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Enhancing engineering education in electric drive systems through integrated computer simulation modules

Rahimi Baharom, Norazlan Hashim, Naeem M. S. Hannoon, Nor Farahaida Abdul Rahman
School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Selangor, Malaysia

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ABSTRACT

The integration of computer simulation modules in electric drive courses plays a pivotal role in modern engineering education by offering students hands-on experience and fostering a deeper understanding of theoretical concepts. This study highlights the significance of enhancing engineering education through an innovative simulation module designed to analyze electric drive systems. The module enables the specification of suitable converters and machines for speed and position control systems while focusing on the steady-state operations of AC and DC drives. Through simulation exercises, students explore converter circuit topologies, control strategies, and the two-quadrant operations of electric machines using fully controlled two-pulse bridge circuits, encompassing motoring and braking modes in the first and fourth quadrants. The proposed module demonstrates its effectiveness in bridging theory and practice, evidenced by significant improvements in students' comprehension of circuit configurations and control algorithms. The approach enhances critical thinking, problem-solving skills, and the ability to relate theoretical knowledge to practical applications. Future research will focus on extending the module's capabilities to incorporate additional quadrants of operation and advanced control strategies. By integrating such tools into the curriculum, educators can better prepare students for the evolving demands of engineering careers.

Corresponding Author:

Rahimi Baharom
School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA
Shah Alam, Selangor 40450, Malaysia
Email: rahimi6579@gmail.com

1. INTRODUCTION

Electric drives are fundamental systems for controlling the motion of electrical machines and have become indispensable across a wide range of applications, including transportation, industrial automation, and renewable energy systems. The history of electric drives dates back to 1838 in Russia, where B.S. Lakobi successfully operated a boat powered by a DC electric motor and a storage battery. Since then, advancements in electric drive technologies have transformed motion control, enabling precise, efficient, and optimized performance that surpasses conventional methods based on applied voltage and frequency of the source current [1]-[4].

A typical electric drive system, as illustrated in Figure 1, consists of key components such as the power source, power modulator, control unit, load, and motor [5]-[6]. In Malaysia, the prevalent electricity supply is a 50 Hz AC system available in both single-phase and three-phase configurations, catering to domestic and commercial requirements. Power modulators, critical for modifying the nature, frequency, and intensity of power, are categorized into converters, variable impedance circuits, and switching circuits. The control unit design depends on the type of power modulator used; for instance, semiconductor converters require firing circuits with linear devices and microprocessors for effective operation.

Electric drive systems offer significant advantages, including adaptability to varying control characteristics for steady-state and dynamic conditions and the ability to operate across all four quadrants of the speed-torque plane [7], [8]. This capability facilitates a range of functionalities such as speed control, electric braking, and forward and reverse motoring, surpassing the flexibility of other prime movers. Additionally, these systems are robust and reliable, capable of withstanding demanding operational environments [9], [10].

Given the critical role of electric drive systems in modern applications, equipping engineering students with both theoretical knowledge and practical experience is essential. The integration of computer simulation modules into educational curricula has proven to be a transformative approach, enabling students to observe, practice, and experiment with circuit configurations and control algorithms. Such hands-on exposure bridges the gap between theoretical learning and practical application while fostering critical thinking and problem-solving skills [11]-[16].

This paper introduces a computer simulation module designed to enhance the understanding of steady-state operations in electric drive systems. The module enables students to specify appropriate converters and machines for speed and position control, analyze various electric drive systems, recognize converter circuit topologies and control strategies, and solve associated problems. Specifically, the module focuses on the two-quadrant operations of electric machines using fully controlled two-pulse bridge circuits, illustrating both motoring and braking modes in the first and fourth quadrants. By combining theoretical and practical learning, this module provides a comprehensive educational tool to prepare students for the complexities of modern engineering challenges.

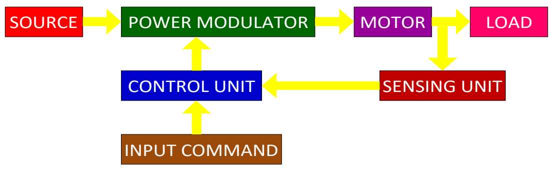

Figure 1. Block diagram of electric drives system

2. FOUR QUADRANT OPERATION OF ELECTRIC MACHINES

The operational behavior of electric machines can be effectively analyzed through their speed-torque characteristics, typically represented in a rectangular coordinate system. By correlating speed and torque, four distinct modes of operation, collectively known as four-quadrant operation, can be identified. These quadrants describe the machine's ability to function in both motoring and braking modes, accommodating forward and reverse directions [17]. Figure 2 illustrates the four-quadrant operation of an electric machine, which provides a comprehensive framework for understanding the machine's operational versatility.

2.1. Quadrant 1: forward motoring

In the first quadrant, both speed and torque are positive. The electric machine operates as a motor, converting electrical energy into mechanical energy to drive the load in the forward direction. The power output, calculated as the product of speed and torque, is positive, indicating energy delivery to the load. This mode, known as forward motoring, is widely used in applications such as electric vehicles and industrial conveyor systems where the rotation and torque align positively for forward motion [18], [19].

2.2. Quadrant 2: forward braking

In the second quadrant, the speed remains positive, but the torque becomes negative. This mode represents forward braking, where the machine converts mechanical energy from the load back into electrical energy. Here, the electric machine operates as a generator, slowing down the forward rotation. The power, derived from the product of positive speed and negative torque, is negative, indicating energy recovery or dissipation into the electrical system. Forward braking is crucial in scenarios requiring deceleration or energy regeneration, such as regenerative braking systems in electric and hybrid vehicles [20], [21].

2.3. Quadrant 3: reverse motoring

The third quadrant is characterized by both negative speed and negative torque. In this mode, the machine acts as a motor in reverse, converting electrical energy into mechanical energy to drive the load backward. Similar to the first quadrant, the power is positive as the product of two negative values (speed and torque) results in a positive value. This reverse motoring mode is essential for applications requiring reverse motion, such as robotic arms or reversing conveyors in industrial automation [22], [23].

2.4. Quadrant 4: reverse braking

In the fourth quadrant, the speed is negative while the torque is positive. The machine operates in a braking mode for reverse motion, converting mechanical energy back into electrical energy. This reverse braking mode is similar to the second quadrant but applies to reverse rotation. The power, being negative, reflects the energy generation from mechanical to electrical during controlled deceleration. This mode is vital for controlled braking in reverse operations, such as in elevators or material handling systems where precise deceleration is required [24], [25].

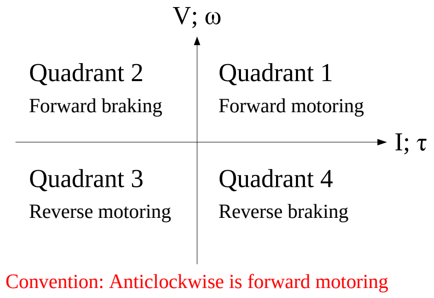

Figure 2. Operating modes of driving machines

Each quadrant's operational mode plays a crucial role in a wide range of applications, from electric vehicles to industrial machinery, providing unmatched versatility, and control over the machine's performance under varying conditions. A thorough understanding of these quadrants is fundamental for designing efficient drive systems capable of meeting complex operational demands. By incorporating computer simulation exercises, students can visualize these operations and observe the transitions between different modes. Simulations enable them to study the effects of speed, torque, and power flow in each quadrant, reinforcing theoretical knowledge while providing practical insights. This approach bridges the gap between conceptual understanding and real-world applications, equipping students with a deeper comprehension of electric machine behavior under diverse operating scenarios.

3. THE COMPUTER SIMULATION MODULE

The integration of computer simulation modules in the electric drive curriculum provides students with an immersive, hands-on experience, enabling them to explore and understand the operation and control of electric drive systems. By simulating real-world scenarios, students can experiment with various configurations, analyze outcomes, and reinforce their theoretical knowledge through practical applications. Figure 3 presents the schematic diagram of the proposed computer simulation module, which emphasizes the importance of bridging theory with practice.

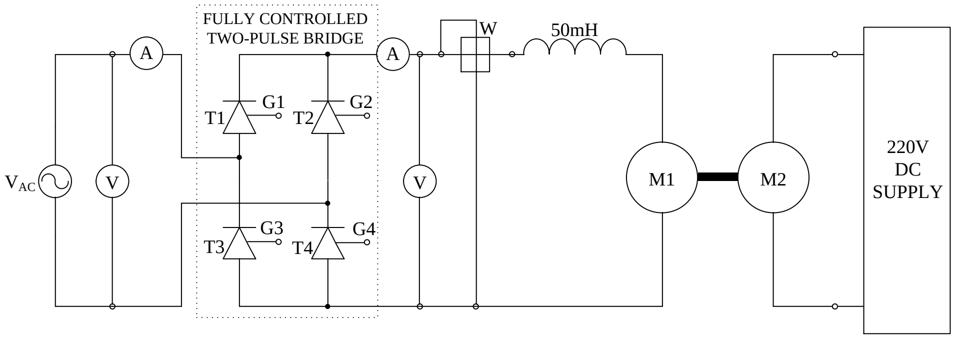

Figure 3. Schematic diagram of the proposed computer simulation module

3.1. The computer simulation module A: operation of quadrant 1

The first quadrant operation focuses on forward motoring, where the machine operates as a motor, converting electrical energy into mechanical energy to drive the load forward. In this module, students utilize a fully controlled two-pulse bridge rectifier to supply power from an AC source to a DC machine, resulting in positive secondary voltage and current waveforms. The setup involves setting the triggering angle of the thyristor to $\alpha = 90°$, corresponding to a time setting of 5ms (since 180° = 10 ms at a fundamental frequency of 50 Hz). This configuration ensures that the DC machine operates in the first quadrant. Students are required to record and analyze the waveforms of the secondary voltage and current, verifying the positive values indicative of forward motoring.

The schematic diagram in Figure 4 illustrates the setup used to perform the computer simulation of the first quadrant operation, focusing on forward motoring as illustrated in Figure 4(a), in an electric drive system. The primary components in this setup include an AC voltage source (V_{AC}), a voltmeter (V), and an ammeter (A), which measure the voltage and current from the AC source. The rectifier operation, central to this configuration, consists of four thyristors (T1, T2, T3, and T4) and four gate-triggering circuits (G1, G2, G3, and G4) arranged in a full-bridge configuration. This rectifier converts the AC voltage into a pulsating DC voltage. During the positive half-cycle of the AC input, thyristors T1 and T4 conduct, allowing current to flow through the motor (M1) and the inductor (50 mH), which smooths the pulsating DC output to provide a stable DC current to the motor. This results in forward motoring, where the motor converts electrical energy into mechanical energy to drive the load (M2), represented by a DC motor connected to a 220V DC supply. During the negative half-cycle, as illustrated in Figure 4(b), thyristors T2 and T3 conduct, maintaining the same polarity of DC voltage and ensuring continuous forward motoring of the motor. The setup also includes a wattmeter (W) to measure the power consumption of the motor circuit. This practical simulation setup enables students to observe the conversion process from AC to DC and understand the control mechanisms of motor operations using rectifier circuits, reinforcing theoretical knowledge with hands-on experience.

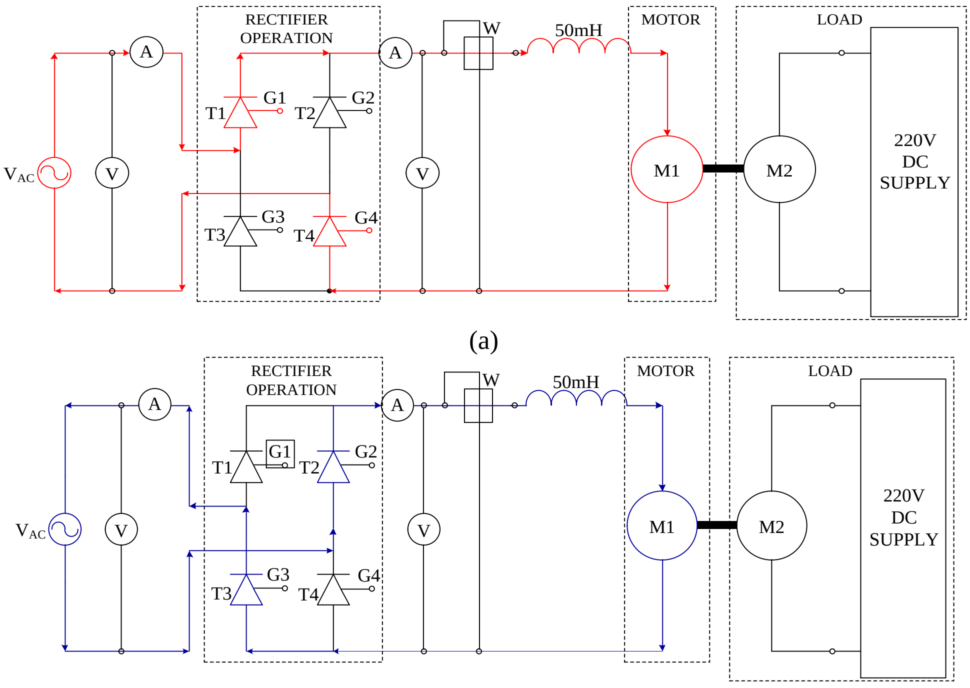

Figure 4. Schematic diagram to perform computer simulation module A: (a) positive cycle rectifier operation and (b) negative cycle rectifier operation

Figure 5 illustrates the computer simulation model designed using PSIM to perform the first quadrant (Q1) operation, focusing on forward motoring in an electric drive system. In this model, an AC voltage source is set at 230 volts to provide the input power. The circuit includes a voltmeter (V) and ammeter (I1) to measure the input voltage and current, respectively. Central to the simulation is the rectifier circuit, which comprises four thyristors arranged in a full-bridge configuration. The gate triggering pulses for the thyristors are set to specific angles to control their conduction. The triggering angles for the thyristors are 90° and 180° for the positive half-cycles and 270° and 360° for the negative half-cycles, ensuring proper rectification of the AC input into a pulsating DC output.

The rectified DC voltage is then smoothed using an inductor to provide a stable DC supply to the motor. The motor, represented in the model, operates in forward motoring mode, converting electrical energy into mechanical energy to drive the connected load. An additional ammeter (I2) and voltmeter are placed after the rectifier to measure the output current and voltage supplied to the motor. The load connected to the motor is depicted with corresponding measurement tools to monitor performance and power consumption.

This PSIM-based simulation model allows students to visualize and understand the process of converting AC to DC using a controlled rectifier and the subsequent operation of an electric motor in quadrant 1. By adjusting the triggering angles and observing the resulting waveforms and measurements, students gain practical insights into the dynamics of electric drive systems and the importance of precise control in achieving desired motor operations. The hands-on approach facilitated by PSIM enhances the learning experience, bridging the gap between theoretical knowledge and practical application.

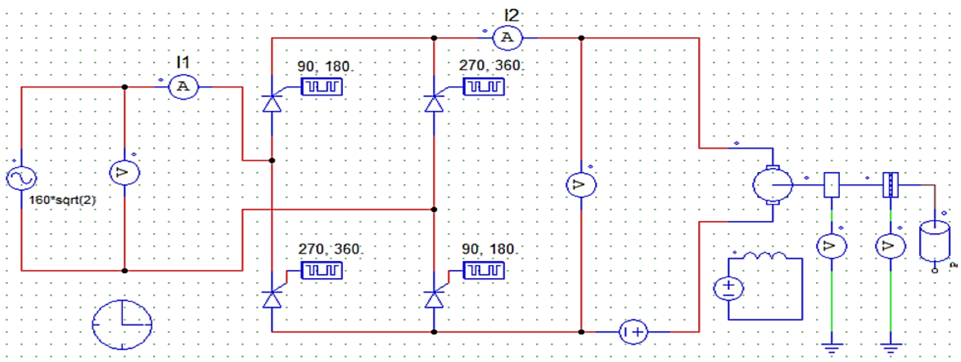

Figure 5. Computer simulation model using PSIM to perform Q1 operation

3.2. The computer simulation module B: operation of quadrant 4

The second module focuses on the fourth quadrant operation, which involves reverse braking. Here, the DC machine operates in reverse, converting mechanical energy from the load back into electrical energy. The rotor of DC machine 1 is set to rotate in the reverse direction, with energy flowing from DC machine 2 to DC machine 1 and then back into the mains AC supply via the inverter mode of the converter.

For this module, students adjust the triggering angle of the thyristor to $\alpha = 155°$, setting the machine to turn over at a lower speed. In this configuration, DC machine 2 acts as a motor, driving DC machine 1, which functions as a generator. The resulting negative secondary voltage confirms the inverter operation. Students must observe the rotational direction of the machine and record the voltage and current measurements, ensuring that the voltage is negative while the current remains positive [2].

Figure 6 illustrates the schematic diagram used to perform the computer simulation of the fourth quadrant (Q4) operation, focusing on reverse braking in an electric drive system. This setup simulates the inverter operation using an AC voltage source (V_{AC}), which provides the input power. A voltmeter (V) and an ammeter (A) are included to measure the input voltage and current. The inverter circuit, essential to this configuration, consists of four thyristors (T1, T2, T3, and T4) arranged in a full-bridge configuration, with their gate triggering circuits (G1, G2, G3, and G4) controlling their conduction.

In the inverter operation mode, thyristors T2 and T3 conduct during the positive half-cycle of the AC input as illustrated in Figure 6(a), while thyristors T1 and T4 conduct during the negative half-cycle as illustrated in Figure 6(b), allowing current to flow in a manner that converts DC voltage into AC. The motor (M1) in this setup operates as a DC generator, converting mechanical energy back into electrical energy. This reverse braking mode is indicated by the negative voltage (-VE) across the motor.

The prime mover (M2), powered by a 220 V DC supply, drives the motor (M1). As M1 operates in reverse braking mode, it generates electrical energy, which flows back into the system. A wattmeter (W) measures the power generated by the motor and fed back to the AC supply. Additional measurement tools, including a voltmeter and an ammeter, are placed in the circuit to monitor the voltage and current during the inverter operation.

Figure 7 presents the computer simulation model designed using PSIM to perform the fourth quadrant (Q4) operation, focusing on reverse braking in an electric drive system. In this model, an AC voltage source provides the input power, and the voltmeter (V) and ammeter (I1) measure the input voltage and current, respectively. The core of the simulation is the inverter circuit, comprising four thyristors arranged in a full-bridge configuration. The gate triggering pulses for these thyristors are set to specific angles: 155° to 180° for thyristors conducting during the positive half-cycle and 335° to 360° for those conducting during the negative half-cycle, ensuring proper conversion of DC to AC.

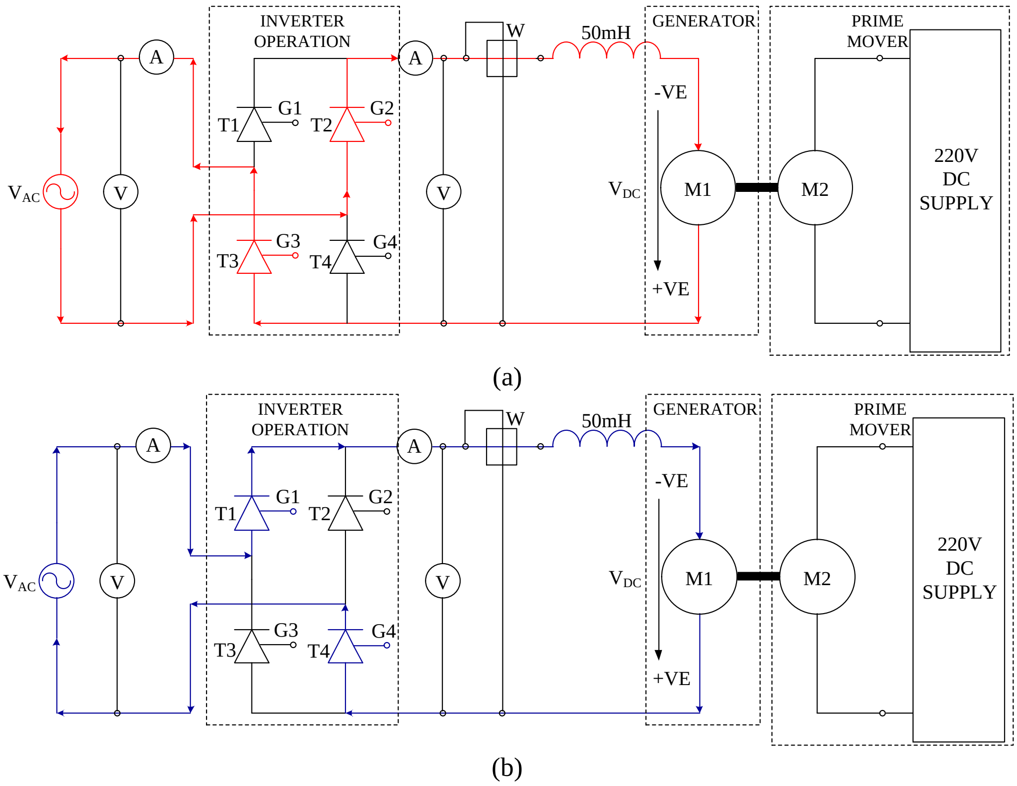

Figure 6. Schematic diagram to perform computer simulation module B: (a) positive cycle inverter operation and (b) negative cycle inverter operation

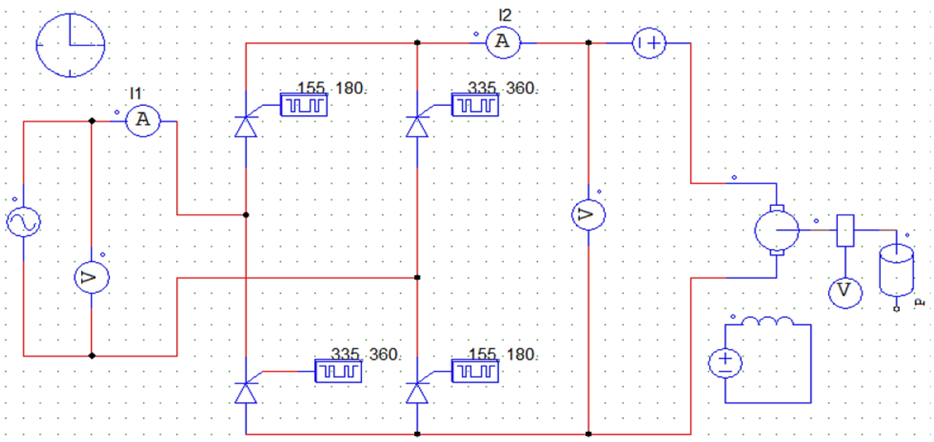

Figure 7. Computer simulation model to perform Q4 operation

During the inverter operation, the controlled conduction of thyristors allows for the flow of current that converts the DC voltage into an AC output. The motor in this setup operates as a generator, converting mechanical energy back into electrical energy during the reverse braking mode. This process is indicated by the negative voltage (-VE) across the motor. The prime mover (M2), driven by a 220 V DC supply, mechanically drives the motor (M1). In reverse braking mode, the motor generates electrical energy, which is fed back into the system. An additional ammeter (I2) and voltmeter are placed in the circuit to monitor the voltage and current during the inverter operation.

These simulation modules provide students with a visual and interactive understanding of electric drive operations in the first and fourth quadrants. By analyzing voltage and current waveforms, observing energy conversions, and experimenting with control parameters, students gain practical insights into electric drive systems. The PSIM-based simulations enhance the learning experience, enabling students to bridge theoretical knowledge with real-world applications, ultimately preparing them for the complexities of engineering challenges in modern electric drive systems.

4. RESULTS AND DISCUSSION

The implementation of the computer simulation modules in the electric drive curriculum provided substantial insights into students' technical understanding and educational development. This section highlights the results obtained from the simulations and discusses their implications in the context of engineering education, focusing on their impact on enhancing theoretical comprehension and practical application. The simulations were conducted using PSIM software, which enabled students to model and analyze electric drive behavior under various operating conditions. Figures 8 and 9 present the simulation results for the first quadrant (Q1) and fourth quadrant (Q4) operations, respectively. These results validate the theoretical expectations and reinforce the educational objectives of the simulation exercises.

4.1. Results for first quadrant operation (Q1)

The simulation for the first quadrant operation (Q1) focused on the forward motoring mode. As shown in Figure 8, both the secondary voltage and current waveforms displayed positive values, confirming the expected operation. The DC voltage and current were also positive, indicating that the machine operated as a motor, converting electrical energy into mechanical energy to drive the load forward.

The waveforms demonstrated smooth and stable behavior due to the inductor’s smoothing effect, which minimized the ripples in the rectified DC output. This aligns with theoretical predictions that in Q1, the machine performs forward motoring with positive power flow from the source to the load. Students gained an in-depth understanding of forward motoring operations by analyzing these results. Observing the interplay between thyristor triggering angles, waveform characteristics, and motor performance provided a practical foundation for understanding motor control strategies. Furthermore, this exercise enhanced their ability to correlate theoretical principles with real-world behavior, fostering critical thinking and problem-solving skills.

4.2. Results for fourth quadrant operation (Q4)

The fourth quadrant simulation focused on the reverse braking mode, where the machine converts mechanical energy back into electrical energy. Figure 9 illustrates the waveforms for this operation, highlighting the negative secondary voltage values while the current remained positive. The negative voltage confirms that the machine operated as a generator, feeding energy back into the system.

The waveforms displayed in the simulation are consistent with theoretical expectations for reverse braking, where the power flow is reversed. The triggering angles for the inverter thyristors were accurately adjusted to ensure proper timing and waveform characteristics. The negative voltage and positive current clearly demonstrate energy recovery, a critical feature in applications requiring regenerative braking.

This simulation exercise enabled students to explore energy recovery processes in electric drives. By observing the conversion of mechanical energy into electrical energy, students gained practical insights into regenerative braking mechanisms. They also learned to analyze the significance of waveform polarity and the role of precise control in achieving desired outcomes. These concepts are essential for modern engineering applications, such as electric vehicles and renewable energy systems. The results of both simulations emphasize the effectiveness of computer simulation modules in enhancing students' comprehension of electric drive operations. The ability to observe and manipulate waveform characteristics, analyze circuit behavior, and evaluate motor performance provided a robust platform for learning.

The key findings of this study highlight the effectiveness of the computer simulation modules in enhancing engineering education. The simulation results aligned closely with theoretical expectations, demonstrating the accuracy and reliability of the PSIM models in replicating real-world electric drive behavior. The hands-on nature of the simulations successfully bridged the gap between theoretical knowledge and practical application, allowing students to actively engage with the subject matter. Furthermore, by manipulating parameters such as thyristor triggering angles and analyzing the resulting waveform changes, students developed critical thinking and problem-solving skills, which are crucial for addressing complex challenges in engineering practice.

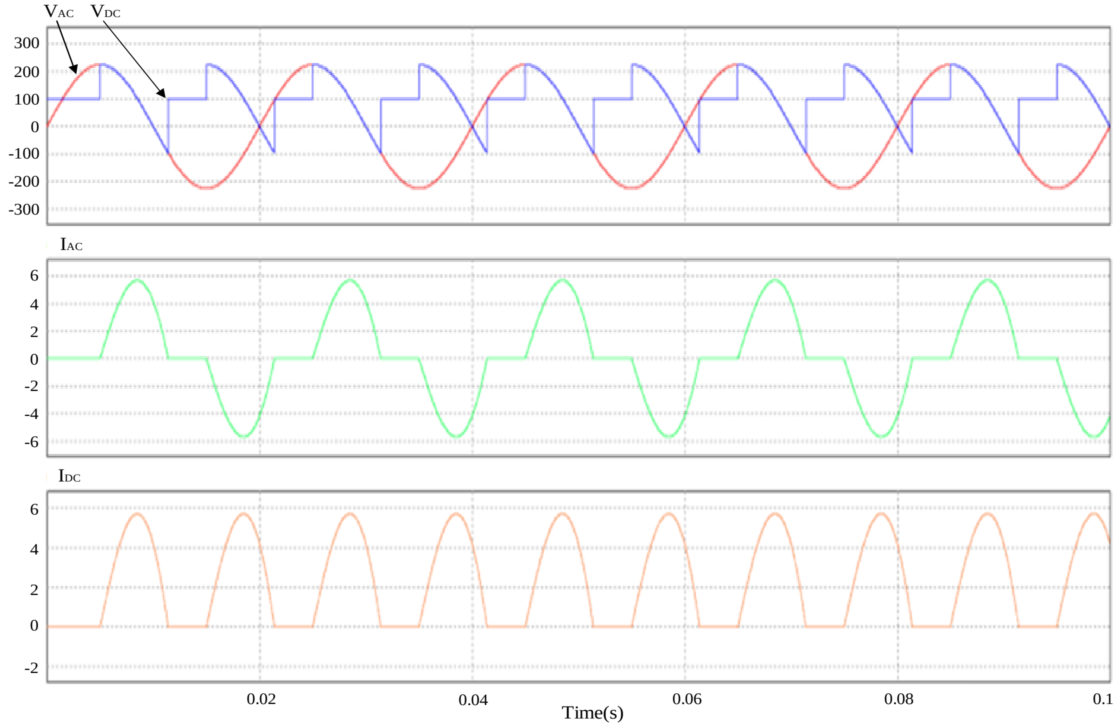

Figure 8. The secondary voltage, DC voltage, secondary current, and DC current for computer simulation module A

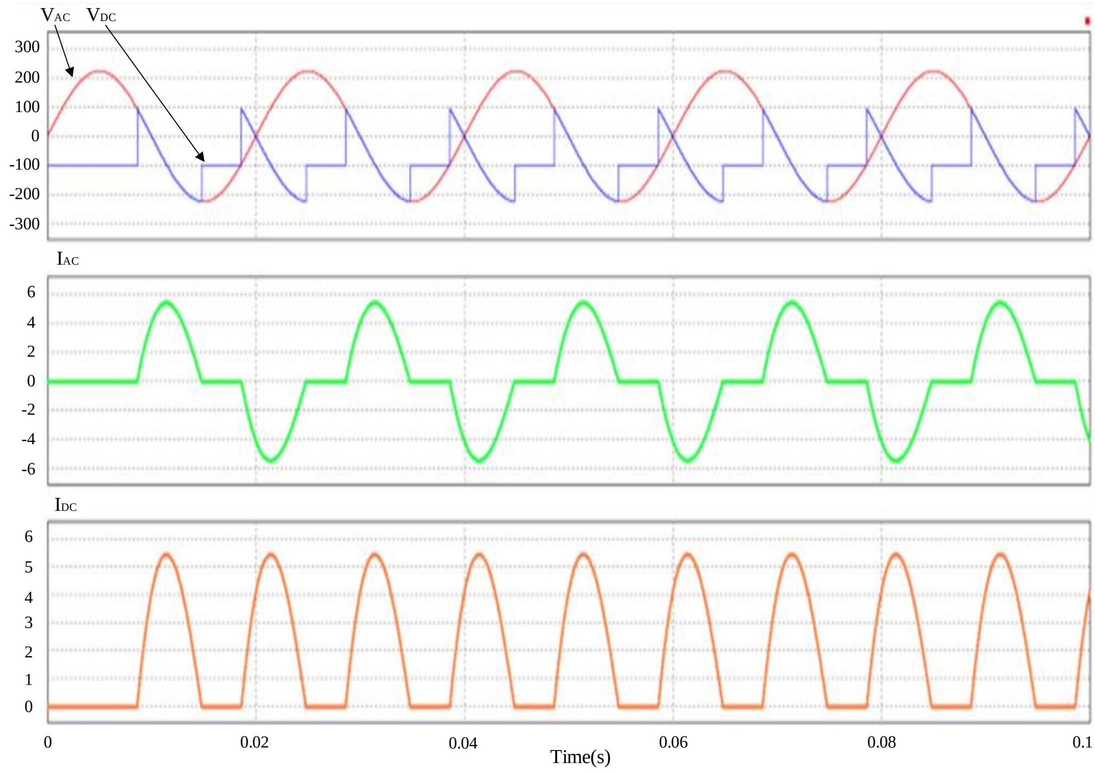

Figure 9. The secondary voltage, DC voltage, secondary current, and DC current for computer simulation module B

The integration of simulation modules into the curriculum enhances the educational experience by providing a safe and interactive environment for exploring complex concepts. Students can visualize the effects of parameter variations, reinforcing their understanding of fundamental principles. This approach not only improves knowledge retention but also prepares students for the challenges of real-world engineering applications. Building on these findings, future research could extend the simulation modules to include additional quadrants, advanced control strategies, and multi-machine systems. Incorporating real-time simulation tools and hardware-in-the-loop (HIL) setups could further enrich the learning experience by providing a closer approximation to real-world scenarios.

5. CONCLUSION

This study has successfully demonstrated the effectiveness of a computer simulation module for analyzing two-quadrant operations in electric drive systems using fully controlled two-pulse bridge circuits. The module focused on the first quadrant (forward motoring) and the fourth quadrant (reverse braking), enabling students to explore and understand the principles governing these operational modes. By setting precise firing angles within the ranges of $0° < \alpha < 90°$ for rectifier operation and $90° < \alpha < 180°$ for inverter operation, students were able to observe and verify the expected voltage and current profiles, aligning closely with theoretical predictions. The simulation results confirmed the theoretical operating modes of electric machines, achieving the objectives of understanding two-pulse bridge circuit operations and their application to DC machines. This hands-on approach bridged the gap between theoretical knowledge and practical application, enhancing students' technical skills and critical thinking capabilities. It also prepared them to tackle real-world engineering challenges with confidence. The findings underscore the importance of integrating simulation modules into the electric drive curriculum, as they provide an interactive and engaging platform for learning complex concepts. By enabling students to experiment with parameters, analyze outcomes, and correlate theoretical principles with practical behavior, these modules significantly enhance the overall learning experience. Future work could extend the simulation module to incorporate four-quadrant operations, advanced control strategies, and real-time simulation tools, further enriching the educational value and aligning with the evolving demands of modern engineering practice.

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BIOGRAPHIES OF AUTHORS

Rahimi Baharom is a lecturer in School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Malaysia since 2009; and He has been a senior lecturer since 2014. He received the B.Eng. degree in electrical engineering and the M.Eng. degree in power electronics, both from Universiti Teknologi MARA, Malaysia, in 2003 and 2008, respectively; and Ph.D. degree in power electronics also from Universiti Teknologi MARA, Malaysia in 2018. He is a senior member of IEEE and also a corporate member of the Board of Engineers Malaysia and the member of Malaysia Board of Technologists. His research interests include the field of power electronics, motor drives, industrial applications, and industrial electronics. He can be contacted at email: rahimi6579@gmail.com.

Norazlan Hashim received his Ph.D. degree in Electrical Engineering from Universiti Teknologi Malaysia (UTM), Skudai in 2022. He obtained his B.Eng. and M.Eng. degrees in Electrical Engineering from University of Malaya (UM), Kuala Lumpur, in 2001 and 2007, respectively. He is currently a senior lecturer in the School of Electrical Engineering at the Universiti Teknologi MARA (UiTM), Shah Alam, Malaysia. His research interests include maximum power point tracking techniques, power electronic converters, artificial intelligence algorithms, and PV systems. He can be contacted at email: azlan4477@uitm.edu.my.

Naeem M. S. Hannoon is an accomplished professional with diverse experience in the field of electrical engineering. He spent four years at a thermal power plant in Kuwait, focusing on maintenance, troubleshooting, and scheduling for generators, motors, and transformers. In Malaysia, he served as a site engineer for two years, contributing to the design and commissioning of substations. As an associate professor, he has provided consultation and technical training to various power industries globally, including in Dubai and London. Currently, he works as a technical consultant for both government and private sectors, alongside his role at the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA. He has authored numerous technical articles and received grants for his research in power generation stability, protection, and AI-control of power systems. He can be contacted at email: naeem@uitm.edu.my.

Nor Farahaida Abdul Rahman works as a senior lecturer at the School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia. She received her B.Eng. (Hons.) and M.Eng. degrees from Universiti Teknologi Malaysia (UTM), and Ph.D. in Power Engineering from Universiti Putra Malaysia (UPM). Her research interests are active filters, power quality, and power electronics. She can be contacted at email: farahaida@uitm.edu.my.