my cell phone. It also comes in handy outside the workshop—as a vegetarian, reading the fine print on supermarket ingredient labels is just as essential.

Currently many motors are being run with VFD, but they can cost 4000% higher than a simple motor starter like an Autotran. A VFD also needs an air condition unit to cool it down especially in the hot and dusty factory environment. VFDs are also not as survivable and when they fail, another 40 times the cost (or 4000% extra cost) needs to be spent because it cannot be repaired due to its multi-layered circuit boards. At the Western Digital (WD) factory in Kuching, a US$5,000 VFD is used to control a 5 HP motor while most of the oil palm mills used VFD that cost US$10,000 to control 40 HP motors and a university in Kuching use a US$20,000 VFD to control an 80HP motor for the centralized air-conditioning system.

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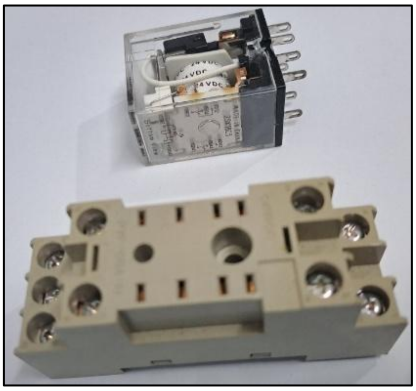

Fig. 1.20: A typical relay and its base

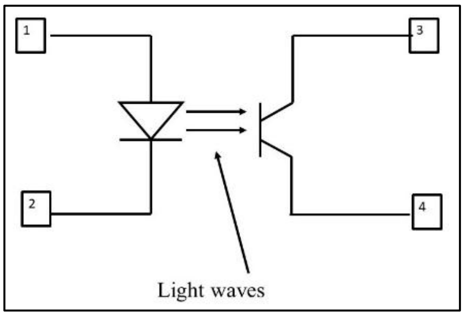

Fig. 1.21: Schematic of an optoisolator providing galvanic isolation between PLC logic and power stages

Comparatively by building an Autotran circuit one can start even an 80 HP motor for only $400. The circuit is simple, and the parts are easily available and therefore serviceable; most probably changing a US$50 contactor is all that is needed. In fact, my home aircon repair person who previously worked with me at the WD factory do not recommend an Inverter (VFD) air conditioner because of the high price of the inverter card if it fails. Therefore, engineers must consider all these costs when deciding on the appropriate controllers for motors.

Currently, many industrial motors are driven by VFDs, but they can cost up to 40 times more (a 4,000% price premium) than a simple electromechanical starter like an autotransformer starter. A VFD also requires dedicated air conditioning to cool it down, especially in hot, dusty factory environments. Furthermore, VFDs are far less robust: when a unit fails, full replacement is often unavoidable because its multi-layer circuit boards cannot easily be repaired in the field.

At the Western Digital (WD) factory, a complete US$5,000 precision vector VFD system to control cost to control a 5 HP motor while a U$8000 VFD controls a 25 HP motor. A university in Kuching uses a US$20,000 VFD to run an 80 HP motor motor that controls the central air-conditioning. When that 80HP VFD controlling the aircon unit of the university failed, numerous students had no air conditioning in classrooms for a span of months because the university did not have the budget to repair it. I talked to the person who eventually repaired it. The technician who eventually fixed it explained that the drive had been installed at the top of the building where heat accumulated; ambient temperatures rose so high that solder joints on the circuit board melted, requiring him to resolder the loose components. A US$400 autotran could have been used to run that motor especially because of the advancement in bearing and coil these days. Its circuit is simple and built from standard, easily serviceable parts; usually, replacing a US$50 contactor is all that is ever needed.

Similarly, local palm oil mills spend roughly US 10,000 on a lower spec VFD. When asked why they incurred such an expense when a US$1,000 autotran could have started that motor, they replied that they needed speed control for the conveyor transporting palm fruit to the boiler. Yet there are far more economical ways to reduce conveyor speed, such as a **cycloconverter**, which can be implemented for around US$200. As shown in Fig. 1.22, its underlying power electronics are simple, explaining its low cost. Fig. 1.23 illustrates how it synthesizes a lower-frequency waveform by combining cycles of the rotating magnetic field (RMF) from the power grid. The output frequency of a three-phase cycloconverter is typically limited

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to one-third to one-half of the grid frequency (16–25 Hz, corresponding to 500–750 RPM on a 4-pole, 50 Hz motor). Notably, the mill had not installed an air conditioner for its US$10,000 VFD. I pointed out that a VFD is essentially an industrial computer: nobody would leave a laptop baking in direct sunlight of tropical heat and factory dust. A small enclosure and a US$300 air conditioner could have protected that VFD. In fact, a former colleague from WD who is now in the air-conditioning service business advises against inverter (VFD) air conditioners due to the exorbitant replacement cost of failed inverter control cards. Engineers must evaluate these full lifecycle and maintenance costs when selecting motor controllers.

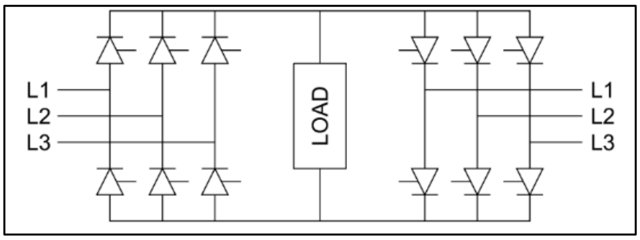

Fig. 1.22: Power circuit schematic of a three-phase cycloconverter

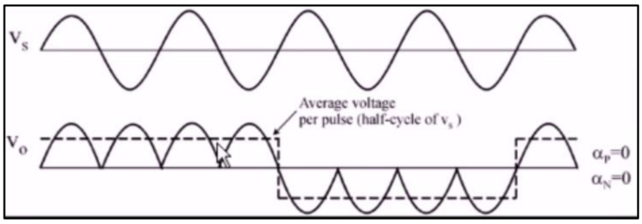

Fig. 1.23: Synthesized motor input voltage waveform (bottom square wave) derived from the incoming supply

The methods of controlling the speed on an induction motor are:

1. Gearbox
2. Rotary – increase speed
3. Cycloconverter – decrease speed
4. Soft starters – using SCR
5. Variable Frequency Drive (VFD)

The main advantage of a VFD during startup is its ability to ramp up voltage and frequency smoothly, unlike an autotransformer starter, which typically steps the motor from a reduced-voltage tap (such as 50% or 65%) to full line voltage. However, modern motors are built with Class H insulation varnishes and heavy-duty bearings capable of withstanding these mechanical and electrical starting stresses—the very issues reduced-voltage starters were designed to mitigate. When speed variation is not required, the justification for a costly VFD diminishes. In fact, major operators like Shell routinely use large industrial contactors for Direct-On-Line (DOL) starting on motors up to 40 HP and beyond.

A VFD becomes indispensable only when dynamic, multi-step process control is required—such as running at 5 RPM for 30 seconds, accelerating to 20 RPM for the next 40 seconds, and then stepping up to 50 RPM for 60 seconds, as seen in automated precision lines at Western Digital. An autotransformer starter cannot modulate speed; once brought to full line voltage, the motor runs locked to grid synchronous speed—1,500 RPM on a 50 Hz supply (or 1,800 RPM on a 60 Hz grid for a 4-pole motor).

The internal operation of a VFD follows the schematic in Fig. 1.24. Incoming AC power at 50 Hz or 60 Hz is first rectified to DC. An array of IGBTs then switches the DC bus voltage on and off with precise timing: while the pulse amplitude remains fixed throughout at the DC bus level, the switch on-time (duty cycle) increases to represent higher amplitude of AC voltages waveform and decreases for lower-amplitude portions of the AC waveform. This technique is known as Pulse Width Modulation (PWM).

In pure sine-wave VFD systems, this discrete pulsed output is filtered into a smooth sinusoidal AC waveform, which reduces harmonic losses and improves motor operating efficiency by approximately 15%.

In sine-wave filtered VFD systems (Pure Sine wave VFD), this discrete PWM output is passed through an external or integrated passive LC low-pass filter (consisting of power inductors and capacitors). The filter strips away the high-frequency switching carrier components, delivering a smooth sinusoidal AC voltage to the

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motor, which eliminates insulation-damaging dV/dt spikes and reduces harmonic heating losses:

- Series Inductors (L): Large iron-core or ferrite-core chokes are placed in series with each phase. Because inductive reactance increases with frequency ($X_L = 2\pi f L$), the inductors act as a high-impedance block to high-frequency PWM switching spikes while allowing the low-frequency (50/60 Hz) fundamental current to pass freely.
- Shunt Capacitors (C): High-voltage capacitors connected phase-to-phase or phase-to-ground provide a low-impedance path ($X_C = \frac{1}{2\pi f C}$) to shunt the remaining high-frequency switching ripple harmlessly away from the motor windings.

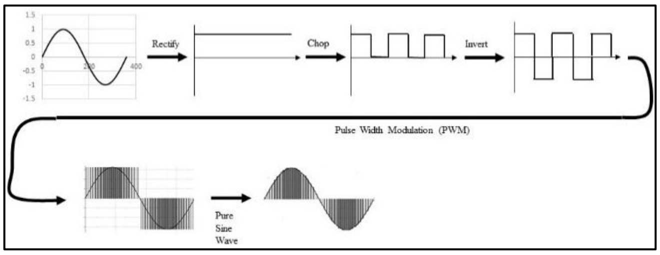

Fig. 1.24: Variable Frequency Drive (VFD) schematic showing the latest pure sine wave output

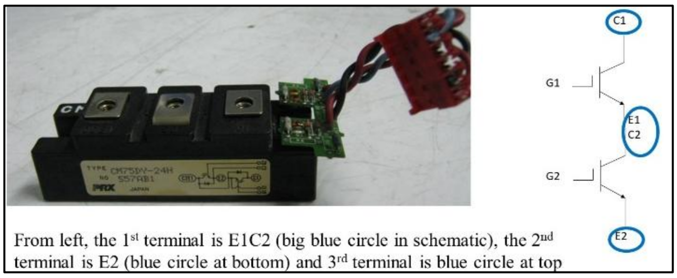

Fig. 1.25: Insulated Gate Bipolar Transistor (IGBT) power module used in an industrial VFD

Fig. 1.25 shows an IGBT. The module houses two IGBTs connected in series to form an inverter half-bridge (phase leg). The small auxiliary terminals (such as the red connector) serve as the Gate (G) connections, receiving low-current switching signals from the microprocessor or gate driver. These control signals switch the heavy-duty power terminals ON and OFF, controlling power flow from the DC bus (Collector) through to the motor phase output (Emitter).

An IGBT combines the simple, low-power gate drive characteristics of a MOSFET with the high current-carrying capacity and low saturation voltage of a Bipolar Junction Transistor (BJT). In short, it integrates an isolated-gate FET input with a robust bipolar output switch in a single package.

Inside a standard VFD, incoming line AC at 50 Hz (or 60 Hz) is first rectified into DC across a capacitor bank and then chopped into high-frequency pulses. Six IGBTs are arranged across three phase legs to reconstruct variable-frequency three-phase AC power. A VFD is a true motor controller—unlike simple starters such as DOL, Star-Delta, or autotransformer starters, which merely limit startup transients and lack continuous operating control. A VFD enables precise regulation of motor speed, acceleration profiles, and torque.

The inverter modulates fixed DC bus voltage pulses at high switching frequencies using Pulse Width Modulation (PWM). As switching frequencies in modern drives have increased, synthesized waveforms have become far smoother. A helpful analogy is building a wall: using two-foot-wide concrete blocks limits you to coarse geometries, whereas using one-inch bricks allows you to craft intricate, customized curves.

In pure sine-wave filtered VFD systems, output filter inductors and capacitors smooth these high-frequency pulses back into a clean sinusoidal waveform, mitigating harmonic losses and boosting overall motor operating efficiency by roughly 15%. In high-power circuits, tapped autotransformers often replace resistive voltage dividers, much like a variable autotransformer in high-voltage work replaces the rheostat of low-voltage circuits.

In industrial practice, a VFD is also called a Variable Speed Drive (VSD) or simply an inverter. Calling the entire drive an "inverter" is technically

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a misnomer, though it has become universally accepted due to commercial appliances—such as inverter air conditioners, washing machines, and refrigerators. In electrical engineering, an *inverter* strictly converts DC to AC (the reverse of a *rectifier*, which converts AC to DC). In the drive schematic (Fig. 1.15), the inverter stage is only one segment of the overall unit, alongside the rectifier, DC link filter, and microprocessor gate control logic. Calling the whole unit an "inverter" is much like using the brand name "Xerox" as a generic synonym for a photocopy.

As power semiconductor costs continue to decline, VFD technology is steadily entering everyday domestic equipment—including ceiling and standing fans—replacing rigid discrete speed settings (1, 2, 3) with stepless, continuous variable-speed dial control.

Upon opening a VFD (Fig. 1.26), one immediately notices one or two large electrolytic capacitors; these form the DC link, smoothing the rectified DC bus voltage. However, high-speed PWM switching introduces a major challenge: severe harmonic distortion. Harmonics are unwanted integer multiples of the fundamental grid frequency (50 Hz or 60 Hz) created whenever continuous waveforms are chopped into rapid square pulses. Switching a DC voltage abruptly to 0 V is unnatural. Just as electromagnetic waves and ocean waves naturally propagate in sinusoidal forms, an abrupt square wave introduces unwanted higher-frequency harmonics that must be eliminated.

This issue is especially severe at the steep rising and falling edges (dV/dt transitions) of each switching pulse. At these transitions, transient voltage spikes and reflected waves can produce localized overvoltages high enough to puncture the thin varnish insulation on stator coils, causing inter-turn insulation breakdown. Consequently, motors driven by VFDs require inverter-duty rated insulation (such as Class H with Corona-resistant magnet wire). Standard motor rewinding shops that use conventional enamel wire cannot properly rewind inverter-fed motors, as standard varnish quickly degrades under these repetitive dielectric stresses.

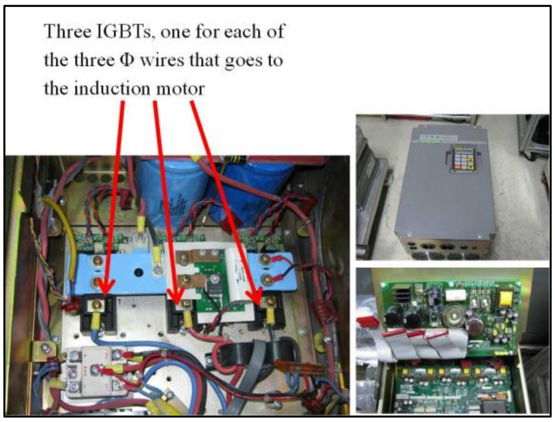

Fig 1.26: Outside and inside of a VFD

In sensitive facilities such as hospitals—where microvolt-level physiological signals (e.g., ECG, EEG) are monitored—and telecommunication data centers—where high bit-rate digital signals are vulnerable to electromagnetic interference—these harmonics can cause severe operational disruption. In such installations, dedicated harmonic mitigation is mandatory. A common passive approach is installing a 1:1 isolation transformer, which attenuates roughly 65% of harmonic currents and blocks triplen harmonics ($3^{rd}, 9^{th}$, etc.). For maximum mitigation, Active Harmonic Filters (AHFs) dynamically inject counter-phase currents, eliminating up to 95% of harmonic distortion. Table 1.1 summarizes the most widely used harmonic filtering technologies [Tripathi, A., & Narayanan, G. 2015].

In hospitals and telecommunication centers, grounding (earthing) must be built to the highest standard by using quality ground rods bonded via Cadweld (exothermic welding which is chemically a copper thermite mixture) or oxy-acetylene welding. The Cadweld joint shown in Fig. 1.27 ensures a solid, continuous molecular bond between the green grounding cable and the ground rod. Fig. 1.28 shows the weld powder used to achieve the high temperature needed to melt and fuse the copper.

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Table 1.1: Various types of harmonic filters in the market

#	Type	% reduction of harmonics
1	Active Harmonic Filters	95%
2	Broadband Blocking Filter-Drive	95%
3	Neutral Blocking Filter	92%
4	Neutral Cancellation Transformer	90%
5	Passive Harmonic Filter	90%
6	Harmonic Mitigating Transformers	85%
7	AC Line Reactors	85%
8	DC Reactors for Drives	65%
9	Isolation Transformers	65%
10	Neutral Oversizing	Just to overcome phase imbalance which causes high current in N

In my opinion, all ground rods should be exothermically welded or oxy-acetylene welded to the ground wire because corrosion between the wire and the rod can render the entire grounding system useless. Most standard ground rods are steel cores plated with a thin copper layer; over time, mechanical joints oxidize into copper oxide and iron oxide (rust), both of which act as electrical insulators. Considering the expense of heavy green ground conductors, high-grade rods, and installation labor, investing in proper welding equipment to protect this critical junction is well worth the cost, as the mechanical clamp joint is often the weakest point in the entire installation [Radhakrishnan, V. M. 2005].

In field practice, many contractors seeking a reliable joint prefer oxy-acetylene welding over Cadweld. As shown in Fig. 1.29, the portable oxy-acetylene apparatus (left) allows a technician to directly join a $1'' \times 1/8''$ copper tape to a ground rod (right). Because a graphite Cadweld mold sits loosely atop the vertical rod and the exothermic powder flashes vigorously upon ignition, technicians naturally step back quickly; this can sometimes cause the mold to shift or tilt during the reaction, compromising the fusion bond. With an oxy-acetylene torch and standard copper/bronze filler rods readily available at local hardware suppliers, the technician can precisely guide the flame by hand to build a solid, well-controlled joint directly on site. While some may argue that oxy-acetylene is non-standard compared to prevalent Cadweld specifications, it is in fact standard manufacturing procedure for high-current copper connections in large industrial motors, as shown in Fig. 1.30.

Fig. 1.27: Cadweld joint connecting a copper tape conductor to ground rods for a telecommunication tower

Fig. 1.28: Exothermic black powder used in the Cadweld process

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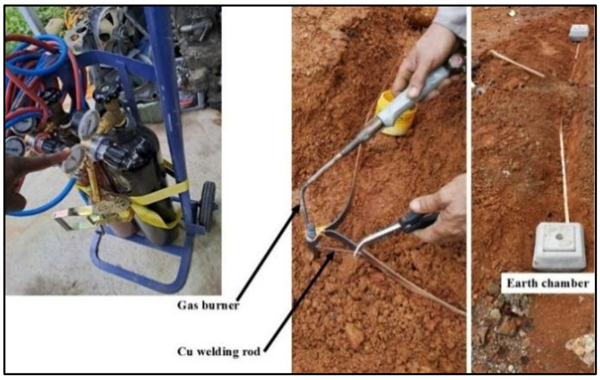

Fig. 1.29: Oxy-acetylene welding equipment (left) and field execution of a copper tape joint to a ground rod (right)

Fig. 1.30: Oxy-acetylene brazing/welding applied during the manufacture of large industrial motors.

SYNCHRONOUS MOTOR

The basic structure and operation of a synchronous motor are very similar to an induction motor. The main difference is that the rotor is not merely a squirrel cage; it contains field coils energized with DC via slip rings and carbon brushes. A synchronous motor operates much like an induction motor, except that the rotor turns synchronously with the stator's Rotating Magnetic Field (RMF), whereas an induction motor requires a difference in speed known as slip.

At standstill, because the rotor has mechanical inertia, it cannot immediately lock onto the fast-moving RMF. A rotor North pole initially attracted to a stator South pole is quickly overtaken by an oncoming North pole, causing the rotor to experience alternating attractive and repulsive forces in rapid succession. Consequently, the average starting torque is zero, making synchronous motors inherently non-self-starting.

To solve this problem, the DC excitation to the rotor coils is initially kept off. A squirrel-cage damper winding embedded in the rotor pole faces allows the motor to start as an induction motor. Once the rotor reaches nearly synchronous speed (leaving only a small slip), the DC supply to the rotor coils is switched on. The rotor field locks onto the opposite poles of the stator RMF, and the motor continues to rotate at true synchronous speed.

Direct current (DC) is fed into the rotor via a pair of slip rings and carbon brushes, making the rotor behave like a radial array of electromagnets. Another option is to use permanent magnets on the rotor. The required slip rings and carbon brushes are among the main disadvantages of a wound-rotor synchronous motor due to regular maintenance and wear.

All large utility-scale generators are synchronous machines, though smaller generators utilize other types of machines.

Wind turbines often use DFIG (Doubly-Fed Induction Generators) or SCIG (Squirrel-Cage Induction Generators). Small-scale hydro plants and industrial energy-recovery systems frequently use standard, cheap, and rugged induction motors driven above synchronous speed (slip $s < 0$) to generate power directly onto the grid without requiring separate DC excitation or synchronization gear. In addition, DC generators use mechanical commutators to convert the generated AC directly to DC at the shaft; these are found in heavy industrial DC cranes, older diesel-electric locomotives, welding generators, and dedicated DC exciters mounted on the shafts of large alternators. Furthermore, solar photovoltaic (PV) generation and full-scale converter-interfaced wind turbines feed power through solid-state power electronics rather than rotating synchronous fields (though some are now programmed as "grid-forming / virtual synchronous" machines).

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In robotics, a prominent application of permanent-magnet synchronous motors is replacing stepper motors in robotic arms. With stepper motors, the coils are electronically energized in sequential discrete steps, as shown in Fig. 1.31. In step one, the top coil is energized as a North pole; next, the side coil is energized as North; then, the top coil is reversed to a South pole; and finally, the side coil is energized as South. Because of this capability, early robotic arms were actuated almost entirely by stepper motors. Control engineers preferred stepper motors because their step-by-step operation is inherently digital, matching the digital nature of computer controllers [Nagamani, C. *et al*., 2015].

But today a software called DSP (Digital Signal Processing) which was developed by the telecommunications industry is being used to run synchronous motors with lots of stator coils. Such a synchronous motor can be utilized to move robot arms. The more coils in the rotor, the more precise will be the robot arm’s movement capability. DSP software can instruct the energizing of coils precisely so synchronous motors can be used. The advantage of synchronous motors is that they are much more powerful than stepper motors. Most stepper motor actuated robot arms can easily be stopped by a human hand whereas there is no limit on the power of a synchronous motor. The current largest motor in the world is the 135,000 HP (96MW) synchronous motor built by ABB for a NASA wind tunnel. Try to imagine the amount of space required to keep 135,000 horses; how big a chariot can that many horses move? An even larger one is the 186,327 HP or 139MW motor currently being used in India for irrigation purposes. It was built in India by the WEG motor manufacturer of Brazil. In 2026, the highest payload capacity for a standard 6-axis articulated industrial robotic arm is 2,300 kg (2.3 metric tons / 5,070 lbs), held by the FANUC M-2000iA/2300 [Kumar, T. S. *et al*., 2018].

Today, Digital Signal Processing (DSP) technology, originally pioneered in the telecommunications industry, is widely used to control synchronous motors with high pole counts. Such synchronous motors are extensively utilized to drive robotic arms. By precisely regulating the energizing of each stator winding in real time, DSP controllers ensure extremely accurate position, velocity, and torque control. A major advantage of synchronous motors over stepper motors is their superior power density. While most small stepper-motor-actuated arms produce limited torque and can easily be stalled by human hand force, synchronous motors scale to virtually limitless power capacities.

In heavy manufacturing, the highest payload capacity for a standard 6-axis articulated industrial robotic arm is 2,300 kg (2.3 metric tons / 5,070 lbs), held by the FANUC M-2000iA/2300. At the extreme industrial scale, ABB engineered a 96 MW (135,000 HP) synchronous motor to power a NASA wind tunnel, while 139 MW (approx. 186,300 HP) vertical synchronous motors drive massive water pumps for the Kaleshwaram Lift Irrigation Project in India—representing the largest dedicated electric motors on Earth [Sreejeth, M. *et al*., 2014].

The widespread adoption of DSP in motor control began in 1997 when Texas Instruments released the TMS320C240—the industry's first DSP chip designed specifically for digital motor control and power conversion. This device integrated a 16-bit DSP core with on-chip hardware PWM generators, dual ADCs, and encoder interfaces on a single silicon die, serving as the precursor to the popular C2000 family [Baratam, A. *et al*., 2014].

By the 2000s, dedicated DSPs and Digital Signal Controllers (DSCs) had become the global standard for AC servo drives, permanent-magnet synchronous motors (PMSMs), brushless DC (BLDC) motors, and multi-axis industrial robots (such as those from FANUC, ABB, and KUKA) [Mishra, M. K. *et al*., 2010].

Around 2015, the industry experienced a widespread migration toward ARM Cortex-M4F (from ARM, the British company whose processor architecture powers most mobile phones) and Cortex-M7 microcontrollers (designed by ARM and manufactured by companies such as STMicroelectronics, NXP Semiconductors, Microchip Technology, Texas Instruments, and Infineon). During this period, Sensorless Field-Oriented Control (Sensorless FOC) became mainstream. This advanced vector control algorithm decouples torque and magnetic flux control for AC synchronous and induction motors without requiring physical rotor position sensors (such as optical encoders, resolvers, or Hall-effect sensors). Concurrently, automated identification frameworks—such as Texas Instruments' InstaSPIN-FOC—enabled digital controllers to measure and compute an unknown motor’s fundamental electrical parameters $(R_s, L_d, L_q, \lambda_m)$ within seconds, eliminating the need for manual

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laboratory bench testing or external dynamometers [Gutierrez-Felix, P. *et al*., 2026; Jadhav, U. *et al*., 2023].

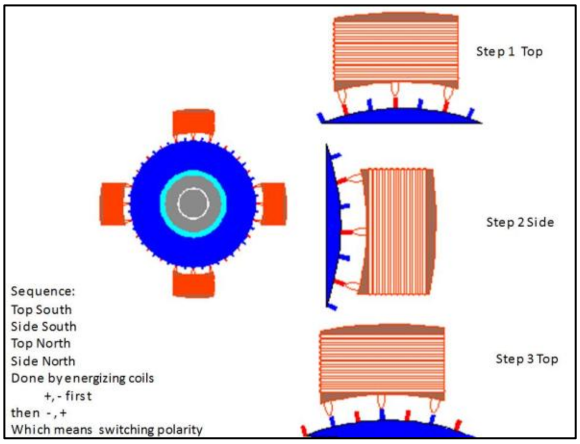

Fig. 1.31: Stepper motor functioning sequence

BRUSHLESS GENERATORS

As mentioned previously, large utility-scale generators historically used carbon brushes and slip rings to send DC to the rotor. However, brushless generators (which range from 100 MW to over 1,200 MW) eliminate brushes by mounting two generator stages on a single common shaft. On smaller units, the shaft and frame look like a single machine, while the two distinct sections are easily visible on larger units.

The larger section is the main generator, and the smaller section supplies DC excitation to the rotor of the larger machine, acting as the exciter. The smaller exciter has stationary stator coils supplied with DC current, which induces AC current in the rotating coils below it. This generated AC is conducted along the shaft to a shaft-mounted rectifier bridge, which converts the AC to DC.

The generator housing features ventilation ports near the rectifier assembly so that convection airflow cools the diodes during operation. The resulting DC current is then fed directly into the rotor coils of the main generator, turning them into rotating electromagnets whose magnetic fields cut the stationary main stator windings to generate the final AC output. The main challenge with this approach is ensuring adequate cooling and ruggedness for the rotating rectifier electronics, which must endure high rotational forces, operating heat, and ambient dust [Kant, K. *et al*., 2017].

UNIVERSAL MOTOR

This motor is called "universal" because it can run on either AC or DC power sources, as shown in the schematic of Fig. 1.32. Most portable power tools use this type of motor because it provides a high horsepower-to-size ratio. Common appliances powered by universal motors include vacuum cleaners, food mixers, portable drills, handheld power saws, and sewing machines [Kulkarni, M. P. *et al*.,].

These motors are typically rated at one horsepower or below and do not operate at constant speeds; instead, the rotational speed varies inversely with the mechanical load. The higher the load, the slower the motor turns—a characteristic that is highly advantageous in practical machining, cutting, and drilling. For instance, when drilling soft concrete, the bit turns rapidly, but when hard aggregate is struck, the motor automatically slows down while increasing torque. Similarly, just as a piece of soft iron can be sawed quickly with a hacksaw whereas hard iron must be sawed slowly to maintain cutting efficiency, the universal motor naturally matches its speed and torque to material resistance.

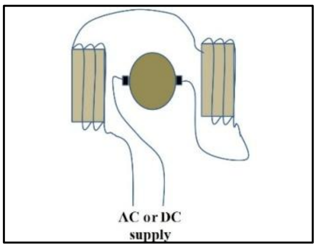

Fig. 1.32: Universal motor schematic

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Under no-load conditions, the motor speed can reach up to 15,000 RPM, whereas under heavy loads it slows to a few hundred RPM.

The rotor of a universal motor is constructed with laminated iron sheets wound with wire coils, similar to other AC machines. Electric current flows through the stator field windings as well as the rotor armature windings via carbon brushes and a commutator. Because the stator and rotor coils are wired in series, when AC power alternates and switches direction, the current in both the stator and rotor coils reverses simultaneously. As a result, the magnetic attraction and repulsion forces between the stator and rotor remain in the same rotational direction, allowing the motor to spin continuously on AC.

For professional electrical contractors, investing in high-quality power tools (such as DeWalt, Hitachi, or Hilti) is essential. There is a substantial performance difference between a 300-watt drill and a 750-watt model: the heavy-duty model can drill a hole in a few seconds compared to up to half an hour with an underpowered unit, drastically improving labor productivity. While cheap drills may look identical from the outside, their motor shafts are often supported directly by the plastic casing without proper bearings. In contrast, professional drills house the universal motor in a rigid metal assembly with high-quality ball bearings at both shaft ends. Fig. 1.33 illustrates a high-grade drill whose carbon brushes lasted for over 33 years of service [Kulkarni, M. P. *et al*.,].

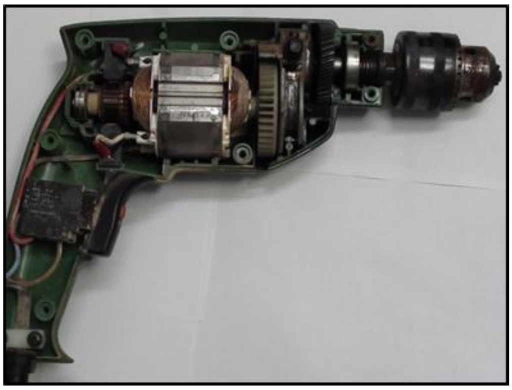

Fig. 1.33: Universal motor in a drill

CONCLUSION

Ac induction motors remain the fundamental workhorse of modern global industry due to their inherent ruggedness, high efficiency, and the absence of sliding contact wear mechanisms. As demonstrated, the integration of high-permeability magnetic cores, skewed rotor bars, and advanced class h winding insulation enables contemporary induction machines to withstand substantial electrical and mechanical starting stresses. While the advent of solid-state power electronics—spearheaded by the commercialization of the igbt and real-time digital signal processing (dsp)—has revolutionized precision vector control and multi-axis robotics via permanent magnet synchronous motors (pmsms), modern drives introduce critical operational trade-offs, including steep dv/dt voltage transients, harmonic distortion, and elevated capital and replacement expenditures. Field evidence indicates that while variable frequency drives (vfds) are indispensable for dynamic, multi-step velocity profiles, they represent costly over-engineering in constant-speed applications where autotransformer (korndörfer) or direct-on-line starters offer superior lifecycle economy, simplified serviceability, and elevated plant uptime. Effective electrical design requires a holistic evaluation balancing starting inrush limitation, mechanical shock mitigation, harmonic attenuation, and robust grounding practices against long-term maintenance costs. Ultimately, aligning the specific operational requirements of the mechanical load with the appropriate machine topology and starter technology remains vital for achieving optimal energy efficiency, reliability, and industrial longevity.

DECLARATION

The authors utilized an artificial intelligence assistant for structural grammar editing, metric formatting, and manuscript refinement. All data, technical analyses, case studies, and engineering conclusions were independently conceived and verified by the authors, who accept full responsibility for the integrity of the content.

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