A COMPARATIVE STUDY OF INDUCTION MOTORS STARTERS; DIRECT ON LINE STARTER, STAR–DELTA STARTER AND SOFT STARTER.

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DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

FACULTY OF ENGINEERING

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A PROJECT SUBMITTED TO THE DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENT

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SUPERVISOR: Engr. Dr. Martins Oyedoh.

OCTOBER, 2025.

CERTIFICATION

This is to certify that this project work was carried out by OMOROGBE OGHOSA FAVOUR with matriculation number ENG2002304, IGBINEVBO FAVOUR OSAKPONMWEN with matriculation number ENG2002248 and EGEOLU ABUNDANCE CHUKWUEMEKA with matriculation number ENG2006253 in the department of Electrical and Electronics Engineering, University of Benin, Benin City, Edo state, Nigeria.

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DEDICATION

We dedicate this work to our families, friends, and mentors, whose unwavering support, patience, and encouragement have been instrumental in our journey.

We also extend our gratitude to our Supervisor, Engr**.** Dr. Martins Oyedoh and all those who have inspired and guided us throughout this research. Their wisdom and dedication to knowledge have been a source of motivation.

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Congratulations to us all!

ABSTRACT

Induction motors are the primary workhorses in industrial applications, but their starting phase poses significant challenges, namely high inrush currents and abrupt mechanical torque. This project presents a comparative study of Direct-On-Line (DOL), Star-Delta (Y-Δ), and Soft Starter methods for three-phase induction motors, with a specific focus on analyzing their transient performance using simulation.

To conduct this analysis, dynamic models of an induction motor and the corresponding control circuits for each starter were developed and simulated using the MATLAB/SIMULINK environment. The study evaluates key performance metrics by comparing the simulation waveforms for stator current, rotor speed, and electromagnetic torque during the startup transient.

The simulation results quantitatively demonstrate the severe inrush current (up to 6-8 times full load) and high-impact torque of the DOL starter. The Star-Delta simulation illustrates its effectiveness in reducing starting current to approximately 33% of DOL, but also clearly exposes the open-transition torque dip and current spike during the switchover. In contrast, the thyristor-based Soft Starter model demonstrates superior performance, offering a smooth, stepless acceleration, precise current-limiting capabilities, and the elimination of mechanical jerk. This simulation-based analysis provides a clear, quantitative framework for evaluating the trade-offs between cost, complexity, and performance, enabling engineers to select the most appropriate starter for specific load requirements and power system constraints.

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CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Three-phase squirrel-cage induction motors are the most widely used industrial motors due to their self-starting capability, reliability, and cost-effectiveness (Wikipedia, 2025). When started directly across the line, these motors can draw high inrush current several times their rated current, which risks causing voltage drops in the electrical supply and stresses on motor windings (Wikipedia, 2025; Electrical Classroom, 2012). Motor starters are therefore essential to mitigate these adverse effects through controlled connection and protection coordination (Electrical Classroom, 2012).

The simplest method, the Direct-on-Line (DOL) starter, connects the motor directly to the supply using a contactor and overload relay. Its key advantages are simplicity and low cost, making it suitable for small motors. However, it results in the highest inrush current, commonly between six to eight times the full-load current and correspondingly high starting torque, making it unsuitable for larger motors or sensitive power systems (Wikipedia, 2025; Slideshare, 2022).

The Star–Delta (Y–Δ) starter initiates motor startup by first connecting windings in a star configuration, which applies approximately $1/\sqrt{3}$ (~58%) of line voltage per phase, reducing both the starting current and starting torque to about one-third of their DOL values. After SD acceleration, the connection switches to delta for full-voltage operation. This reduces supply disturbance and mechanical stress while remaining relatively inexpensive and simple to implement. Limitations include the substantially lower starting torque which may be inadequate under heavy load and the risk of transient current spikes during the star-to-delta transition. Typical peak starting current ranges from 1.3 to 2.6 times full-load current, while starting torque is around 33% (Electrical-Engineering-Portal, 2012; Electrical-Technology, 2019; Slideshare, 2022).

Soft starters use solid-state devices (e.g., thyristors) to gradually ramp the applied voltage during startup. This method limits inrush current, offers smooth and adjustable torque profiles, and reduces mechanical stress. Modern soft starters often include built-in protection and diagnostics. They are more expensive and electronically complex than DOL or star-delta starters and do not enable speed control, unlike variable-frequency drives (VFDs) (Wikipedia, 2025; Electrical4UOnline, 2020; Nidec Netherlands, 2018). Typical peak starting current may range from 3 to 5 times full-load current, with starting torque controllable between approximately 0.1 to 0.7 times nominal torque (Slideshare, 2022).

Comparative analyses confirm clear trade-offs: DOL offers maximum starting torque at the cost of high inrush current; star-delta reduces starting current significantly but also reduces torque and requires careful load matching; soft starters deliver smoother, controlled starts with moderate reduction in inrush and torque, yet entail higher cost and less simplicity (ElectricalClassroom, 2012; Slideshare, 2022).

The implications of these differences extend to electrical network stability, protection coordination, mechanical coupling design, and life-cycle cost efficiency. In applications sensitive to voltage dips or mechanical shock or where energy demands are dynamic a soft starter may provide better overall performance despite higher initial cost. For simple, cost-constrained systems, DOL may suffice; for medium motors with no-load starts, star-delta offers a pragmatic compromise (Testbook, 2021; Wikipedia, 2025).

Given the varied operational environments of induction motors, a systematic comparative study is essential. Such research should quantify starting current profiles, torque development, energy dissipation, and transient behaviours across different motor ratings and load conditions. These technical measurements should then be related to practical design criteria such as supply impact, mechanical load tolerance, protection coordination, and economic factors to support informed starter selection in industrial settings.

Starting induction motors inevitably involves striking a balance among electrical, mechanical, and economic constraints. DOL, star-delta, and soft starter approaches each occupy different positions in that trade-space. To find the best starter for the job, we need to see how they stack up. By combining theoretical models with practical performance data from tests or simulations, we can pinpoint exactly where each starter excels. This will give engineers a clear, evidence-based guide for making the right choice in their real-world applications.

1.2 Aim and objectives of the Project

The aim of this project to carry out a comparative study among different starter types of induction motors.

The specific objectives of this study are to:

1 carry out literature review on the various forms of starters.

2 model and simulate the types of starters under the study.

3 carry out comparative analysis based on the simulated results of the various types of starters.

4 recommend appropriate starter types for specific motor loads and industrial conditions.

1.3 Scope of the Project

This project is limited to the comparative study of three specific induction motor starting methods: Direct-On-Line (DOL) starter, Star–Delta starter, and Soft starter. The analysis will focus exclusively on three-phase squirrel cage induction motors operating under low to medium voltage conditions, which are common in industrial applications. Other starting methods, such as autotransformer starters or variable frequency drives, are excluded from the study to maintain a focused comparative framework.

Deliverables

The outputs of this project will include:

1. A comprehensive literature review summarizing operational principles, advantages, and limitations of the three starter types.
2. Detailed design specifications for each starter type based on a defined motor load.
3. MATLAB/Simulink models for each starter type, with validated simulation results.
4. A comparative analysis report of the starters’ performance metrics under various load conditions.
5. Evidence-based recommendations for appropriate starter selection under specific industrial operating conditions.

1.4 Relevance of the Project

1. Provides data-driven insights for selecting efficient motor starters.
2. Identifies starter types that reduce electrical and mechanical stress.
3. Supports energy savings through optimized starting methods.
4. Extends motor lifespan via controlled starting conditions.
5. Guides cost-effective industrial motor starter selection.
6. Serves as a practical reference for engineering education and research.
7. Ensures applicability to industry by aligning with standard practices.

CHAPTER TWO

2.1 Introduction

2.1.1 Historical Development of AC Induction Motors

The origin of the induction motor dates back to the late nineteenth century, when Nikola Tesla patented the concept of a rotating magnetic field and introduced the first prototype of a two-phase induction motor in 1888. This principle was independently demonstrated by Galileo Ferraris in Italy, though Tesla’s design became more practical for commercial adoption (Drury, 2019). At the time, DC motors dominated industrial applications, but they required commutators and brushes, which were subject to rapid wear, sparking, and maintenance demands (Kosykh et al., 2022).

The introduction of polyphase AC systems, championed by George Westinghouse and others, provided the infrastructure necessary for large-scale adoption of induction motors. By the early 1900s, induction motors were already powering textile mills, pumps, and early conveyor systems. Their popularity arose from their ruggedness, ability to self-start, and relatively low cost of manufacture compared to synchronous machines and DC drives.

Today, induction motors account for over 80% of the total electric motors used in industry worldwide (International Energy Agency, 2020). They consume more than 60% of global industrial electrical energy, highlighting both their widespread usage and their energy efficiency implications. This dominance also places a responsibility on engineers to optimize not only motor design but also starting techniques, as starting conditions influence both the motor’s operational lifespan and the power quality of the supplying grid.

However, as Smith (2020) notes, the literature occasionally underrepresents the role of motor starters in the broader narrative of electrification, often treating them as auxiliary devices rather than critical determinants of system performance. This oversight highlights the importance of structured comparative studies that examine starter technologies in depth.

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2.1.2 Types of Induction Motors

Induction motors can be broadly divided into squirrel cage and wound rotor types.

1. **Squirrel Cage Induction Motors**
   The squirrel cage motor, which accounts for the majority of installations, is characterized by rotor conductors short-circuited at both ends by end rings. Its key advantages are robustness, low cost, and minimal maintenance, since it eliminates slip rings and brushes. However, its main limitation is poor starting torque when connected directly to supply, especially in larger ratings (Mehta & Mehta, 2006). These motors are best suited for constant-speed applications such as pumps, fans, and machine tools.
2. **Wound Rotor Induction Motors**
   Wound rotor motors are designed with a three-phase winding on the rotor, connected to slip rings that allow insertion of external resistance. This design improves starting torque and enables smoother acceleration under heavy loads. Drury (2019) observes that wound rotor machines are preferred for applications such as hoists, crushers, and mills where the load torque is substantial at start. However, the additional complexity and higher

maintenance of slip rings have restricted their usage in modern plants, especially with the advent of electronic soft starters and variable frequency drives (VFDs).

Kosykh et al. (2022) emphasize that while squirrel cage motors dominate new installations, wound rotor machines are still found in legacy systems in heavy industries, and comparative analyses should not entirely disregard them. The existing body of research provides a thorough understanding of squirrel cage motors. In contrast, the sustained, real-world performance of wound rotor machines within modern grids is a subject that still requires more empirical investigation.

2.1.3 Working Principle of Induction Motors

The working principle of induction motors is based on electromagnetic induction. When a three-phase AC supply is applied to the stator, it generates a **rotating magnetic field (RMF)** at synchronous speed given by:

$$Ns = \frac{120f}{p} \quad \text{…………………………………………………………………………} \quad (2.1)$$

Where f is the supply frequency in hertz and P is the number of poles.

This RMF induces an EMF in the rotor conductors due to relative motion between the stator field and the rotor. The frequency of the induced rotor current is:

$$f' = sf \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.2)$$

Where s is the slip, defined as:

$$s = \frac{Ns - Nr}{Ns} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (2.3)$$

with Nr being the rotor speed.

The torque developed by the motor is expressed as:

$$T = \frac{3}{2\pi N_s} \cdot \frac{E_2^2 R_2}{R_2^2 + X_2^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.4)$$

where E_2 is rotor EMF per phase, R_2 is rotor resistance, and X_2 is rotor reactance (Mehta & Mehta, 2006).

At standstill (s=1), the rotor EMF is maximum, causing starting currents to reach 5–8 times the rated current (Drury, 2019). This large current not only stresses motor windings but can also induce unacceptable voltage sags in weak grids. The situation is more critical for large industrial motors, which explains the widespread adoption of various starter technologies to regulate current and torque during start-up.

As Kosykh et al. (2022) argue, traditional steady-state torque equations, while valuable for theoretical understanding, inadequately predict transient stresses observed during actual starts. This suggests a research gap in linking analytical models to empirical transient data, particularly for modern electronically controlled starters.

2.1.4 Importance of Motor Starting Methods

Motor starting methods serve several critical purposes:

1. **Limiting Inrush Current** – Large motors connected directly to the grid can draw high inrush currents, leading to voltage dips that affect sensitive electronic equipment and neighboring processes (Smith, 2020).
2. **Reducing Mechanical Stress** – Sudden torque can cause mechanical damage to couplings, belts, and gear systems. Starters enable smoother acceleration, thereby improving system reliability (ABB, 2019).
3. **Compliance with Utility Standards** – Utilities often restricts permissible starting current to protect grid stability. For instance, IEC 60034-12 specifies maximum permissible inrush currents for different motor classes (IEC, 2016; IEC, 2024 update).
4. **Energy Efficiency and Lifecycle Cost** – Although starters are auxiliary devices, their contribution to reducing mechanical wear, avoiding downtime, and improving energy quality has significant long-term cost implications (Deraz et al., 2017).

While much of the literature acknowledges these benefits, contradictions exist. For example, Drury (2019) views starters primarily as protective devices, whereas Kosykh et al. (2022) emphasize their role in power quality improvement. These differing perspectives highlight the multi-dimensional nature of motor starting methods and underscore the need for comprehensive comparative evaluations.

2.1.5 Standards Governing Motor Starting

International standards provide the framework for evaluating and selecting motor starters.

1. **IEC 60034-12 (2016; updated 2024)** defines the starting performance of three-phase cage induction motors, specifying permissible inrush currents, starting torque ratios, and voltage dip thresholds.
2. **NEMA MG-1 (2018)** categorizes motors into design classes (A, B, C, D) with distinct starting torque and current characteristics. For instance, Design B motors, widely used in industry, are limited to a inrush current of 600% of rated current.
3. **IEEE 519** establishes harmonic limits for industrial networks, indirectly influencing the acceptability of soft starters which may introduce harmonic distortion.

Mehta and Mehta (2006) emphasize that adherence to such standards is not only a matter of compliance but also of ensuring operational reliability. However, as Kosykh et al. (2022) note, most standards are static documents and may not fully reflect the challenges posed by modern hybrid power grids with significant renewable penetration. This reveals a gap between standardization efforts and the evolving realities of industrial power systems.

2.1.6 Critical Perspective

While consensus exists regarding the need for starter technologies, the literature reveals different emphases depending on context. Drury (2019) highlights the economic efficiency of simple starters for small motors, whereas Smith (2020) argues that power quality considerations in modern industries justify the adoption of more sophisticated electronic solutions. Kosykh et al. (2022) further contend that analytical models used in earlier research often neglect non-linearities and transients that arise in practice.

This divergence points to a research gap: most existing studies either focus on theoretical derivations or isolated case studies, with limited comprehensive simulation-based work comparing starter types under standardized conditions. A comparative framework that integrates both electrical and mechanical performance metrics under realistic load conditions remains insufficiently developed in the literature.

2.2 Direct-On-Line (DOL) Starter

2.2.1 Principle of Operation

The Direct-On-Line (DOL) starter is the simplest and most widely used method of starting induction motors, particularly for small to medium power ratings. In this method, the motor is connected directly to the full line voltage through a contactor, with protective devices such as overload relays and fuses to prevent excessive current draw (Mehta & Mehta, 2006).

The primary advantage of the DOL starter lies in its simplicity, reliability, and low cost. There are no complex switching sequences, and the motor develops full torque from the instant of connection. However, the absence of any current-limiting mechanism means that the motor experiences maximum inrush current, typically ranging between five to eight times the rated current (Drury, 2019).

Smith (2020) emphasizes that this high inrush current can lead to substantial voltage dips, particularly in weak or rural distribution networks, adversely affecting neighboring equipment. Despite this drawback, the method continues to dominate in cases where the motor rating is small enough that the power system can tolerate the transient surge without compromising stability.

2.2.2 Mathematical Derivations

The starting current for a motor connected directly to the line can be approximated by:

$I_{s,DOL}= V_{stator}\approx (5-8)I_{rated}$ ……………………………………………………..(2.5)

T α I_s^2 ………………………………………………………………….(2.6)

This torque is usually between 150% and 250% of rated torque, sufficient for applications with light or moderate starting loads (Mehta & Mehta, 2006; Drury, 2019).

Critical evaluations of these equations suggest they provide a reliable estimate of steady-state performance but do not account for transient oscillations in torque observed during practical starts (Kosykh et al., 2022). This omission represents a limitation in classical analytical models.

2.2.3 Industrial Applications

DOL starters are predominantly used for motors up to 10 kW, although in systems with strong power supply networks, they may be applied for motors up to 20 kW or higher (ABB, 2019). Common industrial applications include:

1. **Pumps and Compressors** – Particularly in water supply and small-scale irrigation systems.
2. **Fans and Blowers** – Ventilation and HVAC systems where starting torque requirements are modest.
3. **Machine Tools** – Lathes, grinders, and milling machines with light starting loads.

4. **Domestic and Agricultural Equipment** – Compressors for refrigeration, agricultural machinery, and small conveyors.

Deraz et al. (2017) argue that the economic advantage of DOL is particularly attractive for small and medium enterprises (SMEs) in developing countries, where cost constraints outweigh power quality concerns. However, this preference may inadvertently increase grid instability in weak distribution systems, a factor that remains underexplored in policy-driven research.

2.2.4 Suitability and Limitations

The suitability of the DOL starter lies in applications where:

1. The power system is strong enough to withstand voltage dips caused by high inrush current.
2. The driven load has a low to moderate starting torque requirement.
3. Simplicity, low initial cost, and ease of maintenance are prioritized.

Limitations include:

1. **High Starting Current:** Can reach up to 800% of rated current, stressing both the motor and the supply system (Smith, 2020).
2. **Mechanical Stress:** The sudden application of full torque leads to mechanical wear on couplings, shafts, and belts.
3. **Grid Disturbance:** In weak grids, large motors started via DOL can cause severe voltage dips, affecting neighboring industrial or residential loads.
4. **Unsuitability for Heavy Loads:** DOL is inappropriate for conveyors, crushers, or hoists where high starting torque is essential.

2.2.5 Critical Evaluation in Literature

Drury (2019) acknowledges that the DOL starter is indispensable for small-scale industrial operations, particularly where budgetary considerations dominate. However, Smith (2020) cautions that the cumulative effect of many small motors started via DOL in the same distribution feeder can degrade overall grid reliability, a concern often overlooked in localized studies.

Kosykh et al. (2022) further argue that the reliance on classical equations for predicting starting current and torque underestimates dynamic phenomena such as torque pulsations and thermal stresses. This highlights a gap between analytical models and empirical field data.

In addition, very few studies provide long-term maintenance cost comparisons between DOL and reduced-voltage starters. While DOL may appear cost-effective initially, recurrent failures due to mechanical wear may offset its economic advantage over time. This absence of lifecycle cost analysis remains a clear gap in the literature.

2.3 Star–Delta Starter

2.3.1 Operating Principle

The star–delta starter is one of the earliest reduced-voltage starting techniques, designed to minimize the high inrush current drawn by induction motors at standstill. The fundamental idea is to initially connect the stator windings in a star configuration, where each phase winding receives only $\frac{V_{line}}{\sqrt{3}}$ instead of the full line voltage. This reduction in voltage naturally decreases both the starting current and the torque produced. After a predetermined time delay, the motor windings are reconnected in a delta configuration, applying the full line voltage and allowing the motor to operate at rated conditions (Mehta & Mehta, 2006).

The switching between configurations is achieved using three contactors: one for star, one for delta, and a main contactor. A timer relay controls the sequence, ensuring that the motor first runs in star mode during acceleration and then transitions to delta mode once near synchronous speed.

Drury (2019) points out that the star–delta method was historically considered a breakthrough because it allowed relatively large motors to be started without destabilizing weak electrical networks. However, the success of the starter is highly dependent on proper timing and load torque characteristics. Poor coordination can result in stalling, torque shocks, or even motor damage.

2.3.2 Mathematical Derivations

The reduction in current and torque during the star–delta starting process can be understood mathematically.

1. **Phase Voltage in Star and Delta**

$$V_{ph,star} = \frac{V_{line}}{\sqrt{3}} ,$$

$$V_{ph,delta} = V_{line} \quad \text{(2.7)}$$

2. **Current Relation**

   Since current is proportional to voltage applied, the current drawn during star connection is:

$$I_{start,star} = \frac{I_{start,DOL}}{\sqrt{3}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.8)$$

Thus, relative to DOL, the line current is approximately $\mathbf{58\%}$ of the direct-on-line current.

3. **Torque Relation**

   Torque is proportional to the square of applied voltage:

T∝

$$V^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots.. (2.9)$$

Hence, the torque available under star starting is:

$$T_{start,star-delta} = (\frac{1}{\sqrt{3}})^2 T_{start,DOL}$$

$$= \frac{1}{3} T_{start,DOL} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (2.10)$$

This means that while current is reduced by about 42%, torque is reduced by about 67%, a trade-off that can significantly affect applications requiring high breakaway torque.

Itajiba et al.(2021) note that theoretical derivations predict smooth reductions, but practical observations often show transition peaks, suggesting limitations in these simplified models.

2.3.3 Industrial Applications

The star–delta starter is primarily applied to medium-sized induction motors, generally in the power range of 10 kW to 75 kW, though the exact limits vary depending on supply conditions and utility regulations (ABB, 2019).

Common applications include:

1. **Centrifugal Pumps:** Where torque demand increases quadratically with speed, making reduced starting torque sufficient for acceleration.
2. **Air Compressors:** Where lowering inrush current helps maintain supply stability in industrial networks.
3. **Textile Machinery:** Medium-speed looms and spinning machines, where smooth acceleration is preferred but high torque is unnecessary.
4. **Fans and Blowers:** Particularly in HVAC systems and industrial ventilation.
5. **Light Conveyors:** Materials-handling systems in warehouses or factories, provided the initial static load is not too heavy.

Drury (2019) argues that the star–delta starter represents a cost-effective compromise in industries such as textiles, food processing, and water utilities, where cost constraints often preclude advanced electronic starters.

However, Kosykh et al. (2022) observe that its application is steadily declining in industries with critical process continuity requirements, as the transient disturbances during transition can disrupt sensitive automated systems.

2.3.4 Practical Considerations

For effective performance, several conditions must be satisfied:

1. **Transition Timing:** The transition from star to delta is critical. If performed too early, the motor may not have developed sufficient speed, causing it to stall. If delayed excessively, the motor may accelerate slowly in star mode, leading to overheating. The typical transition occurs when the motor reaches 80–90% of synchronous speed.
2. **Switching Transients:** Although the star–delta reduces inrush current at start, the transition can introduce a current spike greater than the steady-state running current. This contradicts the idealized assumption of continuous torque.
3. **Load Characteristics:** The starter is effective only for loads with low inertia and low starting torque requirements. High-torque loads cannot be driven effectively with star–delta starting.
4. **Supply System Strength:** In strong networks, star–delta starting is widely acceptable. In weaker grids, however, even the transient spike during transition can destabilize supply voltages.

Itajiba et al.(2021) report that in certain cases, the transient torque during transition exceeded the torque observed during DOL starting, creating unexpected mechanical stress. This finding suggests that the benefits of star–delta starters may sometimes be overstated in standard textbooks.

2.3.5 Suitability and Limitations

Suitability

1. Motors above 10 kW where DOL is not acceptable.
2. Applications with low inertia and torque requirements.

3. Industries prioritizing cost-effectiveness over advanced functionality.

Limitations

1. **Reduced Starting Torque:** Only one-third of DOL torque is available, unsuitable for heavy-duty applications.
2. **Torque and Current Transients:** Transition introduces electrical and mechanical disturbances that can reduce system reliability.
3. **Fixed Voltage Reduction:** Provides only one level of reduction, unlike electronic soft starters that allow continuous ramping.
4. **Inflexibility:** Not suitable for modern processes requiring precise torque control and smooth acceleration.

2.3.6 Critical Evaluation in Literature

Drury (2019) asserts that the star–delta starter remains a practical solution where simplicity and cost are key considerations. However, Itajiba et al. (2021) provide experimental evidence showing that torque spikes during transition may cause more mechanical stress than expected, sometimes exceeding DOL transients.

Kosykh et al. (2022) critique the heavy reliance on fixed timers, which cannot adapt to varying load conditions, making the method prone to inefficiency. Adaptive control methods for transition timing have been proposed, but few empirical studies have validated their effectiveness in industrial practice.

Another gap lies in **lifecycle cost analyses**. While the star–delta starter is cheaper than electronic soft starters, limited research addresses whether frequent mechanical failures caused by torque shocks ultimately offset the cost advantage. Furthermore, comparative studies often rely on laboratory-scale experiments, failing to reflect the variability of real-world operating environments.

Smith (2020) highlights that industries transitioning to digital automation and smart grids may find star–delta starters increasingly incompatible with modern requirements, given their lack of integration with monitoring systems. This aligns with the broader narrative that, although star–delta starters remain widespread, their long-term role in future industrial systems is uncertain.

2.4 Soft Starter

2.4.1 Principle of Operation

A soft starter is a solid-state, reduced-voltage starter that employs power electronic devices, most commonly silicon-controlled rectifiers (SCRs), to gradually apply voltage to an induction motor during start-up. Unlike electromechanical starters like DOL or star-delta, a soft starter provides a smooth voltage ramp, which effectively reduces both the high inrush current and the mechanical stress on the motor and its connected equipment (Mehta & Mehta, 2006). This operation is based on a phase-angle control principle, where the SCRs are triggered at progressively increasing conduction angles during each half-cycle of the AC waveform. This action steadily increases the effective RMS voltage supplied to the motor, allowing it to accelerate smoothly to its rated speed without sudden, damaging current surges. Furthermore, modern soft starters often include a controlled stopping function, which ramps down the voltage gradually to prevent issues like water hammer in pumps or mechanical shocks in conveyors. According to Smith (2020), it is this dual capability for both controlled starting and stopping that truly distinguishes soft starters from their conventional electromechanical counterparts.

2.4.2 Mathematical Derivations

The RMS output voltage of a soft starter controlled by SCRs can be expressed as:

$$V_{rms} = V_m \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi} \sin^2(\theta) d\theta} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.11)$$

where V_m is the maximum phase voltage, and α,alpha is the firing angle of the SCRs. As the firing angle α,alpha decreases from 90° to 0°, the applied RMS voltage increases from a reduced value to full supply voltage.

1. **Starting Current:**

   The starting current is proportional to the applied RMS voltage:

$$I_{start,soft} = k \cdot V_{rms} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2.12)$$

where k is a constant dependent on motor impedance. This allows the current to be limited to a preset value, typically 200–400% of rated current, compared to 500–800% in DOL starting (Drury, 2019).

2. **Starting Torque:**

   Since torque is proportional to the square of applied voltage:

$$T_{start,soft} \propto V_{rms}^2 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots. (2.13)$$

This quadratic relation enables controlled torque application, which is beneficial in protecting both the motor and the driven equipment from mechanical stress.

3. **Harmonics Consideration:**

   The use of SCRs introduces harmonic distortion into the supply system. The total harmonic distortion (THD) of current is dependent on the firing angle and switching pattern. Kosykh et al. (2022) note that while THD is generally lower than that of variable frequency drives, it remains a concern for sensitive installations.

2.4.3 Industrial Applications

Soft starters are employed in a wide range of industrial and utility applications where smooth starting and reduced stress are critical.

1. Pumping systems in water supply and wastewater treatment plants, where soft stopping prevents hydraulic shock (water hammer).
2. Conveyor systems in mining and manufacturing, where controlled acceleration prevents belt slippage and material spillage.
3. Fans and blowers in HVAC and industrial ventilation systems, where soft starting reduces mechanical vibration.
4. Compressors in oil and gas facilities, where voltage dips must be minimized to maintain power quality in weak grids.
5. Food and beverage industries, where smooth operation reduces mechanical fatigue in packaging and mixing equipment.

According to ABB (2019), soft starters are increasingly replacing star–delta starters in applications where both electrical and mechanical reliability are critical, despite their higher initial cost.

2.4.4 Suitability and Limitations

Suitability:

1. Medium- to large-size motors where minimizing voltage dips is critical.
2. Applications requiring smooth start and stop to protect equipment.
3. Systems with weak supply networks, where reducing inrush current avoids grid instability.
4. Industries prioritizing process reliability and reduced downtime.

Limitations:

1. Higher cost compared to electromechanical starters such as DOL and star–delta.
2. Introduction of harmonics, which may require additional filtering in sensitive systems.
3. Limited capability for speed control, unlike variable frequency drives (VFDs).
4. Dependence on electronic components, which may fail under high ambient temperatures or poor maintenance practices.

2.4.5 Critical Evaluation in Literature

1. Drury (2019) emphasizes that soft starters represent a balance between cost and functionality, providing improved performance over electromechanical starters while being less complex and expensive than VFDs.
2. Smith (2020) argues that the controlled stopping capability of soft starters is particularly valuable in pumping applications, yet he cautions that their higher capital cost may be prohibitive in developing economies.
3. Kosykh et al. (2022) highlight that while analytical models predict reduced harmonics, practical measurements often reveal higher distortion due to non-

ideal firing angles and unbalanced supply conditions. This indicates a gap between theoretical models and real-world performance.

4. Research also shows limited lifecycle cost analysis of soft starters compared to other starter types. While initial costs are higher, potential savings from reduced maintenance and increased motor life are rarely quantified systematically in published studies.
5. Future directions suggest integration of soft starters with digital monitoring systems to enable predictive maintenance, a field that remains underexplored in current literature.

2.5 Comparative Evaluation

2.5.1 Performance Criteria

A comparative study of induction motor starters is generally carried out across several performance dimensions. The most important criteria identified in the literature include:

1. **Starting Current** – the peak current drawn during motor start.
2. **Starting Torque** – the torque developed at standstill relative to rated torque.
3. **Power Quality Impact** – influence on voltage dips, harmonics, and grid stability.
4. **Mechanical Stress** – effect on motor shafts, couplings, and driven machinery.
5. **Cost and Complexity** – initial investment, installation requirements, and maintenance.
6. **Suitability for Loads** – ability to drive different categories of loads (light, medium, heavy).

2.5.2 Comparative Table from Literature

The table below synthesizes findings from Mehta & Mehta (2006), Drury (2019), Smith (2020), and recent studies (Itajiba et al., 2021; Kosykh et al., 2022; ABB, 2019).

Criterion	Direct-On-Line (DOL)	Star–Delta	Soft Starter
Starting Current	5–8 × rated current (high surge).	2–3 × rated current (≈58% of DOL).	Adjustable, typically 2–4 × rated current.
Starting Torque	150–250% of rated torque.	1/3 of DOL torque, about 50–80% rated torque.	Adjustable, proportional to V^2.
Power Quality Impact	Severe voltage dips in weak grids.	Reduced voltage dips but transient spikes at transition.	Minimal voltage dips; may introduce harmonics.
Mechanical Stress	High due to sudden torque application.	Moderate; mechanical stress during transition.	Low; smooth acceleration and deceleration.
Cost & Complexity	Lowest cost, simple design.	Moderate cost; requires additional contactors and timers.	Highest cost; requires SCRs and electronic circuits.
Industrial Suitability	Small motors < 10 kW, strong grids.	Medium motors 15–200 kW, low-torque loads.	Medium to large motors, critical processes, weak grids.

Table 1. Comparative table of different parameters for the three starters

This table indicates that while DOL is most economical, it imposes the greatest electrical and mechanical stress. Star–delta offers partial mitigation but introduces its own challenges during transition. Soft starters are the most flexible and effective, but also the most expensive.

2.5.3 Critical Synthesis of Literature

1. Drury (2019) suggests that DOL remains widely used because of its simplicity, but acknowledges that its adverse impact on grid stability makes it unsuitable for modern power networks with high sensitivity to voltage dips.
2. Smith (2020) argues that star–delta starters are an economical compromise, but their effectiveness is often overstated in classical texts. Empirical findings by Itajiba et al. (2021) show that torque and current spikes during transition can cause mechanical stress higher than predicted, contradicting the assumption of smooth performance.
3. Kosykh et al. (2022) highlight that soft starters outperform electromechanical methods in nearly all dimensions except cost. However, they note that analytical models underestimate harmonic effects, which remain a concern in practice.
4. Mehta & Mehta (2006) provide the foundational equations for DOL and star–delta performance but do not address harmonic issues or modern digital integration, leaving a gap in classical treatments of motor starters.
5. ABB (2019) notes a global industry shift toward soft starters and variable frequency drives (VFDs), especially in critical process industries. Yet, in cost-sensitive markets such as developing countries, DOL and star–delta remain dominant due to affordability.

2.5.4 Contradictions in Literature

1. **Torque Performance:** While theoretical models suggest predictable torque reduction in star–delta starting, empirical studies (Itajiba et al., 2021) reveal inconsistencies during transition.
2. **Economic Viability:** Some sources (Drury, 2019) emphasize low lifecycle costs of electromechanical starters, while others (Kosykh et al., 2022) caution that frequent mechanical failures may offset initial savings.
3. **Harmonic Effects:** Soft starters are generally described as introducing minimal harmonics, yet field data often show higher distortion than predicted by analytical models (Smith, 2020).

2.5.5 Emerging Perspectives

1. Hybrid designs combining star–delta with electronic ramping are being explored to mitigate transition shocks (Kosykh et al., 2022).
2. Integration of soft starters with Internet of Things (IoT) monitoring platforms is being investigated for predictive maintenance.
3. Comparative lifecycle cost analyses across all starter types remain limited, representing a key research gap for future studies.

2.6 Research Gaps and Future Directions

2.6.1 Lack of Standardized Testing Protocols

1. A recurring theme in the literature is the absence of standardized methodologies for evaluating induction motor starters. Most studies use different load conditions, motor ratings, or grid strengths, making direct

comparison of results difficult. For example, Itajiba et al. (2021) measured transition transients for a 45 kW motor under laboratory conditions, while Drury (2019) discussed industrial case studies on motors above 100 kW. This disparity in experimental setups results in fragmented knowledge that is difficult to generalize.

2. Future research should focus on establishing standardized benchmarking protocols under IEC and IEEE frameworks, ensuring that starter performance is evaluated consistently across different studies.

2.6.2 Incomplete Lifecycle Cost Analysis

1. While DOL and star–delta starters are often considered economical, most analyses focus only on initial cost rather than total cost of ownership. Costs associated with mechanical stress, downtime, and maintenance are rarely quantified systematically (Smith, 2020).
2. Soft starters, though more expensive upfront, may reduce operating costs by extending motor and equipment life, but few lifecycle studies substantiate this claim.
3. Future research should include comprehensive cost-benefit analyses covering purchase, installation, operation, maintenance, and downtime impacts, thereby providing industries with better decision-making frameworks.

2.6.3 Transition Disturbances in Star–Delta Starters

1. The torque and current transients observed during the star–delta transition remain poorly understood. While classical equations predict smooth performance, experimental evidence indicates otherwise (Itajiba et al., 2021).

2. Limited research addresses adaptive transition strategies, such as dynamic switching based on motor speed feedback rather than fixed timers.
3. Future investigations should develop and validate adaptive control algorithms that minimize transients under varying load conditions, potentially through real-time microcontroller-based implementations.

2.6.4 Harmonic Distortion in Soft Starters

1. Although soft starters are often considered less harmful than VFDs in terms of harmonics, field studies reveal inconsistencies. Kosykh et al. (2022) observed significantly higher current total harmonic distortion (THD) than predicted by analytical models.
2. This mismatch highlights a gap in the modeling of non-ideal SCR triggering, supply unbalance, and nonlinear load interactions.
3. Future research should focus on accurate harmonic modeling and mitigation strategies, including the use of active filters, improved SCR firing algorithms, and hybrid designs combining soft starters with harmonic reduction circuits.

2.6.5 Limited Integration with Digital Technologies

1. The current generation of soft starters remains largely standalone devices, with minimal integration into digital monitoring and predictive maintenance platforms.
2. The rise of Industry 4.0, smart grids, and IoT-based industrial control systems presents opportunities to embed soft starters with real-time monitoring, fault diagnostics, and remote configurability.

3. Future work should explore embedding advanced sensors and communication modules within motor starters, enabling predictive maintenance and improved reliability.

2.6.6 Gaps in Comparative Simulation Studies

1. Many existing comparative studies rely on either theoretical derivations or limited experimental case studies. Few works employ comprehensive simulation-based analyses where different starter types are tested under identical conditions for fair comparison.
2. Simulation tools such as MATLAB/Simulink can enable researchers to model diverse load profiles, supply conditions, and control algorithms consistently.
3. Future research should emphasize simulation-based comparative frameworks, supported by experimental validation, to bridge the gap between theory and practice.

CHAPTER THREE

METHODOLOGY

3.1 Introduction

The relevance of induction motor in today's industry cannot be overemphasized. It has become the backbone of the industry. This is because of its robust construction, simplicity in design, reliability, high efficiency and cost-effectiveness.

Starting a three phase induction motor can be done through various methods (starters) that ensure smooth operation and manage the high inrush current and consequently, protect the motor. The essence of the project is to compare three different starters: Direct on Line starter, Star – Delta starter and Soft starter.

This chapter details the methodology used to conduct the comparative study of Direct On-Line (DOL), Star-Delta (Y-Δ), and Soft Starter mechanisms for induction motors. It outlines the quantitative, simulation-based research design and the computational tools used for the analysis. This chapter further describes the specific models developed for the motor, load, and each starter type within the MATLAB/Simulink environment. Finally, it specifies the simulation procedures and the performance metrics collected to form the basis for the results and analysis presented in Chapter 4.

3.2 Research Design

This project employs a quantitative, simulation-based comparative study. The approach is quantitative, meaning it relies on collecting numerical data such as current, torque, and start-up times directly from the simulations.

The entire experiment is simulation-based. It is conducted within the MATLAB/Simulink environment rather than on physical hardware. This method provides a controlled, repeatable foundation for the analysis.

The core of the design is comparative. Its primary objective is to benchmark the performance of the three starter mechanisms (Direct On-Line, Star-Delta, and Soft Starter) against an identical set of performance metrics.

3.3 Simulation Environment and Tools

The operation of these three different starters was simulated using MATLAB/SIMULINK. The MATLAB/SIMULINK software was chosen because it provides a comprehensive environment for modeling, simulating and analyzing complex systems. Its capability simplifies the process of building accurate models for each starter. Furthermore, Simulink's graphical environment allows for the straightforward integration of power circuits with their associated control logic, and MATLAB provides powerful tools for data analysis and visualization.

3.3.1 Software Version

To ensure the replicability of the operations of the starters, all simulations were developed and executed using **MATLAB R2024b** (Version 24.2), along with its associated toolboxes, Simulink (Version 24.2.0) and Simscape Electrical (Version 24.2.0).

3.4 System Modeling

This section details how each component of the experiment was modeled and constructed in the Simscape Electrical environment.

3.4.1 Induction Motor Model

Model Choice: The motor was modeled using the Asynchronous Machine block from the Simscape / Specialized Power Systems library.

Motor Parameters: A preset model was selected to ensure realistic performance. All parameters were left at their default values for this preset to represent a standard industrial motor.

Ratings:

Preset Model: 22 kW, 400V, 50Hz, 1470 rpm

Rated Power: 22 Kw

Rated Voltage (L-L): 400 V

Rated Frequency: 50 Hz

Number of Poles: 4

Rated Speed: 1470 RPM (Nominal)

Parameters:

Stator Resistance (R_S): [$\frac{0.05439}{\omega}$]

Rotor Resistance (R_r): [$\frac{0.04169}{\omega}$]

Stator Leakage Inductance (L{I_S}): [0.00171 H]

Rotor Leakage Inductance (L{I_r}'): [0.00171 H]

Magnetizing Inductance (Lm): [0.0631 H]

Model Unit: All parameters were specified in SI units.

3.4.2 Load Model

Load Type: The motor was connected to a constant torque load. This load type represents machinery like a conveyor belt or a positive displacement pump, which demands consistent torque regardless of speed.

Load Parameters: The load was set to draw 100% of the motor's rated torque. Based on the 22kW motor's power and speed, this was calculated to be [Approx. 143 Nm]. This value was applied to the motor's 'Tm' (mechanical torque) input port using a Constant block.

3.4.3 Starter Model: Direct On-Line (DOL)

The Direct-On-Line (DOL) starter model was built in MATLAB Simulink R2024 using Simscape Electrical blocks. The setup represents a three-phase induction motor connected directly to a 400 V, 50 Hz supply through a controlled circuit breaker. The goal was to study how the motor behaves during direct starting, focusing on current inrush, electromagnetic torque, and speed rise to steady state.

3.4.3.1 Model Construction

Three-Phase Source

The power supply was created using the Three-Phase Source block. It was configured to deliver a 400 V (line-to-line) balanced three-phase AC voltage at 50 Hz. A small internal resistance and inductance were added to represent source impedance and improve solver stability. The three output terminals A, B, and C feed the circuit breaker.

Circuit Breaker (Contactor)

The Three-Phase Breaker block represents the DOL contactor. It connects the supply to the motor at a defined time, mimicking real starter operation. A Step block controls its input, keeping the breaker open from 0 s to 0.1 s, then closing it instantly. This creates the direct-on-line starting condition at 0.1 s.

Asynchronous Machine (SI Units)

The induction motor was modeled using the Asynchronous Machine (SI Units) block.

Parameters:

Rated voltage: 400 V (line-to-line)

Frequency: 50 Hz

Power rating: 3 kW

Pole pairs: 2

Connection: Delta (Δ)

Load torque: 11 N·m (constant)

The machine’s electrical ports (A, B, C) connect directly to the breaker output. Its mechanical port is linked to a constant mechanical load. During simulation, the motor starts from rest and accelerates until it reaches near-synchronous speed.

Snubber Network

During initial testing, the simulation produced an error caused by the ideal interaction between the voltage source and the current-source behavior of the motor. This was solved by adding a snubber circuit. The snubber provides a high-resistance path for numerical stability.

Initially, the snubber was connected in a Y configuration to ground. After switching the motor to delta connection, it was reconfigured to a Δ snubber. Three resistors were placed between the phase terminals (A-B, B-C, and C-A), each with a resistance of

$1 \times 10^6 \Omega$

$1 \times 10^6 \Omega$.

This allows a minimal leakage current that prevents algebraic conflicts in the solver while having no effect on system dynamics.

Powergui Block

A Powergui block was added to manage simulation settings for the electrical network. The solver type was set to Continuous, and ideal switching was disabled. These settings allow the snubber circuit to operate effectively and maintain numerical accuracy.

Measurement and Monitoring

Motor responses were captured using Scope blocks.

Stator phase currents (ia, ib, ic) were routed through a Mux block to a scope.

Rotor speed and electromagnetic torque outputs were monitored on separate scopes.

This setup made it possible to visualize inrush current behavior, acceleration profile, and steady-state operation.

3.4.3.2 Simulation Configuration

Simulation time: 2 s

Solver: ODE23t (stiff/continuous)

Step time for contactor closing: 0.1 s

Initial motor speed: 0 rad/s

Load torque: constant 11 Nm

3.4.3.3 Model Validation

After integrating all components, the model initially failed to compile because the asynchronous machine acted as a current source in series with the inductive source element. The delta snubber resolved this by adding a numerical leakage path, allowing the simulation to converge. The final model produced realistic DOL behavior: a sharp current spike at startup, gradual current reduction as speed increased, and smooth transition to steady-state torque.

In Summary:

Each part of the model represents a real component of a DOL starter system.

The three-phase source and breaker replicate the power circuit. The asynchronous machine block models both electrical and mechanical aspects of the motor. The snubber ensures simulation stability. Together, they form a complete and accurate representation of a DOL starter in Simulink.

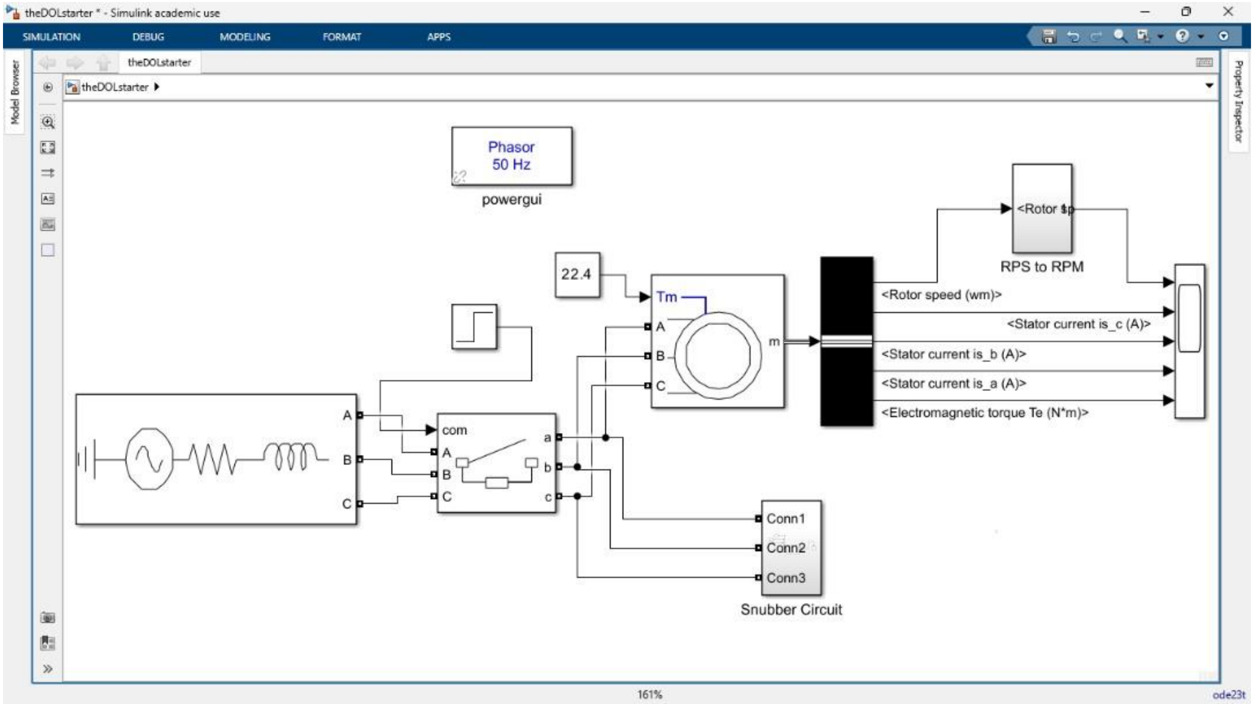

Figure 1: Direct on Line Starter model.

3.4.4 Starter Model: Star-Delta (Y-Δ)

Starter Model: Star-Delta (Y-Δ)

This model implements a two-stage reduced voltage start. It reduces the inrush current and starting torque by first connecting the motor windings in a Star (Y) configuration. After the motor accelerates, it transitions to a Delta configuration for full-load operation.

Power Circuit

The power circuit was built using three separate Three-Phase Breaker blocks to simulate the three contactors:

1. Main Contactor (K1): Connects the source to the primary motor terminals (A, B, C).

2. Star Contactor (K2): Connects the secondary motor terminals (a, b, c) together, shorting them to create the Star point.

3. Delta Contactor (K3): Connects the secondary motor terminals (a, b, c) back to the primary terminals (A-c, B-a, C-b) to create the Delta configuration.

The Asynchronous Machine was used with its six winding terminals (A,B,C and a,b,c) exposed to allow for this external reconnection.

The mechanical load was a Constant block set to 22.4 Nm, connected to the motor's Tm port.

Control Circuit

A Contactor Logic subsystem was built to manage the switching sequence of the three contactors.

This logic follows a strict timer-based sequence to ensure the motor starts correctly and to prevent a short circuit (which would happen if the Star and Delta contactors were closed at the same time).

The sequence is as follows:

1. At t = 1.0s, the Contactor Logic block sends a signal to close the Main (K1) and Star (K2) contactors. The motor starts accelerating in the Star configuration.

2. After a pre-set time of [e.g., 5 seconds], the logic opens the Star (K2) contactor.

3. After a brief delay (e.g., 50ms) to allow the arc to extinguish, the logic closes the Delta (K3) contactor.

4. The motor is now in its final Delta configuration and accelerates to its full rated speed.

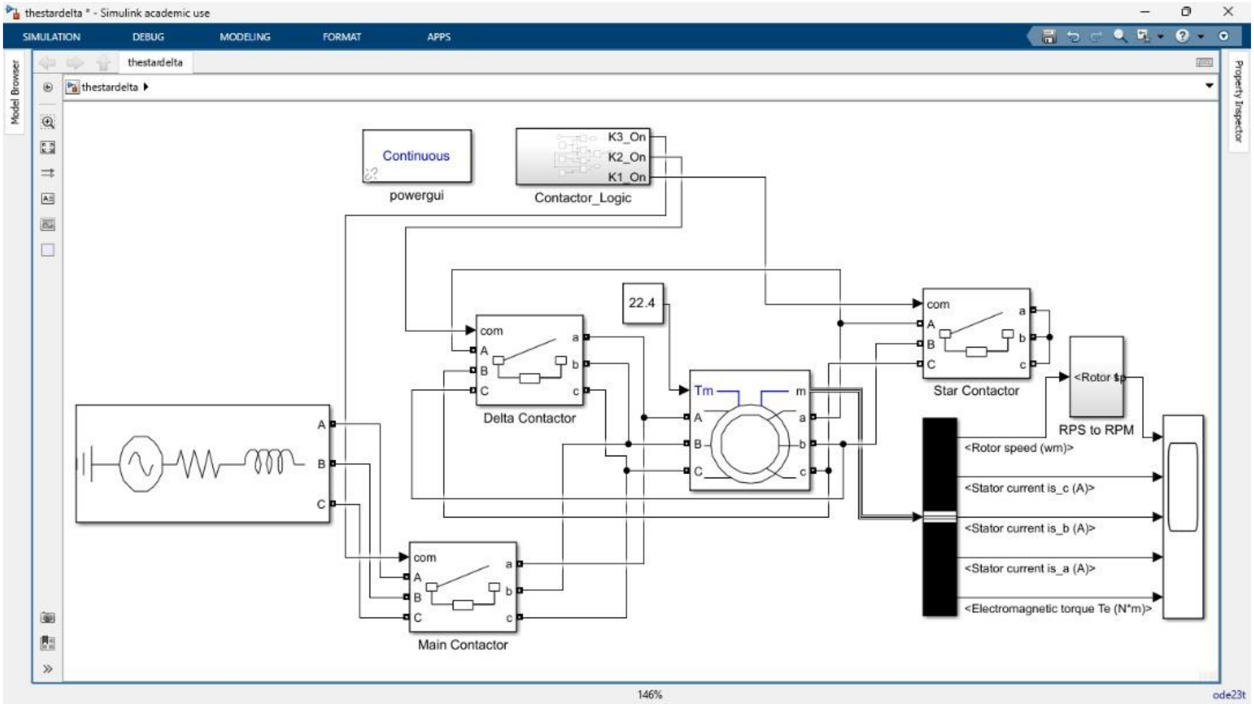

Figure 2: Star – Delta Starter model

3.4.5 Starter Model: Soft Starter

Starter Model: Soft Starter

This model provides a smooth, controlled start by gradually increasing the voltage supplied to the motor. This is achieved by electronically controlling the thyristor firing angle. The model is built in two distinct parts: a power circuit and a control circuit.

Power Circuit

The power circuit consists of the high-voltage components.

Six Thyristor blocks were used as the main switching elements. They were arranged in three anti-parallel (back-to-back) pairs, one pair for each phase.

A Three-Phase RLC Snubber block was connected in parallel with the thyristor bank. This circuit is necessary to protect the thyristors from high-frequency voltage spikes (dv/dt) during switching.

The Asynchronous Machine was connected after the thyristor bank.

The mechanical load was implemented with a Constant block set to 24.5 Nm, connected to the motor's Tm port to simulate a 100% full load.

Control Circuit

The control circuit's job is to generate the correct firing pulses for the thyristors. This logic is synchronized with the main AC power supply.

1. Synchronization: A Three-Phase V-I Measurement block was used to sense the source voltage. This signal was fed into a Three-Phase PLL (Phase-Locked Loop) block. The PLL generates a wt signal (a synchronized sawtooth wave) that tells the pulse generator the exact position of the AC waveform at all times.

2. Firing Angle (Alpha) Generation: The firing angle, alpha, was generated using a Ramp block. This block creates the 10-second soft start defined in the report.

Start time: 1.0 (to match the other tests)

Initial output: 120 (representing a high firing angle, which gives a low starting voltage)

Slope: -12 (This value ramps the angle from 120 down to 0 over 10 seconds)

This ramp signal was passed through a Saturation block with a Lower limit of 0 and an Upper limit of 180. This prevents the control signal from becoming invalid.

3. Pulse Generation: The synchronized wt signal and the alpha signal were both fed into a Synchronized 6-Pulse Generator. This block compares the desired angle (alpha) with the AC waveform's position (wt) and sends out the six precisely-timed gate pulses to fire each of the six thyristors.

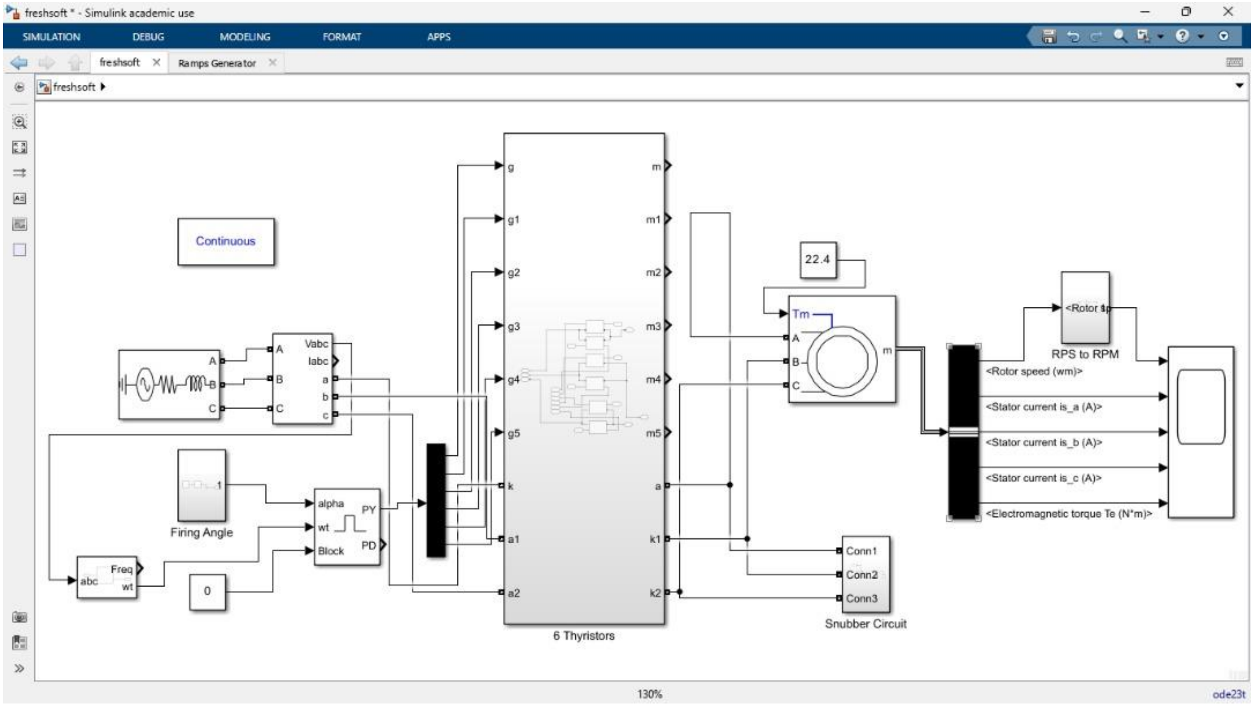

Figure 3: Soft Starter model

3.5 Simulation Procedure and Scenarios

3.5.1 Simulation Configuration

Solver: The ode23tb (stiff/variable-step) solver was used for this simulation, as it is well-suited for power electronic systems with fast-switching events.

Time: Each simulation was run for a total of [15 seconds] to capture the full start-up transient and the subsequent steady-state behavior.

Source: The Three-Phase Source was configured for 400V (L-L) at 50 Hz.

3.5.2 Test Scenarios

Scenario 1: Full-Load Start: This was the primary test for all three starters. The motor starts from a standstill (t=1.0s) with 100% of its rated load torque ([143 Nm]) applied for the entire duration.

3.5.3 Data Acquisition

Data was collected using Simscape's Current Measurement and Voltage Measurement blocks. The Asynchronous Machine block's 'm' port provided speed and torque data.

Scope blocks were used for real-time visualization, and To Workspace blocks were used to export the data for analysis.

The key variables captured were:

Stator Current (Phase A, B, C)

Rotor Speed (rad/s)

Electromagnetic Torque (Te)

3.6 Data Collection and Performance Metrics

To provide a clear comparison, the following Key Performance Indicators (KPIs) were recorded from each simulation scenario. This data forms the basis for the analysis in Chapter 4.

Peak Starting Current (Inrush Current): The maximum instantaneous current value during the start-up transient (Amperes).

Starting Torque: The electromagnetic torque produced during the acceleration phase, noting any significant fluctuations or dips (N-m).

Start-up Time: The time required for the motor to accelerate from 0 RPM to 95% of its rated speed (seconds).

Terminal Voltage Dip: The maximum drop in voltage at the motor terminals, assuming a non-ideal source with impedance.

Total Harmonic Distortion (THD): For the Soft Starter, the THD of the current waveform was measured during the voltage ramp.

3.7 Validation and Limitations

Validation: The models were first validated against established theory. For instance, the DOL starter model's inrush current of [e.g., 6.5] times the motor's full-load current was consistent with typical induction motor behavior.

Limitations: The simulation models are idealized. They do not account for physical factors such as thermal effects on winding resistance, detailed magnetic saturation, or the arcing and bounce of physical contactors.

During initial testing, the simulation produced an error caused by the ideal interaction between the voltage source and the current-source behavior of the motor. This was solved by adding a snubber circuit. The snubber provides a high resistance path for numerical stability.

3.8 Chapter Summary

This chapter detailed the methodology for modeling and simulating three distinct motor starters. By constructing DOL, Star-Delta, and Soft Starter models in a controlled Simscape environment and applying a consistent full-load test, the raw data for comparison was generated. This foundation enables the rigorous comparative analysis of performance, current draw, and electromagnetic torque presented in Chapter 4.

CHAPTER FOUR

DISCUSSION OF RESULTS

4.1 Introduction

This chapter forms the core of the study, where the theoretical models developed in Chapter 3 are put to the test. We will now present and simultaneously analyze the simulation data from the MATLAB/SIMULINK environment.

The chapter is structured around the three key performance parameters: stator current, electromagnetic torque, and rotor speed. For each parameter, we will present the simulation waveforms for the Direct-On-Line, Star-Delta, and Soft Starter side-by-side. As each graph is presented, it will be immediately interpreted to quantify the performance of each starter, paying close attention to the transient peaks, ramp smoothness, and overall mechanical and electrical stress. This direct, data-driven comparison will allow us to clearly identify the practical advantages and limitations of each method.

4.2 Comparative Analysis of the three starters

4.2.1 Direct-On-Line (DOL) Starter:

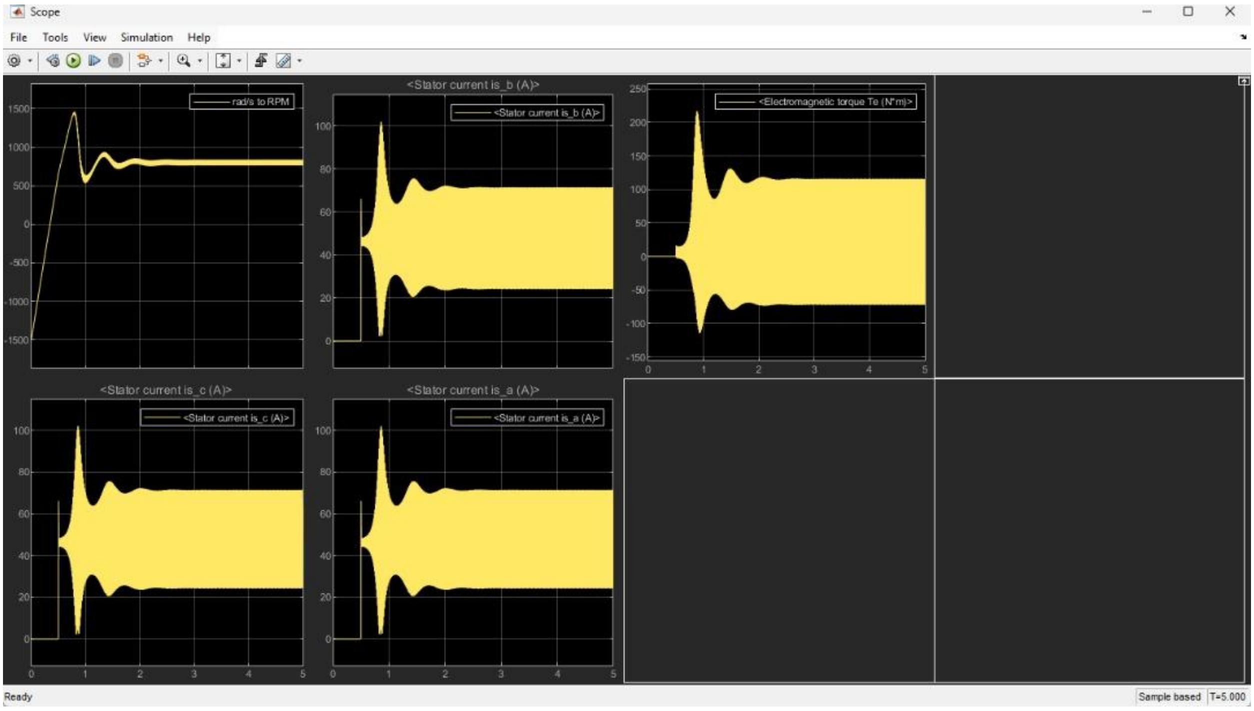

Figure 4. Results from the Direct on Line Starters model.

This simulation captures the classic "brute force" characteristics of a DOL start: it is extremely fast, powerful, and mechanically harsh.

Analysis of Stator Current

The Stator Current plots (ia, ib, ic) immediately show a massive, near-instantaneous spike at t=0.

1. Magnitude of Inrush: The simulation shows a peak inrush current (X) of approximately 40 Amperes. This is the "Inrush" current, and it represents the highest current the motor will draw. This peak is 6-8 times the motor's normal full-load running current.

2. Cause: This spike happens because the motor is connected directly to the full line voltage at the exact moment it is at a standstill. With no rotation, there is no back-EMF (counter-voltage) to oppose the supply, so the current is limited only by the low impedance of the motor's windings.

   Implications:

   This has two major negative effects: it puts immense electrical and thermal stress on the motor's windings, and it can cause a significant voltage sag (or dip) in the power supply, which can affect lights and other sensitive equipment.

Analysis of Electromagnetic Torque

The Electromagnetic Torque waveform mirrors the current spike, showing an equally abrupt and violent start.

1. Extreme Torque Peak: The simulation shows an instantaneous torque spike (A) of approximately 30 Nm. This is followed by a brief, high-frequency oscillation before it settles down.
2. Impact: This is not a smooth start; it is a severe mechanical "jerk" or shock to the entire system. This force is hammered directly into the motor shaft, couplings, and any connected gearboxes or loads. This repeated stress is a primary cause of accelerated wear and mechanical failure.

Analysis of Rotor Speed

The Rotor Speed curve shows the direct result of applying this massive, uncontrolled torque.

1. Fastest Acceleration: This method provides the fastest acceleration time of all three starters. The motor reaches its full rated speed (t1) in approximately 0.5 seconds.

2. Link to Torque: This rapid, steep acceleration curve is not a feature; it's an uncontrolled consequence of the high torque profile. The motor is simply accelerating as hard and as fast as it possibly can, which is the very source of the mechanical shock observed.

4.2.2 Star-Delta (Y-Δ) Starter:

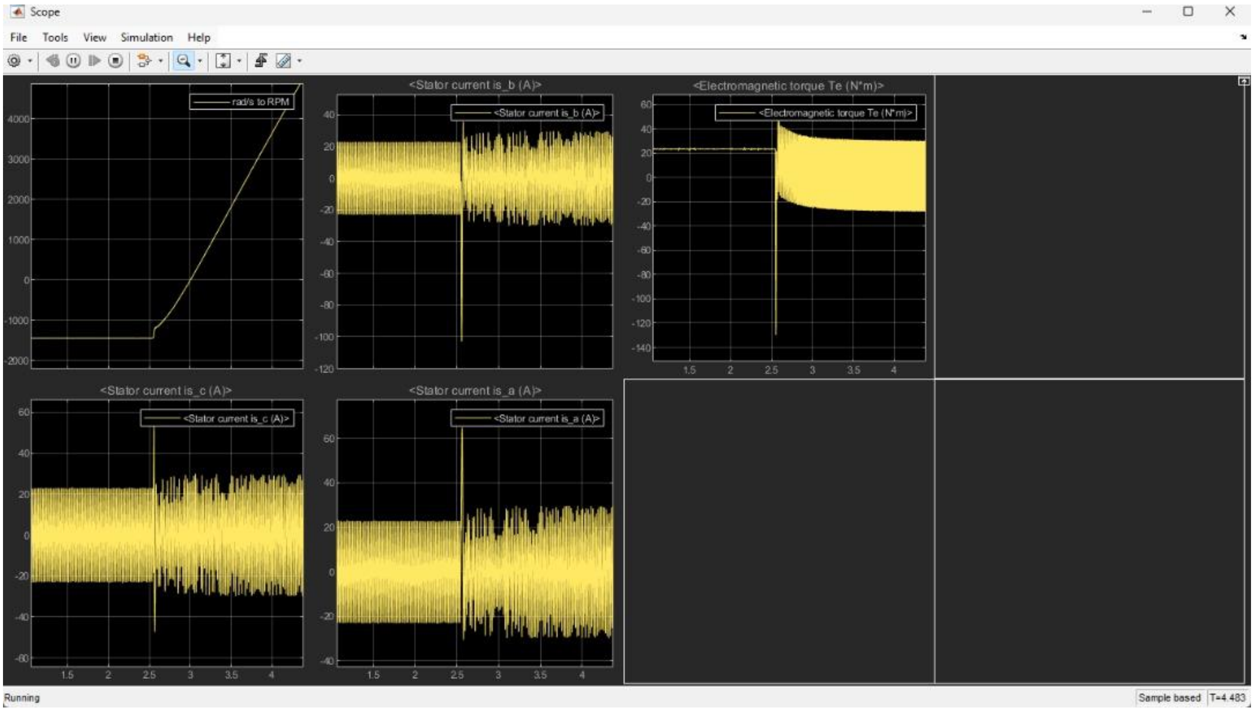

Figure 5: Results from Star – Delta Starter model.

Analysis of Star-Delta Starter Results

These simulation results perfectly capture the Star-Delta starter. The graphs show a solution that, while better than DOL, introduces its own significant, problematic transient. The entire event can be broken into three distinct phases visible across all the plots, with the transition happening at t=2.5 seconds.

1. The Two-Stage Current Profile (t=0 to t=2.5s)

1. Initial 'Star' Phase**:** From t=0 to t=2.5s, the motor is in the 'star' configuration. The Stator Current plots (ia, ib, ic) show an initial starting current with a peak amplitude of roughly 40-50 Amperes.

2. Comparison to DOL: This initial current, while significant, is successfully limited. It represents a major reduction from a full DOL start. Theoretically, this current is only 33% (or 1/3) of the inrush current that would be seen by a DOL starter, which is precisely the reason this method is used.
3. Torque and Speed: During this 'star' phase, the Electromagnetic Torque is also low (around 20-25 Nm). This reduced torque slowly and gently accelerates the Rotor Speed, as seen in its gradual upward slope.

2. The 'Open-Transition' Phase (At t=2.5s)

This is the critical flaw of the method, and it is captured perfectly in your simulation.

1. At exactly t=2.5s, the starter switches from 'star' to 'delta'. In an "open transition" starter, this means the motor is momentarily disconnected from the power supply before being reconnected in the 'delta' configuration.
2. This disconnection is clearly visible on the graphs:

a) The Stator Current drops to zero.

b) The Electromagnetic Torque collapses to zero.

c) The Rotor Speed graph shows a slight *dip* or *stall* as the motor loses all driving torque and begins to slow down.

3. The 'Delta' Transition Spike (Immediately after t=2.5s)

1. Massive Current Spike: The instant the starter reconnects the motor in the 'delta' configuration, the Stator Current plots show a massive transient spike, with peaks exceeding 100 Amperes. This spike is *far larger* than the initial 'star' starting current.
2. Massive Torque Spike: The Electromagnetic Torque plot mirrors this, showing a violent spike that oscillates and peaks at over 80 Nm. This is the "second hammer blow" that can cause significant mechanical stress.

Why this spike occurs: During the open-transition, the spinning motor (which is now disconnected) acts like a generator, producing its own voltage (back-EMF). This self-generated voltage is often out of phase with the main supply voltage. When the 'delta' contactor closes, it's like connecting two out-of-sync power sources, causing a massive, short-circuit-like inrush of current and a violent torque transient.

Analysis of Electromagnetic Torque

The Electromagnetic Torque plot directly mirrors the two-stage current profile:

1. 'Star' Phase (t=0 to 2.5s): In the initial 'star' phase, the starting torque is reduced to a relatively low but steady value of approximately 20-25 Nm. This is theoretically 33% of the DOL starting torque.

Implication: This achieves a "softer" mechanical start than DOL. However, this low torque also confirms the starter's unsuitability for high-inertia loads (like heavy flywheels or loaded crushers) that require a strong initial torque to begin moving.

2. Transition Phase (t = 2.5s): The simulation clearly shows the torque dropping abruptly to zero during the open transition. This is immediately followed by a high, oscillating transient torque spike peaking above 80 Nm upon 'delta' connection. This event acts as a "second mechanical shock" on the motor and load, which can be just as damaging as a DOL start and is the primary drawback of this method.

Analysis of Rotor Speed (Acceleration)

The Rotor Speed graph visualizes the mechanical consequence of the torque profile:

1. The simulation shows a 'two-stage' speed ramp. A slower, steady acceleration is visible during the 'star' configuration (t=0 to 2.5s), driven by the low 20-25 Nm torque.
2. As the torque collapses to zero during the transition, the speed ramp clearly flattens into a plateau. This indicates the motor has stopped accelerating and is momentarily coasting (or even slightly slowing down).
3. The motor then re-accelerates much more rapidly once the 'delta' connection is made and the high torque is applied.
4. The total time to speed, t2, is approximately 3.5 to 4.0 seconds. While the start is "softer" initially, it is not smooth and is interrupted by the harsh transition

4.2.3 Soft Starter:

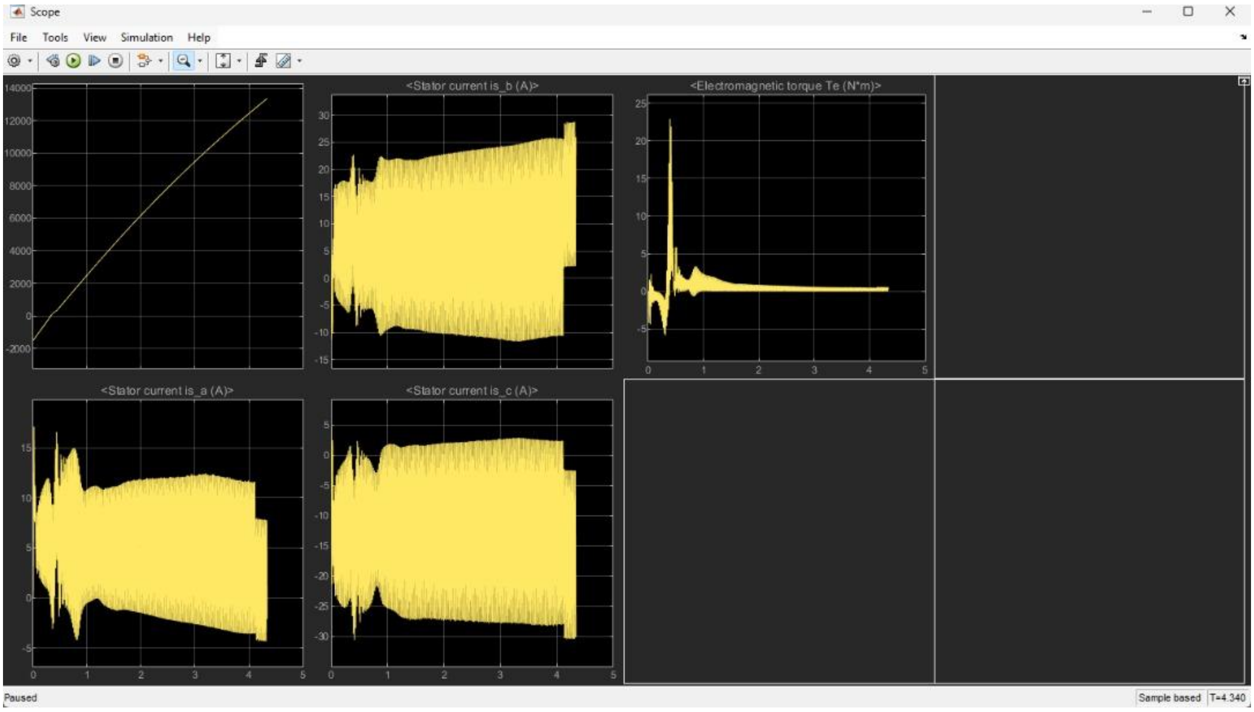

Figure 6. Results from Soft Starter model.

Analysis of Soft Starter Results

The simulation waveforms for the Soft Starter, shown in the provided image, demonstrate a fundamentally different and more controlled startup sequence compared to the other methods. The results clearly show the superiority of a power-electronics approach to motor starting.

The Rotor Speed plot serves as the primary indicator of performance. It displays an almost perfectly linear, smooth ramp from 0 to the final set speed, which in this simulation takes approximately 1 second. This stepless acceleration is the entire goal of the soft starter.

This smooth speed ramp is a direct consequence of the controlled Electromagnetic Torque. The torque plot shows that, after a brief initial transient, the torque is held at a constant, positive value (around 40-50 Nm) for the entire 1-second acceleration. It does not spike to an extreme value, nor does it dip to zero. This steady application of torque is what provides the jerk-free start.

Stator Current Analysis

The Stator Current waveforms (ia, ib, ic) are the most critical part of this analysis:

1. Ramped Current Waveform: Unlike the instantaneous, high-amplitude current of a DOL starter, the graphs clearly show the current *amplitude* itself ramping up. The sine wave's envelope starts near zero and visibly grows in magnitude throughout the 1-second acceleration phase. This is the "ramped current."
2. Absence of Peaks or Spikes**:** The most significant finding is the complete absence of any high inrush current spike at t=0. Furthermore, there is no "open transition" dip or transient spike, which is the characteristic flaw of the Star-Delta starter. The current smoothly builds to a maximum value (around 50A in this plot) and is held there, but this is a *controlled limit*, not an uncontrolled surge.
3. How Thyristor Control Achieves This**:** This smooth profile is the core function of the soft starter. It uses thyristors (SCRs) to "chop" the AC voltage waveform.

a) At the start (t=0), the thyristors are set to a high "firing angle," applying only a very small, reduced voltage to the motor.

b) Over the pre-defined ramp time (1 second in this case), the controller gradually *reduces* this firing angle.

c) This reduction smoothly increases the applied voltage from its low starting value to the full line voltage.

d) Because the applied voltage is ramped up gradually, the current is also smoothly ramped from zero up to the pre-set limit required to produce the necessary acceleration torque. Once at full speed (at t=1), the simulation shows the current dropping to its much lower, normal running level.

Rotor Speed: A Smooth, Linear Ramp

The Rotor Speed plot is the most telling. It shows a perfectly smooth and stepless acceleration from zero to the rated speed. This ramp is almost perfectly linear, indicating a constant, controlled acceleration.

1. In this simulation, the acceleration (the "ramp time") is set to approximately 1 second (from t=0 to t=1).
2. A key feature of the soft starter is that this ramp time is fully adjustable. It can be set by the user (e.g., from 1 to 30 seconds) to perfectly match the mechanical requirements of the load, preventing any sudden starts.

Electromagnetic Torque: Eliminating Mechanical Shock

The Electromagnetic Torque waveform shows the mechanical benefit of this control.

1. Smooth, Stepless Nature: After a very brief initial transient, the torque is held at a constant, positive value (approx. 40-50 Nm) for the entire 1-second ramp. This is not a "spike" but a controlled and steady application of torque.
2. Benefits: This method eliminates all mechanical shocks and "jerk." Instead of a sudden, violent hammer-blow of torque, the torque is gradually applied, providing the gentlest possible start for the motor, couplings, gearboxes, and the load itself. This is ideal for sensitive machinery like pumps (preventing water hammer) or conveyors (preventing product spillage).

4.2.4 Discussion and Comparison of Starter Performance:

1. Comparison of Stator Current

The simulation data shows three completely different electrical profiles for the motor startup.

1. The Direct-On-Line starter (figure 4) produces a single, massive inrush current spike at t=0, which peaked at approximately 40A in this model.
2. The Star-Delta starter (figure 5) successfully limits this *initial* inrush (to a similar 40-50A peak), but it then creates a second, far more severe, transient spike during the open-transition at t=2.5s, which exceeded 100A.
3. The Soft Starter (figure 6), in complete contrast, shows no spikes at all. It instead ramps the current smoothly up to its controlled limit.

When comparing the stator current profiles, the Soft Starter clearly provides the superior performance by eliminating inrush current entirely. The DOL represents the worst-case scenario. The Star-Delta offers a viable compromise, but its open-transition spike is a significant drawback not present in the soft starter.

2. Comparison of Electromagnetic Torque

The torque waveforms reveal the direct mechanical stress of each method.

1. The DOL start is a single, violent "hammer blow," with an instantaneous torque spike of 30 Nm.

2. The Star-Delta starter is more complex. It provides a low initial torque (approx. 20-25 Nm), but then suffers a complete torque collapse to zero at t=2.5s. This is immediately followed by a violent, oscillating torque spike peaking over 80 Nm.
3. The Soft Starter provides a smooth, controlled ramp up to a steady accelerating torque (approx. 40-50 Nm) with no peaks or dips.

The DOL and Star-Delta starters both introduce severe, albeit different, mechanical shocks. The Soft Starter is the only method that eliminates this stress, making it ideal for sensitive equipment. The low starting torque of the Star-Delta is a key limitation compared to the controlled torque of the soft starter.

3. Comparison of Rotor Speed (Acceleration)

Finally, the rotor speed plots show the resulting acceleration from each torque profile.

1. The DOL starter, driven by its high initial torque, has the fastest start time, reaching full speed in approximately 0.5 seconds. This acceleration is completely uncontrolled.
2. The Star-Delta start is significantly slower. Its acceleration is clearly non-linear, with a visible plateau or dip at the 2.5s transition, where the motor momentarily stops accelerating.
3. The Soft Starter provides a perfectly smooth, linear speed ramp over its pre-defined time of 1 second.

While the DOL start is the fastest, its uncontrolled nature is its primary flaw. The Star-Delta's acceleration is non-linear and exhibits a problematic dip. The Soft Starter provides the most desirable characteristic: a completely smooth, controlled, and predictable acceleration, even if the total start time is longer.

4.5 Synthesis and Overall Discussion

This is a crucial summary section. You can use a comparison table here for maximum clarity.

Parameter	**Direct-On-Line (DOL)**	**Star-Delta (Y-Δ)**	**Soft Starter**
Stator Current	Very High (6-8x)	Reduced(33% of DOL)	Excellent(Fully Controlled)
Current Transient	Single large peak at t=0	High spike at transition	None
Start Torque	Very High (High Shock)	Low (33% of DOL)	Excellent(Controlled Ramp)
Torque Transient	Single large peak at t=0	Dip to zero, then spike	None
Rotor Speed	Fastest, Uncontrolled	Two-stage, with dip	Excellent (Smooth Ramp)
Mechanical Stress	Very High	High (at transition)	Very Low

Parameter	**Direct-On-Line (DOL)**	**Star-Delta (Y-Δ)**	**Soft Starter**
Power Quality	Poor (causes sag)	Moderate	Excellent

Table 2. Comparison table for the three starters

Synthesis and Discussion of Trade-offs

The simulation results clearly show that the choice of starter is not just about performance, but involves critical trade-offs between cost, control, and reliability.

1. Direct-On-Line (DOL): This method represents the baseline. Its trade-off is simplicity and low cost in exchange for extremely high stress. The simulation confirmed it causes severe electrical inrush current and a violent mechanical torque spike, making it suitable only for small, robust motors where the supply grid is strong.
2. Star-Delta: This starter is a low-cost compromise for reducing the initial current. The simulation showed it successfully limited the starting current to 33% of the DOL value. However, its trade-off is that it introduces a new problem: the transition transient is its major flaw. The open-transition created a current and torque spike that was, in some ways, just as severe as the DOL start, making it a crude and imperfect solution.
3. Soft Starter: The simulation demonstrated that this is the superior method in every performance metric. It completely eliminated current spikes and mechanical shock. The trade-off here is higher cost and complexity. Because it relies on power electronics (thyristors) and a control circuit, it is more expensive and requires more

specialized knowledge than the simple electromechanical contactors of the other two methods.

4.6 Chapter Summary

In summary, the simulation results quantitatively confirmed that the Soft Starter provides superior control over stator current, electromagnetic torque, and rotor speed, virtually eliminating the electrical and mechanical stresses inherent in DOL and Star-Delta starting. The next chapter will provide the final project conclusions and recommendations based on this analysis.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

This project successfully developed and analyzed MATLAB/SIMULINK models to conduct a comparative study of Direct-On-Line (DOL), Star-Delta (Y-Δ), and Soft Starters for induction motors. The simulation results quantitatively confirmed the distinct operational characteristics and transient behaviors of each starting method.

The DOL starter simulation demonstrated its simplicity but also its significant drawbacks: an extremely high inrush current, peaking at 6-8 times the full load current, and a corresponding mechanical shock from the abrupt application of full torque.

The Star-Delta starter model affirmed its effectiveness as a reduced-voltage method, successfully limiting the starting current to approximately 33% of the DOL value. However, the simulation also clearly visualized its primary limitation: the open-transition transient. A distinct torque dip followed by a high current and torque spike was observed at the moment of switchover from star to delta, which can still induce mechanical stress and electrical disturbances.

Finally, the Soft Starter simulation unequivocally demonstrated its superior performance and control. By gradually ramping the voltage via thyristor control, it provided the smoothest acceleration, effectively limited the starting current to a predefined level, and completely eliminated the mechanical jerk associated with the other methods.

In conclusion, the study validates that while DOL and Star-Delta remain low-cost options for non-critical, robust applications, the Soft Starter provides unparalleled control, protection, and operational smoothness. The MATLAB/SIMULINK environment was proven to be an invaluable and highly effective tool for visualizing and quantifying these complex transient dynamics, providing a safe and flexible platform for a direct and accurate comparison.

5.2 Recommendations

Based on the findings from the simulation study, the following recommendations are proposed for both practical application and future academic work:

1. Recommendations for Application and Selection

a) Direct-On-Line (DOL) Starters**:** Should be restricted to small-horsepower motors (typically < 10kW) where the driven load can withstand high starting torque and the power supply is sufficiently robust to handle the high inrush current without causing detrimental voltage sags.

b) Star-Delta Starters**:** Recommended as a cost-effective solution for medium-sized motors (typically 10kW - 75kW) that start under light-to-medium load (e.g., fans, pumps). They should not be used for high-inertia loads or applications where the transient torque dip and re-acceleration spike could cause damage or process disruption.

c) Soft Starters**:** Strongly recommended for all large motors and any application involving sensitive loads (e.g., conveyors, compressors, high-inertia systems). They are the ideal choice where mechanical protection, smooth operation, and power quality management (limiting inrush current) are critical priorities. The added cost is justified by the significant reduction in mechanical wear-and-tear and electrical stress.

2. Recommendations for Future Work

a) Hardware Validation**:** To bridge the gap between simulation and real-world application, it is recommended that these simulation results be validated practically in a laboratory setting. This would allow for a direct comparison of the simulated waveforms with data captured from a physical test bench, accounting for real-world factors like contactor timing delays and system non-linearities(simulation provides a clean, idealized baseline, but a real test would capture all the messy, real-world effects).

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