NEW POWERTRAIN CONFIGURATIONS BASED ON SIX -PHASE CURRENT SOURCE INVERTERS FOR HEAVY-DUTY ELECTRIC VEHICLES

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ABSTRACT

In this paper, new powertrain configurations for heavy-duty electric vehicles (HDEV) are proposed based on current-source inverters (CSI) and asymmetrical six-phase motors. Voltage-source inverters (VSI) are widespread in many applications; however, VSI-based powertrains require a bulky bank of capacitors with a limited lifetime. Recently, powertrains based on the current-source inverter (CSI) are getting more attention to be a more reliable structure for EVs by replacing the dc-link capacitor with a choke inductor. To the authors' best knowledge, a six-phase CSI-based powertrain is not fully addressed yet. Since the six-phase CSI comprises two three-phase CSIs, multiple configurations can arise based on the connection between the two CSIs. In this context, the proposed powertrain configurations are based on parallel, cascaded, and standalone six-phase CSIs. The standalone topology is based on separating the two three-phase converters by supplying each converter with a dedicated dc-dc converter. All the proposed configurations are studied from the perspective of structure, modulation, and stresses/sizing. A case study highlights the differences and compares the three structures. The comparison is backed by experimental results, and a detailed discussion is provided for concluding a suggested selection of the best-suited topology.

INTRODUCTION

Current-source inverters (CSI) are prominent in medium to high-power converters applications such as offshore wind farms [1] and industrial motor drives applications [2]. A powertrain topology based on three-phase CSI has received attention recently for electric vehicle applications. The attraction towards the CSI-based powertrains is due to several merit's [3], [4]. The paradigm of this shift is the reliability enhancement prospect by replacing the limited lifetime bank of capacitors in the VSI powertrain with a choke dc-inductor in CSI powertrains [5]. Other merits of the CSI system can be summarized as inherent short-circuit protection capability [6], elimination of dv/dt problems [7], motor friendly output waveforms [8], embedded voltage boosting capability [4].

Multiphase systems are gaining more popularity nowadays, not only in academic circles but also in industrial applications. For example, several multiphase drives are currently manufactured for electric vehicle (EV) applications by Dana TM4 [9]. One of the main merits of multiphase drives is splitting the drive's full power into a higher number of phases compared to their three-phase counterparts [10]. This feature enables the selection of semiconductors with lower ratings without parallel devices to achieve high current ratings, as in the traction inverter of the Tesla Model S [11], which is based on the three-phase topology. The increased number of phases reflects an increased number of degrees of freedom. This feature can be utilized in the fault-tolerant operation of such drives with higher torque than the three-phase counterparts [12], [13]. Furthermore, a high torque density can be achieved by harmonic injection to either produce more torque or allow higher torque production by the fundamental flux component.

The powertrains based on three-phase CSI [3], [4], [20], [21], [22], [23] inspire this work to expand the concept to multiphase powertrains. The stages of conversion as voltage to current converter followed by the CSI are reviewed briefly before introducing the new proposed configurations. The voltage to current converter is often implemented as an asymmetrical h-bridge dc-dc converter that maintains the dc-link current with the aid of a dc-link choke. The implementation of the dc-dc conversion in this work is crucial because of the move from three-phase to six-phase CSI. The modulation scheme used in all the configurations is based on the extension of the SVM of three-phase CSIs to double three-phase CSIs with the proper adaptation for the scheme to each proposed configuration. Three configurations are developed and proposed in this paper to struct the powertrain. The idea behind the powertrain variations is based on the different possibilities of connecting the two three-phase CSIs and the dc-dc converter so that the powertrain can be adequately sized to perform optimally. The proposed configurations connect the two three-phase CSIs in parallel or cascade with one dc-dc converter to provide.

LITERATURE SURVEY

A number of articles were surveyed to know about the present advances in the scientific community in our field of interest. Some of the honorable mentions and there work contribution includes as follows: In [6], the authors consider a few information identified with the PEVs' every day travel. (Dis) charging profiles of a PEV in a parking garage depends on delayed time and minimal loading on the grid. It has considered the parking lot stop amidst every day travel and the likelihood of charging at home for a PEV.

The authors in [7] approach the self-planning issue of a PEV aggregator who offers in the day-ahead market to buy vitality for a PEV fleet. The aggregator must guarantee that the enduser limitations of the PEVs under its administration are not disregarded. These individual imperatives are coordinated into a collected "virtual battery". These limitations are parameterized utilizing singular driving examples (arrival and departure times, trip energy consumption) obtained from a transport simulation. This work presents a model of an electric vehicle which can act as a storage system in conjuncture with the power system. A decision-making strategy is built up for the organization of the battery vitality put away, assessing the condition of charge, time of day, power costs and vehicle charging necessities. The development of a battery based energy storage model has been done for the purpose of power system analysis within the IEEE 30-bus test system [8].

In another work, the issue of optimal parallel bidding process of V2G energy and ancillary services for aggregator benefit expansion is detailed. [9]. In paper [10], the authors concentrate on the effect of charging the electric vehicles on network of residential distribution. Diverse EV types and entrance levels, and various charging profiles are considered. With a specific end goal to limit the effect of charging EVs on a distribution circuit, a demand response strategy is proposed with regards to a keen appropriation arrange.

[11] gives the general conditions utilized as a part of the counts of the value and cost of V2G for direction. Cost and income counts are presented. The authors in [12] propose a decentralized charging method for PEVs and discusses on Plug-in electric vehicles (PEVs) which sees a shift in usage of energy for individual transports from oil to electricity. The results obtained from the proposed scheme shows satisfactory outputs for load valley filling [12].

The authors in [13] propose a technique based on decentralized charging for a substantial populace of PEVs to neutralize the fluctuations in wind power in order to enhance the direction of framework recurrence. Without depending on a focal control element, each self-governing PEV alters its G2V/V2G power because of a collective virtual signal and in view of its own direness level of charging.

A vehicle with V2G abilities can offer various features such as active power regulation, reactive power support, balancing the load, harmonics filtering in the load current [14]. Also, this presents a general overview of a vehicle-to-grid (V2G) technology, in association with different charging/discharging techniques of electric vehicles (EVs), and a detailed analysis of EVs impact on the electricity network. The work in [15] exhibits a theoretical structure to effectively incorporate EVs into electric power frameworks. The proposed system covers two distinct areas the technical operation of the grid and the environment of electricity market. Every one of the players associated with both these procedures, and additionally their exercises, are portrayed in detail. The principal contextual analysis tends to the effects of EVs in a MV arrange, and in addition the advantages for the DSO emerging from the selection of an intelligent charging approach. The second contextual investigation tends to the effects of EVs in the dynamic conduct of a little LV grid and of a bigger MV grid, both worked in islanded way. A large portion of the earlier work has concentrated on controlling the charging of EV [3].

As far as the Indian region is concerned, it is available almost throughout the year. On the contrary to the solar PV array, the wind and hydro energies are location specific. The wind energy is mostly useful in the coastal region, and hydro energy is useful for hilly region. Though, the renewable energy based charging stations are the most feasible solution for the EV charging, however, their integration to the existing charging system introduces the additional power conversion stage, which increases the complexity and power loss in the system. Moreover, each conversion stage needs an individual controller, which needs to be integrated with the existing control. Therefore, it is imperative to design an integrated system with multifunctional and multimode operating capability, for which a unified control and coordination between the various sources are essential. Many efforts have been made to develop the renewable energy based charging station.

Ugirumurera et al. [3] have discussed the importance of renewable energy for the sustainability of the EV charging station. Mouli et al. [4] have utilized the solar power for charging of EVs using the high power bidirectional EV charger. However, the designed charger does not provide the AC charging. Monterio et al. [5] have presented a three port converter for integrating PV array with the EV charger. However, the designed charger does not consider the current distortions in the grid current created by the charger. Singh et al. [6] have proposed a modified z-source converter for designing of PV array/grid connected EV charger. However, the charger is not designed for the islanded mode of operation. Therefore, it cannot provide the EV charging in absence of grid. Chaudhari et al. [7] have discussed a hybrid optimization model for managing the battery storage such that the running cost of charging station can be minimized and the solar PV array power is utilised maximally.

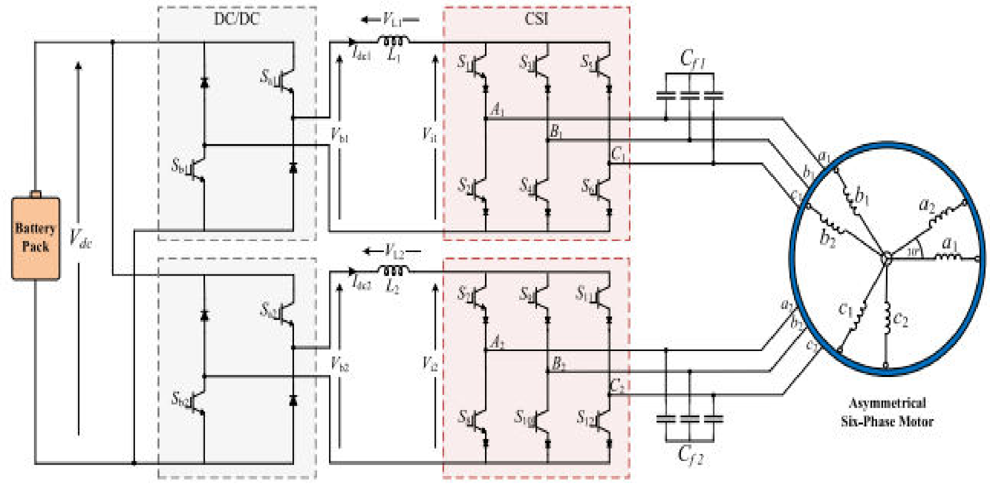
Kineavy et al. [8] have proposed to use the on-site PV generated power (deployed on the commercial building) in coordination with the EV charging station for maximum utilisation of solar PV array (under uncertainties) with less impact on the grid. Zhang et al. [9] have studied the optimal scheduling of the EV charging station in workplace with dual charging modes. The PV array powered charging station (CS) is also suitable for the onsite deployment for the best quality of service at a minimum cost while reducing the grid impact of charging [10].

Kandasamy et al. [11] have investigated the loss of life of a storage battery used with the commercial building based solar PV array system. The wind energy powered CS is also beneficial for EV due to its availability in both day and night time, and many publications are available in this area [12]-[14]. EVs nowadays are also used as a distributed energy resource for providing various ancillary services due to the huge amount of energy stored in EV batteries.

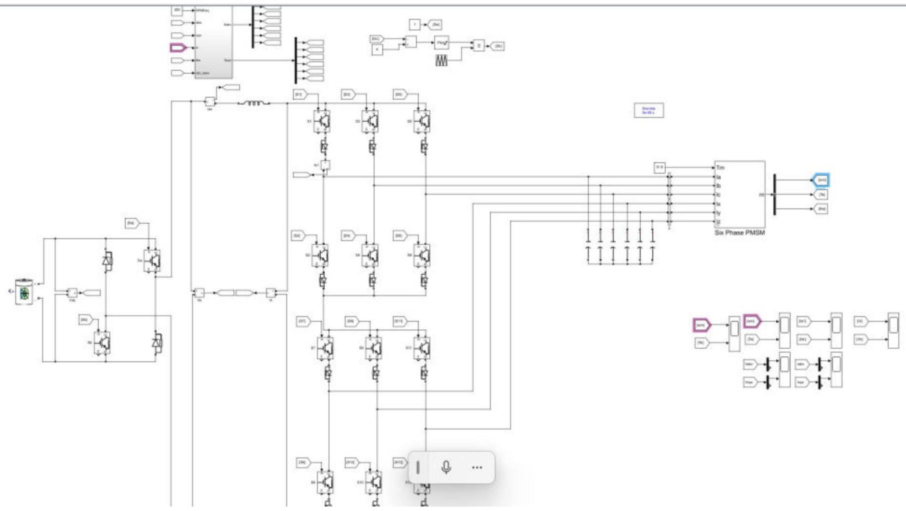
Singh et al. [15] have presented a PV array based CS for providing charging facility along-with the vehicle-to-grid reactive/active power, active power filtering and vehicle-to-home. Saxena et al. [16] have implemented a grid tied PV array system for EV and residential application. Razmi et al. [17] have proposed the power management strategy with multi-mode control of an integrated residential PV-storage battery system for both grid-connected and islanded operation. Erdinc et al. [18] and Kikusato et al. [19], Hafiz et al. [20] have presented the smart household operation such that EV can be used as a storage for providing.

PROPOSED SYSTEM

This subsection reviews the three-phase CSI-based powertrains, starting with their structure as shown in FIGURE 1. The three-phase CSI consists of six unidirectional power semiconductors, called switches in this context. Every two switches are connected in series to form a converter leg. The switches can be reverse blocking IGBTs, IGCTs, or even IGBTs with one forward series diode to block reverse voltages and conduct in one direction only. A filtering stage consisting of ac capacitors is entailed in such topology for proper operation. In CSI-based powertrains, the constant dc voltage supplied by the battery pack is converted to a controllable dc current via a dc-dc converter coupled with a choke inductor. Several previous works [4], [19] reported that the simplest topology is a bidirectional chopper converter topology. The converter consists of two half bridges that can be implemented by combining only one switch and one diode in each leg. The dc-dc converter connects the battery terminals to the output terminals in either positive or negative polarity or even disconnects the battery from the system. The goal is to either charge, discharge or freewheel the dc-link current depending on the dc-link controller’s effort to regulate the current. The switching states and the required design of the battery voltage



(a)



(b)

Fig 1 (a) proposed system configuration (b) simulation circuit

Proposed System Configuration for New Powertrain Configurations Based on Six-Phase Current Source Inverters for Heavy-Duty Electric Vehicles The continuous evolution of electric vehicle (EV) technologies demands innovative powertrain configurations to address the specific challenges posed by heavy-duty electric vehicles (HDEVs). This paper proposes a novel powertrain system based on six-phase current source inverters (CSI) tailored to meet the unique demands of heavy-duty applications.

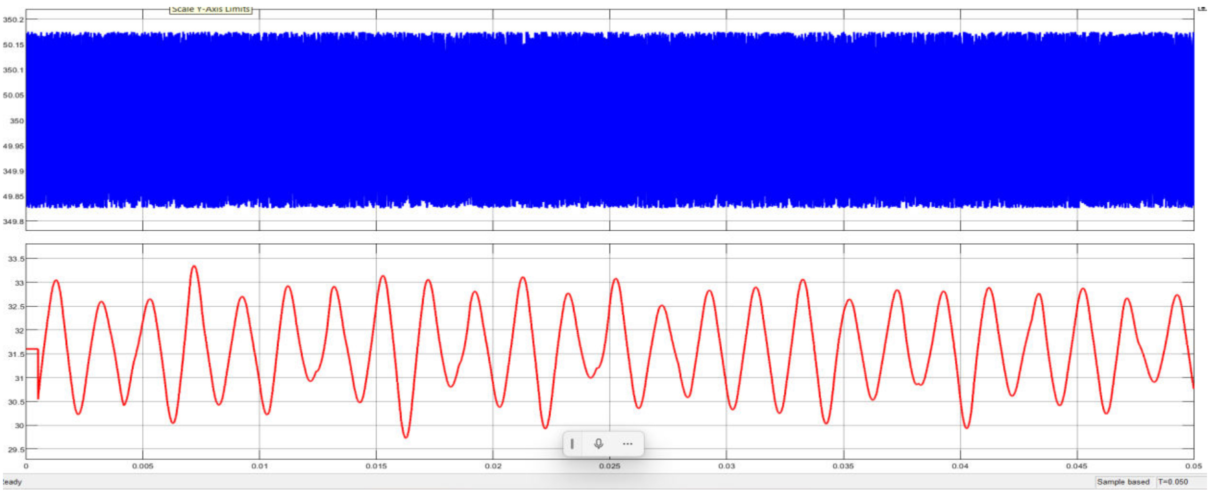


Fig 2 Output motor speed torque

The design aims to enhance efficiency, reliability, and performance, while also considering the inherent characteristics of electric propulsion for larger and more demanding vehicles. The surge in global interest and investments in electric mobility has spurred the need for advanced powertrain configurations capable of catering to the diverse requirements of heavy-duty electric vehicles. Traditional powertrains face limitations in terms of efficiency, torque capabilities, and thermal management when applied to larger and heavier vehicles. This paper explores the potential benefits of adopting a six-phase current source inverter architecture to overcome these challenges and optimize the powertrain for heavy-duty electric mobility.

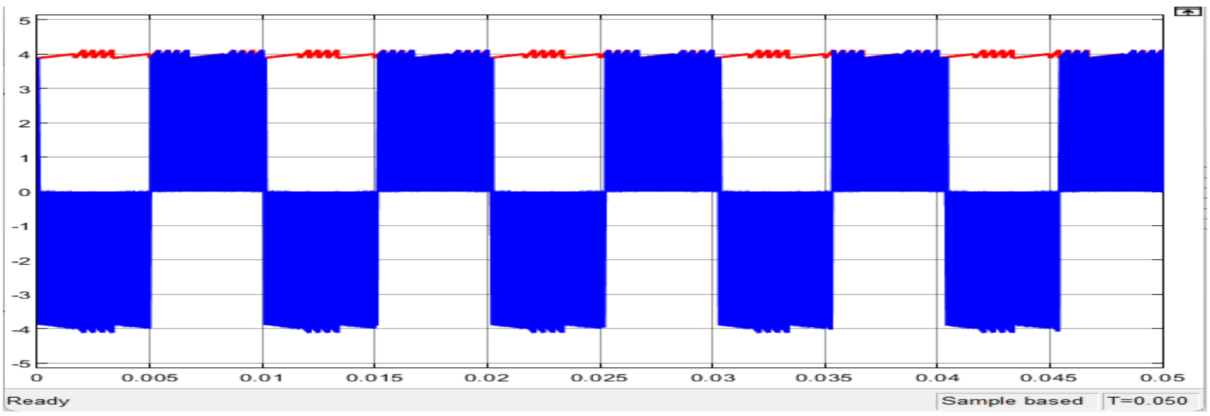


Fig 3 Dc link inverter and output currents

Electric vehicles have gained traction in various transportation sectors, but heavy-duty applications present unique challenges such as increased load, extended operating hours, and varying terrains. The limitations of three-phase powertrains in addressing these challenges necessitate a paradigm shift towards advanced configurations. The motivation for exploring six-phase current source inverters lies in their ability to offer improved torque density, fault tolerance, and thermal performance compared to traditional three-phase systems.

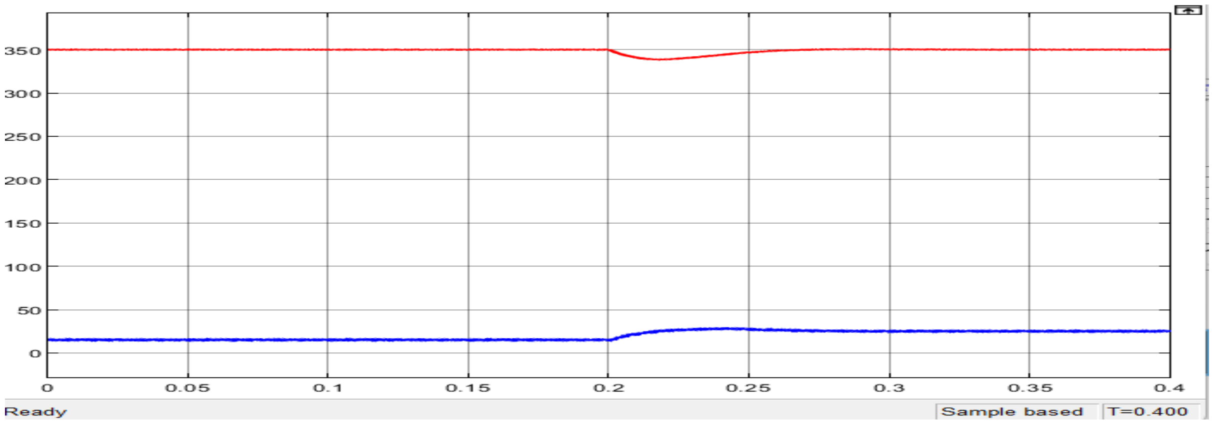


Fig 4 Motor speed and torque

The fundamental structure of a six-phase current source inverter involves six arms, each connected to a power source. This configuration introduces additional degrees of freedom, enabling more versatile control of the electric machine. The inherent advantages of six-phase systems include higher torque capability, fault tolerance, and improved current waveform quality. These attributes make them particularly appealing for heavy-duty applications where robustness and reliability are paramount.

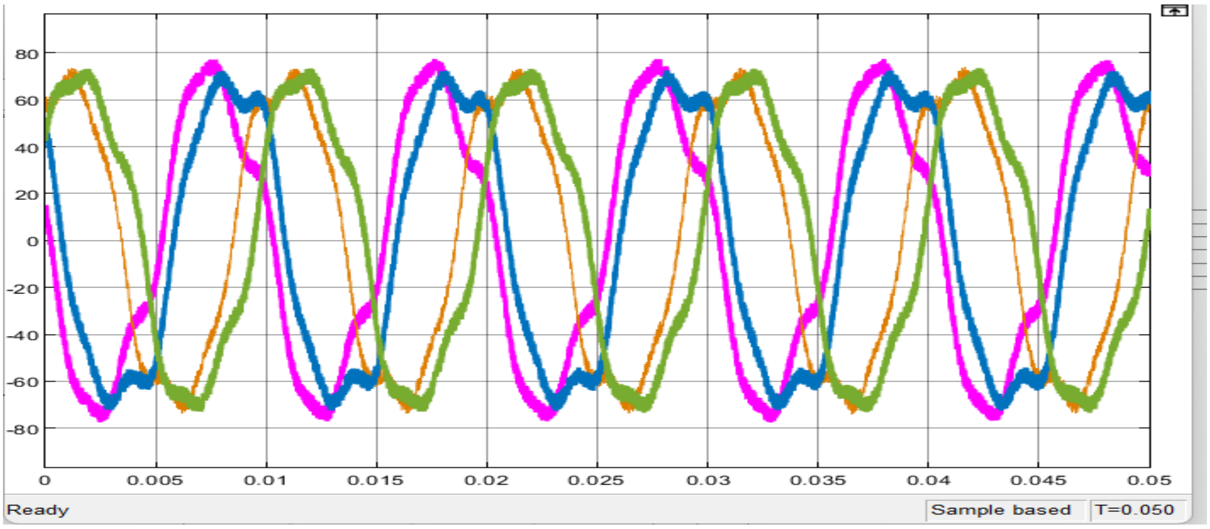


Fig 5 Motor Phase voltages

The proposed powertrain configuration integrates the six-phase current source inverters with advanced electric machines suitable for heavy-duty electric vehicles. Key components include the electric motor, power electronics, and energy storage system. The six-phase inverters are strategically positioned within the powertrain to optimize power distribution, efficiency, and thermal management.

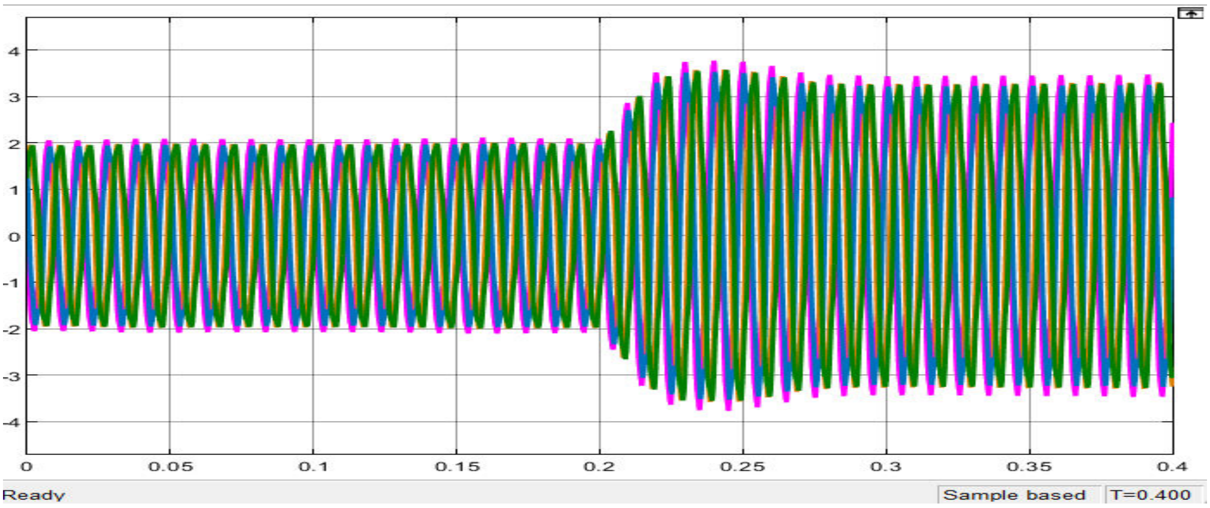


Fig 6 Step loading in Motor phase currents

The choice of an electric machine is critical in determining the overall performance of the powertrain. High-torque density and efficiency are essential for heavy-duty applications. Various electric machine topologies, such as permanent magnet synchronous machines (PMSM) or induction machines, can be adapted to the six-phase system. The integration involves careful consideration of the mechanical, thermal, and electromagnetic aspects to ensure seamless compatibility with the overall powertrain.

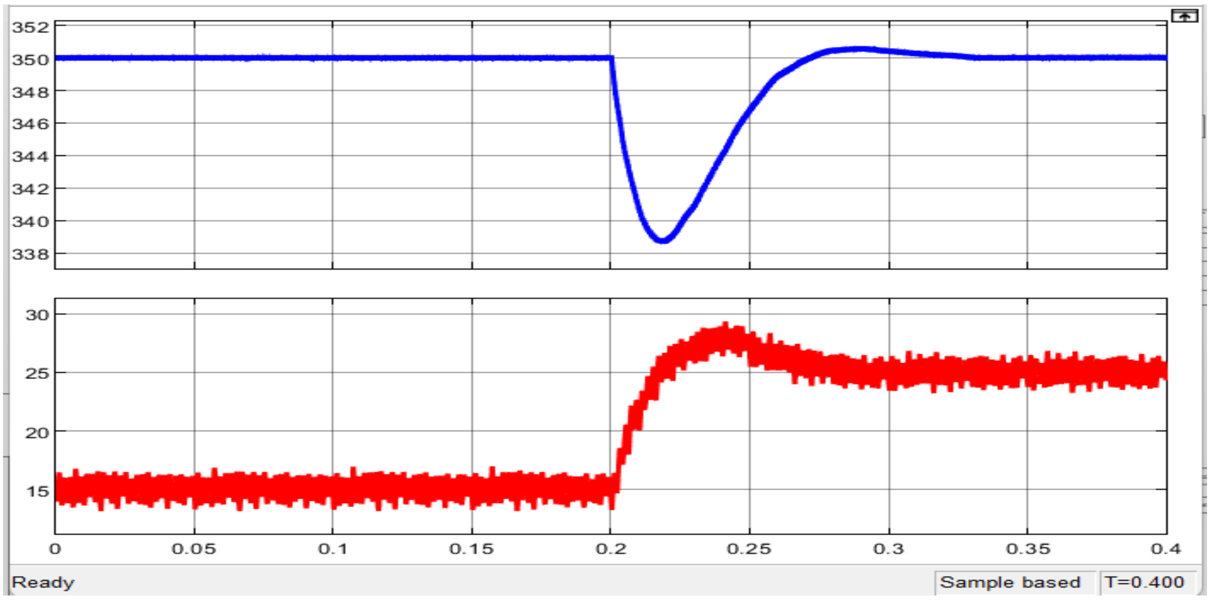


Fig 7 Step loading in csi motor speed and torque

A robust control strategy is pivotal for harnessing the full potential of the six-phase current source inverters. Advanced modulation techniques, such as space vector modulation, can be employed to optimize the inverter's switching patterns. The control system must address dynamic load variations, ensure balanced current distribution among the phases, and provide fault tolerance mechanisms. Intelligent algorithms, possibly based on machine learning, can enhance the adaptability and predictive maintenance capabilities of the powertrain.

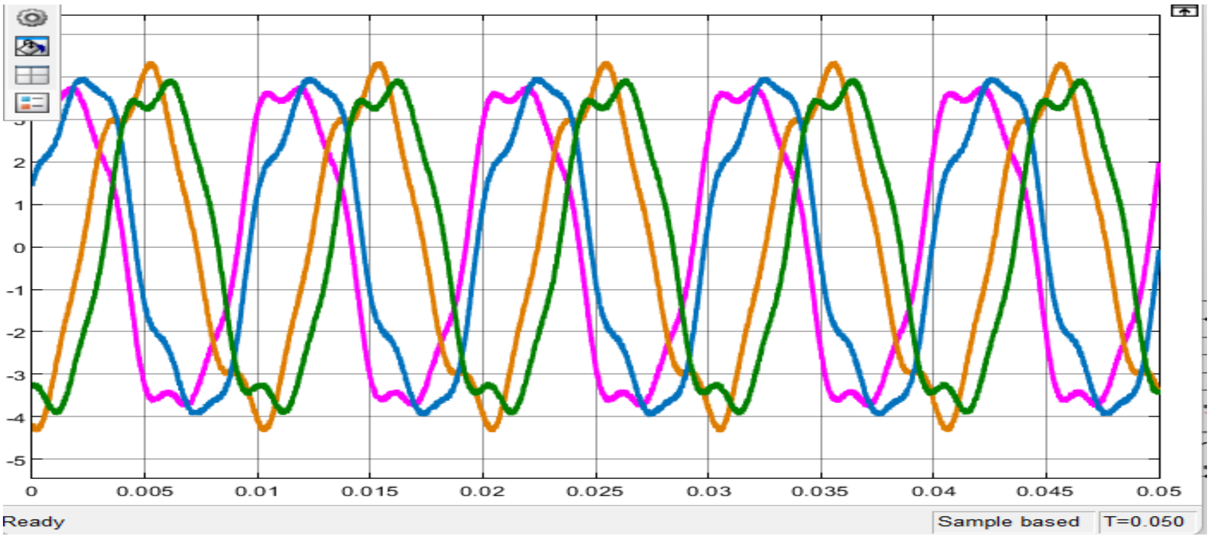


Fig 8 Phase currents

Heavy-duty applications inherently generate higher thermal loads, demanding efficient cooling and thermal management strategies. The powertrain configuration should incorporate innovative thermal management solutions, such as liquid cooling or advanced heat exchangers, to maintain optimal operating temperatures. Additionally, the efficiency of the powertrain can be further optimized through regenerative braking systems and energy recuperation mechanisms.

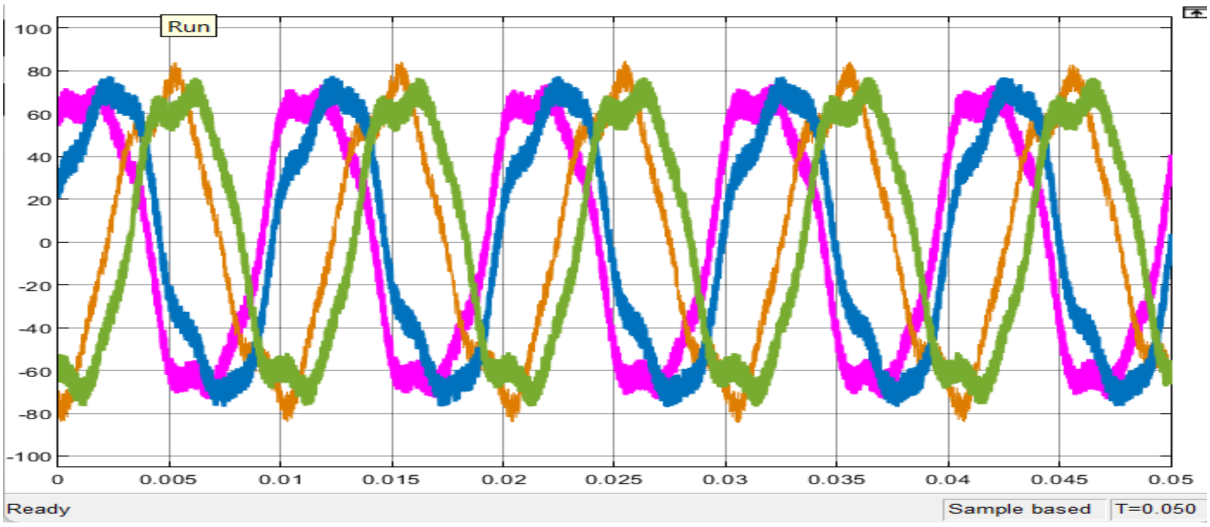


Fig 9 Phase voltages

The six-phase configuration inherently enhances fault tolerance due to the redundancy in the system. The powertrain should be designed to detect and mitigate faults in real-time, ensuring uninterrupted operation. Redundant components and advanced fault detection algorithms can contribute to the overall reliability of the powertrain, crucial for heavy-duty applications where downtime can have significant economic implications.

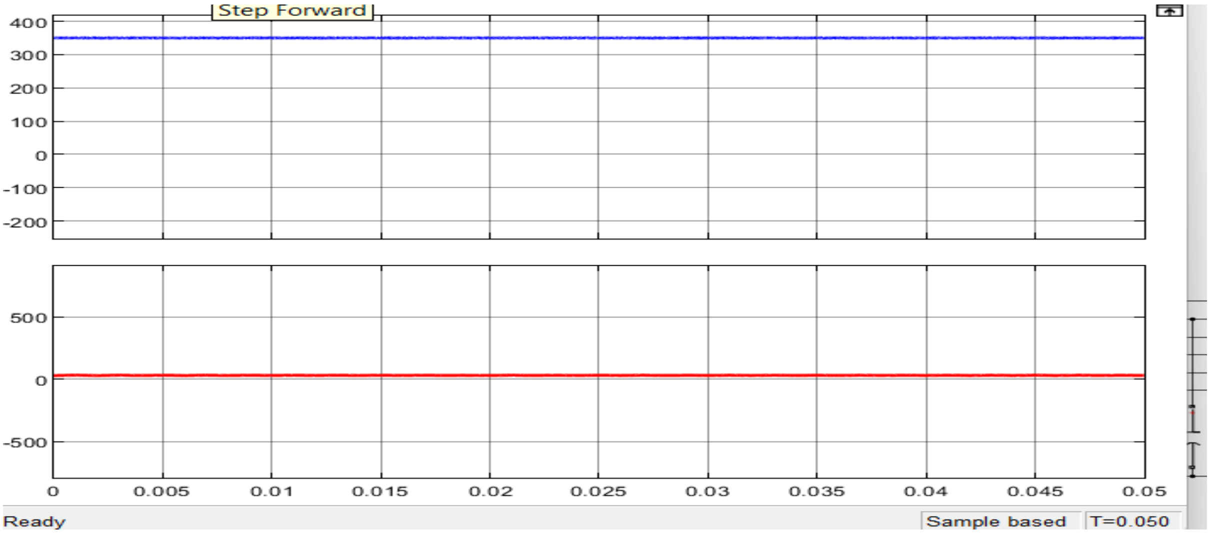


Fig 10 Speed and torque

To address the dynamic energy requirements of heavy-duty electric vehicles, the powertrain can be coupled with energy storage systems, such as lithium-ion batteries or advanced capacitors. The integration should consider factors like charging/discharging rates, energy density, and cycle life to ensure a harmonious interaction between the powertrain and the energy storage system.

Rigorous simulation studies and performance evaluations are essential to validate the proposed powertrain configuration. Advanced simulation tools can model various operating conditions, load scenarios, and fault conditions to assess the system's robustness and efficiency. Real-world testing on prototype vehicles can further validate the simulation results and provide insights for fine-tuning the powertrain configuration.

The proposed powertrain configuration based on six-phase current source inverters offers a promising solution to the unique challenges posed by heavy-duty electric vehicles. By leveraging the advantages of six-phase systems, such as increased torque density, fault tolerance, and improved efficiency, this configuration has the potential to revolutionize electric mobility in the heavy-duty sector. The integration of advanced control strategies, thermal management techniques, and fault-tolerant design principles ensures a comprehensive and reliable solution for the evolving landscape of heavy-duty electric transportation. Continued research, development, and validation efforts will be crucial to realizing the full potential of this innovative powertrain configuration and contributing to the sustainable future of heavy-duty electric mobility.

CONCLUSION

Three proposed configurations for powertrains based on sixphase CSI are studied in this paper from the perspective of the HDEV applications. The case study followed by the experimental results of a scaled-down prototype shows that the most suitable configuration is the S-CSI-based configuration. This configuration best utilizes the semiconductors for the dc-dc converters and the CSI. P-CSI configuration requires double the dc-link current compared to C-CSI and S-CSI ones. Meanwhile, the C-CSI configuration requires doubling the battery voltage compared to the P-CSI and S-CSI ones. Consequently, neither raising the battery voltage nor the dc-link current is necessary in the case of the S-CSI configuration. The S-CSI configuration has the same number of semiconductors with the same rating as the other configurations, which alleviates the need for extra components. Furthermore, the S-CSI is based on modularity, accounting for more reliability and a more straightforward manufacturing process.

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