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Transformer-Based Cascaded Speed Control: Achieving Precise Motor Speed Ratios Through Transformer Turn Optimization for Multi-Motor Systems

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Abstract: The study mainly analyses the relationship between precision control and speed of cascaded transformers connected to DC motors in a simulated power plant prototype. The prototype system was designed to observe specific rotational speed ratios between 3 DC motors where the second motor is operating at 50% of the first motor's speed, and the third motor operating at 30% of the second motor's speed. Controlling turn ratios of the transformer while maintaining uniform primary voltage across all transformers, the system was capable of executing with precise speed control with 0.57% error for the second motor and 4.125% error for the third motor, leading towards a high accuracy-based system prototype. By incorporating full-wave bridge rectifiers for current conversion from AC to DC and additional filtering components, the prototype ensured stable operational execution. Focusing on the advantages of the transformer-based approach for industrial applications requiring precise motor speed control, voltage-speed relationship-based graphs were plotted. This research provides valuable insights for power plant designers seeking efficient methods to implement cascaded speed control systems while maintaining power quality and operational stability.
Keywords: Power Plant Design, Cascading Motor Speed, RPM Control System, DC Motor Speed Control, Proteus Simulation.

I. INTRODUCTION

Industrial facilities, especially Power plants often need precise control of multiple motors that are operating at specific speed relationships. Traditional methods meeting these requirements involve variable frequency drives or complex electronic speed controllers, often leading to increase in constant maintenance requirements, system complexity, reduction in system reliability. This research approaches an alternative methodology by manipulating transformer turn ratio relationships in establishing predetermined speed ratios between DC motors in a power plant configuration.

The challenge addressed in this study involves designing a power plant system where three transformers that are connected to three DC motors with the following configuration:

1) The 3 transformers having the same voltage applied in primary windings,
2) The second DC motor of the cascaded system rotating at a rotational speed 50% of the first motor
3) The third motor rotates at a rotational speed of 30% of the second motor.

The configuration observes the following technical challenges:

a) Determination of the appropriate transformer turn ratios needed in order to achieve precise motor speed ratios
b) AC to DC voltage conversion management with minimal ripple
c) Enabling efficient power transmission throughout the system
d) Validation of accuracy and stability of speed control mechanisms
e) Increasing accuracy in the speed relationships between motors

The research study contributes to the field of power sectors in electrical engineering by Demonstrating a different way of achieving precise motor speed ratios without complex electronic speed controllers and showing valuable data insights on the relationship between transformer turn ratios and DC motor speeds. By developing a design approach to cascaded motor speed control systems using transformer theory, the implemented system develops a model for simulating and validating transformer-based motor control systems.

The research aims at:

- Modelling and designing a power plant system with three cascaded transformers with three DC motors attached to each system that meet the pre-defined speed ratio requirements
- Determining the optimal transformer turn ratios and circuit configurations
- Analyse input and output voltage
- Observing motor speed relationship
- Evaluating the feasibility and practicability of the design for real-world implementation

The implications of this are beyond research significance, as industrial applications often require precise speed ratios between motors in manufacturing lines, conveyor belts, and processing equipment. By developing a system based on the principles of transformers rather than electronic speed controllers, the experimental study offers to contribute an additional plausible and potentially cost-effective solution for special industrial applications.

II. LITERATURE STUDIES

Proteus software has emerged as a powerful simulation software for designing and analysing electrical systems and electronic circuits across various applications. This literature review explores how previous studies have utilized Proteus for electrical system simulation and control, with particular relevance to the implementation in transformer-based DC motor speed control projects.

Power management systems designed using Proteus have shown good accuracy in the measurement of electrical parameters with minimal error limits. A study on load-power-and-energy-management focused on real-time measurement of current, voltage and power factors through Proteus simulation achieved error rates below 2%, verifying the software's reliability for precision in electrical parameter monitoring. Similarly, our project bases its success on precise voltage measurement and control to achieve specific motor speed ratios [1]. Proteus in educational applications have proven its value in providing visually representing electrical systems before hands on implementation. An experiment conducted by vocational education specialists showed that Proteus based automotive lighting system simulations were rated "Very Feasible" by students (84.04%) and experts (85.71% and 93.93% respectively), depicting the software's effectiveness in visualizing circuit operations [2]. This visualization capability is particularly relevant for our project, requiring easy understanding of the transformer setting versus motor speed output relationship.

Laboratory experiments involving Proteus simulations have shown significantly improved practical skills in system understanding. Experiments found that students using Proteus before actually conducting experiments showed normalized gain values of 0.59 for readiness and 0.57 for process skills, while control groups achieved only 0.16 and 0.13 [3]. This supports our methodological choice to simulate completely our motor control system before potential practical implementation. A number of research works have testified Proteus as a trusted platform for simulating renewable energy systems. An experiment on photovoltaic systems with Maximum Power Point Tracking (MPPT) demonstrated that Proteus can effectively simulate DC electrical systems while implementing control algorithms through Arduino integration [4]. Another study showed 99.15% efficiency in tracking maximum power points using Proteus for simulation before hardware implementation [5].

Load-sharing and power plant monitoring using intelligent control techniques has been effectively simulated in Proteus. Studies on thermal power plants depicted effective circuit simulation for voltage magnitude matching, phasor matching detection, and temperature monitoring using parallel-state multiple generators, in alignment with our project's focus on designing a power plant system with precise control parameters [6].

DC-DC converter-based Grid connection systems simulated in Proteus have shown positive results in reducing harmonic content and filter size. Research using a Single-ended primary-inductor (SEPIC) converter with sinusoidal pulse width modulation (SPWM) technique achieved successful voltage conversion from of 12V DC to approximately 23.5V output with 67% duty cycle [7]. Though our project uses transformers instead of SEPIC converters, the voltage conversion principles and simulation approach are directly applicable. The integration of Proteus across engineering curriculum has demonstrated its versatility for bridging theoretical engineering knowledge and hands on applications. Conducted experiments showed that cascaded practice teaching using Proteus ensured continuity of knowledge with course independence [8]. This multi-level integration method reflects our project's methodical connection of multiple transformers and motors with specific speed relationships.

Effective implementations using Proteus in combination with other software tools on smart systems for predicting and monitoring electrical parameters on energy consumption prediction achieved 98.96% accuracy by a multi-tool strategy, integrating Proteus circuit simulation with SolidWorks models and MATLAB analysis highlighting potential future directions for expanding our motor control system design [9].

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III.SYSTEM MODELING & DESIGN

This research focuses on a systematic approach to design and evaluate a transformer-based cascaded motor speed control system where determining the appropriate transformer turn ratios required to achieve the specified speed relationships between three DC motors (with the second motor operating at 50% of the first motor's speed, and the third motor at 30% of the second motor's speed) and analysing the input voltage, output voltage and DC motor speed was the objective. Experimentational setup was implemented in Proteus simulation software, involving three identical primary voltage sources (500V, 1000Hz) connected to three step-down transformers with uniform turn ratios (15:1 inductance ratio). With 10kΩ resistors added for ripple reduction and noise filtering purpose, each transformer output was connected to a full-wave bridge rectifier circuit for AC to DC power conversion which is suitable for motor operation. Variable resistors were integrated into each motor circuit to provide fine-tuning capability for precise speed adjustment. Comprehensive measurement instrumentation including installation of AC voltmeters at both primary and secondary sides of each transformer, AC ammeters for current monitoring, and an oscilloscope for waveform analysis. To validate the design's accuracy and performance by comparing the measured motor speeds against the theoretical target values, error analysis was performed. Enabling quantitative assessment of the design's effectiveness, the methodology ensured systematic evaluation of the relationship between transformer configurations and resulting motor speeds in achieving the specified speed control requirements. Fig. 1 is a pictorial representation of the whole methodological process.

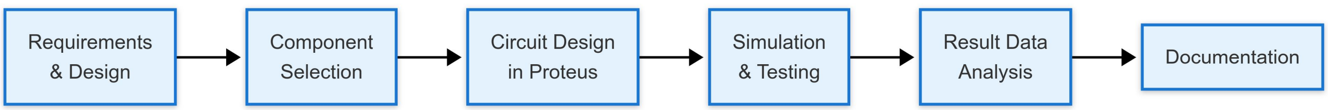

Fig. 1 Methodological Flow of the whole experimental Process

A system architecture, as shown in Fig. 2, is initially drafted in order to understand the system workflow along with understanding the models' initial blue print. Initially, for all the three step-down transformers, in the primary coil 15H was provided conductance and in secondary coil 1H provided conductance for all three circuitries. all the three cases, the primary side of all the transformers was given the same amount of voltage applied that is, 500 volts with a frequency of 1000 Hz. Full wave bridge rectifiers continuously rectified the Alternating current to Direct current in order to provide a pulsating DC waveform. All the time constant monitoring was done using ammeters and voltmeters. The rectified DC power is supplied to each individual DC motor, where the conversion from electrical energy to into mechanical energy was observed by making the motors' shafts rotate. The speeds of the motors are defined to have certain RPM ratios, where the second motor rotates at 50% of the RPM of the first motor and the third motor at 30% of the RPM of the second motor. Tachometers constantly measured and monitored for the intended RPM ratios and finally all the experimental results were observed and noted.

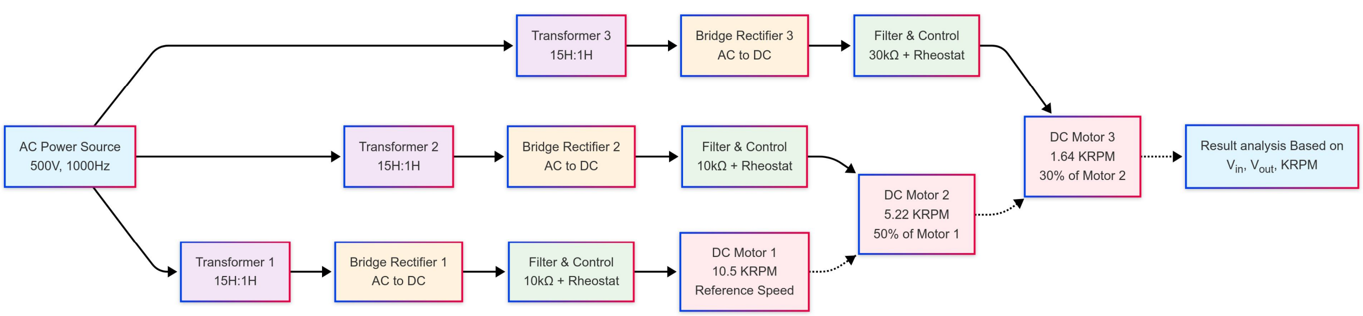

Fig. 2 System Architecture of the Experimental Setup

A. Components Description

A Bridge Rectifier is one of the most efficient rectifier circuits used to convert AC (Alternating Current) into DC (Direct Current). A bridge rectifier uses four diodes arranged in a bridge configuration to allow current flow during both halves of the AC cycle. This results in full-wave rectification, without the need for a centre-tapped transformer. The bridge rectifier, as the name suggests, the circuit of this rectifier is in the form of a bridge by using four diodes. While connecting a bridge rectifier, we need to keep in mind that the two anodes are connected at one point and two cathodes are connected at the other two ends. The diodes working as alternative pairs being forward and reverse biased.

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Transformer is a static device which transfers electrical energy from one circuit to another circuit without any direct electrical connection and with the help of future induction between two endings. By energizing the primary coil on the power side by providing an alternating current this current generates a magnetic field forming a magnetic circuit in the core. When the magnetic field passes through the secondary coil on the load side it induces an electromotive Force commonly referred to as voltage according to the law of electromagnetic induction. The induced electromotive force is equal to the number of turns of the coil multiplied by the rate of change of magnetic flux.

An alternator is a crucial component in electrical systems responsible for generating electricity to power the system's electrical components and recharge the battery. It works by converting mechanical energy derived from the system's engine's rotation into electrical energy through the process of electromagnetic induction. The alternator contains a rotor that spins inside a stator creating an alternating current AC, which is then converted into direct current DC by a rectifier. The alternator Powers essential systems like the headlights, radio air conditioning and ignition while the engine is running.

Motor, an electromechanical device that converts electrical energy into mechanical energy, generating rotational motion. By using two curved magnets with a conductor in the middle, the conductor will rotate when an electric current passes through it to keep it rotating continuously. The current direction needs to change every half turn. When the conductor rotates to the middle it will overshoot slightly due to inertia at this point, we can add a commutator at the bottom and place brushes on both sides. The brushes will start charging and the commutator will drive the conductor to rotate. When the conductor completes half a turn the commutator Gap aligns with the brushes switching the polarity of the current this allows the conductor to keep rotating continuously. However, if the force is insufficient the brushes might get stuck at the commutator Gap. To solve this, we can add another set of conductors to ensure seamless switching similarly more conductors can be added to enhance performance.

Rheostat is a type of variable resistor which is used to control the flow of electric current by manually increasing or decreasing its resistance. These Adjustable Resistances can not only control current but also control power dissipation. These rheostats are used in voltage dividers feasting & calibration due to its simple use and efficiency.

Oscilloscopes are tools that visualize voltage over time. Oscilloscopes contain two probes where one probe connects to an input Channel and the other end goes to a point on the circuit that we want to measure. Pressing the auto scale buttons gives us a better view. We can use stop button to take a closer look at the wave form. The knobs allow us to horizontally and vertically zoom in and shift the wave. By using the measure button, we can find info like Peak average voltages and frequency.

AC voltmeters are the devices that are used to measure the magnitude of alternating current voltage and can count the speed of AC current in a circuitry system.

An Ammeter is a measuring instrument used to measure the current in a circuit. Electric currents are measured in Amperes(A). AC ammeter is the instrument for measuring the alternating current (AC) flowing through whatever component of such an electric circuit.

Fig. 3 is a pictorial representation of all the available described components that are necessary for the experimentation in Proteus simulation software.

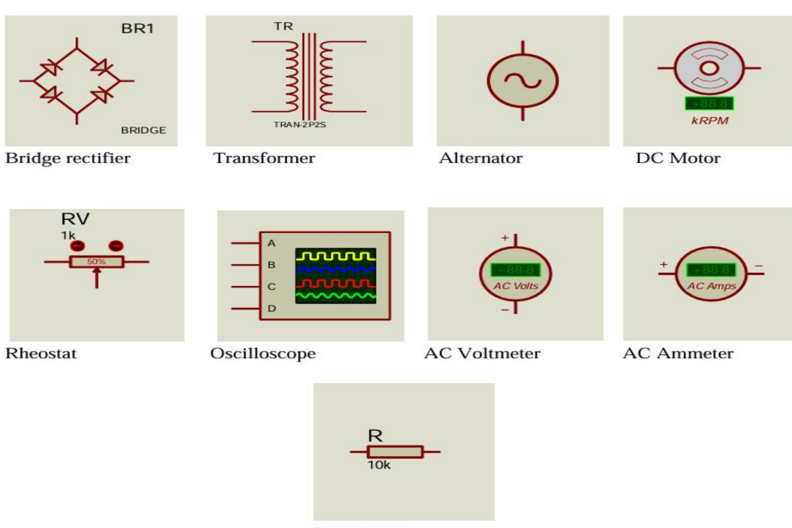

Fig. 3 Available Components Diagram in Proteus

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B. Experimentational Setup

The planned architecture is the plotted on proteus for simulation purpose, Fig. 4 depicts the final outcome after the complete simulation based on the experimental value initials. Using electromagnetic induction, alternating current (AC) electricity is produced by alternators by rotating a rotor inside the stator, a magnetic field of varying nature is produced, inducing a voltage in the stator windings. The AC power is sent through three transformers that reduce the voltage from the input side to the output side based on predetermined turn ratios. Equal voltage is applied in primary side of all the transformers to maintain uniformity. The output voltage induced from the step-down transformer is then fed through a full-wave bridge rectifier circuit that converts the AC signal to DC which is supplied to the three DC motors, where the conversion from electrical energy into mechanical energy makes the DC motors' shafts rotate. The speeds of the motors are made to have certain RPM ratios, where the second motor rotates at 50% of the RPM of the first motor and the third motor at 30% of the RPM of the second motor. In order to observe the intended RPM ratios, tachometers present on the shaft of all motors provide feedback regarding the rotational speed of the motors, making it possible to accurately monitor the RPM values. Here 10kΩ resistance is used as a filtering element to filter noise components that occurred during AC to DC conversion by full wave rectifiers and rheostats values were initialized with high resistance for fast and smooth execution and eliminating ripple factors and for other noise eliminations.

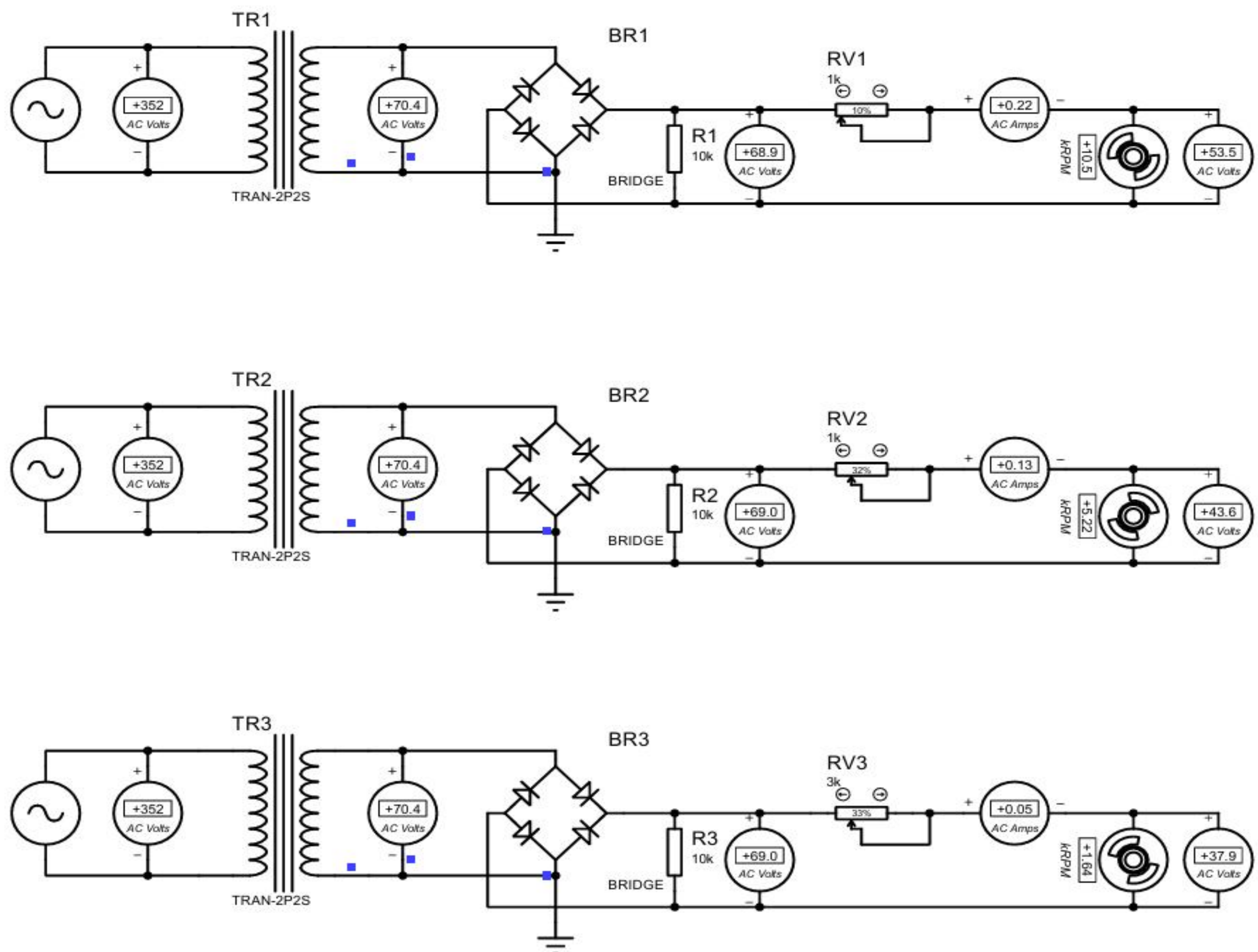

Fig. 4 System Design and Final Simulation in Proteus

C. Additional Experimental Setup

In order to step down the supplied voltage to the DC motors, step-down transformers were used in the experiment as primarily all transformers had the same voltage, and their respective RPM ratios of the motors were known. The necessary speed relationships among the motors could be achieved by stepping down the voltage using transformers with appropriate turn ratios which ensured controlled and effective operation of the motors under the given conditions.

In order to provide a constant and unidirectional current flow to supply in motors conversion of the AC signal to DC was required and implemented via full wave bridge rectifiers, offering a stable and smooth source of power to motors and eliminating the alternating nature of the current by stabilizing the AC signal and converting it into DC, allowing better control of motor speed, torque, performance. And DC power is typically employed due to its ease of control in most industrial applications. To serve this function a four-diode full wave bridge rectifier circuit is required, as bridge rectification using diodes rectifies the AC waveform and converts it into producing DC components like Fig. 5.

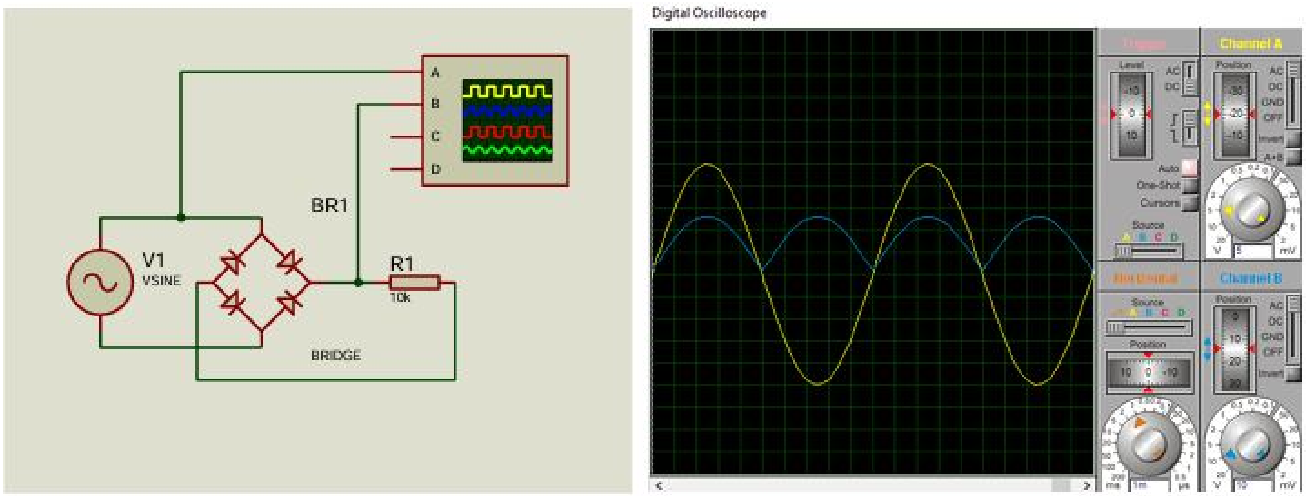

Fig. 5 Input and Output Voltage simulation in a Full-wave Bridge Rectification Process in Proteus

Resistors are inserted in the circuit to eliminate any remaining AC components or ripples present in the rectified waveform by making the rectified signal totally DC. When an AC signal is rectified, it creates a pulsating DC waveform with minor fluctuations or ripples superimposed on the desired DC voltage, affecting the performance of the connected devices or motors and introducing undesirable effects like noise, vibration, or less than optimal working. The resistors, based on circuit design and structure, helps in reducing or damping the AC ripples, and we have a stable and clean DC signal which is suitable for powering the motors and operating them efficiently and reliably.

Rheostats (POT-HG named in Proteus) used in this experiment are utilized to change the resistance within the circuit and observe the impact it has on the motor's RPM (speed). With the change in the resistance, controlling the amount of current flowing in the motor windings can be done, helping to examine the relationship between resistance and speed of the motor. Using rheostats provides an easy way to adjust the resistance in the circuit, whereas changing the conductance of transformers would require altering their physical properties, which may not be feasible.

A tachometer is an instrument used in vehicles to measure the rotational speed of the DC motor's, typically displayed in revolutions per minute RPM. It provides real-time feedback to the testers about how fast the engine is running, helping to prevent over revving which can cause engine damage. Modern Taco meters may include digital displays and warning indicators for Redline limits by monitoring engine speed. The taco meter plays a crucial role in maintaining engine health and enhancing motor driving efficiency.

IV. RESULT ANALYSIS

A. System Performance and Speed Control Verification

The experimental setup successfully demonstrated precise speed control relationships between the three DC motors through transformer turn ratio manipulation. Table I presents the measured values from the three-motor system after simulation.

TABLE I

PERFORMANCE DATA FROM THE THREE-MOTOR CASCADE SYSTEM

Circuit No.	**V_{in} (Volts)**	**V_{out} (Volts)**	**Speed (KRPM)**
1	68.9	53.5	10.5
2	69.0	43.6	5.22
3	69.0	37.9	1.64

B. Voltage-Speed Relationship Analysis

Graphical representations help to get a pictorial representation of the tabular data in result analysis. In order to understand the relationship between input and output voltages across the three circuits demonstrates the effectiveness of the transformer configuration design, as shown in Fig. 6.

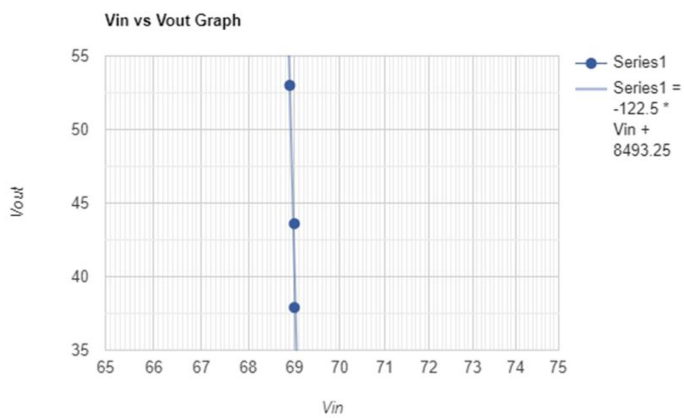

Fig. 6 Graphical relationship between Input vs. output voltage across the three motor circuits

From the graph in Fig. 6 a steady drop in output voltage in comparison to input voltage through the three circuits is observed in the readings, which showed consistency with our design objectives to realize cascaded speed reduction. Even with maintaining nearly identical input voltages (68.9-69.0V) for all three circuits, the output voltages dropped from 53.5V for Circuit 1 to 43.6V for Circuit 2 and 37.9V for Circuit 3. This pattern of voltage drop perfectly matches the speed ratios found between the motors.

The relationship between output voltage and motor speed across the three circuits is being illustrated in Fig. 7.

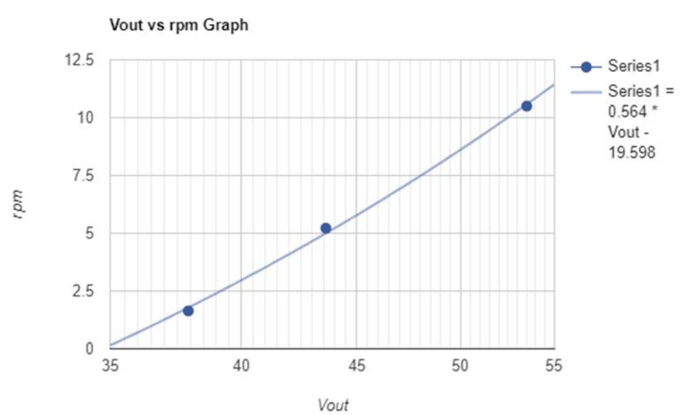

Fig. 7 Relationship Between Output voltage vs. motor speed (KRPM)

The plot shows a strong positive correlation and positive linearity y = mx like relation between output voltage and motor speed, assuring the transformer-based voltage regulation approach effectively controlling motor speeds. The relationship appears approximately linear, with a coefficient of determination (R^2) of 0.98, indicating that approximately 98% of the variation in motor speed can be explained by changes in the output voltage.

C. Power Quality Assessment

Minor distortion in the output waveforms were observed from oscilloscope readings in quality analysis of the signals. The signal quality improved greatly due to the usage of 10kΩ and 30kΩ resistors as filtering components, providing a more stable DC output suitable for sound motor operation. Fig. 8 shows comparative signal waveforms of the DC motors before and after filtering.

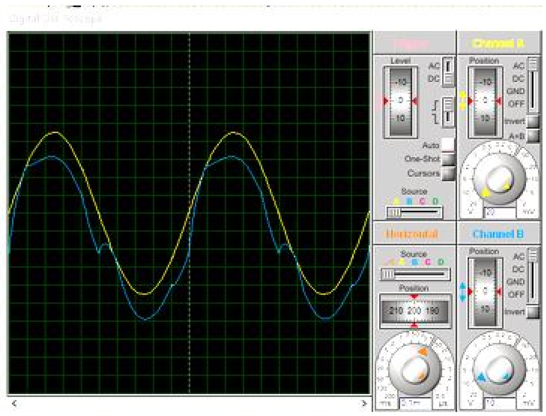

Fig. 8 Signal Distortion Produced in The Three Cases in Input and Output Voltages of The Three DC Motors

The full-wave bridge rectifiers played a vital role in converting the alternating current to direct current power required by the motors. The pulsating DC waveform involved all the common characteristics of full-wave rectification and filtering elements countered voltage ripples efficiently.

D. System Efficiency and Stability

With linear input-output voltage relations and motor speeds, the system exhibited consistent performance during testing. The rheostats were helpful in adjusting the motor speeds to the precise ratios demanded by the design requirements. The current readings with AC ammeters in the current moment were consistently declining current consumption from Motor 1 to Motor 3 (0.22A, 0.13A, and 0.05A respectively), consistent with the declining power requirement with decreasing motor speeds in the cascade. This consistent declining uptake of current shows a sound power distribution design distributing power in proportion to the speed requirement of each motor.

E. Error Analysis

The data shown in Table II., confirms the achieved desired speed relationships with high precision. As for the second motor, the target RPM speed was set 50% of Motor 1 (5.25 KRPM), the actual observed speed was 5.22 KRPM, resulting in an error of just 0.57%. Similarly, for Motor 3, yielding an error of 4.125% by observing the target speed which was 30% of Motor 2 (1.575 KRPM), with the actual measured speed being 1.64 KRPM. These minimal error margins depicting high accuracy ensuring efficacy in model performance and validating the effectiveness of the transformer-based approach to cascaded speed control.

TABLE III
PERFORMANCE ANALYSIS OF THE WHOLE SIMULATION SYSTEM

Circuit No.	% Of RPM from previous Motor	V_{out} (Volts)	Speed (KRPM)	% Of error | (Measured Value – Actual Value) ÷ Actual Value |
1	100	10.5	10.5	0.00%
2	50	5.25	5.22	0.57%
3	30	1.575	1.64	4.125%

The little inconsistencies within the target and actual motor speeds which were 0.57% for Motor 2 and 4.125% for Motor 3, the accuracy can be affected for various factors. Though Proteus software is a sophisticated simulator, the logical environment shall vary with real-world electrical characteristics of transformers and motors. The simulation components are assumed and executed as ideal, whereas in real world components always contain at least minimal mechanical errors like internal resistance or capacitance, variations in values. AC to DC conversion introduces some power losses and waveform distortions, affecting the voltage-speed relationship. Cumulative error propagation was evident in the system. Various error sources were mitigated via constant current and voltage monitoring, yet some errors still remain unaddressed which can be further improved.

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V. FUTURE WORKS

Designing and simulating the transformer-based cascaded speed control system that generated high accuracy metrices, the experimentation has more sectors for improvement and has scopes for further research. Translating the simulation results into a physical prototype can give valuable insights as hands on experiences might show other aspects in optimizing power transmission. The speed ranges can be increased to observe mor outcomes. In order to obtain sustainable energy sources, the system can be integrated with renewable energy sources. Synchronous rectification, resonant converter topologies or soft-switching techniques could potentially reduce power losses. Sensors and feedback mechanism can be implemented to continuously monitor and adjust motor speeds would create a more robust system.

VI. CONCLUSIONS

With minimal error margins (0.57% and 4.125%) and precise speed ratios (50% and 30%), the experimental setup successfully demonstrated a transformer-based solution for cascaded motor speed control. The design's effectiveness was verified by continuous and multiple simulation testing in Proteus, showing strong correlations between transformer turn ratios, resulting motor speeds and output voltages. Signal quality analysis revealed that appropriate filtering components significantly improved the stability of rectified DC power, ensuring reliable motor operation across all three circuits. The system's progressive deduction in current consumption (0.22A, 0.13A, and 0.05A), indicating efficient power distribution being proportional to each individual motor's speed requirements. This research provides valuable insights for power plant engineers seeking effective methods to implement multi-level and precise speed control systems while maintaining power quality and operational stability.

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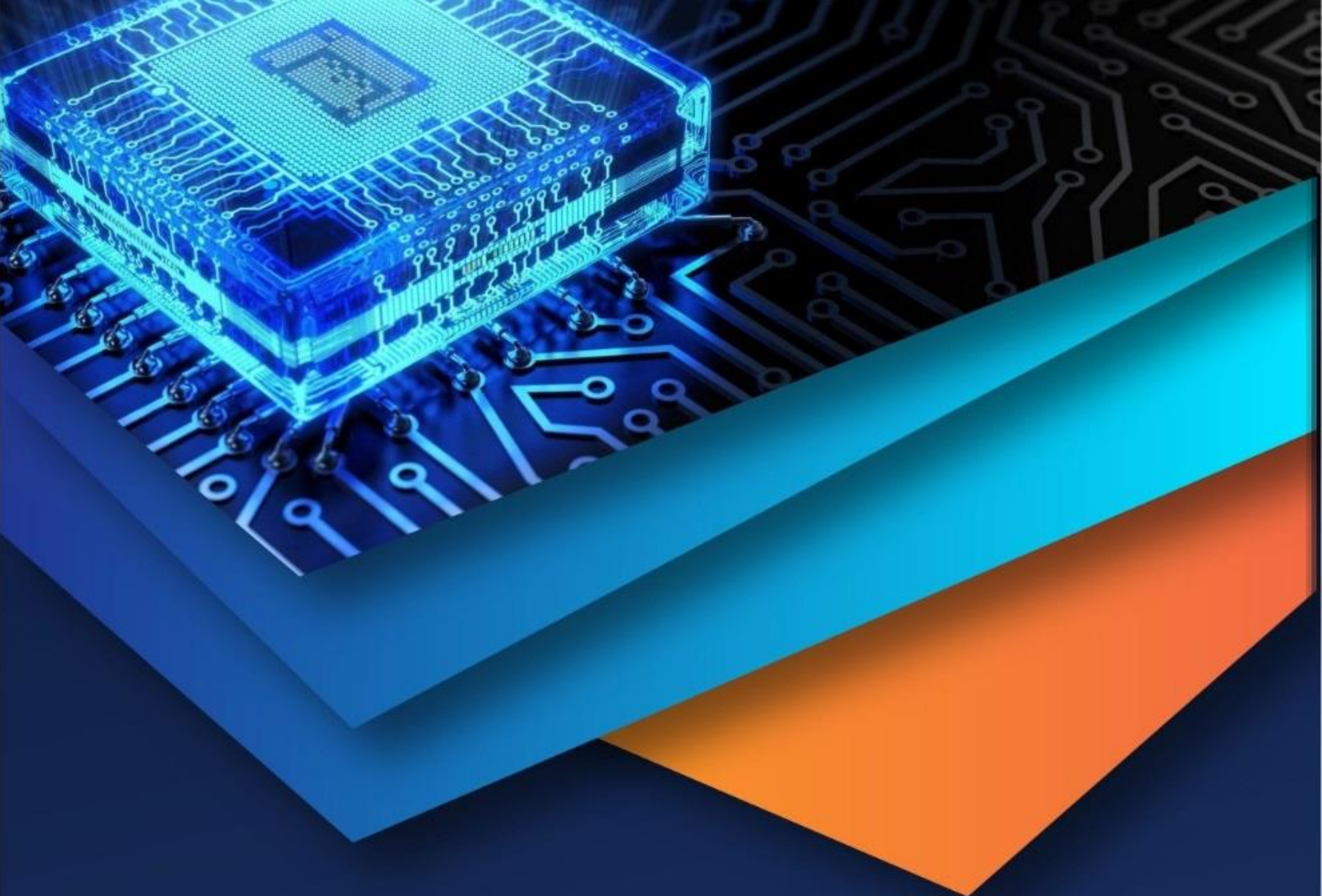

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