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Modular Motor drives for Permenant Magnet Synchronous Motors, an Overview

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Abstract— Permanent magnet synchronous machines (PMSMs) have got a wide range of application in different power ratings and different reliability levels required. To satisfy the requirements for a wide range of the applications, while increasing the system reliability and power ratings and decreasing the weight, cost and repair time, modular motor drives for PMSMs could play an important role in improving the maturity of the technology. However, parallel operation of motor drives will introduce other challenges to the system, some of which will increase the power losses and reduce the system efficiency. There have been some solutions for similar issues in the literature, but not all of them can be applied in PMSM drive applications for the limits associated with specific applications. So, in this paper, a throughout review has been performed on solutions to mitigate the parallelization challenges which is accompanied by relative stability analysis for software-based methods.

***Index Terms*—Modular motor drives, Permanent Magnet Synchronous Motor (PMSM), zero sequence circulating current (ZSCC), synchronous reference frame control method**

I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) have become very popular motors in industrial and transportation applications for its unique characteristics. PMSMs offer higher efficiency, higher power density, higher reliability, increased service life, reduced rotor inertia (which leads to quicker dynamic response), reduced size and weight and requiring nearly no maintenance during the entire operational period. Simpler control compared to other AC motors such as induction motors, switched reluctance motors, etc., is another merit that makes PMSMs more popular for industry and transportation specially where adjustable speed characteristics are required. Previously application of PMSMs was limited to some specific applications because of the higher manufacturing cost of these motors, which was due to using expensive magnetic material with higher values of specific magnetic properties, but as the prices for those material are decreasing, PMSMs are dominate in most of the applications [1-3].

Various control methods have been applied to control the PMSMs to have a smooth torque and speed control, including different variants of vector control methods, proportional integral (PI) control method, fuzzy logic controller, sliding mode control methods, etc. [4-7]. Since PMSMs are mostly associated with higher efficiency and higher reliability applications, where loss minimization and redundancy play a significant role, these characteristics should be considered while selecting a controller for different applications. Some of the industrial applications, require PMSMs with higher power ratings, and respectively higher rated motor drives. Higher capacity PMSMs, cover a wide range of critical industrial and transportation applications, where reliability, weight, and capability of redundancy is of an important significance. To increase the motor drive system reliability, redundancy and to enable the plug & play maintenance characteristics, modular motor drives for which a high-level scheme is shown in Fig. 1, could be an alternative to bulky stand-alone drives.

Although modularity offers considerable amount of reliability, redundancy, lower total system weight, lower maintenance cost, and other advantages, it might also introduce some new issues to the motor drive system. Parallel operation of modular power electronic drives, as shown in Fig. 1 requires considerations on accurate power sharing between modules, circulating current and communicational links, otherwise some new challenges will be introduced to the system.

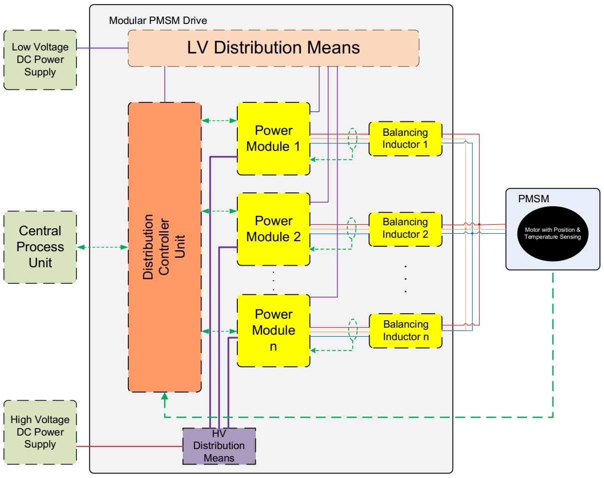

Fig. 1. A high-level scheme of modular motor drive system for PMSMs

II. INVERTER PARALLELIZATION ISSUES

If the power sharing is not performed accurately, it will cause issues for the parallel modules such as unbalanced aging of devices, decreasing the efficiency and the reliability of the entire system while increasing the overall power losses. There are several different control methods, which has been utilized to share the power between parallel inverters. These methods could be classified to two main categories of communication dependent and communication independent methods. Communication independent methods mostly include different

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variants of droop controllers, which can help the system operate autonomously. The conventional droop controller has issues of not being capable of accurately sharing the power, slow transient response, poor harmonic power sharing, and lack of black start up capability. Although, researchers have proposed different variants of droop control methods to cover mentioned drawbacks, these methods are still not the preferred option for accurate power sharing applications such as motor drive applications. Droop controllers are mostly applicable to applications in which absence of critical communication link comes prior to accurate power sharing such as different AC microgrid applications capability [8-12]. Other control approaches applied to parallel operation of inverters are dependent on communicational links to different extents. These methods include, centralized control methods, current chain controller, model predictive control, average load sharing, master-slave control methods, hierarchical control approaches etc. [8, 13-17]. The control method for each application could be selected based on the requirements of the application, and capabilities of the method.

The second important issue in parallelizing the inverters for motor drive applications, is the power loss generated by circulating current between parallel inverters. As shown in Fig. 1, when inverters share a common DC link and a common AC output, the switching pulses for the parallel inverters are synchronized to accurately share the power between inverters, which have the exact same output voltages, if the hardware characteristics of the inverters are identical and the measurements and calculations are seamless. In real world scenarios, however, for different types of mismatches, measurement errors, and computational delays as categorized in Fig. 3, there would be differences in hardware characteristics of even the most identical inverters. The difference in hardware characteristics of the inverters or the other types of mismatches and measurement errors, will lead to a mismatch in output voltage of the parallel inverters. The difference in between output voltages of different inverters, will generate a circulating current in between inverters as shown in Fig. 2, which is called as the zero-sequence circulating current (ZSCC) [18, 19].

Presence of ZSCC, will create several issues for the parallel operation of inverters. For motor applications for instance, presence of the ZSCC, will create unbalanced current sharing between inverters, decreased torque quality, and increased loss in inverters and the balancing inductors which will finally lead to reduced system efficiency and reliability [18, 19].

The parameters impacting the difference in the output voltage can be categorized in four main groups as shown in Fig. 3, the built-in characteristics, device aging/environmental impacts, measurement accuracy and processor related issues. The difference between the built-in characteristics of the inverter hardware is very common, because of the manufacturing process faults, component design tolerances, device aging and impact of environmental conditions on the devices. These differences could be minimized by applying strict rules on component selection and operating the devices in controlled environmental conditions. However, the mismatches originated from processor issues and measurement accuracy are more challenging to and could not be easily avoided/mitigated.

To overcome the circulating current issue, there has been hardware solutions proposed, for which the options are to use single phase inductances between AC terminals of the parallel inverters, or interphase/common mode chokes at AC side of the inverters or isolating transformers on AC side of the parallel inverters which are discussed in details in sectionIII.A [19, 20]. The mentioned solutions are simple and cost effective but unfortunately not feasible in some of the applications for the weight limits or other concerns associated with the specific application.

The size of the inductance mentioned in the hardware solutions, is dependent on the switching frequency of the inverter and the value of the ZSCC. The first one is usually defined when designing the converter and based on the application requirements and could not be easily altered. However, if the ZSCC could be minimized by the control method based solutions, the value of the balancing inductor could be minimized to fit within the application related design limits [18]. Therefore, the other alternative solutions for mitigating the circulating current, which is through controlling the inverters in a modified way as in [18, 19, 21-25] have attracted attention of researchers. Different approaches for mitigating the ZSCC using control methods, (software solutions) are discussed in detail in section III.

This paper considers inverter parallelization for modular motor drive applications, therefore, the power sharing between inverters should have the accurate power sharing, and the black start up capability. In this regard, the preferred control methods can be selected from a range of communication-based control methods such as centralized control methods, slave-master or circular chain current control. To keep the scope of the paper, focused on mitigating the ZSCC, study of control methods for power sharing will be integrated into control solutions for ZSCC mitigation.

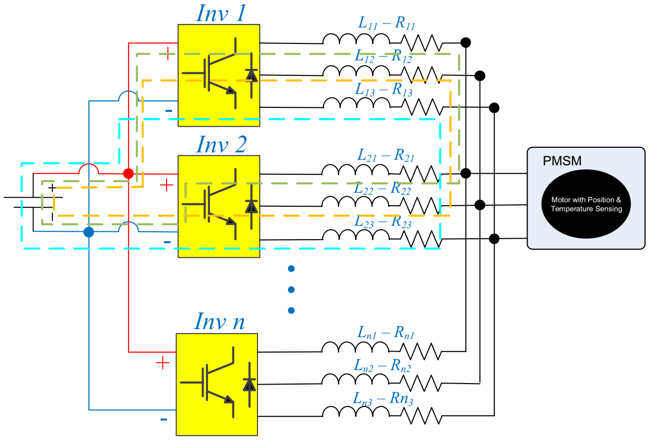

Fig. 2. ZSCC between two inverters operating in parallel

III. ZERO SEQUENCE CIRCULATING CURRENT MITIGATION METHODS

As mentioned in the previous section, to mitigate the ZSCC, there are hardware and software-based solutions, which could be utilized based on the specific application. Hardware solutions are usually simple to apply but they add weight to the entire modular system, and it might not be the preferred option

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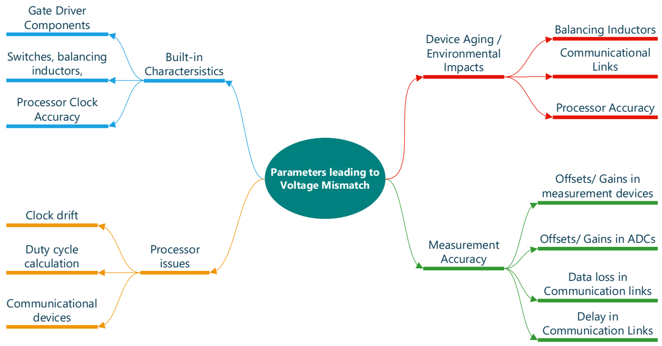

Fig. 3. Different Parameters leading to output voltage mismatch in parallel operation of inverters

for some applications but could be useful in others.

In this section, both hardware and software-based solutions will be discussed in detail, to have a better comparison on advantages and drawbacks of each.

A. Hardware based solutions for ZSCC mitigation

In the literature, there has been several approaches to mitigate the ZSCC using isolating transformers, and different configurations of the inductances. In this paper, there will be discussions on three different combinations of transformers to mitigate the ZSCC [20, 26, 27].

1) Multiple isolated transformer winding

In this configuration, as it can be seen in Fig. 4, a transformer is present on the AC side of the converters which can deal with ZSCC, and phase shifted harmonic components (originated from interleaved PWM signals). However, this is not the most efficient solution, but the efficiency could be improved if a higher value inductor is used in the converter side, which comes at a price of reduced transient response speed and increased system weight [26, 27].

2) Single phase inverter side inductor

Another topology of inductors for suppressing ZSCC is to use single phase inductors as the converter side inductors of the LCL filter, and to connect it to the load through a single input isolation transformer as shown in Fig. 5. In this approach, the volume and weight of three single phase inductors might be more than a single, three phase inductor. This architecture also has bigger amounts of power loss which could be reduced by increasing the value of the inductor which will decrease the transient response speed as well as increasing the DC voltage value. It is worth mentioning that the harmonic filtering inductors would not be effective in suppressing ZSCC. The advantage of this solution to multiple input transformer, is using a standard two-winding transformer [26, 27].

3) Coupled inductors / 3-phase inverter side inductors

The other hardware solution, as it can be seen in Fig. 6, is using coupled inductors to mitigate the ZSCC in parallel operation of inverters.

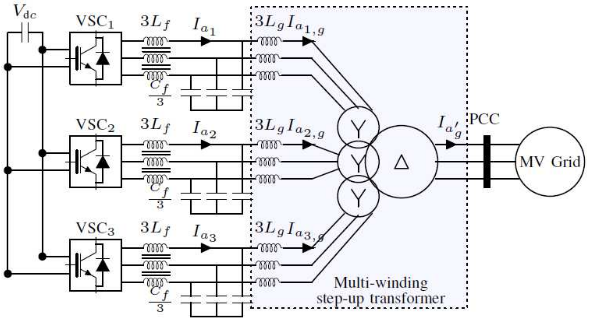

Fig. 4. Parallel-connected inverter using multiple isolated transformer windings [20]

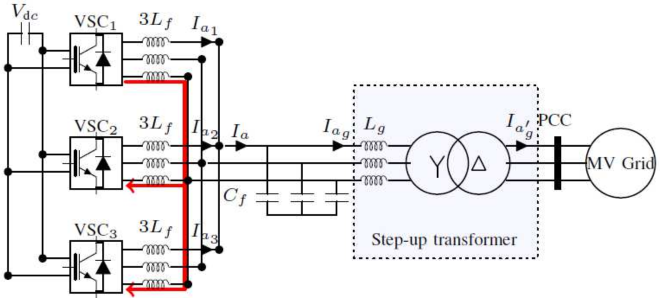

Fig. 5. Parallel-connected inverter with single-phase converter side inductor [20]

Coupled inductors can mitigate the ZSCC, but it would not impact the load current, consequently not impacting the DC voltage requirement. Therefore, there is no need to make the inductors bulky and reduce the transient response rate while increasing the system weight and cost. For the mentioned reasons coupled inductance-based solution also offers the minimum loss in between all three discussed hardware solutions.

B. Control methods for mitigating ZSCC (1st Method)

Different hardware solutions are reviewed in section III.A but since in most of the motor drive applications, system weight is a key factor, software-based solutions are prioritized in this paper. Software based solutions include the control methods which directly mitigate the ZSCC in parallel operation of Inverters by modifying the switching patterns of the inverters.

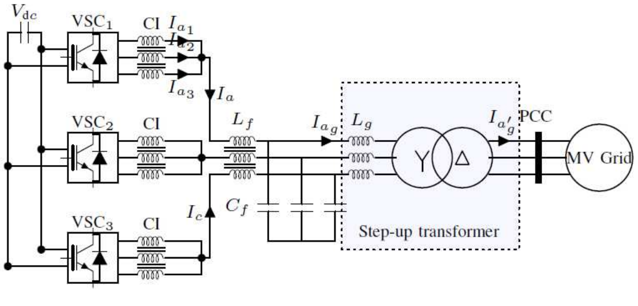

Fig. 6. Parallel-connected inverter three phase converter-side inductor [20]

There are several control methods which perform this task requiring different levels of communicational links, but for the comparison reasons, the control methods discussed in this paper are limited to two methods, one with high communication requirements and the other one less dependent on communicational links. The main difference in between two different methods discussed in this paper, other than the differences in the inner control loop details, is on the level of their dependency on communicational links.

1) Control method with least dependancy on communcation (1st Control method)

This control method is almost autonomous and does not require high band-width communication links. The control method is applied to the parallel PMSM drive configuration, is shown in Fig. 2. Applying the Kirchhoff law to the average model of the parallel system, reveals that the sum of ZSCC in the inverter AC side, is equal to zero [22].

$$\sum_{i=1}^{n} i_{gzi} = \sum_{i=1}^{n} i_{lzi} = 0 \qquad (1)$$

In which, $I_{Lzi} = I_{Lai} + I_{Lbi} + I_{Lci}$.

This equation, means that, in a parallel system of “n” inverters, controlling ZSCC in “n-1” inverters, is enough to control the ZSCC in all of them [19, 22, 23]. This is the concept summary for this control method. In this method, the output currents of three phases are measured in abc stationary frame, then it is converted to dq0 synchronous frame using park transformation [28] to make the analysis simpler.

Then the inner loop control, consisting of d, q and 0 axes are applied in the synchronous frame to obtain sinusoidal waveform in all inverters except for the first one which just has the d and q axis controllers. The mentioned controllers for 1st and n-1 inverters are shown in Fig. 7 and Fig. 8. The d, q reference for n-1 inverters could be either calculated using the dc voltage link loop in the controller of first inverter (as shown in Fig. 7) or could be fixed references which are pre-defined based on the number of parallel inverters. The first option requires a basic communication link, to transfer d and q frames reference values to the controller of each inverter. This control method in total uses 3n-1 PI controllers to control the motor while mitigating the ZSCC. The minimum dependency on communication and the modular nature are the merits of this control method.

To evaluate the relative stability of the control approach, a sensitivity analysis has been performed on five different factors that impact the stability of the control method output, using the Matlab/Simulink model of the system, including two PI controller coefficients, switching frequency, balancing inductor, and balancing inductor resistance. The simplified reduced complexity block diagram of the control system in d, q and 0 axes for this control method is as shown in Fig. 9, based on which the relative sensitivity analysis is performed. The open loop transfer function for d, q and 0 axes of the control system shown in Fig. 9, could be written as;

$$G(H) = K_p\left(\frac{1+T_i.s}{T_i.s}\right) * \frac{1}{1+T_a.s}.\frac{1}{R} * \frac{1}{1+\tau.s} \qquad (2)$$

Based on the open-loop transfer function in (2), and the assumed system parameters mentioned in Table I, the Bode plot for stability analysis is shown in Fig. 10, which results in a phase margin of 24.6 degrees.

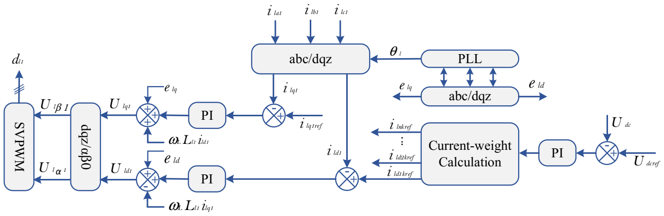

Fig. 7. Detailed control strategy for first line-side converter for system topology studied in [22]

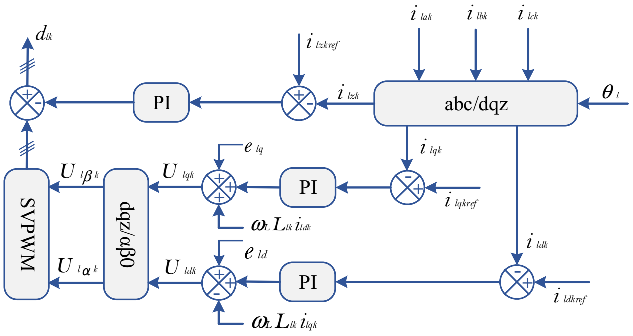

Fig. 8. Detailed control strategy for Kth (k=2,3,..n) line-side converter for topology studied in [22]

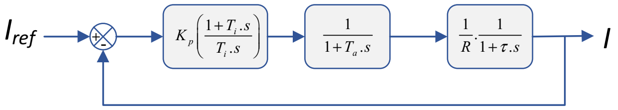

Fig. 9. Reduced block diagram in d, q and 0 axes

Based on the open-loop transfer function in (2), and the assumed system parameters mentioned in Table I, the Bode plot for stability analysis is shown in Fig. 10, which results in a phase margin of 24.6 degrees. A sensitivity analysis also has been performed on switching frequency, by changing the switching frequency of inverters while having the ZSCC capability ON, the results for which are shown in Fig. 10. In Fig. 10, output currents for phase A of three parallel inverters have been presented in per units, along with the residue amount of the ZSCC after mitigation in percentage to the load current of each phase which reveals the minimum stable switching frequency for this control method as 12 kHz.

Table I. ASSUMPTIONS FOR 1ST ZSCC MITIGATION CONTROL METHOD

K_p	K_i	f_s	R	L
2.5	2500	12000 Hz	0.2 W	0.1 mH

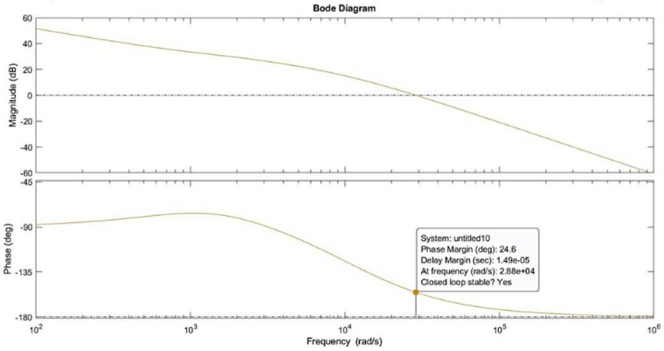

Fig. 10. Bode Plot for 1st control method, based on assumptions in Table I.

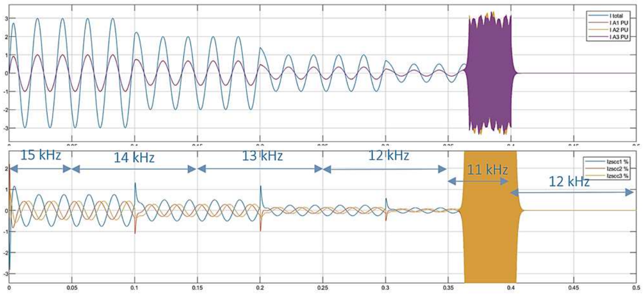

Fig. 10. Total current, current for each Inverter, ZSCC current for 3 different inverters, comparison of each inverter phase A, 1st control method [PU, %]

2) Communication based Control method for ZSCC Mitigation (2nd control method)

This method, in contrary to the first one, requires measurement from neighboring inverters, to mitigate the ZSCC. The method also uses 3n-1, PI controllers in d, q and 0 axis to control n parallel inverters while mitigating the ZSCC.

To explain the control method for the parallel operation of inverters for the configuration shown in Fig. 2, control details for first and the kth (k=2, …, n-1) inverters are shown in Fig. 11. The main difference between this controller and the first one is the way the controllers are designed in two types of Sum-controllers and difference controllers. The role of Sum controllers is to make sure that the parallel inverters together are generating the total required reference values (torque producing current) in d and q frames, while the difference controllers in d and q frame are to make sure that inverters are equally sharing d and q frame references. For 0 frame, there is no Sum controller, since as mentioned in (1), sum of ZSCCs will be 0 in a parallel system, however there are difference controllers in 0 frame, to make sure that parallel inverters are sharing the ZSCC equally while keeping the sum of 0 frame references at zero. There are 2 sum PI controllers and 3n-3 difference PI controllers to control n parallel inverters in this control method [29]. While not being as modular as the first control method, this method has the advantage of separating the controllers for torque generating currents and the ZSCC, which leads to flexibility in defining the PI coefficients to meet the requirements of both. It is worth mentioning that this method improves the control accuracy and extends the stability margins.

To evaluate this, a sensitivity analysis has been performed for the 2nd control method on five different factors impacting the stability of the controller using the Matlab/Simulink model of the system including two PI controller coefficients, switching frequency, balancing inductor, and balancing inductor resistance. The simplified reduced complexity block diagram of the control system in d, q and 0 axes for this control method is as shown in Fig. 12 based on which the sensitivity analysis is performed. The open loop transfer function for d, q and 0 axes of the control system shown in Fig. 12, could be written as;

$$G(H) = K_p * \left(\frac{1+T_i.s}{T_i\,.s}\right) * \frac{1}{1+T_a.s} * \frac{1}{R} * \frac{1}{1+\tau.s} \tag{3}$$

In which, $T_i = {}^{K_p}\!/_{K_i}$ and $\tau = \frac{L}{R}$.

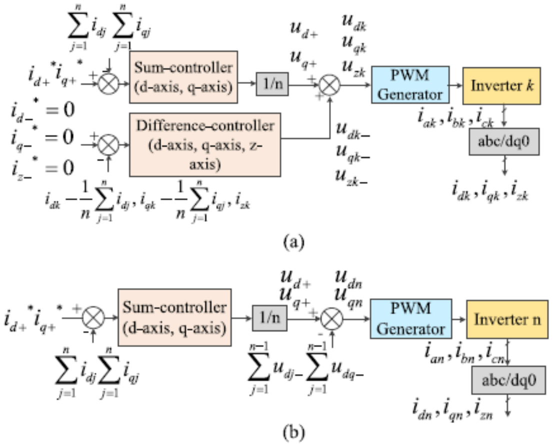

Fig. 11. Control strategy for inverters. (a) Proposed Control strategy for the kth (k = 1, . . ., n − 1) inverter. (b) Control strategy for the nth inverter in [29]

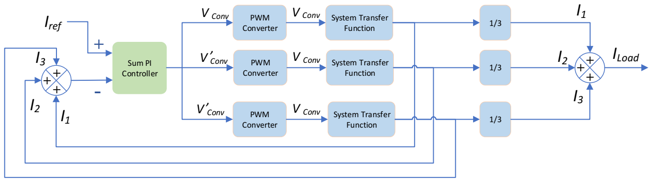

Fig. 12. Simplified block Diagram of Control system proposed in [29] for three parallel inverters

Based on the open-loop transfer function in (3), and the assumed system parameters defined in Table II, the Bode plot [30] for relative stability analysis is shown in Fig. 13, which reveals the stability phase margins of 36.5, 37.6 and 87.7 degrees for sum in d, q and difference controllers in d, q and 0 axes which are higher than the phase margins for 1st control method. A sensitivity analysis also has been performed on switching frequency, by changing the switching frequency of inverters while having the ZSCC capability ON, the results for which are shown in Fig. 14. In Fig. 14, output currents for phase A of three parallel inverters have been presented in PU. along with the residue amount of the ZSCC after mitigation in percentage to the load current of each phase which reveals the minimum switching frequency for this control method to be 6 kHz.

Table II. ASSUMPTIONS FOR 2ND ZSCC CONTROL CONTROL METHOD

	K_p	K_i	f_s	R	L
Sum PI s	2.5	2500	12500 Hz	0.2 W	0.1 mH
Diff – d - q	0.01	500	12500 Hz	0.2 W	0.1 mH
Diff – Z	0.6	100	12500 Hz	0.2 W	0.1 mH

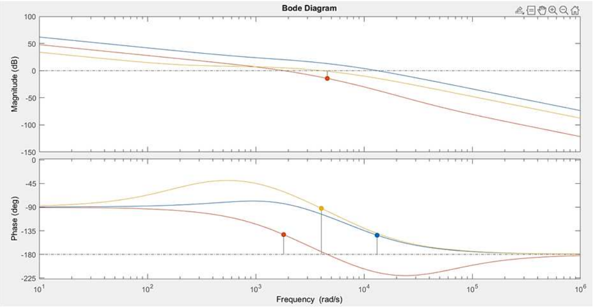

Fig. 13. Bode Plot for 2nd control method, based on assumptions in Table I.

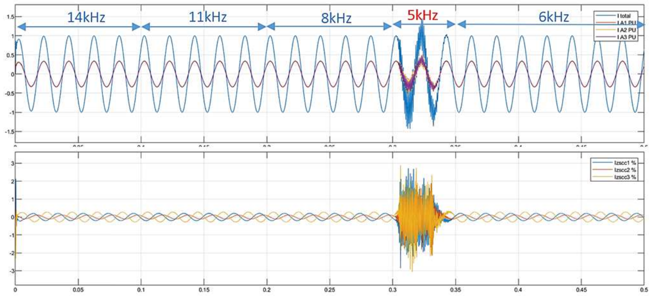

Fig. 14. Total current, current for each Inverter, ZSCC current for 3 different inverters, comparison of each inverter phase A, 2nd control method [PU, %]

IV. CONCLUSIONS

In this paper, a throughout review has been performed on modular motor drives for PMSMs, considering the challenges around parallelization of motor drives. For the significance of the ZSCC, this paper concentrates on this issue more and a classification of the parameters leading to mismatches in the output voltage of inverters has been done. Different hardware and software-based solutions to mitigate ZSCC with concentration on control methods has been studied to evaluate the effectiveness, and feasibility of solution in dealing with the issue. Hardware solutions are effective, but they are not the preferred solution for all applications. Comparing the stability range and accuracy of the control methods, reveals that the second control method has a wider stability range compared to the first one.

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