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RESEARCH ARTICLE

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.

INDEX TERMS Multiphase systems, current-source inverters (CSI), traction motor drives, topology.

I. 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 merits [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].

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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 [14], [15].

One of the most used multiphase drives is the six-phase one because of its multiple three-phase structures [16]. The symmetrical and asymmetrical configurations are two arrangements of the six-phase motor windings. The symmetrical ones have an electrical displacement angle of 60° in space between the two sets of three-phase windings. In contrast, the asymmetrical ones, also referred to as semi-twelve-phase, have an angle of 30° . The asymmetrical six-phase motors have an advantage in eliminating the fifth and seven space harmonics in the airgap magnetomotive force [17].

Several CSI-based multiphase drives have been investigated lately, including the five-phase and six-phase ones. For example, space vector modulation (SVM) techniques are introduced to operate the motor with controlled harmonics as in [18] and minimized common-mode voltage (CMV) as in [5]. The six-phase drives are studied in [1] for the offshore wind farm applications and to address the mitigation of the dc-link choke ripple currents and fault-tolerant operation under open-circuit phase faults. The configuration in the five-phase case is discussed in [5] and [18] as the legs are connected in parallel to the supply. Meanwhile, in the sixphase CSI case [1], the two three-phase CSIs are connected in the cascaded configuration.

Since both multiphase drives and CSI are suitable for medium power applications, this paper focuses on developing powertrains based on an asymmetrical six-phase drive fed from a CSI. One of the attractions to propose a CSI-based powertrain is the reliability increase of the inverter compared to using large dc-link capacitors. For example, the total calculated capacitance for the proposed configurations is much lower that the capacitance required in the Chevrolet Spark EV which is estimated around 850 μ F [19]. Meanwhile, the inductors used add to the size and weight of the powertrains is a trade-off between reliability, size, and weight.

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 a steady, controlled current to the inverter. The authors also propose a different configuration called the standalone configuration. The standalone arrangement is based on separating the two three-phase CSIs so that each one of them is supplied from a different dc-dc converter. To the authors' best knowledge, the different configurations (parallel, cascaded, and standalone) CSI have not been appropriately studied for the EV applications yet. This paper has studied the selection of the most appropriate configuration that comprises both conversion stages (dc-dc converter and six-phase CSI).

The objectives and research contributions are summarized in the following points:

- A Proposal of three different configurations of six-phase CSI-based powertrains is made in dedicated subsections, including all the stages of the powertrain from the battery to the motor.
- A detailed case study with comparison is presented and followed by a discussion about which configuration is the most suitable for the application of HDEV.

This paper is organized in the following manner. An overview of the three-phase CSI-based powertrains is presented in section II. Section III proposes and studies the parallel, cascaded, and standalone configurations, including their structure, modulation, and sizing of components. Then, a comparative analysis is performed in the form of a case study in section IV. The experimental results are shown in section V. Finally, the conclusion section summarizes all the findings and presents the authors' take on which topology is the best fit for the mentioned application.

II. OVERVIEW OF THE THREE-PHASE CSI-BASED POWERTRAINS

A. STRUCTURE

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



FIGURE 1. Common CSI-based three-phase powertrain structure.



FIGURE 2. Possible switching states for three-phase CSI.

level should be considered to achieve the required dc-link current levels flowing in the dc-choke. Afterward, the power is delivered to the motor by the CSI with the filtering capacitors at the output.

B. MODULATION

The modulation of three-phase CSI is covered as a step before extending it into the details of the six-phase topologies.

1) THREE-PHASE CSI

SVM modulation of three-phase CSI has been established previously, as in [24] and [25]. The main rules that must be fulfilled while operating CSIs are listed here as:

- The output currents of the inverter must be defined regardless of the nature of the connection of the load.
- The dc-link current cannot be interrupted due to switching actions.

Based on these rules, only two semiconductor switches out of the total number of switches connected to the same dc-bus can be turned on per switching cycle. Hence, the allowable switching states are nine (6 active + 3 null). As shown in FIGURE 1, a three-phase CSI is implemented by six switches $(S_1 \text{ to } S_6)$. The mapping of the output currents produced by the possible nine combinations using the Park transformation from the original three-phase frame to an equivalent two-axis frame is shown in FIGURE 2 [24]. The calculations of the dwelling times can be done using [25].

2) DC-DC CONVERTER OPERATION

Based on the structure of the dc-dc converter, four switching states can be applied. The four states are shown in FIGURE 3, with the path of the current colored in red. The first possible



FIGURE 3. Possible switching states for dc-dc converter. (a) Battery discharging mode. (b) Battery charging mode. (c) Free wheeling mode. (d) Free wheeling mode.

state is achieved by turning on S_a , and S_b switches simultaneously, as shown in FIGURE 3(a). In this state, the chopper voltage V_b that appears at the terminals of the converter equals the battery voltage V_{dc} . This mode is often called the motoring mode. The power flows from the supply to the inverter side in this mode. Another state can be activated by turning off both switches, forcing the two diodes to conduct and returning the dc-link current back to the battery, as shown in FIGURE 3(b), which is called the regenerative mode. The power flows from the inverter side to the battery to cause a charging action in this mode. FIGURE 3(c), (d) represents a freewheeling state. The battery is disconnected in this mode, and the dc-link current freewheels on the side of the inverter. The chopper converter output voltage is described in III as a function of the switching states of the two switches, S_a and S_b .

$$V_{\rm b} = (S_{\rm a} + S_{\rm b} - 1)V_{\rm dc} \tag{1}$$

III. NEW CSI-BASED POWERTRAIN CONFIGURATIONS

The three new proposed configurations are introduced in this section. The structure, modulation, stresses, and sizing of the semiconductors are aspects of the study of each proposed configuration. The considerations regarding the dc-link



FIGURE 4. New powertrain configuration based on six-phase parallel CSI. (Configuration 1.)

inductor and simplified selection criteria are developed in the subsection of stresses and sizing in the P-CSI configuration and then followed to deduce the stresses for the other configurations in their dedicated sections.

A. PROPOSED PARALLEL CSI (P-CSI) POWERTRAIN CONFIGURATION (CONFIGURATION 1)

1) STRUCTURE

The two-three phase inverters CSI1 and CSI2 are connected in parallel in this configuration, as shown in FIGURE 4. The six legs of the inverter are all connected to the same dc-link terminals in this topology, which means that one dc-dc converter is needed to provide the dc current source. In this topology, the six phases of the motor can be connected in two arrangements: either the two isolated neutral points or the single isolated neutral point. However, the modulation scheme should control the zero-sequence currents in the single neutral point arrangement.

2) MODULATION

Two approaches can be used to apply SVM to six-phase inverters, namely, the vector space decomposition (VSD) [26] method and the vector classification technique (VCT) [27]. The VCT method is adopted in this context for its simplicity in implementation. Following the abovementioned rules, just two out of the twelve switches in the six-phase inverter can be turned on per switching cycle. Consequently, there are only $2^6 = 36$ available combinations for this type of six-phase topology. Out of the 36 possibilities, 18 states (12 active + 6 null) represent a separate operation of the two CSIs by turning on two switches from the same three-phase CSI wholly and only turning off the other CSI.

These 18 states have an advantage over the other remaining available ones because selecting between these states prevents the problem of compensating for zero sequence components. The problem originates from the fact that while operating two phases from two different CSIs, only one phase is activated during the switching cycle in each three-phase group leading to possible zero sequence components. For this reason, these 18 states are selected, which in principle represent duplicating the available states in the three-phase case.

3) STRESSES AND SIZING

In this subsection, the stresses of the inverter semiconductors are analyzed first, followed by the dc-link inductor and chopper converter discussion. An assumption is implemented here that either the phase current or voltage ratings are halved in six-phase systems compared to three-phase counterparts while both systems have the same power rating.

The stresses of the semiconductor switches of the inverter in P-CSI can be deduced from its operation. The switch onstate current stress is the same as the dc-link current since no current split occurs in CSI at any switching state. Since only one CSI can be turned on at a time during each modulation cycle, the utilization of the dc-link current in the P-CSI is halved compared to the three-phase CSI. This point is crucial regarding the sizing of the whole powertrain components that employ the P-CSI. For the six-phase systems running at half the current rating of their equivalent three-phase counterparts, the dc-link current required in P-CSI is equal to the same as the one needed in the three-phase case.

The blocked voltage stress is considered the voltage that appears between the terminals of the turned-off semiconductors during the states of operation. For the turned-off switches of the legs that have other turned-on switches, The appearing voltage is the load line-to-line voltage (V_m) which is the difference between the phase voltage associated with that leg and the phase voltage associated with the other active leg. Meanwhile, the switches in the legs that do not have any active switches share the line-to-line load voltage. For example, the switching state I_2 is applied to CSI₁ as shown in FIGURE 5 to show the voltage and current stresses. According to Kirchhoff's Voltage Law (KVL), The Stresses on switches S_2 and S_5 , the off switches in the active legs, equal the dc-bus voltage. Meanwhile, the stresses on switches S_7 and S_8 , switches of an inactive leg, share the dc-link voltage as $V_{S_7} + V_{S_8} = V_i$. It can be easily deduced also that the dc-link voltage is equal to the line-to-line voltage as $V_i = V_{A_1C_1}$. Based on the analysis, the highest possible blocked voltage that can appear across any switch is the maximum value of the line-to-line load voltage.

The chopper converter operates to compensate for the switching nature of V_i (is the voltage that appears across the input of the CSI). The blocked voltage stress for all the



FIGURE 5. P-CSI operating in the switching state I_2 { S_1 + S_6 } for CSI₁ as an example to show the voltage and current stresses.

semiconductors of the chopper converter is the battery voltage. At any switching state, the two devices conducting are connecting the battery to the output terminals. Meanwhile, the current stress is still the dc-link current.

The inductor coil must withstand the dc-link current and the maximum expected ripple current regarding the dc choke. In addition, the inductance of the choke and the controllers tuning determine the current ripples in the dc-link current. Furthermore, the average inductor current should follow a dc reference with minimal current ripples at a certain steady-state operating point, assuming properly tuned controllers and ideal conditions. Hence, it is vital to choose a minimized inductance value so that the ripples are within an acceptable range and the cross-sectional area of the wiring of the choke coil and the overall size of the choke is also acceptable. To develop a simplified selection method, the voltage equation of the inductor is shown in terms of the CSI's input and chopper converter's output voltages as in (2).

$$V_{\rm L} = V_{\rm b} - V_{\rm i} = L \frac{dI_{\rm dc}}{dt}$$
(2)

Since the voltage V_i varies over time due to the switching actions nature of the CSI, compensation is applied from the chopper converter at the other side of the dc choke voltage so that a zero-average voltage of $V_{\rm L}$ can be achieved each sampling period. Hence, the excitation part, the left side of Eq (2), can be minimized, and the change in the dc-link current is minimized. This rule maintains the current level of the dc-link. Hence, the choke's inductance should have a high enough inductance to suppress the current ripples accompanying the dc-link current. The ripples are generated because the voltages $V_{\rm b}$ and $V_{\rm i}$ are not equal instantaneously. They are equal over a sampling period T_s as the controller attempts to make the average appearing voltage $V_{\rm b}$ is equal to V_i at each sample. The criteria chosen in this context is a simplified approach to picking an appropriate value of the choke's inductance. The discretized version of (2) is shown in (3) and rearranged to get the expression for calculating the inductance.

$$V_{\rm L}(k) = V_{\rm b}(k) - V_{\rm i}(k) = L \frac{\Delta I_{\rm dc}(k)}{T_{\rm s}}$$

And after rearranging:

$$L = \frac{V_{\rm b}\left(k\right) - V_{i}\left(k\right)}{\Delta I_{\rm dc}\left(k\right) f_{\rm s}} \tag{3}$$

In the next section, the case study of the proposed powertrains, some assumptions are made, and Eq. (3) is employed after modifications to estimate the inductance required for proper operation.

An important note is that the battery voltage should be at least high enough as the highest possible voltage that can appear as V_i . From the analysis of the P-CSI stresses earlier, the voltage V_i is equal to the line-to-line voltage, which depends on the switching state of the P-CSI. Hence the battery voltage must be equal to or greater than the maximum of the line-to-line voltage of the motor without applying boosting capability [4]. The blocked voltage stress for all the semiconductors of the chopper converter is the battery voltage. At any switching state, the two devices conducting are connecting the battery to the output terminals. Meanwhile, the current stress is still the dc-link current.

B. PROPOSED CASCADED-CSI (C-CSI) POWERTRAIN CONFIGURATION (CONFIGURATION 2)

1) STRUCTURE

In the C-CSI topology, the two three-phase inverters are connected in cascade as shown in FIGURE 6 and fed from a single dc-dc converter. The dc-current flows from CSI_1 and the load group abc_1 , then to CSI_2 and group abc_2 , then back to the supply. By connecting the two CSIs in this configuration, higher dc-link voltages can be maintained. Unlike P-CSI, the six-phase load cannot be connected in a single neutral configuration for proper operation reasons, as explained later in the modulation section.

2) MODULATION

In the C-CSI topology, the two CSIs are connected in a cascade, allowing the current to flow from one group (CSI and load) to the other, resulting in more than two legs operating simultaneously. The upper CSI does not disrupt the operation of the lower CSI and vice versa if the dc-link current is not interrupted at the coupling point P, as shown in FIGURE 6. All the possible nine states of three-phase CSI can be applied to both inverters CSI1 and CSI2, enabling the opportunity to maximize the utilization of the dc-link current. FIGURE 7 illustrates the difference in the modulation strategies between P-CSI and C-CSI for better understanding. A modulation method adopted from the VCT of VSI is presented and discussed in [1], where the two inverters are operated based on the realizing two references displaced by 30°. The SVM switching patterns are optimized to minimize the dc-link current ripples between the ac rectifier and motor side inverter.

3) STRESSES AND SIZING

The current stress is similar across all the switches in all the CSI topologies, which are equal to the dc-link current.



FIGURE 6. New powertrain configuration based on six-phase cascaded CSI. (Configuration 2.)



FIGURE 7. Time diagram to show the key difference between the modulation of P-CSI and C-CSI.

However, two essential points must be highlighted here. First, the dc-link current required in the C-CSI topology is half the value of the one in the P-CSI case. Secondly, the conduction time of each semiconductor is increased compared to the P-CSI case since both CSIs have switches turned on all the time. Consequently, the reduced current stress and increased conduction instants affect the conduction loss, resulting in approximately the same power loss as P-CSI. Regarding the blocked voltage on the inverter switches, like the P-CSI, the turned-off switches of the C-CSI must withstand the line-to-line voltage of the active phases in each CSI. For example, if switching state I_2 is applied to CSI₁ and I_6 to CSI₂, V_{s2} becomes equal to V_{A1C1} , and V_{s2} equals V_{C2B2} , as shown in FIGURE 8.

Regarding the dc-dc converter, the switches must withstand the dc-link current, which is reduced to half compared to the P-CSI case. The blocked voltage is the same as the battery voltage V_{dc} , which is different in the case of C-CSI. Following the evaluation done in the P-CSI section, the battery voltage must be at least equal to the highest instantaneous value of V_i . The voltage V_i is the summation of the two voltages resulting in the input of both CSI₁ and CSI₂, V_{i1} and V_{i2} , respectively. Both V_{i1} and V_{i2} are equal to the line-to-line voltage of their corresponding CSI. The highest possible V_i can be calculated by summing one phase from group 1 with the three possible voltages from group 2 individually since the



FIGURE 8. C-CSI operating in the switching state I_2 { $S_1 + S_6$ } for CSI₁ and I_6 { $S_5 + S_4$ } for CSI2 as an example to show the voltage and current stresses.

other combinations will give similar results, just different in phase shift. For example, considering line voltage $V_{A_1B_1}$ from the first group, the three possible combinations are shown in FIGURE 9 with the aid of phasor diagrams. The phasors are drawn assuming that the line voltage $V_{A_1B_1}$ is the reference and the other voltages are at the same magnitude and shifted in time by the correct phase shift in asymmetrical six-phase systems. Apparently, the highest combination in magnitude is the one between voltages $V_{A_1B_1}$ and $V_{A_2B_2}$.

It is worth mentioning that this deduction is subject to the power factor angle and the switching instants. From a design perspective, the worst-case scenario must be taken into consideration. The occurrence of the maximum value $1.932 |V_{A_1B_1}|$ is dependent on the coincidence between two events. One event is that the voltage V_i is at its peak value. The other is when the same active switching states are applied to both CSIs. Consequently, the battery voltage and the semiconductor devices must be designed to be at around double the level employed in P-CSI. The choke inductor design is also affected by this change.



FIGURE 9. Phasor diagram of the summations of line voltages V_{A1B1} and $V_{A2B2}, V_{B2C2}, V_{C2A2}.$

C. PROPOSED STANDALONE-CSI (S-CSI) POWERTRAIN CONFIGURATION (CONFIGURATION 3) 1) STRUCTURE

Unlike in P-CSI and C-CSI, the two three-phase CSIs are fed from one dc-dc converter, and they are supplied separately from a dedicated dc-dc converter as in FIGURE 10. The benefits of this variation are getting a similar dc-link current utilization as the C-CSI while eliminating the requirement almost to double the system's battery voltage to ensure proper operation of the dc-dc converter. The separation of the two inverters makes the only possible configuration of the load connections is the two isolated neutral points as in the C-CSI. In this topology, the two dc-dc converters can be connected to a separate dedicated battery pack or both converters to one main battery pack. However, this point is not covered in this context.

2) MODULATION

The modulation of the S-CSI is dependent on the dc-link currents to be adequately controlled. Assuming the two currents are held at the same level as in the C-CSI case, the exact strategy applied to the C-CSI topology can be used in the S-CSI. The current level needed for both converters would be equal to the one in the C-CSI, which is half the three-phase case. The controllers of the dc-dc converters work separately based on the measurements of the two dc-link currents. The possibility to operate at different levels of dc-link currents is not covered in this context.

3) STRESSES AND SIZING

The current stress in the two CSIs is the same as in the C-CSI case, as the same dc-link currents are assumed to be achieved for a proper operation. The blocked voltages are again the same as the C-CSI since, in any active case, the maximum blocked voltage is the line-to-line voltage which is the difference between the phase voltage of the two active phases. As for the dc-dc converters, the current stresses are the same as in the case of the C-CSI powertrain. However, the blocked voltages are different since, in this case, the two CSIs are separated. The separation results in lower values of the voltages V_{i1} and V_{i2} compared to the C-CSI case. Each

input voltage to the two CSIs, V_{i1} and V_{i2} , is equal to the line voltage correspondent to the applied active switching states. Unlike the C-CSI configuration, these two voltages are not summed up. The two dc-dc converters compensate them for maintaining the currents I_{dc1} and I_{dc2} with minimum ripple currents. Consequently, the required level of the battery voltage is the same as in the three-phase and P-CSI cases.

This configuration has mixed merits from the P-CSI and C-CSI simultaneously. Still, the increased number of components might come across as a concern regarding the power density of the powertrain. However, a critical remark that must be highlighted while comparing all the configurations is the sizing aspect. Since the stresses on the semiconductors are the lowest overall compared to P-CSI and C-CSI configurations, the need to connect switches in parallel or series to withstand specific stresses is eliminated. Instead, the same number of semiconductors can be used and controlled separately. This approach is better from a control and operation perspective because turning on and off switches in series or parallel has many problems. These problems arise from the difference in the characteristics due to the manufacturing processes and the gate drivers. These differences result in non-concurrent timings of turning on/off actions and the load sharing difference between the connected devices resulting in a challenging thermal management design to account for these problems.

IV. CASE STUDY

This study compares the proposed configurations with the three-phase one, considered the benchmark. An eight-pole PMSM rated at 150 kW peak power is used as the traction motor. The motor is rated at 250 V line voltage (V_m) , 175 A phase currents (I_m) to develop 244 N.m torque at 1200 RPM base speed. The assumptions made to size all the components in the powertrain are enlisted as follows:

- 1) The sizing in all the configurations should accommodate the power levels required by both supply and load sides so that every stage can work properly.
- Every component is selected to withstand 150% to 200% (or the following rating of commercially available modules) of the voltage and current stresses.
- Maximum dc-link ripple currents are at 10% of the average dc current (*I*_{dc,av}).
- The switching frequency for the chopper *f_{s,Chopper}* and CSIs *f_{s,CSI}* in all configurations are fixed to 50 kHz and 10 kHz, respectively.
- 5) The maximum inductor voltage is selected based on the maximum value of the inverter input voltage ($V_{i,max}$) that can occur while applying $V_b = 0$.
- 6) The filtering capacitors are the same in all the configurations since the selection is based on fixed features such as motor characteristics and the switching frequency of inverters.

The sizing methodology starts by assessing the motor needs and accommodating them from the CSI side. Then, the



FIGURE 10. New powertrain configuration based on six-phase standalone CSI. (Configuration 3.)

TABLE 1. Comparison between three-phase CSI, P-CSI, C-CSI and S-CSI.

		Three-phase CSI	P-CSI	C-CSI	S-CSI
Battery	Voltage	400 V	400 V	800 V	400 V
Chopper		(4 IGBTs + 4 diodes)	(4 IGBTs + 4 diodes)	(4 IGBTs + 4 diodes)	(4 IGBTs + 4 Diodes)
	Components	Each 2 IGBTs/diodes are connected in parallel	Each 2 IGBTs/diodes are connected in parallel	Each 2 IGBTs/diodes are connected in series	Each 2 IGBTs/diodes form a separate chopper
	Ratings	600 V, 400 A	600 V, 400 A	600 V, 400 A	600 V, 400 A
DC-link Choke	Current	500 A	500 A	250 A	250 A
	Inductance	$140\mu\mathrm{H}$	140 µH	532 μH	$2 \times 280 \mu\mathrm{H}$
	Insulation	1 kV	1 kV	2 kV	1 kV
Inverter	Components	12 RB-IGBTs	24 RB-IGBTs		12 RB-IGBTs
		Each 2 IGBTs/diodes are connected in parallel	Each 2 IGBTs/diodes are connected in parallel	12 RB-IGBTs	
	Ratings	600 V - 400 A	600 V - 400 A	600 V - 400 A	600 V - 400 A
AC filter	Total Capacitance	30 µF	60 µF	60 µF	60 µF

dc-link requirements and finally the dc-dc converter side. The dc-link current and the battery voltage must be appropriately selected to deliver power to the motor at the rated values. Starting with the dc-link current, the utilization limits that have been discussed earlier are employed in this section. For P-CSI, the dc-link current must be at least double the value of the maximum rated motor current ($2\sqrt{2} I_{ph} = 500A$). However, for C-CSI and S-CSI, the required dc-link value must be at least ($\sqrt{2} I_{ph} = 250A$).

The battery voltage is discussed in the previous section, and the required voltages are at least $(2\sqrt{2}V_m = 707V)$ for the C-CSI case while $(\sqrt{2}V_m = 353V)$ are sufficient for the P-CSI and S-CSI. Hence, the selected voltages are 800 for the C-CSI and 400 for both the P-CSI and S-CSI. Based on assumptions (1) and (2), the sizing for the IGBTs for the CSI in every configuration is shown in TABLE 1. All the cases use the same ratings for fair comparison based on the required number of switches. As illustrated in TABLE 1, the lowest overall stresses on the inverter switches are associated with the S-CSI configuration. The ratings selected can completely withstand the stresses of the S-CSI, and in all the other cases, the stresses are higher than the selected ratings. Consequently, an increased number of switches is required in all the other configurations. The stresses in the other configurations, such as the three-phase case, are twice the rating of the selected current rating of the switches, so every two switches are connected in parallel. The exact sizing is applied to the P-CSI case since the same current stress is unavoidable.

The voltage ratings of all the switches are based on the maximum line-to-line voltage of the motor. The filtering capacitors are appropriately selected to avoid placing the resonance effect with the motor inductances at the fundamental harmonic. The leakage inductance per phase for the model is at 10 μ H. The capacitance is selected to place the resonance

effect at the 12th harmonic resulting in a 10 μ F per phase based on (4) [28].

$$C_f = \frac{1}{\left(2\pi f_{res}\right)^2 L} \tag{4}$$

Regarding the dc-link inductor sizing, the selection requirements are the minimum inductance to meet the assumptions, withstanding the maximum instantaneous and average dc-link current and insulation level higher than the voltage stress across the inductor. Building on Eq (3), the selection of the dc-link inductor is executed based on (5) accounts for assumptions (3), (4), and (5).

$$L = \frac{10V_{\rm i,max}}{I_{\rm dc,av}f_{\rm s}} \tag{5}$$

The inductance values are stated in TABLE 1 and the lowest values are achieved in the P-CSI and three-phase cases. However, a higher ampacity rating is required for both cases since the dc-link currents must be 500 A. The maximum instantaneous current is around 550 A in the worst-case scenario since 10% ripple currents are assumed to be achieved. As for the C-CSI, higher possible instantaneous dc-link inverter voltage results in a higher inductance value to maintain the same ripple current constraint. The S-CSI has a lower inductance value per dc-link; however, two inductors are required.

The dc-dc converter switches are sized based on the stresses determined by the voltage battery and dc-link current. Both the three-phase CSI and P-CSI cases have the exact sizing. Four switches and four diodes are used to implement one dc-dc converter by paralleling every two semiconductors to withstand the current stress. Meanwhile, the dc-dc converter in the C-CSI case is comprised of the same number of switches and diodes, but every two are connected in series to withstand the voltage stress. The S-CSI has two dc-dc converters. Each one is implemented by two switches and two diodes with ratings stated in TABLE 1.

An evaluation of the power loss of the three configurations is done using PLECS software. A model is built based on the reverse-blocking IGBT (RB-IGBT) module from Fuji (FGW85N60RB) to implement the CSI in the three configurations. The output load consumes 1.5 kW at a power factor of 0.85 lagging and the temperature of the inverter is kept at 125 °C. The parameters of the module are extracted from the datasheet of the RB-IGBT module and fed to the model in the PLECS environment. The parameters of the system are described in TABLE 2.

The models have different dc-link current values based on the maximum modulation index results obtained in the previous subsection. The results of the conduction $P_{\rm cd}$, switching $P_{\rm sw}$ losses, and efficiency η of running the models at maximum modulation index are shown in TABLE 2.

Regarding the overall efficiency, the C-CSI and the S-CSI score similar efficiencies. Meanwhile, the P-CSI falls behind the other topologies because of the increased switching losses as mentioned in subsection III A.2. In terms of conduction

TABLE 2. Parameters of the C-CSI power loss simulation models.

Symbol	Parameter	Value
V _{T,IGBT}	IGBT Threshold voltage	6.5 V
$r_{\mathrm{T,IGBT}}$	IGBT slope resistance	$18 \text{ m}\Omega$
$P_{\rm out}$	Output power	1.5 kW
pf	Power factor	0.85
Tj	Junction temperature	125 °C

TABLE 3. Results of the C-CSI power loss simulation models.

	P-CSI	C-CSI	S-CSI
I _{dc}	8 A	4 A	4 A
$P_{\rm cd}$	38.2 W	37.1 W	36.54 W
$P_{\rm sw}$	22.8 W	11 W	8.55 W
η	95.93 %	96.8 %	97 %



FIGURE 11. The experimental setup to test the proposed scheme.

losses, the three configurations are at almost the same level. The higher number of active switches in the C-CSI and S-CSI opposes the higher dc-link level in the P-CSI.

The modulation of P-CSI necessitates a higher number of switching transitions compared to the other configurations which reflect the switching losses. Furthermore, the higher dc-link requirements reflect on the conduction loss as well. However, quantitatively, the difference in efficiency is not significant between all the modulation schemes.

V. EXPERIMENTAL RESULTS

A. EXPERIMENTAL SETUP

A scaled-down prototype is used for the experimental test, as illustrated in TABLE 4, to verify the feasibility of the proposed configurations. The dc-dc converter is implemented using the IGBT modules PM50RL1A120 from Mitsubishi rated at $V_{ces} = 1200V$ and $I_c = 50A$. Two switches and two diodes are utilized to implement the dc-dc converter from each module. A six-phase C-CSI is implemented by six half-bridges SKM50GB12V IGBT modules connected to



FIGURE 12. Experimental results of the P-CSI configuration at motor speed = 350 rpm at load torque = 31.6N.m.



FIGURE 13. Experimental results of the C-CSI configuration at motor speed = 350 rpm at load torque = 31.6N.m.

SKHI 22 A/B H4 gate drivers from Semikron. The reverse blocking is achieved by connecting each half-bridge to a DSEI2x31.06C diode module one diode to clamp each IGBT to the positive and negative rails. A LAUNCHXL-F28379D digital signal processor generates the firing signals. A sixphase IPMSM is used as the load in the experiment. The parameters of the motor are enlisted in TABLE 4.

The motor in the experiments is operated at 350 rpm, which is the same load torque of 31.6 N.m. The dc-link current is set to 8A for the P-CSI case and 4A for C-CSI and S-CSI. The dc voltage is set to 200V for the P-CSI and S-CSI cases and 400V for the C-CSI case. The loading is achieved by coupling the motor mechanically to a belt starter generator (BSG) from D&V Electronics (model: HT-250). The BSG also regulates



(g) Motor phase currents.

(h) Harmonic Spectrum of motor phase current I_{a1} .



TABLE 4. Parameters of the motor load.

Symbol	Parameter	Value
P_n	Rated power	3 kW
T_n	Rated torque	70 N.m.
ω_n	Rated speed	405 rpm
Р	Pair of poles	17
R_s	Stator resistance	1.3 Ω
L_d	D-axis inductance	13.576 mH
L_q	Q-axis inductance	13.926 mH
L_{xy}	xy inductance	4.076 mH
ψ_d	PM flux	0.156 Wb
f_s	Switching frequency	10 kHz
C_f	Filtering capacitor	10 µF

the dc-supply by providing a battery emulator. The motor is controlled using FOC, and the operational mechanical point is kept the same to validate and compare the proposed configurations. The D&V Pro software sets the dc-supply voltage and the loading torque.

B. EXPERIMENTAL RESULTS

The motor runs at 350 rpm for the three configurations, meeting a load torque requirement at 31.6 N.m. by adjusting the dc voltage and dc-link current values. In the P-CSI topology, the dc-link current is set to 8A since the dc-link utilization is limited to half the full range. The results acquired for the P-CSI configuration are shown in FIGURE 12. The speed and torque of the motor are shown in FIGURE 12 (a). The speed is settled around the reference point 350 rpm. The dc-link current Idc and the inverter output i_{A1} are illustrated in FIGURE 12 (b), which shows that the dc-link current is regulated at 8A, and the ripples are minimized. The buck voltage V_b and the inverter dc-link voltage V_i , i.e., the voltages before and after the dc-link inductor, are presented in FIGURE 12 (c). The buck converter attempts to counter the voltage across the inductor so that the dc-link current remains



FIGURE 15. Experimental results of step loading in the P-CSI configuration.

constant. The results emphasize that this operational point could only be achieved by setting the dc-link current and battery voltage to the values mentioned earlier. The motor phase currents $(i_{a1}, i_{b1}, i_{a2}, i_{b2})$ and phase voltages $(v_{a1}, v_{b1}, v_{a2}, v_{b2})$ are presented in FIGURE 12 (d) and (e). The currents and voltages are nearly sinusoidal and are at the correct phase shifting in asymmetrical six-phase loads. The harmonic spectrum of phase current i_{a1} is shown in FIGURE 1(f). It shows small harmonic magnitudes except for a small spike at the resonance frequency.

Regarding the C-CSI, the battery voltage is changed to 400V, and the dc-link current is set to 4A. The speed and torque, in this case, are shown in FIGURE 13(a). They are similar to the P-CSI case for a fair comparison. The dc-link current and inverter phase currents for phase A1 are shown in FIGURE 13 (b), and the difference in the C-CSI case is that the current is fixed at 4A, which can be fully utilized for the motor currents. The second difference is the level of the inverter voltage that appears in this configuration which is higher as analyzed in earlier sections. The voltages before and after the inductor are shown in FIGURE 13 (c) which confirms that a higher battery voltage is necessary to compensate for the inverter dc-link voltage, which can be at almost double the line-to-line voltage. The motor phase currents and voltages are shown in FIGURE 13 (d) and (e), and they are at the same level as the ones from the P-CSI but at half the value required for the dc-link. The FFT analysis shows that the phase a_1 current and the spectrum show low harmonic content.

Regarding the S-CSI, the mechanical conditions are satisfied as in the previous cases as shown in FIGURE 14(a). The





(b) Motor phase currents.

FIGURE 16. Experimental results of step loading in the C-CSI configuration.



(b) Motor phase currents.

FIGURE 17. Experimental results of step loading in the S-CSI configuration.

setting of the dc side in the S-CSI configuration is modified to be 200 V for the battery and 4A to the dc-link current. FIGURE 14 (b) and (c) show both groups' dc-link currents and inverter currents. The figures show that the results are similar to the other configurations. However, the results of the two dc-dc converters are different in this case, as shown in FIGURE 14 (d) and (e). The dc-link currents are regulated efficiently by the two dc-dc converters. At the same time, FIGURE 14 (f) and (g) show the motor phase voltages and currents. Low harmonic content is shown in FIGURE 1 (h) coinciding with the sinusoidal phase currents.

The three configurations are tested against step loading to show the system dynamics. A load torque change from 15 N.m. to 25 N.m. at the same speed reference 350 rpm. The results for P-CSI, C-CSI, and S-CSI are shown in FIGURE 15, FIGURE 16, and FIGURE 17, respectively. The speed and torque are shown in part (a) of the figures and the motor currents in part (b). The figures show that the step loading affects the speed of the motor for a short period then quickly recovers to meet the reference. The torque production of the motor is increased during the transition to account for the sudden load and then settles at the mechanical equilibrium. From the comparison of the transient response, the P-CSI configuration has the slowest dynamics, and both the C-CSI and S-CSI are relatively faster. The best torque ripples performance is achieved at the S-CSI configuration compared to the other ones.

VI. 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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