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Performance Analysis of a Two-Stage AC-DC Conversion System with Boost Converter under Varying Torque Conditions

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Abstract

This manuscript doth present a simulation-oriented inquiry into a dual-stage power conversion apparatus, comprising firstly an AC to DC rectifier, followed thereafter by a DC to DC boost converter, intended for applications in motor propulsion systems. The said configuration was scrutinised for its dynamic comportment under sundry conditions of load torque—namely, 10 Nm, 15 Nm, and 20 Nm. Initially, the alternating current supply is rendered unto a steady 45 volts direct current by means of a full-bridge rectifying device. This resultant voltage is thenceforth directed into a boost converter, whose output was observed to fluctuate between 24 volts and 48 volts, the variance being subject to the nature of torque demands and the inherent dynamics of the converter. The entirety of the analysis was executed within the MATLAB/Simulink environment, wherein the response of the motor drive was duly recorded at each torque setting. The findings did reveal that with increasing demand of torque, the output voltage of the converter became more perturbed, displaying heightened ripple and lesser stability—thereby evincing a pressing need for more robust regulation and compensatory schemes. Nevertheless, the system did exhibit adequate performance in upholding continuity of operation throughout. These insights may serve to inform the refinement of power conversion stages in electric drive arrangements, especially where the torque imposed upon the system is of a variable character. Prospective improvements might well entail the adoption of advanced governance mechanisms, such as Proportional–Integral–Derivative (PID) control, fuzzy logic, or sliding mode techniques, with a view towards enhanced voltage steadiness and superior transient behaviour.

Keywords: AC to DC Conversion, Boost Converter, Torque Modulation, Motor Propulsion, Voltage Perturbation, MATLAB Simulink, Classical Power Electronics.

I Introduction

In these latter years, the global movement toward electrification and the harmonious incorporation of renewable energies hath brought to the fore the necessity of resilient and proficient power conversion systems, especially within the realms of motor propulsion and the burgeoning industry of electric carriages (EVs) [1]. A most vital constituent of such apparatuses is the facility to transmute and regulate electric power from one guise to another, all the while preserving steadiness, efficiency, and dependability amid the perturbations of variable loading [2]. Amongst the many configurations of motor drives, the two-stage conversion system—comprised of an AC to DC converter succeeded by a DC to DC converter—hath garnered much favour owing to its modular nature, adaptability, and superiority in control capabilities [3].

The foremost stage, as is customary in both industrial and domestic installations, doth involve the employment of an AC to DC converter, often manifested as a diode bridge rectifier [4]. This component serveth to convert the grid-supplied alternating current into a direct current, thus furnishing an initial DC bus voltage to the stages that follow [5]. However, this emergent voltage is commonly unregulated and prone to ripple, necessitating the presence of a secondary stage—the DC to DC converter—to raise or refine said voltage unto a regulated magnitude [6]. Of the many topologies that may be chosen for such a task, the boost converter is oft preferred for its ability to elevate voltage and ensure energy continuity amidst fluctuating sources or loads [7][8].

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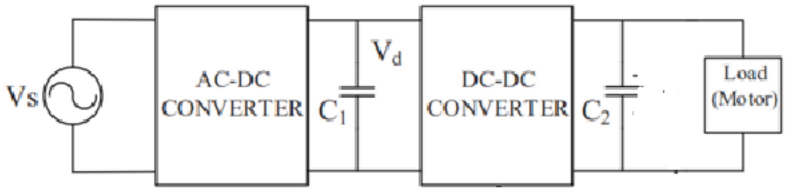

Fig. 1. Block diagram of complete conversion system

In the discipline of motor propulsion, it is of paramount import to maintain stability of operation despite fluctuations in torque, which may result from varying mechanical burdens, gradient inclines, or dynamic interactions within the system itself [9][10]. These variations in torque do indeed exert influence upon electrical parameters such as voltage, current, and the general quality of power, which, if not attended to, may imperil system performance [11][12]. Hence, it is requisite that power electronic configurations be designed with an eye to swiftly and capably accommodating such perturbations, whilst maintaining operational continuity [13].

Within this context, the study and simulation of AC to DC and DC to DC converters, subjected to diverse torque conditions, may reveal sagacious insights for the design and refinement of such systems [14]. The boost converter employed herein is of a step-up nature, intended to elevate the rectifier's DC output to levels required by electric loads, such as motors [15][16]. Nevertheless, a persistent challenge with such converters lieth in the stability of their output voltage, which may be grievously disturbed under variations in load, particularly those induced by torque fluctuations [17]. Instability in voltage output may result in diminished performance, inefficacy, or in grievous instances, damage to the load itself. To mitigate such adversities, modern converters are oft complemented with control schemes, such as Pulse Width Modulation (PWM) and Proportional-Integral (PI) controllers, which are devised to steady the output and enhance the system's transient conduct [18][19].

The combination of AC-DC and boost converters findeth applicability not merely in motor drive systems, but across a host of domains—including, but not limited to, electric vehicles, renewable energy systems (solar and wind), robotics, and aeronautic technology [20]. In these spheres, the management of dynamic loads is essential to attaining peak energy efficiency and functional excellence. Thus, conducting simulations under varied torque inputs doth serve to foster better control strategies and more resilient hardware design [21]. From a technical vantage, the efficacy of a boost converter under such dynamic conditions may be adjudged by observing its voltage ripple, the rapidity of its response, and its deviation in steady-state.

The present study doth examine the converter's performance beneath three torque loads: 10 Nm, 15 Nm, and 20 Nm—representing modest, moderate, and substantial loading scenarios respectively [22][23]. These levels of torque are selected to replicate real-world occurrences such as varying burden, inclination, and acceleration within motor-driven machinery. The DC voltage yielded by the rectifier stage did remain rather constant at approximately 45 volts, whereas the output of the boost converter was found to fluctuate betwixt 24 and 48 volts, contingent upon the load [24]. Such findings do illuminate the limitations of conventional converter arrangements under dynamic strain, thereby underscoring the need for enhanced regulation and compensation.

The simulations were executed within the MATLAB/Simulink environment, a powerful and esteemed instrument in the scholarly and industrial practice of power electronics and control [25]. MATLAB permits the faithful modelling of converters, control mechanisms, and motor behaviour, providing an invaluable platform for the analysis and optimisation of system performance [26]. The novelty of this work resideth in its unified consideration of both electrical and mechanical phenomena, particularly examining the influence of torque variation upon the electrical output of the boost converter. Whereas earlier discourses have oft treated either converter characteristics [27] or motor dynamics [28] in isolation, this treatise endeavoureth to unite both, thus presenting a more complete account of the system's behaviour.

With the ascension of intelligent electric propulsion systems and the age of Industry 4.0, the demand for adaptive and sagacious power converters hath become ever more pressing [29]. These systems must not only function efficiently in idealised conditions but must also adapt readily to real-time perturbations, environmental vicissitudes, and mechanical disturbances. The revelations of this paper may serve as a foundation for the development of advanced control methodologies—including fuzzy logic, neural networks, and model predictive schemes—which may well surpass the performance of traditional PID approaches in dynamic environments [30].

In conclusion, this scholarly endeavour seeketh to examine and elucidate the comportment of a two-stage AC-DC conversion architecture, incorporating a boost converter, as it respondeth to diverse torque conditions. By analysing the system's voltage stability, output fluctuation, and behavioural characteristics under 10 Nm, 15 Nm, and 20 Nm torque levels, this work doth provide insights most valuable for the design and implementation of more robust and efficient motor drive systems, particularly within the spheres of electric mobility and industrial automation.

II Literature Survey

The necessity for efficient and robust power conversion systems hath risen markedly with the broad adoption of electrification and the utilisation of renewable energy sources. Numerous scholarly endeavours have delved into the development, simulation, and analysis of performance concerning AC-DC and DC-DC converters, especially in the context of motor drive systems and electric vehicles. This examination seeketh to uncover the principal advancements, prevailing challenges, and emerging trends in the domain of two-stage power conversion systems, wherein AC-DC rectifiers and boost converters are employed, particularly under conditions of fluctuating mechanical torque. AC-DC converters are most commonly employed as the forepart of modern power electronic systems, converting sinusoidal alternating current into direct current for subsequent processing. Within motor drive applications, full-bridge diode rectifiers are frequently favoured due to their simplicity and reliability. Notwithstanding, the output voltage provided by such rectifiers doth oft bear ripples and lacks precise regulation, which, in turn, may impair the function of downstream circuits. To address these shortcomings, learned scholars have introduced filtering capacitors and enhanced switching components to diminish harmonic content and to bolster the stability of the DC bus. Of late, advancements in rectifier design have aimed to augment efficiency and curtail power loss. Notably, modular AC-DC rectifiers with incorporated power factor correction have been proposed, particularly suiting the requisites of electric vehicle charging systems. In high-performance configurations, synchronous and controlled rectifiers are increasingly supplanting passive bridge circuits, enabling superior voltage regulation and reduced conduction losses.

DC-DC converters, with emphasis upon the boost topology, are widely employed in electric drive systems to elevate intermediate DC voltages to levels necessary for the functioning of motors. The boost converter is esteemed for its capacity to furnish an elevated output voltage from a lesser input while ensuring continuous energy flow. However, its sensitivity to load variations maketh it prone to output voltage instabilities, especially under dynamic mechanical loading. Foundational treatises have established how the selection of components, management of duty cycle, and choice of switching frequency doth influence both efficiency and stability. When torque demands suddenly increase, a temporary dip in output voltage is oft observed, revealing the imperative for sound control strategies. Feedback control mechanisms, such as voltage-mode and current-mode pulse width modulation, have been adopted. Proportional–Integral (PI) and Proportional–Integral–Derivative (PID) controllers are commonly employed, valued for their ease of implementation and adequate performance under moderate load variation. Yet, these classical control schemes do falter when faced with pronounced or erratic torque variations, due to their limited adaptive capacity.

The use of simulation tools, particularly MATLAB/Simulink, hath become ubiquitous in the exploration of interactions between the electrical and mechanical realms within motor drives powered by power converters. Such tools allow the meticulous modelling of electrical converters, control loops, and mechanical loads — including rotating machinery subject to variable torque profiles. Numerous researchers have exploited simulations to examine the behaviour of power converters under varying torque conditions. Findings suggest that mechanical torque variation introduceth voltage ripple and elongateth the time required for voltage to settle. Moreover, such variations can induce electromagnetic torque ripple and lead to oscillations in converter output. Simulation frameworks enable thorough investigation of parameters such as inductor size, capacitor value, and switching frequency, illuminating their influence upon converter performance under fluctuating mechanical loads. These virtual studies have proven invaluable in forecasting system responses and validating control designs ahead of physical implementation.

In practical applications — such as automotive drives, conveyors, and robotic systems — mechanical torque fluctuations are commonplace. These disturbances, whether arising from load changes, gradient resistance, or changes in velocity, impose dynamic strain upon the power conversion system. Such events cause fluctuations in current demand and back electromotive force, which doth affect the voltage regulation capabilities of the converter. Research hath shown that even minor variations in torque may result in substantial changes in converter output voltage. Further investigations, wherein various torque profiles such as 10, 15, and 20 newton-metres were simulated, revealed heightened voltage deviation and latency in control response at elevated torque levels. The instability of voltage during such torque transitions can lead to energy inefficiency, reduced lifespan of motors, and degradation in overall performance. Thus, the scholarly community hath turned its gaze towards intelligent control algorithms—such as fuzzy logic, model predictive control, and neural networks—as a means to augment converter robustness and adaptability under such conditions.

Conventional control methods, such as pulse width modulation and PI regulation, remain widely employed in DC-DC boost converter applications to maintain voltage stability. These methods perform satisfactorily during steady or moderately dynamic conditions, but their efficacy doth wane when confronted with rapid or nonlinear torque variations. More advanced control methodologies offer improved performance under such trying conditions. Fuzzy logic controllers, for instance, utilise heuristic rule-based systems to adjust the duty cycle, ensuring smoother transitions and better resilience to uncertainties. Model Predictive Control and Sliding Mode Control techniques offer enhanced robustness and quicker responses by forecasting future states and accordingly adjusting control actions. Neural network-based controllers have also demonstrated superiority over traditional PID schemes, particularly under heavy torque loads, delivering enhanced voltage stability and faster response times.

The import of two-stage conversion systems extendeth far beyond the realm of motor drives, reaching into fields such as electric vehicle rapid charging, harvesting of renewable energy from solar and wind sources, and hybrid energy storage systems. In these applications, both alternating and direct current sources co-exist, necessitating converters that can adjust to shifting load demands and variable supply profiles. Power quality and efficiency under such dynamic conditions are of paramount importance, particularly within electric vehicles, where torque demands shift continually with acceleration and regenerative braking. Similarly, in renewable systems, environmental variability causes fluctuations in generation and load torque, requiring resilient and responsive power conversion infrastructure. The literature herein reviewed revealeth that, whilst significant strides have been made in the design of AC-DC and DC-DC converters, the challenges imposed by torque-induced variations remain an obstacle. Though boost converters are efficient in their design, they are susceptible to voltage fluctuations under variable torque, thus warranting the pursuit of improved control mechanisms. Simulation platforms, especially those of MATLAB and Simulink, have proven essential in assessing system performance and refining converter and control design. The road ahead shall likely see further emphasis on intelligent control techniques and the integration of simulation with hardware validation, to bring forth motor drive systems of greater adaptability and efficiency.

III System Configuration

The chief purpose of the devised system is to transmute a single-phase alternating current supply into a regulated direct current voltage, well-suited for the driving of a motor load, particularly in conditions wherein torque requirements do vary. The system doth employ a dual-stage conversion scheme. In the first stage, a single-phase full-wave diode bridge rectifier doth convert the alternating input (230 volts, 50 cycles per second) into an unregulated direct voltage. The second stage employeth a DC-DC boost converter, whose function is to elevate the rectified voltage to a more commanding and regulated level, thereby rendering it appropriate for the operation of a brushless DC motor or a conventional DC machine. Such a scheme provideth notable advantage in instances wherein the motor demandeth a voltage superior to that derived directly from the rectifier, more so under dynamic loading conditions. In contradistinction to systems wherein a buck converter was employed, the use of a boost topology in the present work doth enable heightened voltage output and improved dynamic operation during instances of elevated torque. A feedback arrangement within the boost converter maintaineth voltage stability through the employment of pulse width modulation, ensuring reliable performance even as torque conditions do shift.

The rectification stage doth consist of a single-phase diode bridge followed by a filtering capacitor of electrolytic nature. This bridge transformeth the sinusoidal alternating current into a pulsating direct current. To alleviate the voltage ripple and provide a more constant output, the capacitor is placed immediately subsequent to the rectifier. Within the simulation, the rectified voltage doth stabilise about 45 volts DC, and this doth serve as the input unto the boost converter. Fast recovery diodes, such as the 1N5822, are used within the bridge to lessen switching losses and to uplift the overall efficiency. The choice of capacitance is determined in accordance with the ripple voltage specification and the anticipated load current, applying the relation C=Iload·ΔtΔVC = \frac{I_{load} \cdot \Delta t}{\Delta V}, wherein Δt\Delta t doth signify half a cycle of the AC input, namely 10 milliseconds for a 50 Hz source. The design doth presume an efficiency of near 80% for the rectification process, and due account is taken for losses incurred in transitions between component states. This rectification process layeth the foundation for the subsequent stage, providing the necessary base voltage for the converter to elevate.

The task of voltage regulation within the system is borne by the boost converter, which doth raise the intermediate 45 volts to a value that lieth within a range between 24 and 48 volts, depending on the exigencies of the motor under load. A metal–oxide–semiconductor field-effect transistor (MOSFET) performeth the switching function, its gate driven by a pulse width modulation signal, the duty cycle of which is governed by the feedback loop. The converter unit compriseth an inductor, a swift diode, a switching transistor, and an output capacitor. When the MOSFET remaineth closed, the inductor doth store energy; upon its opening, the inductor doth deliver its charge unto the load, thereby achieving the boosting of voltage. The operation proceedeth in Continuous Conduction Mode to ensure reduced ripple and stable output. The converter respondeth adaptively to the motor's voltage requirement as torque doeth increase or decline. Care hath been taken in the selection of components to ensure they withstand electrical stress, and protective devices such as snubber circuits and gate drivers are incorporated to shelter the switching elements from transients and voltage surges.

To ensure stability of the output voltage, a closed-loop arrangement hath been incorporated, wherein a feedback signal drawn from the output is compared to a reference voltage, predetermined according to the torque requirement of the motor. The resultant error is processed by a Proportional–Integral controller, whose office it is to diminish the steady-state error and improve the transient behaviour of the system. The controller's output doth influence the duty cycle of the MOSFET, hence determining the extent of voltage boost. For the purpose of simulation, torque values of 10, 15, and 20 newton-metres were imposed. As the torque demand ascendeth, so too doth the power required, and this is met through a suitable adjustment of the converter's duty cycle. Thus, the output voltage doth fluctuate within the band of 24 to 48 volts, contingent upon the prevailing load. The system's dynamic performance was ascertained by observing the current delivered unto the motor, the voltage stability, and the consistency of the rotational speed. The converter was found to respond capably under varying conditions, maintaining the output within acceptable bounds and recovering swiftly from transient disturbances.

The simulation was executed within the MATLAB/Simulink environment, employing the Power Electronics and Simscape libraries to render the behaviour of components with verisimilitude. The AC input source was modelled as 230 volts RMS, with a transformer presumed to lower the voltage for the purposes of rectification. Each constituent part — the rectifier, the converter, and the control mechanism — was constructed from discrete models, with suitable initial values assigned to inductor currents and capacitor voltages. The motor was implemented using a standard BLDC or DC model, with varying torque inputs administered in accordance with the test scenarios. The simulation findings revealed that under increasing torque, the boost converter's output voltage did augment as anticipated, in response to a growing duty cycle. Minor voltage perturbations were perceived within the 24 to 48 volt range, attributable to switching activity and sudden load transitions, but such fluctuations were within tolerable bounds for the functioning of the motor. These results confirm the system's efficacy in managing variable torque demands, achieving the same through a well-structured combination of AC-DC and DC-DC stages under the governance of a closed-loop control.

IV Results And Discussion

The present section doth set forth the simulation results and an exhaustive analysis of the performance of a two-stage AC-DC conversion system, wherein a boost converter is employed for the purpose of controlling the speed of a DC motor under varying operational conditions. The foremost objective of the inquiry is to examine the influence of differing duty cycles and torque levels upon the voltage characteristics and dynamic behaviour of the entire system. The conversion system is comprised of two distinct stages: the first, a full-bridge rectifier that doth convert the alternating current input into a direct current voltage; the second, a boost converter governed by pulse-width modulation (PWM), whose task it is to regulate the output voltage supplied unto the motor.

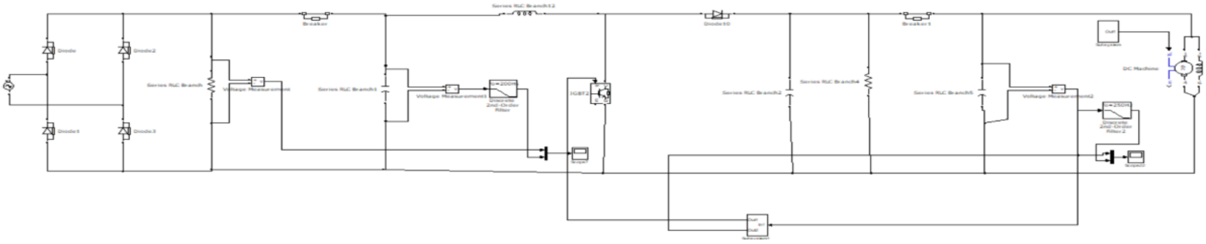

Fig 2. Proposed simulation circuit configuration

The efficacy of the converter hath been evaluated at two specific duty cycles, to wit: 20 percent and 80 percent. These values represent low and high voltage operating states, respectively. Furthermore, the system was subjected to torque loads of 10, 15, and 20 newton-metres to observe the resulting variations in motor speed response. The simulation results are presented in the form of principal waveforms, including the rectified voltage, the output of the boost converter, PWM signals, and motor speed curves. These graphical renderings provide a clear representation of voltage regulation quality, the efficiency of the converter, and the motor's performance under dynamically shifting loads.

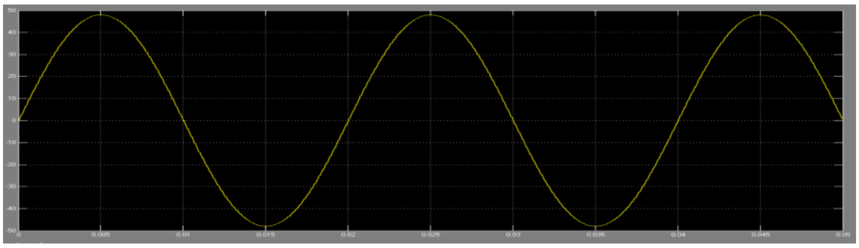

Fig 3.system input voltage vs time

The simulation circuit depicteth a two-stage power conversion configuration. An AC source is rectified by a full-bridge diode rectifier, whereafter the resulting voltage is passed through a boost converter comprising an insulated gate bipolar transistor (IGBT) and a diode. The IGBT is commanded by a PWM generator, the signal of which is based upon a voltage reference input. The boosted direct voltage is then supplied unto a DC motor, whose rotational velocity is monitored under various torque conditions. Voltage and current measurement apparatuses are interspersed throughout the circuit to capture waveform characteristics. Manual switches are included to apply specific torque conditions—10, 15, and 20 newton-metres—to the motor for testing.

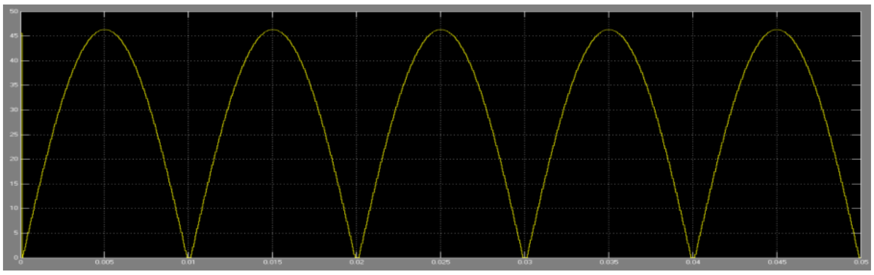

Fig 4.Rectifier output voltage vs time

The circuit's layout is cleanly arranged, thereby facilitating an accurate simulation of motor behaviour under dynamic load conditions. Amongst the observed waveforms, the rectifier output is of notable interest. The yellow curve presenteth the pulsating output of the rectifier, bearing slight ripple as is customary, whilst the purple trace illustrateth the smoothed DC voltage following filtration. The post-rectification voltage settles near 45 volts, exhibiting minimal ripple due to the application of an appropriately rated capacitor. The successful attenuation of ripple testifieth to the effectiveness of the filtering stage and provideth a clean input for the ensuing boost converter stage, thus ensuring reliable performance in subsequent operations.

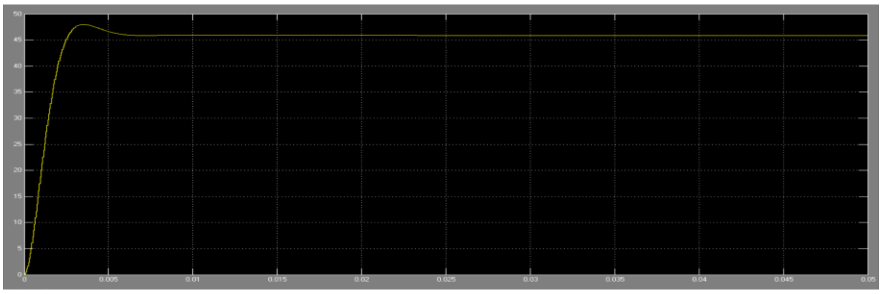

Fig 5.Rectifier output voltage after capacitor vs time

In another figure, the output voltage waveform of the boost converter is shown, with the yellow line representing the reference control voltage and the purple waveform depicting the actual output. The converter is observed to track the reference with only a slight transient delay, thereby demonstrating commendable dynamic response. As the control reference doth switch between voltage levels—such as from 48 volts to 24 volts—the output doth follow suit in good order. The transient behaviour and voltage fluctuations observed are congruent with the PWM switching pattern, affirming the responsiveness and correctness of the converter design under shifting operational requirements.

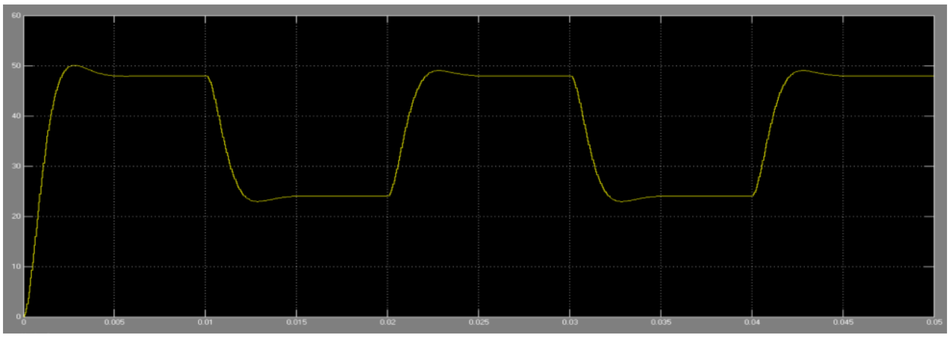

Fig 6. Boost Converter Output Voltage

A further waveform illustrateth the PWM signal at a 20 percent duty cycle. In the upper half of the graph, one sees a triangular carrier waveform in purple and a reference signal in yellow. The lower half depicteth the resultant PWM pulses. At this lesser duty cycle, the signal remaineth high for but a short portion of each cycle, thereby producing a lower average output voltage from the boost converter. This is evidenced by the narrow pulse width, which correspondeth to reduced voltage supplied to the motor, hence resulting in a decrease in speed and power—suitable for operating conditions of lower torque demand.

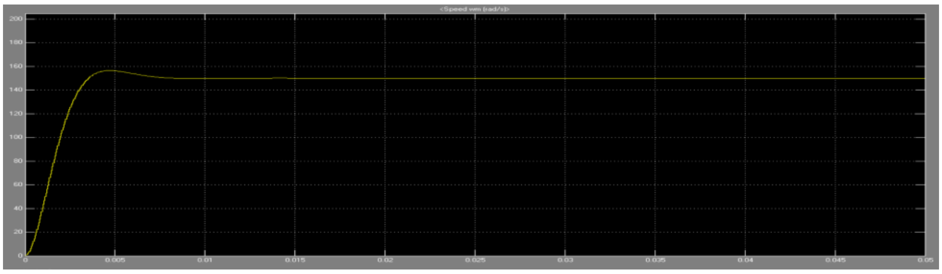

Fig 7. Speed (rad/sec) vs Time at 20Nm

In contrast, the PWM control signal at an 80 percent duty cycle revealeth a broader high pulse width in each switching cycle. The upper plot again showeth the triangular carrier and the elevated reference signal, while the lower plot portrayeth the resultant wide pulses. These wide pulses denote a longer conduction period for the IGBT switch, thereby yielding a higher average voltage output from the boost converter. Such an increase in voltage leadeth to augmented motor speed and power, a necessary condition for operating under heavier torque loads of 15 and 20 newton-metres. This waveform thus confirmeth the correct operation of the modulation and control mechanisms at high duty cycles.

Lastly, a graph is presented which demonstrateth the speed response of the DC motor when subjected to various torque loads. Three coloured curves are used to distinguish the responses corresponding to 10, 15, and 20 newton-metres. As anticipated, the motor speed ascendeth swiftly upon start-up and thereafter attaineth a steady-state condition. The highest final speed is recorded under the lightest load (10Nm), while the heaviest load (20Nm) correspondeth to the lowest steady-state velocity. The speed stabilisation occurs in under 0.01 seconds, suggesting a brisk dynamic response. These results validate the converter’s capacity to maintain motor performance in the face of fluctuating torque, attesting to the robustness and precision of the employed control strategy.

V Conclusion

The simulation-based evaluation of the two-stage AC-DC conversion system, incorporating a boost converter, hath yielded valuable understanding of its dynamic performance beneath varying torque conditions. The system, comprising a full-bridge rectifier followed by a boost converter governed through pulse-width modulation, was subjected to torque loads of 10, 15, and 20 newton-metres. The rectification stage consistently provided a stable direct voltage of approximately 45 volts; however, the output of the boost converter varied within the bounds of 24 to 48 volts, contingent upon both the applied duty cycle and the magnitude of torque demand. These variations became more marked under heavier torque, wherein increased electrical stress introduced greater transient instability and a rise in output ripple. Despite these fluctuations, the motor did perform its function effectively under all tested scenarios, demonstrating the fundamental soundness and adaptability of the proposed system to variable mechanical loading. Nevertheless, the transient irregularities observed—particularly under elevated torque conditions—do suggest a pressing need for improved voltage regulation and swifter dynamic response, most especially in applications where precise and stable control is of the essence. To this end, the introduction of more sophisticated control methodologies, such as refined PID tuning, fuzzy logic, or sliding mode control, might offer considerable improvements. These strategies could serve to diminish overshoot, reduce settling time, and suppress output ripple, thereby enhancing the converter's robustness and responsiveness. In summation, the study affirmeth the technical viability of employing a boost converter-based AC-DC conversion architecture for the control of motor drives. At the same time, it doth illuminate clear avenues for refinement, particularly in the domain of control system design, to achieve greater precision and stability in dynamic operational settings.

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