



Contemporary Methods for the Smooth Startup of Asynchronous Motors and Their Practical Uses

Otabayev Boburxon Odil o'g'li, Qurvonboyev Botirjon Isroiljon o'g'li

Phd at Namangan State Technical University. Namangan, Uzbekistan.

Phd at Namangan State Technical University. Namangan, Uzbekistan.

ABSTRACT: This article analyzes modern methods for the smooth starting of asynchronous motors. The problems that arise during the startup process of asynchronous motors and various effective methods to address them are discussed in detail, including soft starters, star-delta control, inverter-based control, and other technologies. The advantages, disadvantages, and industrial applications of each method are explained, along with the conditions and systems where they are most effective. Modern control systems and intelligent technologies are examined for their role in increasing motor efficiency, ensuring stable power supply, and optimizing production processes. The article provides important recommendations for optimizing asynchronous motors in various industrial sectors, contributing to energy efficiency, safety, and the long-term operation of equipment. This study serves as a valuable resource for implementing advanced technologies in asynchronous motor control.

KEYWORDS: Asynchronous motor, soft starter, starting current, voltage, inverter, thyristor.

I. INTRODUCTION

Asynchronous motors are among the most widely used electric motors in industry and technology. However, the startup process of asynchronous motors can present certain challenges, as these motors require a high starting current, which can negatively affect the system's operation. Soft starters are designed to ensure precision and flexibility during motor startup. Soft starting technologies regulate the motor's speed or voltage to smooth out the startup process. These devices reduce the inrush current of asynchronous motors and facilitate a smoother startup. The primary goals of such devices are to reduce energy consumption, protect the system, and extend the operational lifespan of asynchronous motors. Modern technologies are used to decrease the starting current, optimize the startup process, and conserve energy. A proper and smooth startup process ensures the long-term operation of an asynchronous motor. If an asynchronous motor starts too quickly, it can impose excessive loads on its mechanical and electrical components, leading to energy waste and accelerated wear. If such conditions persist, they can cause disruptions in production processes, catastrophic motor failure, and significant financial losses[1.1, 1]. Therefore, soft-starting systems play a crucial role.

Asynchronous motors are superior to other types of motors due to their reliability, durability, brushless design (which reduces frictional forces), and ease of installation, use, and maintenance[1, 2]. They are widely used as primary drive components in pumps, fans, compressors, transportation systems, and similar equipment. Approximately 40-50% of the electricity generated is consumed by asynchronous motors. These motors operate using alternating current, and their working principle is based on the force generated by the changing magnetic field between the rotor and the stator. However, during startup, significant attraction forces are generated between the stator and rotor, leading to high current surges and mechanical stresses. To mitigate these issues, various methods for the smooth starting of asynchronous motors have been developed. This article presents information on the advantages of smooth start methods and improvements to thyristor-based voltage regulators.

**II. MATERIAL AND METHODS****Objectives of Smooth Starting of Asynchronous Motors**

The main objectives of smooth starting of asynchronous motors include:

- Ensuring uniform acceleration and deceleration;
- Reducing starting current;
- Matching motor torque with load torque.

Depending on the nature of the load, smooth start technologies offer various motor control modes[5, 3]. Currently, several methods exist for the smooth starting of asynchronous motors, including:

- Direct connection to the power grid;
- Star-to-delta switching;
- Starting via an autotransformer;
- Starting via a frequency converter (which also regulates motor operation);
- Starting via a thyristor-based voltage regulator.

Additionally, methods such as reactor-based starting and capacitor-assisted starting exist. However, these do not fully achieve the primary objectives of smooth starting.

Direct Connection to the Power Grid for Starting

According to source [1.1], directly connecting an asynchronous motor to the power grid is the simplest method of starting. However, the current drawn from the power grid can be 5 to 8 times higher than the nominal current, and the motor torque can increase by 0.5 to 1.5 times. The direct connection startup method is one of the simplest and most cost-effective ways to start a motor. In this method, the motor is directly connected to the power source, requiring only a magnetic starter (MIT) and a few protective components for control. A Q1 protection device (a circuit breaker or fuse switch) is connected to the power grid. Then, a three-phase magnetic starter (KM1) is activated. The magnetic starter allows the motor to be switched on and off. Additionally, an F2 thermal relay is used to protect the motor from overheating (Figure 1). Although the direct connection method is simple and cost-effective, it has both advantages and disadvantages. Below is a summary of its key pros and cons.

Advantages.

1. **Simplicity and Cost-effectiveness:**
 - This method is very simple to implement and has low costs. It does not require special devices or complex control systems;
 - The motor can be started quickly by directly connecting it to the power grid, without the need for additional equipment.
2. **Fast Startup:**
 - An asynchronous motor can be started quickly by direct connection, as this method requires only a contactor and protective systems for operation.
3. **Simple Maintenance:**
 - This method is very straightforward and does not require automated control systems, making maintenance easier;
 - The initial installation and connection process are relatively inexpensive. This method is the most cost-effective for small and medium-power motors.

Disadvantages.

1. **High Starting Current:**
 - When the motor is directly connected to the power grid, it generates a very high starting current, which puts significant stress on the system components. This current can be 5 to 8 times higher than the nominal current;
 - High starting current can be harmful to the power network, potentially causing overloading and failures in the system.

2. Low Energy Efficiency:
 - Due to the high starting current, energy consumption is also high, as there is no mechanism to improve energy efficiency;
 - This method may lead to increased energy losses and excessive heat generation during motor operation.
3. Potential Damage to the Motor and System:
 - High starting currents and excessive stress can damage the motor's mechanical components, as well as transformers and other electrical equipment in the network. Over time, this can shorten the motor's lifespan.
4. Impact on the Power Grid:
 - This method can negatively affect other equipment and systems connected to the same power network. The high inrush current may cause voltage drops or disturbances in the system.
5. Unsuitable for High-Power Motors:
 - This method is not recommended for high-power asynchronous motors, as excessive starting currents can weaken the system and create risks. For such motors, soft starters or frequency converters are preferred as more efficient alternatives.
6. No Speed Control Capability:
 - With direct connection, it is impossible to control the motor's speed. For example, during startup, there is no way to optimize the acceleration or reduce the load.

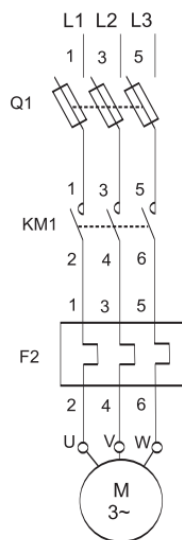


Figure 1. Direct Connection Startup of an Asynchronous Motor to the Power Grid.

Star-Delta Starting Method for Asynchronous Motors

The star-delta starting method is one of the most popular and effective techniques used for starting asynchronous motors. This method ensures that the motor starts with a lower initial voltage, which helps reduce the inrush current during startup. The control is achieved by switching the stator windings of the motor between star and delta configurations. According to sources [1.1, 2], two main conditions must be met for using the star-delta starting method:

1. The three-phase asynchronous motor must have all six ends of its stator windings accessible at the terminal block (i.e., brought out for external connection).
2. The motor must have a rated voltage of 380/660 V for operation in 380 V networks.

It is stated that when the stator windings of an asynchronous motor are connected in a delta configuration, the motor operates normally at 380 V. In this case, each winding receives the full 380 V voltage. However, during the starting

phase, when the motor is connected in a star configuration, the voltage applied to each winding is reduced by a factor of $\sqrt{3}$, meaning the motor receives a voltage that is $\sqrt{3}$ times lower than its nominal voltage.

Starting an Asynchronous Motor Using the Star-Delta Method.

Initial State (Star Connection):

- During startup, the motor is connected in a star (Y) configuration. In this configuration, the three-phase windings of the motor stator are connected together and supplied with power.
- Each phase of the motor receives a reduced voltage ($1/\sqrt{3}$ of the nominal voltage), which allows the motor to start with a lower starting torque.
- Even though the voltage applied to each stator phase is reduced in the star configuration, the motor does not generate a high inrush current. This helps reduce voltage drops in the network and results in lower energy consumption.

Transition to Full Voltage (Delta Connection):

- Once the motor starts and reaches a certain speed, it is switched to the delta (Δ) configuration. In this mode, each phase winding is directly connected to the full line voltage, enabling the motor to reach its nominal speed and torque.
- The transition from star to delta typically occurs a few seconds after startup or once the motor reaches approximately 75–80% of its nominal speed.

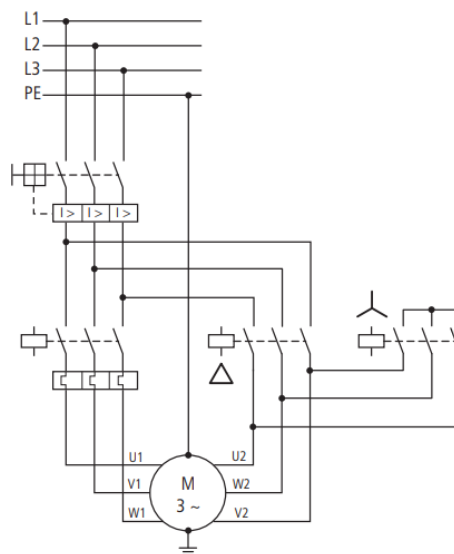


Figure 2. Diagram of Star-Delta Starting Method for an Asynchronous Motor

Main Components of the Star-Delta Starting Circuit:

1. Asynchronous Motor – The motor used with this starting method.
2. Magnetic Contactors (Star-Delta Switch) – Switches between the star and delta configurations to control the motor windings.
3. Overload Relay – Protects the motor from excessive current or short circuits.
4. Automatic Control System – Manages the transition from star to delta automatically.

According to sources [6], during normal operation, the motor is connected in a delta configuration, but during startup, it should be connected in a star configuration. Since the motor receives a lower voltage at startup, the inrush current is reduced. A reduction of approximately 30% in current also results in a decrease of up to 25% in starting torque. Because of this, this method is most suitable for pumps, as they do not require high torque during startup[1.2]. To implement this method, the circuit requires:

- Three magnetic contactors (MIT)

- A time relay
- Control stages

The star contactor and the main contactor work together to connect the motor in a star configuration[6]. The time relay waits until the motor reaches approximately 75–80% of its nominal speed before disconnecting the star contactor and activating the delta contactor (as illustrated in Figure 2).

Advantages of the Star-Delta Starting Method.

1. Reduced Starting Current:
 - Since the motor starts in a star connection with reduced voltage, the starting current is significantly lower. This prevents high electrical stress on the network.
 - The lower inrush current minimizes disturbances in the power supply and prevents voltage drops.
2. Lower Energy Consumption:
 - During startup in the star configuration, the motor consumes less energy. Since a lower voltage is applied, energy efficiency is improved.
3. Simple and Cost-Effective Implementation:
 - The star-delta method is relatively easy and inexpensive to implement as it does not require advanced technological components.

Disadvantages of the Star-Delta Starting Method.

1. Lower Initial Torque and Speed:
 - Because of the reduced voltage in the star configuration, the motor starts with a lower torque. This can be problematic for applications that require high starting torque.
2. Not Suitable for High-Power Motors:
 - This method is only effective for small to medium-sized motors. High-power motors typically require more torque and speed at startup, making other starting methods more suitable.
3. Additional Control Components Required:
 - Extra magnetic contactors and a control system are needed to switch from star to delta. This increases the overall system cost.
4. Complexity in Automatic Switching:
 - The transition from star to delta must be precisely controlled. If any issue arises, manual intervention or adjustments may be necessary.

The star-delta starting method is an effective and cost-efficient way to start asynchronous motors, especially for small and medium-sized applications. By reducing the inrush current, this method improves system reliability and minimizes network disturbances. However, it is not ideal for high-power motors or applications requiring high starting torque.

Starting an Asynchronous Motor Using an Autotransformer.

Starting asynchronous motors with an autotransformer is one of the methods used to reduce the initial voltage applied to the motor and, consequently, decrease the high inrush current drawn from the power supply. In this method, the autotransformer lowers the voltage supplied to the motor during startup, effectively reducing the high starting current. The primary function of an autotransformer is to modify the voltage level. This function is also utilized in starting asynchronous motors. Studies [7, 1.1] indicate that motors with a power rating above 150 kW can be controlled smoothly using an autotransformer. In this case, the current drawn during startup can be reduced to 50%, 65%, or 80% of the typical starting current, while the starting torque is reduced to 25%, 42%, or 64% of its nominal value. The autotransformer ensures a smooth current transition and provides a higher torque. During this process, the motor speed reaches up to 95% of its nominal value. One of the main drawbacks of this method is the cost of the autotransformer. Due to advancements in power electronics and the decreasing cost of modern electronic devices, the use of autotransformer-based starting methods has declined.

Starting an Asynchronous Motor Using an Autotransformer.

1. Reduction of Initial Voltage:
 - The autotransformer reduces the voltage supplied to the stator windings of the motor.
 - The wiring configuration of the autotransformer ensures that the motor receives a reduced voltage at startup.
 - This allows the motor to start at a lower voltage while also reducing the inrush current drawn from the power supply.



2. Motor Startup Process:

- Once the motor starts running through the autotransformer, its rotational speed gradually increases.
- During startup, the stator windings receive a reduced voltage, which lowers the initial current and minimizes power supply disturbances.

3. Disconnection of the Autotransformer:

- When the motor reaches a predetermined speed (typically 70–80% of the nominal speed), the autotransformer is disconnected from the stator, and the motor is directly connected to the full line voltage.
- This transition ensures that the motor operates at its nominal voltage and performance.

Key Components in Autotransformer-Based Motor Starting.

- ✓ **Autotransformer** – A device that reduces the voltage during startup. The three-phase windings of the autotransformer are connected in such a way that the voltage supplied to the motor stator is reduced.
- ✓ **Magnetic Contactors (MIT) and Control System** – The MIT and control system are required to manage the connection and disconnection of the autotransformer. The control system ensures a smooth transition from the autotransformer to direct full voltage operation.
- ✓ **Protective Devices** – These protect the motor from overloading, short circuits, and other potential hazards.

Advantages of Starting with an Autotransformer.

- 1. Reduced Starting Current:**
 - The autotransformer reduces the initial voltage, which significantly lowers the starting current of the motor. This helps minimize surges in the power network and ensures a smoother startup process.
- 2. Energy Efficiency:**
 - The reduced voltage and starting current decrease energy consumption in the network, preventing additional load and improving overall energy efficiency.
- 3. Safe Startup for the System:**
 - Since the starting current is lower, the forces that could negatively affect system operation are reduced. This allows for a smoother startup, minimizing stress on the motor and other system components.

Disadvantages

- 1. System Cost:**
 - Additional equipment, such as an autotransformer, magnetic induction transformer (MIT), and control system, is required to start the motor using an autotransformer. This increases the overall cost of the system.
- 2. Voltage Increase:**
 - After the motor starts through the autotransformer, the voltage needs to increase once the autotransformer is disconnected. This process must be executed accurately and on time.
- 3. Not Suitable for High-Power Motors:**
 - This starting method is effective only for small and medium-power motors. It is not recommended for high-power motors, as they require higher voltage and torque.

Starting asynchronous motors using an autotransformer is an efficient and reliable method for small and medium-power systems. This approach helps reduce the starting current, enhances motor efficiency, and enables a safer startup for the power network. However, the need for additional equipment and higher costs may make this method less favorable in some cases.

Starting an Asynchronous Motor Using a Frequency Converter (VFD)

Starting asynchronous motors using a frequency converter (Variable Frequency Drive - VFD) is an effective method for controlling motor startup and operation. Frequency converters allow precise control over the motor's speed, torque, and startup current. This method is mainly used to optimize motor performance, increase energy efficiency, and ensure the reliable operation of the system.

Principle of Starting with a Frequency Converter.

1. Reduction of Initial Frequency:

- Frequency converters adjust the frequency of the supplied voltage to control the motor's speed;
- At startup, the frequency converter operates at a low frequency (low rotational speed);
- This initial low frequency reduces the motor's starting speed and, consequently, the starting current.



2. Control of Frequency and Torque:

- The frequency converter controls the motor's speed and torque throughout the startup process;
- Initially, the motor operates at a low frequency and speed, and the frequency is gradually increased;
- This smooth acceleration ensures that the motor starts efficiently with optimal torque, reducing startup current and preventing sudden electrical surges in the power supply.

According to source [1.1], the frequency converter is considered the best option for seamless and stepless starting of three-phase asynchronous motors. It minimizes the startup current, prevents voltage fluctuations in the power grid, and avoids sudden load changes in mechanical systems. In addition to starting the motor, a frequency converter allows smooth and continuous speed control. This technology is especially useful in applications where precise speed regulation is required. The frequency converter can adjust the supply frequency from 0 to 400 Hz.

Advantages of Starting with a Frequency Converter

1. **Reduced Starting Current:**
 - Using a frequency converter significantly lowers the starting current of the motor. By starting the motor at a lower frequency, sudden current and voltage surges are prevented.
2. **Precise Speed and Torque Control:**
 - A frequency converter allows for accurate control of the motor's rotational speed and torque. This ensures high efficiency for systems, as the motor can be started and operated at the required speed.
3. **Energy Savings:**
 - Frequency converters help significantly reduce energy consumption. When operating at lower speeds, the motor uses less energy, which enhances the system's overall energy efficiency in the long run.
4. **Reduced Mechanical Stress:**
 - The gradual increase in the motor's rotational speed reduces the load on mechanical components and enables a smooth startup. This contributes to the system's long-term reliability.
5. **System Monitoring and Optimization:**
 - Frequency converters not only assist in starting the motor but also optimize its operating modes. This allows for greater efficiency over prolonged use.

Disadvantages of Starting with a Frequency Converter.

1. **High Cost:**
 - Frequency converters are relatively expensive. These devices are based on advanced technologies and can significantly increase system costs in some cases.
2. **Complex Control System:**
 - Using frequency converters requires complex control systems. The initial installation and configuration of these systems can be challenging in certain situations.
3. **Operational Uncertainties:**
 - The setup and adjustment of frequency converters can sometimes be uncertain. If the device is not configured correctly, operational issues may arise when running the motor.

Applications of Starting with a Frequency Converter.

- **Industrial Production Lines:**
 - Controlling asynchronous motors with frequency converters allows for precise speed and torque control in manufacturing processes.
- **Elevators and Lifts:**
 - Frequency converters are used in elevator and lift systems, where precise speed control is essential for smooth and efficient operation.
- **Fans, Pumps, and Compressors:**
 - In systems such as fans, pumps, and compressors, frequency converters ensure efficient motor operation and reduce energy consumption.
- **Small and Medium Power Energy Generation Systems:**
 - In small and medium-scale power generation plants, controlling motors with frequency converters enhances energy efficiency.
- **High-Power Mechanical Systems:**

- Frequency converters are used in industries such as metallurgy, construction, and other heavy industries where high-power mechanical systems are required.

Starting asynchronous motors using a frequency converter is a highly efficient and reliable method, particularly in applications requiring precise speed control and energy efficiency. While the initial investment cost is high, the benefits of reduced startup current, improved system control, and lower energy consumption make it a valuable technology in modern industrial and commercial applications.

Starting an Induction Motor Using a Thyristor Voltage Converter

Starting and controlling induction motors using a thyristor voltage converter is a highly efficient and precise method. With the help of thyristor voltage converters (SCR – Silicon-Controlled Rectifier), the initial voltage and speed of the motor are regulated. This method is used to ensure smooth motor startup and high efficiency.

In [4], it is stated that after the development of high-power electronic components, their application in power systems has increased. Both DC and AC circuits are now controlled using power electronics components. One example of this is the thyristor voltage converter. The core components of a thyristor voltage converter are thyristors and a control block. Typically, a thyristor voltage converter consists of six thyristors, arranged in pairs for each phase in an antiparallel configuration (Figure 3). This method allows for the control of the starting torque and current of the motor. One of the key advantages of this method over others is the use of thyristors, which enable contactless switching.

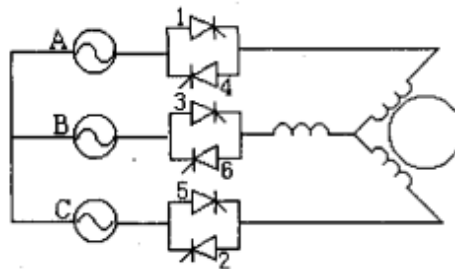


Figure 3. Arrangement of Thyristors in a Thyristor Voltage Converter

Principle of Starting an Induction Motor Using a Thyristor Voltage Converter

1. Controlling the Initial Voltage:

- Using thyristor voltage converters, the voltage supplied to the stator of the motor can be regulated.
- At startup, the voltage is reduced through the converter, which helps to minimize high current and voltage surges during motor startup.

2. Flexible Voltage Control:

- Thyristor voltage converters allow precise adjustment of the initial voltage of the motor;
- This variable voltage enables control over the motor's rotational speed and torque;
- By gradually increasing the voltage through thyristors, the motor can be controlled with accurate parameters.

3. Smooth Startup:

- When starting the motor with a thyristor voltage converter, the initial voltage is low, reducing inrush current and minimizing impact on the system;
- The motor's speed gradually increases, ensuring a smooth startup process.

4. Transition to Normal Operation Mode:

- After the motor starts, the voltage supplied through the thyristor converter is gradually increased;
- Once the motor reaches its nominal speed, the normal voltage is connected to the system (via MIT), allowing the motor to operate at full voltage.

Advantages of Starting with a Thyristor Voltage Converter

1. Reduced Starting Current:
 - The initial voltage can be reduced using a thyristor voltage converter, which decreases the starting current;
 - This minimizes power surges in the network and ensures a smooth startup process.
2. Smooth Startup:
 - The motor speed increases gradually, reducing mechanical stress and ensuring long-term operation.
3. High Torque Startup:
 - Motors can start with high initial torque using thyristor converters;
 - This is useful for handling heavy loads effectively.
4. Energy Savings:
 - Thyristor voltage converters optimize power consumption, improving motor efficiency and reducing energy costs.
5. Precise Speed and Torque Control:
 - Thyristor converters enable accurate control of motor speed and torque, ensuring optimal system performance.

Disadvantages of Starting with a Thyristor Voltage Converter.

1. System Complexity:
 - Using thyristor converters requires complex control systems, making installation and configuration challenging.
2. High Cost:
 - Thyristor voltage converters are relatively expensive due to their advanced technology, increasing overall system costs.
3. High Technical Requirements:
 - Skilled specialists are required for proper installation and operation, as incorrect settings may negatively impact the system.
4. Electrical Interference:
 - When thyristors operate, voltage conversion can cause electrical disturbances that may affect system performance.

Applications of Thyristor Voltage Converter-Based Startup.

- Industrial Production Lines:
 - Ensures smooth and efficient startup by operating motors at reduced initial voltage.
- Elevators and Lifts:
 - Provides precise control over speed and torque, making it ideal for elevator systems.
- Compressors and Pumps:
 - Improves energy efficiency and ensures a smooth startup process.
- High-Power Mechanical Systems:
 - Used in heavy industries such as metallurgy and construction for high-power mechanical applications.
- Energy Generation and Distribution Systems:
 - Helps regulate and optimize voltage in power generation and distribution networks.

III. EXPERIMENTAL RESULTS

The article [8] describes the development of a thyristor-based voltage converter for a single-phase motor. It consists of two single-phase full bridges, with the single-phase motor placed between the bridges (Figure 4). Each bridge comprises four thyristors controlled by a microcontroller. If the input frequency of this device is F , the output can provide frequencies of F , $F/2$, and $F/3$. This allows for controlling the motor's rotation speed. If the conduction time of the first bridge is 20ms and the conduction time of the second bridge is also 20ms, then a complete cycle takes 40ms. As a result, the output frequency is $F/2$ (if connected to a 50 Hz power grid, the output frequency will be 25 Hz).

In study [9], a new, simple, and reliable digital control circuit has been developed for controlling the speed of a three-phase asynchronous motor using a thyristor-based voltage converter. A zero-crossing detector is required for the precise operation of the thyristor-based voltage converter. The article also provides information about the zero-crossing detector.

According to it, the control system requires a signal with two pulses for each cycle. The first pulse occurs when the signal changes from 0 to +V, and the second pulse occurs when it changes from +V to 0 [12].

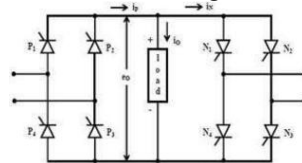


Figure 4. Arrangement of Thyristors in a Single-Phase Voltage Converter.

In [10], the electrical schematic, operating principle, and virtual implementation of a two-phase controlled thyristor voltage converter using computer software, along with the obtained results, are presented (Figure 5).

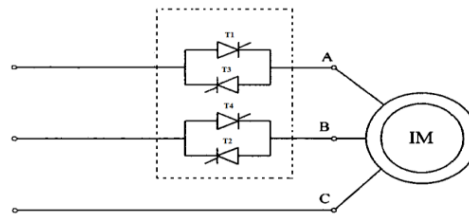


Figure 5. Arrangement of Thyristors in a Two-Phase Controlled TVC.

In [11], it is demonstrated that motors operating in high-humidity environments, such as oil refining, chemical processing, water and wastewater treatment, marine transportation, and similar industries, can be protected using a thyristor voltage converter. In these environments, high humidity leads to moisture condensation inside the motor, which can cause severe damage. The biggest risk for the motor is insulation failure in the windings. To prevent moisture condensation, the temperature of the motor windings should be at least 5°C higher than the ambient temperature. In [11], it is explained that an idle motor can be periodically connected to the power supply using thyristors to generate heat. The sequentially applied voltage does not create a rotational torque in the motor. This process can be implemented by programming the microcontroller in the control unit of any thyristor voltage converter (Figure 6).

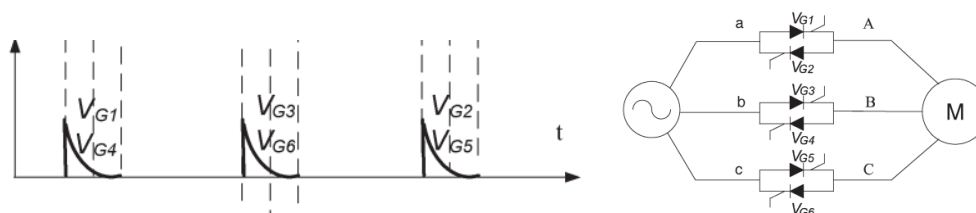


Figure 6. Arrangement of Thyristors and Signal Application Graph.

In [14], the necessity of a smooth start-up device for belt conveyors is discussed in detail. According to the technological characteristics of the transportation process, directly starting a loaded conveyor increases inertial forces, leading to excessive loads on the drive system and traction chains. Due to the increase in starting torque, issues such as belt slippage and oscillations may occur, and there is a risk of slipping between the conveyor belt and the drum. This significantly affects the belt and can disrupt the technological process. The study suggests that if the conveyor speed needs to be regulated, a frequency converter should be used. However, if the conveyor operates at a constant speed throughout its

working cycle, an asynchronous motor with a thyristor voltage converter can be used for starting and stopping the system smoothly, eliminating the mentioned problems.

In [13], research was conducted on detecting rotor faults in squirrel-cage asynchronous motors. More than 600 experiments were carried out using a 1.1 kW, 4-pole asynchronous motor operated with a thyristor voltage converter. The experiments were performed using thyristor voltage converters from well-known brands, and three types of faults were successfully identified. The study obtained successful results in fault detection. Additionally, the article provides the technical specifications of branded thyristor voltage converters (Table 1).

Table 1

Model	SIEMENS 3RW30	ABB PSR3-600- 70	OMRON G3JT405BL	SCHNEIDER Electric ATS01N109FT
Power (kW)	1.5	1.5	2.2	4
Controlled Phases	A-C	A-C	A-B-C	A-C
Nominal Voltage (V)	380-400	380-400	380-400	380-400
Nominal Current (A)	3.6	3.9	5.5	9
Starting Torque (%)	16...100	16...49	33...75	30...80
Starting Time (s)	0...20	0...20	1...25	1...5

IV. FUTURE WORK

Latest Trends and Innovations in Soft Starters. Recent trends and developments in soft starter technologies are primarily focused on automation and control systems, the application of new materials and technologies, and improving overall efficiency. These advancements aim to make the motor starting process more efficient, precise, and energy-saving. Below, we examine the latest trends in soft starter technology that contribute to enhancing the performance and energy efficiency of asynchronous motor starting methods.

Development of Electronic Devices and Technologies. Electronic devices and technologies are evolving to make the smooth startup process more efficient. The following technologies are particularly emerging as key development areas:

- **Intelligent Control Systems for Smooth Startup:**
 - Intelligent control systems are being developed for smooth startup. These systems primarily analyze the motor's startup process in detail and automatically adjust the settings accordingly.
- **Control Units and Electronic Relays:**
 - Using electronic control units and relays allows for more precise and reliable motor control. Automation of mechanical operations through electronic systems increases system efficiency.
- **High-Tech Sensors:**
 - Advanced sensors are used to monitor the operational status of motors. These sensors enable real-time monitoring of parameters such as temperature, voltage, and current.

Energy Saving and Efficiency Improvement. Innovations in technology and materials are also driving improvements in energy saving and efficiency. The following trends focus on enhancing energy efficiency:

- **Energy Recovery Systems:**



- Some systems offer the ability to recover and store the energy used by motors. By reusing energy, these innovations contribute to energy-saving efforts.
- High-Efficiency Startup Current Reduction Systems:
 - New electronic devices and materials are being developed to reduce startup current. These systems not only decrease startup current but also improve overall efficiency.
- Modular Systems:
 - Modular control systems and voltage converters enhance energy efficiency. These systems optimize power supply and ensure reliable operation.

V. CONCLUSION

The increasing demand for electrical energy and the need to optimize existing power networks require the implementation of energy-efficient and smooth startup technologies for motors. Among the most economical and adaptable methods for smooth startup of asynchronous motors are frequency converters and thyristor-based voltage regulators. Despite their advantages, these technologies have certain limitations. Addressing these drawbacks, improving reliability, and introducing new functionalities are crucial tasks for enhancing the efficiency of these systems in the future.

REFERENCES AND ONLINE SOURCES:

- [1] N. Rajeswaran, M. Lakshmi Swarupa, T. Sanjeeva Rao, K. Chetaswi. Hybrid artificial intelligence-based fault diagnosis of SVPWM voltage source inverters for induction motor. *Materials Today: Proceedings* 5 (2018) 565–571.
- [2] Toto Tohir, Abdullah Assegaf. Design and development of a simulator for the star-delta induction motor starting system with a closed transition model. *Journal of Academic Research*, Vol. 2 No. 5, 2021.
- [3] Lyubitsky A.M., Marichev A.A., Mitsney I.M., Chebanov K.A. Analysis and research on optimization methods for starting modes of asynchronous drives with autonomous power sources. *Sciences of Europe* # 21 (21), 2017 | *Technical Sciences*.
- [4] LU Guangqiang, Ji Yanchao, Yu Hongxiang, and Zhang Ke. Analysis of a novel topology of soft starter for induction motors. *Department of Electrical Engineering, Harbin Institute of Technology, Harbin, 150001, China*.
- [5] Nwachukwu Celestine Onyewuchi, Izuegbunam Fabian I., Olubiwe Mathew. Simulation of the impact of soft starter controller on induction motor transients. *International Journal of Science and Research (IJSR)* ISSN (Online): 2319-7064. Index Copernicus Value (2015): 78.96 | Impact Factor (2015): 6.391.
- [6] H.H. Goh, M.S. Looi, B.C. Kok. Comparison between direct-on-line, star-delta, and auto-transformer induction motor starting methods in terms of power quality. *Proceedings of the International Multiconference of Engineers and Computer Scientists 2009*, Vol. II, IMECS 2009, March 18–20, 2009, Hong Kong.
- [7] Joseph Nevelsteen, Humberto Aragon. Starting of large motors – methods and economics. *IEEE Transactions on Industry Applications*, Vol. 25, No. 6, November/December 1989.
- [8] Prasenjit Sontakke, Alok Ranjan. Induction motor drive using thyristor-based cycloconverter for variable torque load application. *IJIRST – International Journal for Innovative Research in Science & Technology*, Volume 4, Issue 1, June 2017.
- [9] Ali M. Eltamaly, A. I. Alolah, R. Hamouda, M. Y. Abdulghany. A novel digital implementation of an AC voltage controller for speed control of induction motor. *World Academy of Science, Engineering, and Technology International Journal of Mechanical and Mechatronics Engineering*, Vol. 3, No. 1, 2009.
- [10] Ashish D. Ginoya, Sunil Bhatt. Simulation of 2-phase soft starter control for induction motor with minimized starting torque pulsation. *International Journal of Engineering Research & Technology (IJERT)* ISSN: 2278-0181, IJERTV3IS051072, Vol. 3, Issue 5, May 2014.
- [11] Pinjia Zhang, Yi Du, Thomas G. Habetler, Bin Lu. A nonintrusive winding heating method for induction motor using a soft starter for preventing moisture condensation. *IEEE Transactions on Industry Applications*, Vol. 48, No. 1, January/February 2012.
- [12] Yao Lu, Jun Tong, Qian Zhang, Lei Sun. Research and design of a multifunctional soft starter. 978-1-5386-2901-7/17/\$31.00 ©2017 IEEE.
- [13] J. Corral-Hernandez, J. Antonino-Daviu. Startup-based rotor fault detection in soft-started induction motors for different soft-starter topologies. 978-1-5090-3474-1/16/\$31.00 ©2016 IEEE.
- [14] V. V. Dmitrieva, P. E. Sizin, A. A. Sobyannin. Application of the soft starter for the asynchronous motor of the belt conveyor. *IOP Conf. Series: Earth and Environmental Science* 942 (2021) 012003. doi:10.1088/1755-1315/942/1/012003.
- [15] S.K. Sahdev. *Electrical Machines*. Cambridge University Press, 2018.
- [16] Basem Elhady, Mohamed M. Ismail, Ahmed F. Bendary. Variable voltage control of three-phase induction motor for energy saving. *ERJ Engineering Research Journal, Faculty of Engineering, Menoufia University*, Vol. 44 (4), October 2021, pp. 377–383.
- [17] Adhi Kusmantoro, Theodora Indriati W, Sigit Ristanto. Soft starter induction motor three-phase with fuzzy logic controller inside delta. *International Journal of Applied Engineering Research*, ISSN 0973-4562, Volume 12, Number 19 (2017), pp. 8338-8345.

Online Sources:

- 1.1 AC Motors: Starting and Protection Systems Presentation [Link to Academia.edu](https://www.academia.edu)
- 1.2 Technical Paper on Motor Starting Methods [Moeller.net Technical Paper](https://www.moeller.net)