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DESIGN AND CONSTRUCTION OF A POWER ELECTRONIC CONVERTER FOR HIGH-POWER APPLICATIONS: AC-AC CONVERTER MOTOR STARTER

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ABSTRACT

Direct Online starter for electric motors have been found to exhibit various challenges, which include high power consumption during startup, low efficiency, harmonic distortion, and high operational cost. This study presents the design, construction and performance evaluation of a three-phase AC-AC power converter-based motor starter to address most of these challenges. It incorporates digital control, monitoring and protection features for efficient industrial motor operation and energy management. This was achieved using an Arduino microcontroller, TRIAC-based firing circuit, voltage and current sensors, thermal and humidity sensors, and an LCD interface to display operation parameters in real time. The designed and developed AC-AC converter was tested using a three-phase inductor motor with a capacity less than the rated capacity of the converter (8KW). The results of the performance when using the AC-AC converter were compared with the conventional Direct-On-Line (DOL) starter and the Proteus simulation model. The experimental results revealed that the AC-AC converter effectively minimised inrush current and power demand both at startup by 3.5A and during continuous operation by 765.42W compared to the DOL system. Steady-state analysis indicated a 34.6% energy saving, attributed to improved phase-controlled voltage regulation. Furthermore, the system maintained a steady voltage output with minimal drop between 3V and 4V per phase. Overall, the study demonstrated improved soft-starting, monitoring, protection, and extended motor lifespan, confirming suitability for industrial applications.

KEYWORDS: Power electronics, AC-AC converter, Soft-start, Motor starter, TRIAC, Energy efficiency.

1.0.INTRODUCTION

The increasing global energy demand has established a strong focus on the development of reliable and sustainable energy and electrical power systems (Strielkowski, et al., 2021). Industrialisation, technological advancement and the urgent need for decarbonization have all necessitated improvements in energy conversion efficiency in relation to energy savings and usage. Playing a significant role in this transformational shift lies the concept of power electronics. This is seen as a field of science and engineering that is concerned with the conversion and control of electrical energy through the switching of semiconductors (Dhameliya, 2022); (Maza-Ortega, et al., 2017). Consequently, power electronics systems are central to modern energy infrastructure, thereby bridging the gap between generation, transmission and utilisation (Lipu, et al., 2022). By enabling precise control of voltage, current and frequency, improvement in conversion efficiency across diverse applications ranging from renewable energy integration to industrial automation (Zhang, et al., 2018).

Practically, electrical energy exists in two forms: alternating current (AC) and direct current (DC). Power electronics help to facilitate the conversion of power from one form to another, which comprises AC-DC (rectifiers), DC-AC (Inverters), DC-DC (choppers) and AC-AC (voltage and frequency converters), dedicated to meet specific needs (Maza-Ortega, et al., 2017). Among the AC-AC converters are high-profile technologies such as variable speed motor drives, high voltage transmission control, aerospace and industrial heating systems (Ashraf, et al., 2022). Nevertheless, conventional converter topologies such as AC voltage converters and cycloconverters, though widely used, suffer certain limitations which include low efficiency, harmonic distortion and limited scalability (Azizi, et al., 2025). AC-DC-AC and matrix converters offer superior waveform quality and energy efficiency (Gupta & Sahay, 2024; Mahmud & Gao). However, their industrial applications remain limited due to implementation, complexity, cost barriers and safety issues (Bakar, et al., 2023).

In industrial systems involving three phase system, such as inductor motors, employing the conventional direct-on-line (DOL) starters often results in high inrush currents accompanied by efficiency losses and mechanical stress (Sangwongwanich, et al., 2018). Traditional AC-AC converters, such as AC voltage converters and cycloconverters, appear bulky, susceptible to harmonics and higher inefficiency (Azizi, et al., 2025). In another context, modern converters can achieve better performance compared to traditional converters; however, they are challenged by design complexity, electromagnetic interference (EMI), and thermal management (Bakar, et al., 2023). Consequently, there is a need to optimise converters and create solutions that combine better efficiency, energy consumption and management, reliability and compactness, without compromising safety. Therefore, the study aimed to design and construct an AC-AC power converter that enhances energy efficiency, performance, scalability, and reliability of high-power applications, tailored towards three-phase motor starters.

1.1. Review of High-Power Converter Types

There are several types of high-power converters, which include AC-DC, DC-DC, DC-AC and AC-AC. AC-DC converters can also be referred to as rectifiers based on the application. Hence, a system that converts AC power to DC power, such as an electric battery charger, DC motor drivers, etc. (Ikeri, et al., 2024). They convert alternating current to direct current, with various configurations like half-wave, full-wave, and bridge rectifiers, as seen in Figure 1. Advanced rectifiers, such as Pulse Width Modulation (PWM) rectifiers, offer improved control over output voltage and current, enhancing efficiency and reducing harmonic distortion (Iwaszkiewicz, et al., 2025). A study developed a cascaded AC-DC power conversion system to convert AC power to charge a battery set with the inclusion of power factor correction and a full-bridge converter, and a bridgeless rectifier (Wu, et al., 2023). Findings revealed that a maximum power efficiency of 96.68% was attained with less than 5% total harmonic distortion.

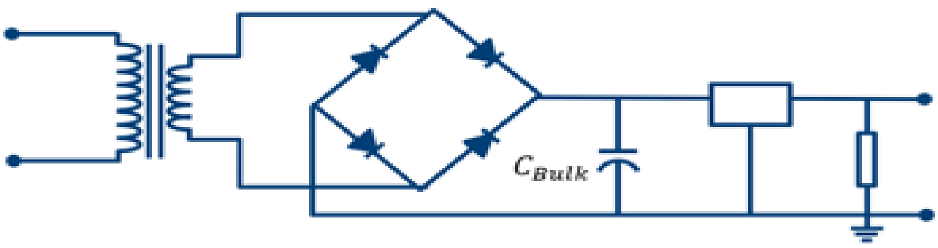

Figure 1: AC to DC Converter Circuit.

In another light, DC-AC converters are seen as power electronic converters referred to as inverters. Inverters convert DC to AC and are widely used in renewable energy systems, uninterruptible power supplies (UPS), and motor drives (Dokic & Blanusa, 2015). PWM inverters, including sinusoidal and space vector modulation techniques, provide high-quality output waveforms, improving the performance of connected loads. Figure 2 shows a picture of a DC to AC converter circuit.

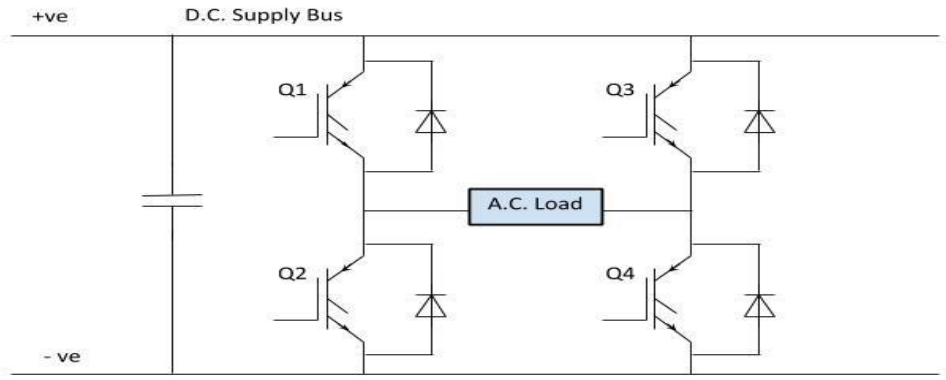

Figure 2: DC to AC Converter Circuit.

DC-DC converters function in transmitting up and down voltage levels but in DC circuitry (Lopa, et al., 2016). Examples of DC-to-DC converter topologies comprise buck, boost, and buck-boost converters, which are the most common (Lopa, et al., 2016). These converters are crucial in applications like power supplies for electronic devices and electric vehicles. Figure 3 shows a picture of different DC to DC converter circuits, such as buck converter, boost converter, buck-boost converter and CUK converter.

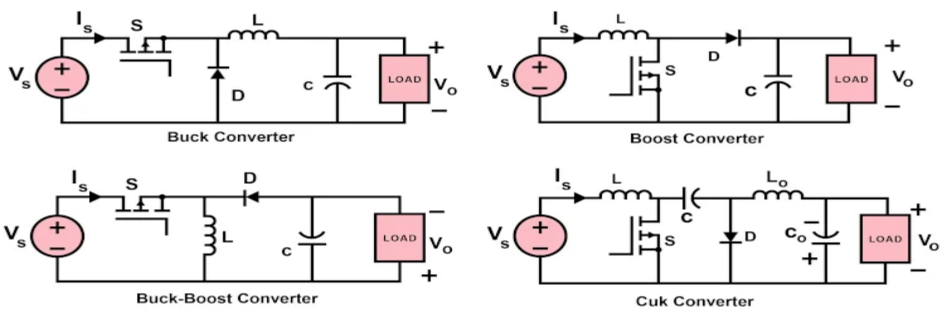

Figure 3: DC to DC Converter Circuits.

Wei and Wen (2022) took to designing a high-frequency oscillation of an active-bridge-transformer-based DC to DC converter (Wei & Wen, 2022). Based on the simplified model, the oscillation voltage generated by an active bridge was analysed in the time domain, while a universal active voltage-oscillation-suppression method, selected harmonic-elimination phase-shift (SHE PS) modulation method, is proposed. The experimental results show the excellent performance of the proposed active suppression method, with voltage spike amplitude (VSA) reductions of 92.1% and 77.8% for the DAB and MAB prototypes, respectively. On the other hand, Zaid et al (2022) designed and modelled a DC-DC converter with a high gain, continuous input current, and common ground, which are usually employed in renewable energy applications to boost the generated output voltage of renewable energy sources. The converter was found to produce an ideal voltage gain of 11 times at a duty ratio of 30%, with an ideal voltage gain of 14.44 at a duty ratio of 40%. (Zaid, et al., 2022).

An AC-AC converter is a power electronic converter that helps to convert AC power from one frequency to another AC power without the implementation of any DC stage (Nandakumar, et al., 2024). Mostly used in applications requiring variable frequency drives, such as in the control of large motors in industries like cement and steel manufacturing. Figure 4 shows a picture of an AC-to-AC converter.

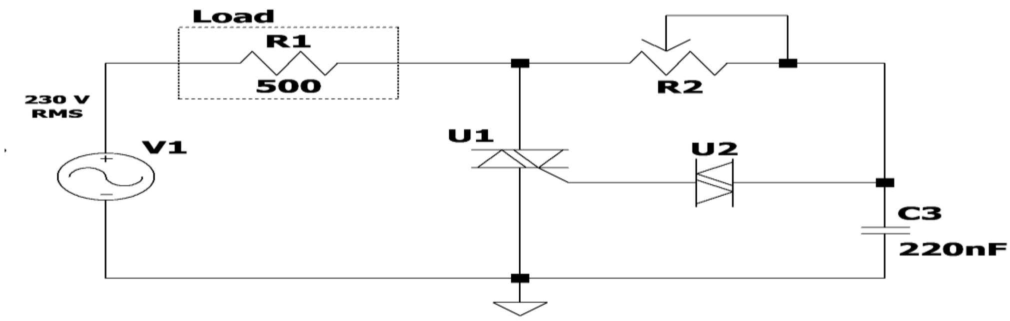

Figure 4: AC to AC Converter Circuit.

Some of the traditional AC to AC converters include AC voltage controllers, cycloconverters and AC choppers. An AC voltage controller functions by controlling output voltage amplitude while keeping frequency constant using thyristors to adjust the AC waveform delivered to the load (Nandakumar, et al., 2024). Cycloconverters function by converting input AC of fixed frequency to an AC output of usually lower frequency using thyristor arrays to switch segments of the input waveform (Tahmid, et al., 2025). Therefore, among these, AC-AC converters remain the most relevant when it comes to motor control and high-power regulation, offering bidirectional energy flow and compact system architecture.

1.2. Review of Past Related Works

Uddin et al. (2020) took to designing a generalised step-down single-stage AC to AC power converter. The system uses line frequency switching and does not require any form of pulse width modulation techniques, high frequency switching and a DC link between the AC-to-AC converter to address issues related to electromagnetic interference (EMI), power losses during switching, harmonic distortion, bulkiness and cost. Balachandran et al. (2019) took a different approach with a focus on designing, constructing and testing an aero-engine starter generator for more efficient aircraft usage. It implied developing a motor starter for turbofan application with a converter integrated into the machine to give it a multi-faceted performance specification. The design employed the use of machine-facing converters, network-facing converters and contactors, and DC links for three-phase applications. Conseptar et al. (2024) designed and implemented a DC to AC power electronic-based converter that produces a pure sine wave output for electrical engineering applications. Hence, an inverter circuit that produces stable electric power during switching and remote terminal unit monitoring. By using a MOSFET and KA3525 integrated circuit, the project was designed and constructed to convert a DC power source to an AC power source in a single phase. Emenike et al. (2020) considered the design and construction of multi-mode induction motor starters, which include Variable Frequency Drive (VFD), Direct online (DOL) and delta-star starting modes. The design involved three phase system and the use of Arduino microcontrollers to control the start and stop sequence. Using DOL, the recorded peak current was 1.61A, while VFD was recorded at 0.31A.

A study was designed to construct a DC to AC converter motor starter. Hence, a system is designed to convert a DC power source and supply an AC output to operate a single-phase motor (Alcocer, 2017). The design employed the use of a thyristor for the switching to transform the DC voltage source into an AC voltage source. In another study, Flaxer (2022) considered the principles, design and implementation of a direct AC to AC power converter. The device was regulated using an electronic transformer and included a DC link between the AC-to-AC conversion (Flaxer, 2022). The system was designed to operate using single phase power supply, and the electronic transformer serves the purpose of stabilising, controlling and protecting any line voltage with a frequency between 45Hz and 55Hz and achieved 97% efficiency in power consumption. Similarly, Alves et al. (2018) took to designing a highly efficient AC to DC to AC three-phase converter using SiC for uninterrupted power supply applications. The focus of the work was to minimise volume and maximise efficiency by applying MOSFET for switching and RC networks (Alves, et al., 2018). The system converts AC power to DC to charge the battery and converts it back to AC to supply to electronics. Nandakumar et al. (2024) focused on designing and analysing a solitary AC to AC converter using reduced components for an efficient power generation system. The concept is to design an isolated converter to enable transmission of AC power sources to reduce losses and enhance system efficiency for a single-phase system (Nandakumar, et al., 2024). Hence, a buck-boost AC to AC converter with the use of minimal components (Insulated Gate Bipolar Transistor, IGBT). However, the design was simulated using MATLAB and Simulink. The system recorded a power factor of 0.97 and an overall efficiency of 98%, Gangula et al. (2024) presented a self-learning-based output voltage control system that tracks DC-DC buck power converters with application in a high precision performance environment with large load uncertainties. The design involved a computational concept of a single hidden-layer neural network to monitor both output voltage and inductor current based on the control strategies to achieve settling time in fast dynamic performances (Gangula, et al., 2024). Tightiz et al (2025) took to designing a novel AC to AC converter for high-efficiency wireless electric vehicle charging systems. A design that substitutes a single integrated AC–AC converter on the input side for the conventional AC–DC and DC–AC converters, and this not only makes the system simpler but also more efficient (Tightiz & Al-Shibli, 2025). To further reduce the voltage stress on the switches, the design considered an additional multilevel diode clamp inverter, which not only helps to reduce the size of the switches but also greatly increases the efficiency of the system.

2.0. MATERIALS AND METHODS

2.1. Design of Converter

The design concept of the AC-to-AC converter is presented in Figure 5. The system consists of a three-phase input controlled via a circuit breaker for isolation and protection. Each phase (R, Y, B) is connected to a TRIAC-based firing circuit that regulates conduction angle and, consequently, output voltage supplied to the motor.

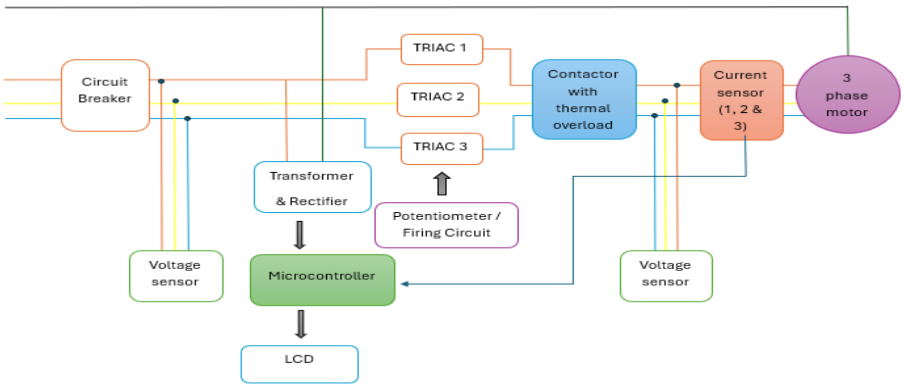

Figure 5: Block Diagram showing Design Concept of AC-AC Converter 3P Circuit.

The firing control is achieved through an RC phase-shifting network combined with a potentiometer-controlled triggering circuit. When the potentiometer is set to a high resistance value, insufficient current flows to trigger the TRIAC gate, keeping it in the non-conductive state. Gradual reduction in resistance allows gate current flow, initiating conduction and controlling the firing angle, thereby achieving soft-start functionality. Downstream of the TRIAC network, a three-phase contactor serves as a mechanical isolation unit and overload protection device. The contactor is equipped with an internal thermal relay that trips under excessive load conditions. A single-phase supply (R and Neutral) is stepped down via a transformer-rectifier system to 5 VDC, powering the microcontroller and auxiliary devices. Voltage and current sensors are installed at both input and output terminals to facilitate real-time monitoring and energy consumption estimation. Temperature and humidity within the converter enclosure are monitored using a DHT11 sensor, enabling the microcontroller to control a 12 VDC extractor fan for automated thermal regulation.

2.2. Design Circuit, Analysis and Calculations

As seen in Figure 6, there is a 3-phase power supply which is fed to the circuit breaker serving as a switch to the circuit. Upon turn-on of the circuit breaker, current flows to the TRIAC and RC network circuit used to regulate the power consumption to the 3-phase electric motor. However, there is a tapping at L1 used to energise the 4-pole contactor coil.

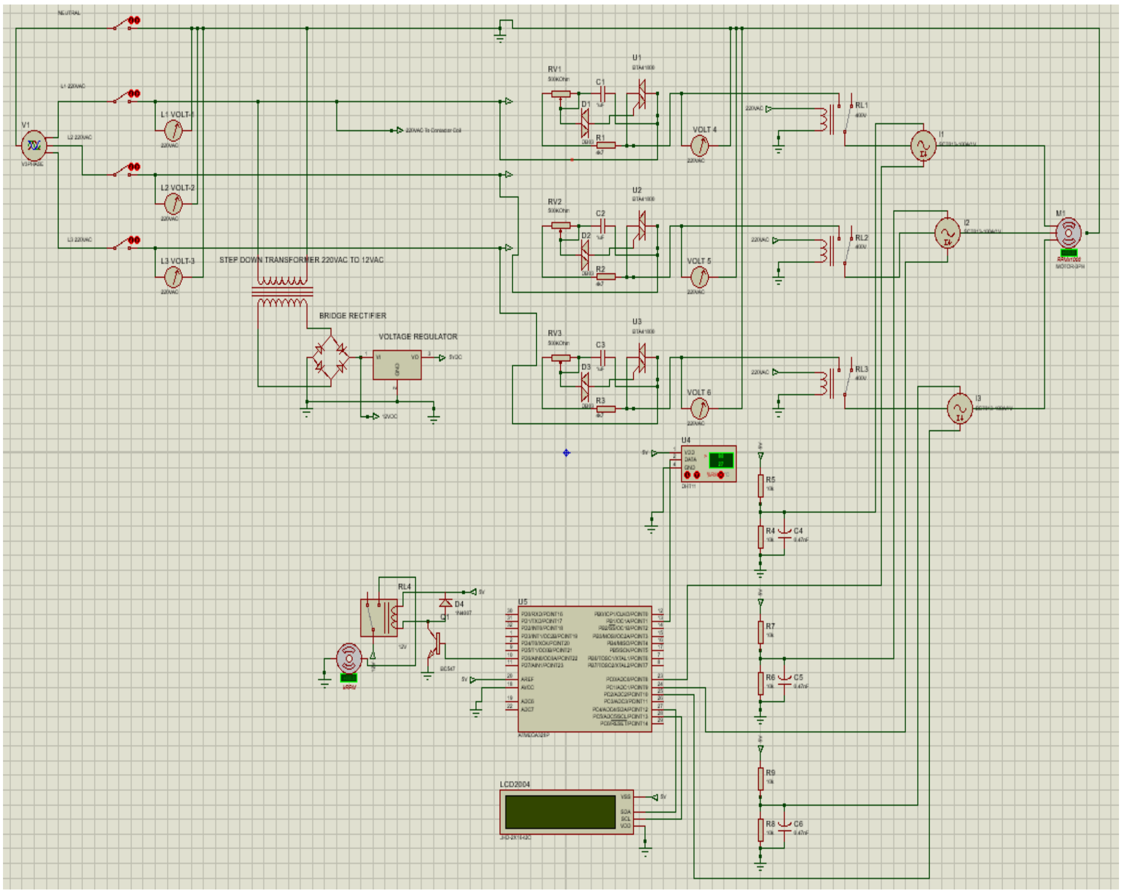

Figure 6: Complete Circuitry for AC-to-AC Power Converter Motor Starter.

2.2.1 Firing delay and Angle for the Phase Control Circuit

To calculate the firing delay for a phase-control circuit using a DB3 DIAC, BTA12600B TRIAC, and an RC network composed of:

- $R_1 = 10k\Omega\ (fixed\ resistor)$
- $R_2 = 500k\Omega$ (potentiometer)
- $C = CBB22\ 400V$ capacitor (assume a value like 0.1 µF or 100 nF for calculation)

1. RC Time Constant (τ)

The RC time constant is

$\tau = (R_1 + R_2) \times C$

Let’s calculate the range of τ for.

- Minimum R (10kΩ)

$\tau_{min} = (10k\Omega) \times (100nF) = 0.001\ \text{seconds} = 1\ \text{ms}$

- Maximum R $(10k\Omega + 500k\Omega = 510k\Omega)$:

$\tau_{max} = (510k\Omega) \times (100nF) = 0.051\ seconds = 51\ ms$

2. AC Half-Cycle Duration (for 50 Hz)

- $One\ AC\ cycle = 20\ ms$, for a 50Hz system (Basamma, 2019)
- $Half\ cycle = 10\ ms$

This is the time window for firing the TRIAC each half-cycle. So.

- If the capacitor reaches DB3 breakover voltage (≈ 30V) early → early firing, more power to the load.
- If it takes longer to reach 30V → late firing, less power.

3. Estimating Firing Angle (α)

$V_c(t) = V_m \times (1 - e - t/RC)$

$Solve\ for\ time\ t\ when\ V_c(t) = VBO = 30V$

$Assuming\ peak\ AC\ voltage\ Vm = 325V\ (for\ 230V\ RMS\ system):$

$30 = 325 \times (1 - e - t/\tau)$

$30/325 = 1 - e - t/\tau \Rightarrow e - t/\tau$

$= 1 - 0.0923 = 0.9077 \Rightarrow -t/\tau = ln(0.9077) = -0.0966$

$t = 0.0966 \times \tau$

So, for each τ.

- $\tau = 1ms \rightarrow t = 0.0966\ ms$
- $\tau = 51ms \rightarrow t = 4.9266\ ms$

Now convert t to firing angle (α) in degrees.

$\alpha = t \times 180°/T/2 = t/10\ ms \times 180°$

$At\ 1\ ms\ \tau \rightarrow \alpha \approx 1.74°$

$At\ 51\ ms\ \tau \rightarrow \alpha \approx 88.7°$

Hence, the firing angle range is between 1.7° and 88.7°

2.3. Construction Process

The construction phase involved systematic prototyping, testing, and final assembly, divided into various subsystems, including testing and calibration, controller circuitry, and firing circuit systems. The final assembly incorporated all subsystems shown in Plates 1, 2 and 3 into a single enclosure. Power Supply and Distribution Unit supplied multi-level voltages (415 VAC, 220 VAC, 12 VDC, and 5 VDC), seen in Plate 1.

Plate 1: Assembled Power Supply and Distribution Circuit.

Controller and Sensor Unit handled signal processing, display, and cooling control. The Arduino controller interfaces with the SCT013 current sensor, receiving signals that are processed and displayed together with temperature and humidity values on the LCD2004 screen, as shown in Plate 2.

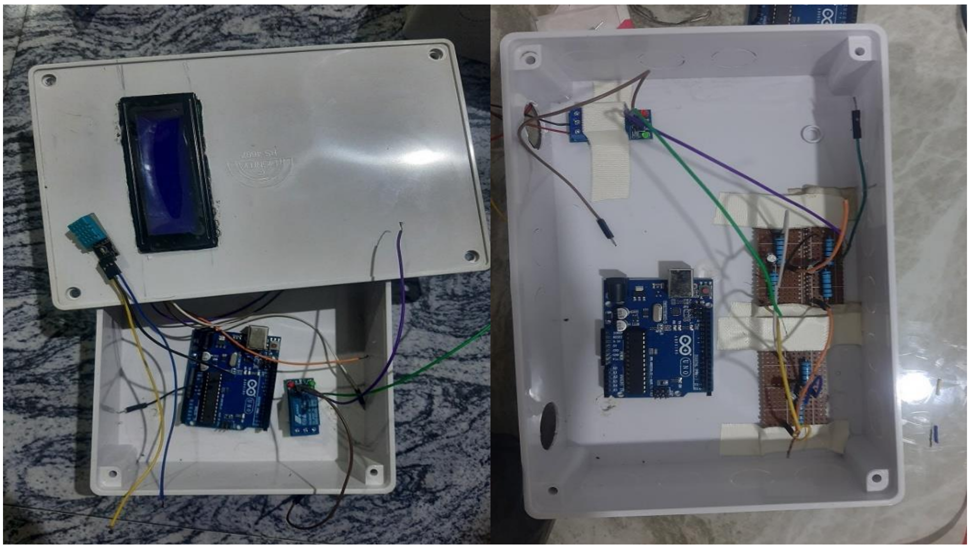

Plate 2: Sensors and Arduino Installation Process.

AC–AC Converter Unit managed motor voltage regulation and phase control. Each 3-phase, 4 wire cables coming from the power supply and distribution compartment was connected to the firing circuits, as observed in Plate 3.

Plate 3: AC to AC Converter Installation Process.

3.0. RESULTS AND DISCUSSION

This section presents and discusses the experimental results from the design, construction and performance evaluation of the developed AC-AC converter motor starter for application in a three-phase induction motor. The system consists of both software and hardware components, including a current sensor, a voltmeter, a liquid crystal display, a temperature and humidity sensor, an extractor fan, a potentiometer firing circuit, and an Arduino microcontroller, which utilises the C language in its IDE as seen in Plate 4. The fundamental goal was to minimise inrush current, improve the energy efficiency of the system, provide dynamic voltage, and current control.

Plate 4: Constructed AC to AC Converter for 3-phase Electric Motor Control.

Therefore, the system was evaluated for its performance under the established performance tests: current reduction, voltage regulation, and speed control.

3.1. Current Reduction

To assess current reduction capability, the converter's performance was compared with a traditional Direct-On-Line (DOL) starter and a Proteus simulation model, as seen in Table 1 and Figure 7.

Table 1: Inrush Current of Direct Online Starter, AC to AC Converter Motor Starter and Proteus Simulation.

	Direct Online Starter			AC to AC Converter			Proteus Simulation (AC to AC Converter)		
	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)	Voltage (V)	Current (A)	Power (W)
Phase 1	225	4.4	990	221	3.74	826.5	220	3.79	833.8
Phase 2	226	4.3	971.8	222	2.97	659.3	219	3.77	825.63
Phase 3	226	4.2	949.2	223	2.60	579.8	221	3.75	828.8
Total			**2911**			**2065.6**			**2488.2**

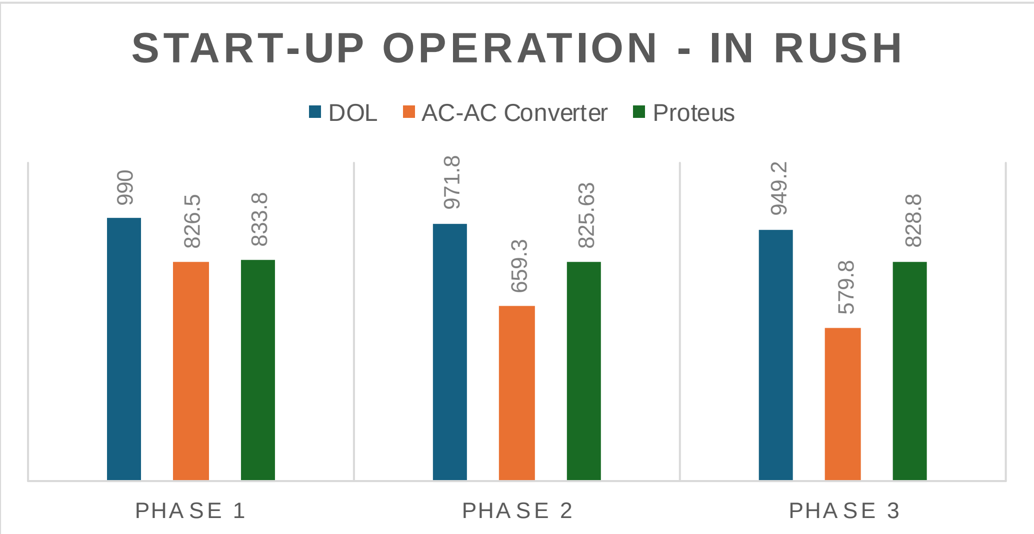

Figure 7: Start-up Operation – Inrush.

The AC–AC converter minimised startup power consumption by 846 W compared to the DOL. This validates the system's soft-start capability and confirms simulation accuracy with experimental data.

Table 2: Operating Current of Direct Online Starter and AC to AC Converter Motor Starter.

	Direct Online Starter			AC to AC Converter		
	Voltage (V)	**Current (A)**	**Power (W)**	**Voltage (V)**	**Current (A)**	**Power (W)**
Phase 1	226	3.2	723.2	221	2.02	446.42
Phase 2	226	3.1	700.6	222	2.03	450.66
Phase 3	226	3.0	678	223	1.97	439.3
Total			**2101.8**			**1336.38**

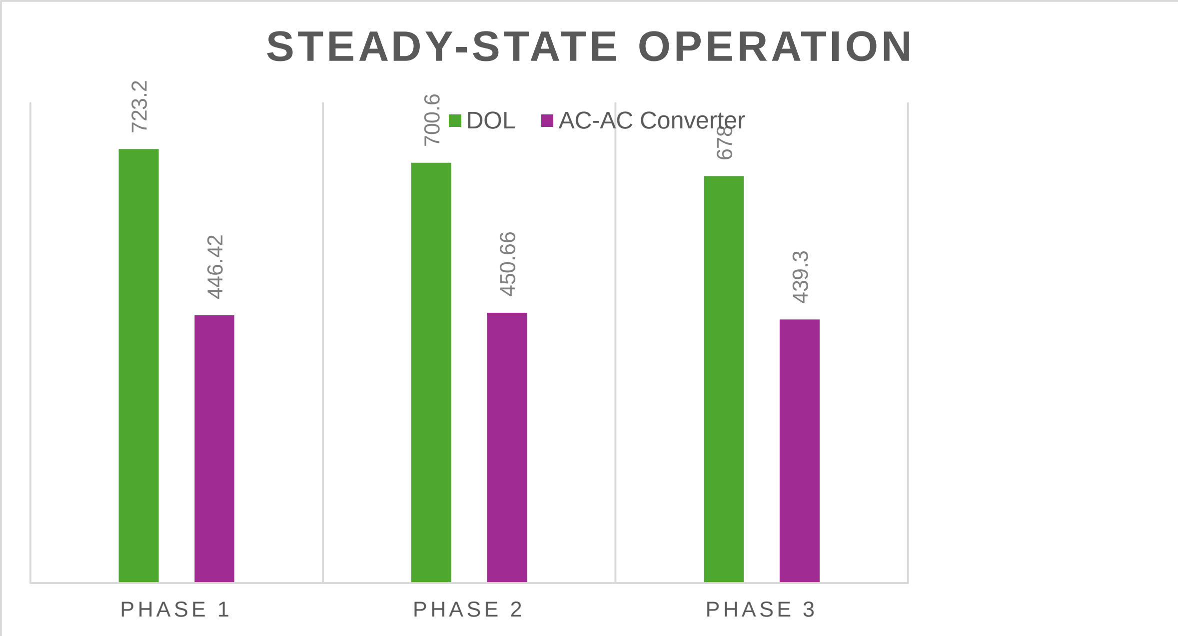

Figure 8: Steady State Operation.

At steady-state operation (Table 2 and Figure 8), power consumption using the AC–AC converter was 1336.4 W, compared to 2101.8 W with DOL, indicating a 36.4% energy saving under similar load conditions. This efficiency improvement aligns with the converter's voltage-phase modulation design, which limits mechanical stress and electrical transients.

3.2. Voltage Regulation

Voltage regulation tests compared input and output voltages at full firing were presented in Table 3. The observed drops were minor: 4 V (L1), 3 V (L2), and 3 V (L3), within acceptable limits for TRIAC-based circuits (Uslu, 2023).

Table 3: Input and Output Voltage of AC to AC Converter Motor Starter.

	Input Voltage (V)	Output Voltage (V)	Voltage Drop (V)
L1	225	221	4
L2	225	222	3
L3	226	223	3

Further testing demonstrated that the converter allowed dynamic voltage variation. As the firing angle for the different firing circuit were adjusted, there was corresponding effect on the voltage, reduction from 100%, 90% to 80%, output voltage decreased progressively from ~221 V, 213V to ~168 V respectively for line 1, 100%, 90% to 80%, output voltage decreased progressively from ~221 V, 215V to ~167 V respectively for line 2, and 100%, 90% to 80%, output voltage decreased progressively from ~222 V, 215V to ~166 V respectively for line 1.

3.3. Speed Control

A. Vibration Analysis

Vibration analysis using a seismometer revealed average and maximum acceleration levels as seen in Figures 9, 10 and 11, with a summary of result data shown in Table 4.

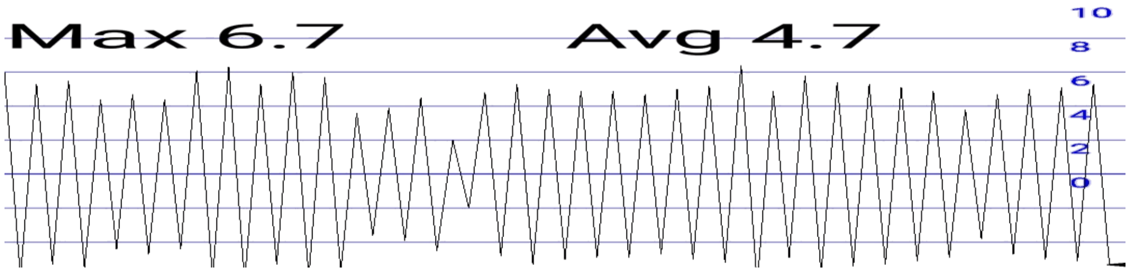

Figure 9: Vibration Profile of Electric Motor using Direct Online Starter.

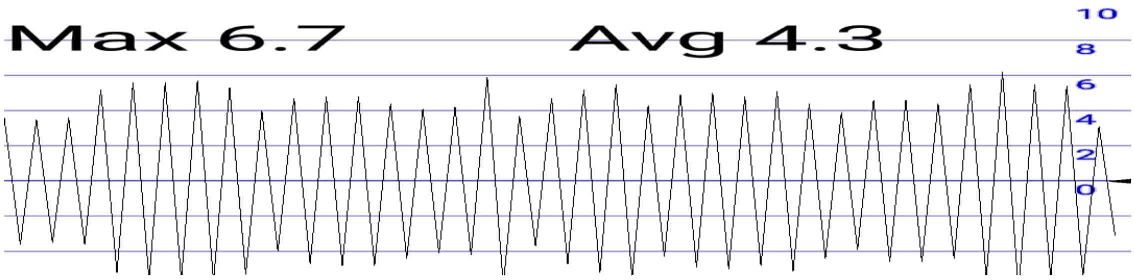

Figure 10: Vibration Profile of Electric Motor using AC to AC Converter Motor Starter at 100% firing.

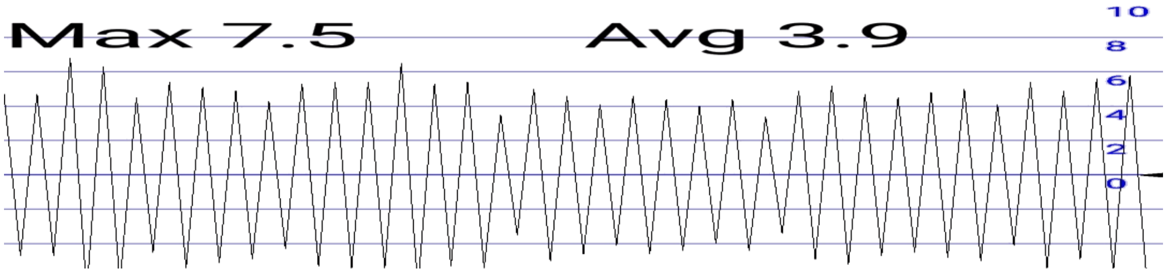

Figure 11: Vibration Profile of Electric Motor using AC to AC Converter Motor Starter at 90% firing.

Table 4: Vibration Analysis of Electric Motor using Direct Online Starter versus AC-to-AC Converter Motor Starter.

Vibration	Direct Online Starter	Full Firing AC to AC Converter Starter	Part Firing AC to AC Converter Starter
Average (m/s^2)	4.7	4.3	3.9
Maximum Level (m/s^2)	6.7	6.7	7.5

Results indicate a notable reduction in vibration amplitude when using the AC–AC converter. At partial firing (lower speed), vibration decreased further, corroborating findings by Mikolajczak (2019) that reduced motor speed minimises dynamic forces on rotor and bearing assemblies, thereby extending motor lifespan (Mikolajczak, 2019).

B. Sound Analysis

Sound analysis of an electric motor is crucial to monitoring the performance, efficiency and health of the motor. Sound level measurements using an FFT-based sound meter are seen in Figures 12, 13 and 14, with a summary of result data shown in Table 5.

Figure 12: Sound Profile of Electric Motor using Direct Online Starter.

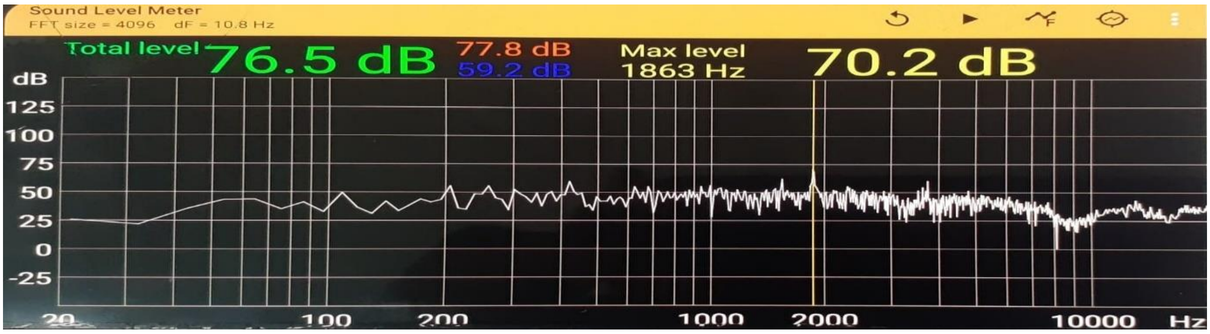

Figure 13: Sound Profile of Electric Motor using AC to AC Converter Motor Starter at 100% firing.

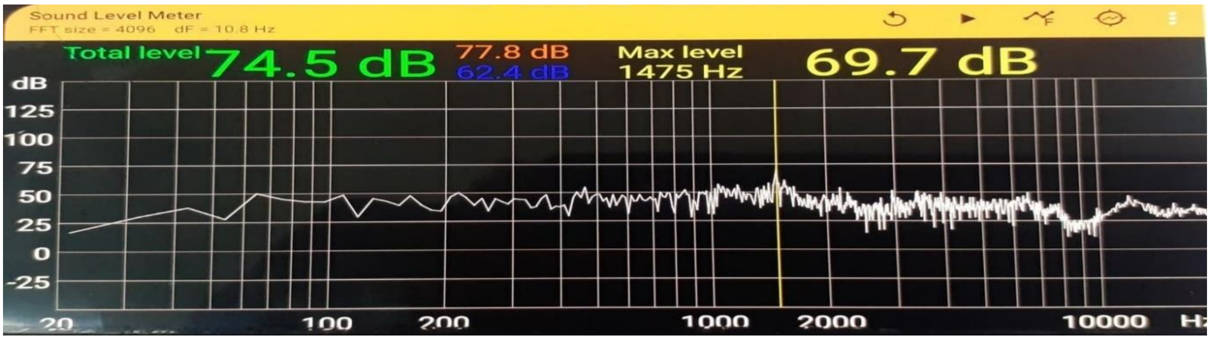

Figure 14: Sound Profile of Electric Motor using AC to AC Converter Motor Starter at 90% firing.

Table 5: Sound Analysis of Electric Motor using Direct Online Starter versus AC-to-AC Converter Motor Starter.

Parameters	Direct Online Starter	Full Firing AC to AC Converter Starter	Part Firing AC to AC Converter Starter
Total Level (dB)	76.1	76.5	74.5
Maximum Level (dB)	71.3	70.2	69.7
Pitch (Hz)	1970	1863	1475

Although total sound energy remained similar, both maximum sound level and pitch were reduced when using the AC–AC converter, especially at partial firing. The lower pitch and decibel levels imply smoother operation and reduced mechanical stress (Bilgin, et al., 2019); (Huan, et al., 2022), further validating the system's effective speed control and soft-start characteristics.

4.0. CONCLUSION

The design AC-AC converter underwent various stages during its development and build-up to ensure reliability and standard. The aim of the study was centred on optimisation of energy efficiency, performance improvement, scalability, and reliability for high-power applications

(3-phase motor starter). As a replacement for a traditional motor starter (DOL), the AC-AC power converter soft starter offered superior functionality. Firstly, it achieved a reduction in inrush current by 3.5A and steady -state energy consumption by 765.2W through efficient phase angle modulation. Hence, indicating a 36.4% improvement in energy efficiency during continuous operation. The embedded Arduino controller, coupled with voltage, current, temperature and humidity sensors, provided real-time system parameters to aid monitoring, responsive control and adaptive protection. Furthermore, the ability to vary firing angles using potentiometers and TRIAC circuitry allowed precise voltage supply to the induction motor and speed control, which minimised vibration and acoustic noise. Overall, the system was able to integrate control, monitoring and protection into a compact, cost-effective solution suitable for both domestic and industrial applications. However, recommendations for future work should focus on integrating a higher current rating TRIAC configuration to accommodate higher capacity electric motors. Also, the analogue RC triggering should be replaced with digital control using a microcontroller-based system for more precise firing, real-time adjustments and programmability for complex loads. Nevertheless, power factor correction circuitry can be introduced to help reduce harmonic distortion for inductive loads because of a lagging power factor.

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