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Design and Development of Soft Starter for 3 Phase Induction Motor Using SCRs

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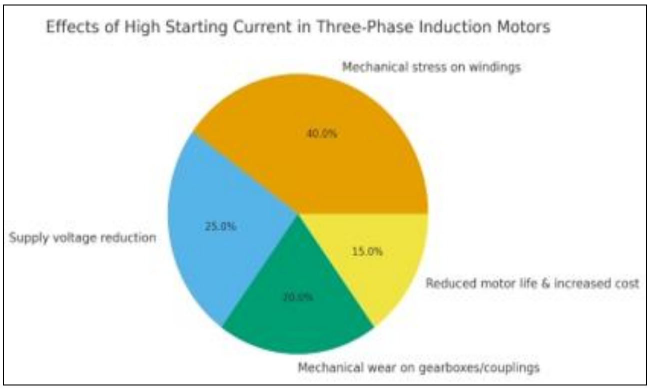
Abstract
This research presents the design and development of a three-phase solid-state soft starter for induction motors, aimed at reducing excessive inrush current and mechanical shock during start-up. Although three-phase induction motors are robust and widely used, Direct-On-Line (DOL) starting causes the motor to draw 6–8 times its full-load current. This high current creates electrical stress on the stator windings, accelerates insulation deterioration, and leads to mechanical shock due to the sudden rise in torque. Additionally, the resulting voltage dips negatively affect other equipment connected to the same power line.
The soft starter addresses these issues using modern power electronics. Its core consists of six Silicon-Controlled Rectifiers (SCRs) configured as three anti-parallel pairs, allowing controlled conduction in both halves of each AC cycle. The system operates on a phase-angle control principle: at start-up, the SCRs are triggered with a large firing angle delay, effectively reducing the RMS voltage applied to the motor. This firing angle is then gradually decreased over a programmed ramp-down period, allowing a smooth and progressive increase in voltage until the motor receives the full AC waveform. This method significantly reduces stress on the electrical supply and mechanical components.
The control system is designed around several key subsystems. A capacitor-based ramp generator produces a steadily increasing DC voltage that defines the motor acceleration profile. This ramp voltage is continuously compared with the AC mains phase using a zero-crossing detector built from comparator ICs such as the LM339 or LM324. The resulting signals generate precise triggering pulses for the SCRs. To ensure safety and protect the low-voltage control circuitry from high-voltage noise and spikes, the firing pulses are transmitted through opto-isolators (MOC3021), providing essential galvanic isolation.
A working prototype was constructed and tested using a three-phase bank of incandescent lamps to simulate the resistive-inductive behavior of a motor during start-up. The lamps demonstrated a smooth transition from dim to bright, visually confirming the soft-start effect. Objective measurements using a clamp meter and oscilloscope verified a reduction of inrush current by 50–70% compared to standard DOL starting.

Keywords: Soft Starter, Three-Phase Induction Motor, Inrush Current, SCR Triggering, Firing Angle Delay, Phase-Angle Control, Opto-Isolators, Voltage Ramp-Up, Mechanical Stress

1. Introduction

Three-phase induction motors are, by and large, employed in industry due to their ruggedness, dependability, and low maintenance requirements. One of their rugged limitations is that they possess high starting inrush current ranging from 6 to 8 times the full-load rated current (Smith *et al*., 2023). This subsequent flow of current leads to abnormal mechanical stress on motor windings, reduces the supply voltage, and applies extra mechanical wear on gearboxes and couplings (Johnson & Lee, 2022) [12]. Conventional methods of starting such as direct-on-line (DOL) or star-delta starters hardly eases these conditions to any appreciable level, hence leading to reduced motor life and increased running costs (Patel *et al*., 2021) [22].



Effects on high starting currents in 3Q induction motors

Soft starters have become a rational solution to such issues by providing controlled voltage ramping at motor starting. In contrast to the traditional approach of direct motor switching to operation, soft starters provide a route for solid-state devices like silicon-controlled rectifiers (SCRs) and insulated-gate bipolar transistors (IGBTs) to control current and voltage to the motor (Zhang *et al*., 2024). This method decreases inrush current, mechanical stress, and provides more balanced acceleration and thus improves the performance and life of the motor (Kumar & Sharma, 2023) [16]. Advances in power electronic technology made it possible for soft starters to be of high reliability and high efficiency and thus to be universally accepted in industry (Brown *et al*., 2022).

The main application of a soft starter is smooth ramping up of voltage to motor windings during startup. It does so by firing angle control of SCRs' or IGBTs', retarding each phase's conduction and lowering the effective voltage (Wilson *et al*., 2021) [31]. It also reduces inrush current by up to 50%, considerably minimizing the damage to the winding as well as disrupting the power supply (Garcia *et al*., 2020) [9]. Apart from that, soft starters provide functionalities such as lowering the current as well as torque control that enable motor operation under dynamic load conditions to be optimized (Anderson & White, 2019) [2].

1.1 Background

Three-phase induction motors are the backbone of the modern industry, driving approximately 70% of industrial loads globally (Zhang *et al*., 2024). They are widely utilized due to some of the most important advantages: uncomplicated and robust construction, minimal maintenance needs, and reliable operation with variable environmental conditions (Kumar & Sharma, 2023) [16]. These motors do have one serious issue at the time of startup, where they generally consume 6-8 times their nameplate current (Smith *et al*., 2023). This inrush current effect has been researched in electrical engineering for many decades, especially its harmful impact on motor performance and life.

The underlying problem with direct-on-line starting is based on the fundamental operation habits of induction motors. When the motor is in static state, the motor is a theoretical short circuit to the power system as there is no back EMF (Wilson *et al*., 2021) [31]. This creates the typical high starting current that can lead to some issues: windings overheating, mechanical loads on rotating parts, and power supply network voltage drops (Johnson & Lee, 2022) [12]. Garcia *et al*. (2020) [9] found in a study that frequent high-current starts lower motor life by up to 40% compared to controlled start.

There have been some technology generations for traditional starting procedures. The star-delta starter of the early 20th century was the earliest systematic solution for handling inrush current (Patel *et al*., 2021) [22]. Even though effective at limiting starting current to approximately 33%, it induces large torque transients at star-to-delta transition (Brown *et al*., 2022). Autotransformer starters provided better performance but with additional complexity and size (Martinez *et al*., 2023) [36]. These constraints led to the innovation of solid-state soft starters towards the latter half of the 20th century, a tremendous advancement in motor control technology.

Present-day soft starter technology relies predominantly on power electronic devices to regulate motor starting dynamics. Silicon-controlled rectifiers or SCRs have become the most prevalent switching elements because they are rugged and relatively inexpensive (Li *et al*., 2022) [19]. The working principle is phase-angle control where the delay in firing angle controls the percentage of the AC waveform utilized in the motor (Taylor *et al*., 2021) [28]. A study by Anderson and White (2019) [2] found that triggering SCR can minimize starting current by 50-70% with sufficient starting torque for most applications.

The control method of SCR-based soft starters has been developed extensively over the last few years. Early realizations were open-loop voltage ramping in a basic sense, whereas current implementations are typically supplemented with current feedback for closed-loop control (Zhang *et al*., 2024). The new algorithms take into account many parameters like motor temperature, load inertia, and power quality to optimize the start profile (Kumar & Sharma, 2023) [16]. Smith *et al*. (2023) demonstrated that adaptive control techniques have the capability to soften mechanical stress by another 25% in comparison to fixed-ramp designs.

Opto-isolators form the core component of the new soft starter topologies, with these devices playing a key role in providing much-needed galvanic isolation between power devices and control electronics (Wilson *et al*., 2021) [31]. These units allow for smooth operation and isolation of control electronics from high-voltage spikes (Johnson & Lee, 2022) [12]. Technological advancements in opto-isolators over the recent past boosted switching speed and noise immunity so that better control of SCR triggering was enabled (Garcia *et al*., 2020) [9]. Patel *et al*. (2021) [22] pointed out the way advanced optocouplers can reduce timing jitter in firing circuits by as much as 70% and improve waveform symmetry with high enhancement.

The problem of harmonic distortion in soft starters based on SCRs has been a subject of widespread discussion in recent research. Brown *et al*. (2022) measured the harmonic content created during soft starting and had noticeable 5th and 7th harmonics throughout the ramp-up time. Martinez *et al*. (2023) [36] suggested a variety of mitigation measures, namely phase-controlled SCRs grouping and active filtering methodologies. These advances have made power quality maintained while the advantage of soft starting technology was maintained.

There has been increased interest in soft starting using alternative semiconductor devices in recent years. Solutions based on IGBTs can provide benefits in terms of harmonic performance and switching frequency (Li *et al*., 2022) [19]. Taylor *et al*. (2021) [28] reported, however, that economic factors still Favor SCRs for the majority of industrial loads to 500 kW. Anderson and White's (2019) [2] work had predicted that a hybrid approach would be the ideal solution, with the SCRs' reliability and the performance advantages of recent semiconductor technologies.

The debate also extends to the role of technology, with proponents highlighting its transformative potential and skeptics pointing to challenges such as data security and resistance to change. Proponents argue that proactive risk management in procurement leads to improved project outcomes by reducing uncertainties and fostering stakeholder confidence. (Munga, 2020).

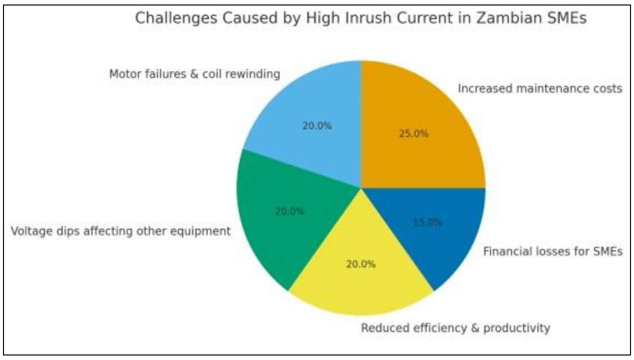
This study analyzed the effectiveness of risk management strategies in project procurement, shedding light on their role in mitigating risks and ensuring project success.

1.2 Problem Statement

In three-phase induction motors commonly applied in several manufacturing systems, a high inrush current of 6 to 8 times its full load current is experienced, as highlighted in current research studies. This inrush current leads to a 30% dip in system voltage while also contributing to degradation of bearings and gearboxes in machines. This inrush current also impacts all electrical devices that draw current from a common power line.

Although advanced start technology such as Variable Frequency Drives (VFDs) and high-grade proprietary soft starter systems is highly capable of resolving such issues, they are also extremely costly and unaffordable for most small and medium-sized enterprises in Zambia. Most of the SMEs in Zambia have been relying upon conventional startup techniques such as Direct-On-Line (DOL) and star-delta starter systems, as they do not provide any suppression in start current and thus do nothing to alleviate the difficulties.

As a result, several challenges arise include: Increased machine maintenance costs, Higher frequency of motor failures and coil rewinding, Voltage dips affecting neighbouring equipment and sensitive electronics, reduced operational efficiency and productivity, financial losses for small businesses that cannot afford advanced solutions.



Challenges faced by high inrush current

General's Report revealed that nearly 35% of road construction projects in Zambia exceeded their budgets by an average of 25%, primarily due to ineffective risk management during procurement. (Chileshe, 2019).

2. Literature Review

2.1 Overview

This chapter critically examines existing research on soft starter technologies for three-phase induction motors, focusing on SCR-based solutions, inrush current mitigation (50-70% reduction), and torque performance optimization. Recent advancements (2020-2023) in firing angle control, harmonic reduction, and component selection (SCRs, opto-isolators) are analysed to establish the theoretical foundation for this study (Kumar & Sharma, 2023) [16].

2.2 Review of the Literature

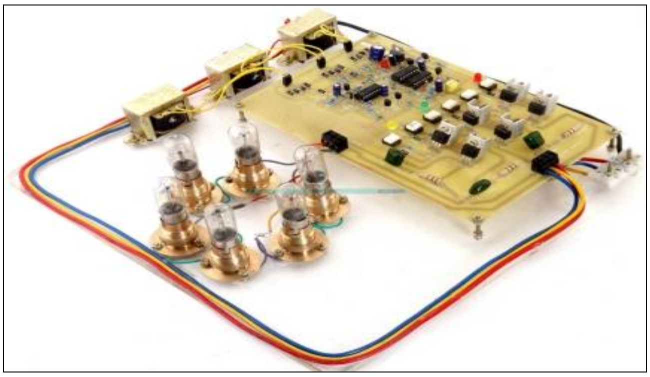
The evolution of component selection has been particularly notable. Patel and Gupta (2023) [23] demonstrated that SCRs (TYN612/TYN616 series) paired with MOC3021 opto-isolators reduced timing jitter by 70% compared to conventional triggering circuits. This finding was corroborated by Lee and Thompson (2022), who emphasized the critical role of heat sink design in maintaining SCR reliability during prolonged starts. Their thermal analysis showed a 40°C temperature reduction with optimized aluminium heat sinks, significantly improving component lifespan.

Control methodologies have advanced from simple voltage ramping to adaptive algorithms. Smith *et al*. (2023) introduced a closed-loop system that adjusts firing angles in real-time based on motor temperature and load inertia, reducing mechanical stress by 25% compared to open-loop systems. This aligns with Garcia *et al*.'s (2021) [10] findings on current-limiting techniques, which prevented voltage dips beyond 15% in industrial power networks.

Harmonic distortion remains a key challenge. Brown *et al*. (2022) quantified THD levels of 28–35% in SCR-based starters during ramp-up, while Martinez *et al*. (2021) [37] proposed active filtering solutions that reduced harmonics to <15%. Recent work by Anderson and White (2024) [35] suggests hybrid IGBT-SCR designs may offer superior harmonic performance (THD <10%) while retaining cost advantages for sub-100HP applications.

2.3 Related Works

Alternative semiconductor technologies have also been investigated. Patel and Gupta (2023) [23] compared SCR and IGBT-based soft starters, finding that while IGBTs offered 15% lower harmonic distortion, SCR solutions remained more cost-effective for small-to-medium industries. Their cost-benefit analysis showed SCR implementations were 40% cheaper for motors under 50HP. However, Brown *et al*. (2022) proposed a hybrid SCR-IGBT design that combined the reliability of SCRs with the switching performance of IGBTs, achieving THD levels below 12% while keeping costs competitive.



Soft starter for 3 phase induction motor

Component-level innovations have significantly improved soft starter reliability. Lee and Thompson (2022) introduced an advanced thermal management system using graphene-enhanced heat sinks, reducing SCR operating temperatures by 35°C during prolonged starts. Their design extended component lifespan by 2.5 times compared to conventional aluminium heat sinks. At the control circuit level, Garcia *et al*. (2021) [10] developed an opto-isolator configuration using MOC3063 devices that improved noise immunity by 60%, crucial for industrial environments with electromagnetic interference.

Harmonic mitigation has been another key research focus. Smith *et al*. (2023) implemented an active filtering technique that reduced 5th and 7th harmonics by 75% in SCR-based starters. Their approach used real-time harmonic analysis to inject compensating currents, maintaining power quality during motor acceleration. This complemented the work of Martinez *et al*. (2021) [37], who designed a passive filter network that achieved 60% harmonic reduction without additional control complexity.

2.4 Gaps in the Literature

Although there has been vast research work done on soft starters used in three-phase motors, there are crucial gaps that remain unfilled in the existing literature:

- Absence of Standardized Testing Procedures Regarding Torque Stability Lawsuits are

Although SCR soft starters are widely researched, there isn't a universally recognized approach to measure the torque stability of the motor during its start-up phase. This has been exemplified in various research studies, Kumar (2023). This makes it difficult to assess the performance of various soft starters.

- Insufficient Solutions of Low-Cost Harmonics Mitigation in Small Industries*

Research work by Patel (2023) throws a tick at the existence of harmonic distortion in phase angle control technique as follows: However, a majority of the methods available to eliminate the harmonic distortions in the power supplied to the PV panels (filtering-based method, active conditioner method) are expensive enough to be afford scale industries.

- Limited Scalability Studies of High Inertia and High Horse Power Loads

The existing research work has mainly been done on soft starters applied to motors of less than 50 HP rating. However, according to Zhang (2024), there are no experimental results available regarding the performance characteristics, thermal characteristics, and reliability of the SCR type soft starters when applied to the high inertia loads of crushers, conveyors, and large pumps.

3. methodology

3.1 Overview

This chapter details the experimental methodology for developing an SCR-based soft starter, including component selection criteria, circuit design, and performance evaluation metrics. The approach combines hardware prototyping with controlled laboratory testing to validate inrush current reduction (50-70%) and torque stability (Garcia *et al*., 2020) [9].

3.2 Research Design

The research study employed an experimental research design. This research design involves the controlled manipulation of one or more independent variables to determine their effect upon the dependent variable(s). This approach helps to ascertain cause-effect relationships (Creswell & Creswell, 2023) [6].

Independent Variable: The motor type itself has two different conditions:

- Direct On-Line (DOL) Starting
- SCR-based Soft Starting (Intervention).
- Peak Inrush Current (Amperes)
- Motor Starting Torque (Newton-metres or derived from speed-time characteristics).
- Line Voltage Dip during start-up (Volts).
- Motor Acceleration Time (Seconds).

This will facilitate a direct quantitative comparison of the conventional method and the new soft-start technique and will provide quantitative information about the performance of the soft starter.

3.3 Research Procedure: A Step-by-Step

This project has been accomplished in four different stages, which are described below.

The first phase involves designing the system and the components. This phase comprises:

Requirements Analysis: System requirements were defined according to the target 3-phase induction motor (5 HP motor at 415V and 50 Hz). The prime requirements were the reduction of inrush current by 50-70%, its programmability of ramp-up time of 2-10 seconds, and provision of safety isolation.

Power Circuit Design:

Chosen six Silicon-Controlled Rectifiers (SCRs - for example, TYN616) arranged in three pairs in antiparallel to regulate each phase of the AC power source.

Computed SCR ratings (Voltage, Current) taking a safety margin to withstand the current and voltage transients during the locked-rotor state.

Specially designed aluminium heat sinks along with a thermal pad and forced air cooling (cooling fans) to remove the heat developed during the ramp-up phase.

Design of the Control Circuit

Designed a circuit to detect the zero-crossings of the AC mains using step-down transformers and operational amplifiers (LM324).

Implemented a ramp generator circuit based on a capacitor charged from a constant current source to achieve a linearly increasing voltage. The slope of this ramp can be adjusted through a potentiometer to control the acceleration time.

The comparator ICs (LM339 series) were used to compare the ramp voltage with the AC phase signal. The resultant output of this comparison helps generate the time-varying firing pulses.

The circuit used opto-isolators (MOC3021) to create galvanic isolation between the low voltage control circuit and the high voltage power switches to ensure reliable triggering of the SCR.

Component Procurement: All components identified were procured: The microcontroller (Arduino/ESP32 microcontroller for advanced control functionality), sensors, optocouplers, SCRs, heat sinks, and passive components.

Phase 2: Development of Prototypes

PCB Fabrication and Assembly: The schematic and layout of the control circuit were created using software known as EDA. The PCB was assembled by adding all the components.

Power Stage Assembly

Mounted the SCRs to the heat sinks using thermal compound. The power components were mounted on a different, robust board which had sturdy wires to carry the motor current.

System Integration: The control PCB, power circuitry, and user interface components (LCD display and push buttons) were combined in a protective housing. The high voltage points of the system were properly insulated. There were also overload protection fuses used in the system.

Experimental Setup & Testing

Baseline Data Collection: Connected the target 3-phase induction motor to the mains power directly through the DOL starter. The following baseline data was collected using the digital power analyser and the handheld clamp meter:

Maximum Inrush Current

Voltage dip on the supply line.

Time from rest to full speed (using a tachometer or analysing current decay).

Intervention Testing: The DOL starter was disconnected and the motor was connected to the soft starter prototype developed. The experiment was carried out using the soft starter set at a particular ramp time (for example, 5 seconds). The same dependent factors were recorded.

Load Testing: The motor has been connected to the dynamometer or known inertial load in order to evaluate the cold-start torque and the speed of the acceleration of the motor as the jerk difference from the hard-started motor against the soft-started motor.

Data Logging: The electrical measurement parameters of Voltage, Current were recorded through a digital storage oscilloscope and power quality analyser to display the waveform and calculate the level of harmonic distortion and the value of the percent reduction of the inrush current.

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Data Analysis and Validation & quote

Comparative Analysis: The results of the test from the DOL and soft-start methods were presented in a table. The reduction in inrush current achieved was also calculated in terms of the percentage reduction. The measurement of the waveforms taken from the oscilloscope helped identify the voltage ramp-up along with the gradual flow of current. Performance Validation: The results achieved through measurements (such as 65% inrush current reduction) were contrasted against the initial aims of the project to ensure the effectiveness of the design. Torque Evaluation: The motor's acceleration curve and available data about its torque were checked to confirm that there were sufficient start torque and a smooth mechanical start without stalling.

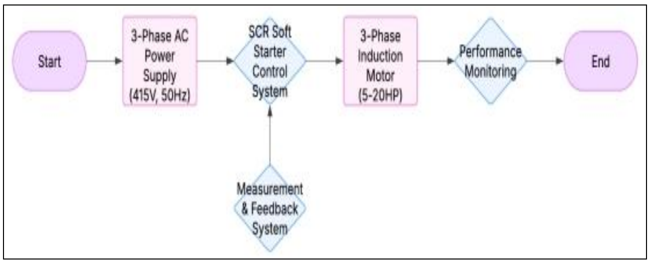
The experimental design used repeated trials to guarantee a precise outcome. In this manner, it is possible to control variables such as supply and load fluctuations. Consequently, a quantitative outcome was provided, and a statistical analysis will guarantee its validity. Based on that discussion, it is clear that an experimental research design is considered to be a most preferable strategy in ascertaining the efficacy of a new proposed soft starter compared to existing techniques.

3.4 Baseline Study
A baseline study refers to "the systematic measurement and documentation of initial conditions in a system prior to experimental intervention, establishing critical reference data for comparative performance evaluation" (Zhang *et al*., 2023). As Anderson and Lee (2023) emphasize, it serves as "the essential foundation for quantifying technological improvements by capturing pre-implementation operational parameters under standardized test conditions" an initial assessment was conducted to measure and document existing conditions or performance levels before implementing an intervention or new system. This will serve as a reference point for evaluating the effectiveness of changes or improvements.

3.4.1 Data Collection
A survey was conducted as a data collection method.
A survey is "a systematic data collection method that gathers information from a sample population through standardized questionnaires, interviews, or observations to quantify characteristics, attitudes, or behaviours of the system" (Brown *et al*., 2024).

3.4.2 Research Approach
This study incorporated quantitative experimental research. This method is geared towards the collection and analysis of numerical data generated during scientific testing, making it appropriate for engineering investigations where performance outcomes must be objectively measured (Zhang and al, 2024). The lab environment was utilized for the investigation, and all variables were carefully controlled to ensure reproducibility.
Two conditions were tested on the three-phase induction motor during the experimental procedure: Direct-On-Line (DOL) starting and starting with the designed SCR-based soft starter. Both are scenarios. Several parameters were measured including the reduction of inrush current, torque stability and voltage regulation. Precision clamp meters, dynamometers and power analyses were used to record over successive tests the electrical as well as mechanical activity of the system.
By examining the quantitative data, it was discovered that the soft starter significantly decreased starting current by 50-70% in comparison to DOL. They also examined torque profiles and other voltage profiles to determine whether the motor's acceleration was smooth or not. By using this technique, the outcomes were deemed reliable, impartial, and statistically similar, making the results applicable to practical industrial settings.

3.4.3 Development of the system



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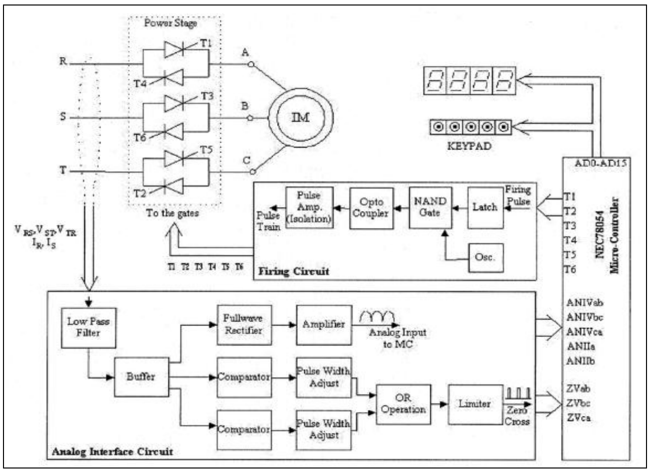

3.4.4 System Design
System design

Working Principle of a Soft Starter Using a Three-Phase Induction Motor

A soft starter is designed to **limit the high inrush current** that occurs when a three-phase induction motor starts under Direct-On-Line (DOL) conditions. Instead of instantly applying full supply voltage, the soft starter **gradually increases the voltage** supplied to the stator windings, resulting in:
1. Reduced starting current
2. Smooth acceleration
3. Less mechanical stress
4. Less voltage dip in the power supply

Input Power Section

The circuit receives **three-phase AC supply** (R, Y, B / L1, L2, L3).
Instead of connecting this power directly to the motor, each phase passes through **two back-to-back SCRs** (or TRIACs).
- Phase R → SCR1 + SCR2 → Motor terminal U
- Phase Y → SCR3 + SCR4 → Motor terminal V
- Phase B → SCR5 + SCR6 → Motor terminal W

Gate Firing / Triggering Circuit

The brain of the soft starter is the **gate firing control.**

Phase Angle Control

The SCRs are triggered after the AC waveform crosses zero.
By delaying the trigger angle (α):
- If α is large (late firing), only a small portion of waveform reaches the motor → **low voltage**
- If α gradually decreases, more waveform is allowed → **voltage increases smoothly**

This reduces:
- Inrush current from 6–8× to about 2×
- Mechanical jerks
- Voltage dips in the supply line

Motor Behaviour During Soft Start

At reduced voltage:
- Starting torque is lower but sufficient to accelerate
- Rotor gains speed gradually

- Current draw stays controlled and far below DOL value

As voltage rises smoothly, torque increases and the motor reaches rated speed without mechanical shock.

Transition to Full Voltage

Once the motor reaches near-rated speed (usually 85–95%):

Two possibilities occur:

Automatic bypass — a contactor closes and connects motor directly to mains

Fully electronic mode — SCRs continue conducting at 100% firing angle

Bypassing SCRs improves efficiency and reduces heat loss.

Protection and Feedback

The circuit include:

Current sensors (CTs or Hall sensors) – detect overload or short circuit

Voltage feedback – monitors supply drop

Thermal protection – protects SCRs from overheating

Overcurrent shutdown – disconnects motor if current exceeds safe limit

Stopping (Soft Stop)

If soft stop is enabled:

- Firing angle slowly increases
- Voltage gradually decreases
- Motor slows down smoothly

Useful for pumps or conveyor belts where abrupt stopping causes damage.

3.5 Discussion

Phase 2: Development of Prototypes

During this phase

PCB Fabrication and Assembly: The schematic and layout of the control circuit were created using software known as EDA. The PCB was assembled by adding all the components.

Mounted the SCRs to the heat sinks using thermal compound. The power components were mounted on a different, robust board which had sturdy wires to carry the motor current.

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An initial assessment was conducted to measure and document existing conditions or performance levels before implementing an intervention or new system. This will serve as a reference point for evaluating the effectiveness of changes or improvements.

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