A Review of Drive Techniques for Multiphase Machines

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***Abstract*—Multiphase machines are gaining increasing popularity because of their distinct advantages over three-phase counterparts, such as reduced per phase power rating, improved reliability and increased degrees of freedom. This paper overviews the development history of multiphase machines and drive techniques in Section II. Three kinds of drive algorithms, including Field-Oriented Control (FOC), Direct Torque Control (DTC) and Model Predictive Control (MPC), are introduced in Section III. Then two types of fault-tolerant methods are compared in Section IV, which are the Vector Space Decomposition (VSD) strategy and Optimal Current Control (OCC) method. Furthermore, different types of existing multiphase converter topologies are listed in Section V, and various kinds of multiphase PWM methods are discussed in Section VI. Finally, based on the review, developing trends of multiphase drive techniques are forecasted.**

***Index Terms*—Converter topology, fault-tolerant control, multiphase machine, motor drive control, pulse width modulation (PWM).**

I. INTRODUCTION

DUE to the three-phase architecture of the traditional power system, three-phase machines fed by three-phase inverters are widely applied in the variable-speed drive occasions. With the increasing demand for power ratings in variable-speed drive industrial applications [1] , such as steel rolling, mine hoisting, locomotive traction and electric ship propulsion, higher voltage and/or larger current of the drive system are preferred. However, owing to the limited voltage and current ratings of existing power semiconductor devices, the high-power three-phase inverters are usually constructed by the serial and/or parallel connection of switching devices [2]-[3].

Actually, even with the limited power rating per phase, high-power drive can be realized by increasing the number of phase legs. With the wide application of power converters, the machines are able to free themselves from the constraint of the traditional three-phase power system, and the multiphase machines are gaining increasing popularity in recent years.

Compared with the three-phase drive systems, the multiphase ones provide the following advantages [4]-[7]:

1) High-power variable-speed drive can be achieved utilizing low-power rating switching devices in multiphase drive applications. When a three-phase drive system is reformed into a multiphase one, the rated voltage per phase can be effectively reduced. This is particularly suitable for electric ship propulsion and locomotive attraction applications, where the power supply voltage is limited.

2) The frequency of torque ripples can be increased while the torque oscillation amplitude can be decreased. The torque ripples are caused by the spatial harmonics of Magneto-Motive Force (MMF). The MMF is mainly excited by the fundamental current in the stator phases. With the increased phase number, the harmonic orders of MMF are also increased while respective amplitudes are reduced. Consequently, the torque ripples could be suppressed and the efficiency of the machine would be improved.

3) Multiphase machines have a greater fault-tolerant ability than the three-phase ones. When one or more stator phases are open-circuited, the redundancy of the phase number enables the multiphase machines to operate with the remaining healthy phases, though at a derated power level.

4) The number of control degrees of a drive system equals to the number of independent stator phases of the machine. Consequently, multiphase machines have more degrees of freedom (DOFs) than the three-phase counterparts. These DOFs provide additional ways to enhance the drive performance. For example, the air-gap flux of multiphase machines with concentrated windings can be optimized by injecting low-order current harmonics, which would improve the iron utilization and the power density.

The above advantages accelerate the penetration of multiphase machines in industry applications, such as wind power generation [8], ultrahigh-seed elevators [9], and electric transportation including electric vehicles [10], electric ships [11], more-electric aircraft [12] and spacecraft [13].

II. HISTORY OF MULTIPHASE DRIVE

In the 1960s, theoretical analysis and experimental exploration of five-phase induction machine (IM) were conducted by *E. E. Ward* and *H. Harer* [14], and they found that the increase in phase number leads to reduced amplitude and increased frequency of the torque ripples. In the year of

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1980, multiphase drive was proposed to improve the fault-tolerant ability and reliability of the AC drive systems [15]. However, the multiphase drive scheme is very difficult to implement due to the technical limitations of that time. As a result, little research was conducted on multiphase drive.

Since the 1990s, the development of technologies, such as power electronics, microcontrollers and variable-speed drive, paves the way for the realization of multiphase drive. With the growing demand for motor drive systems in high-power, low-voltage and high-reliability applications like electric ship propulsion, the last thirty years witnessed the unprecedented increase of research on multiphase machines and drive techniques. A large number of novel multiphase machine designs, multiphase converter topologies and multiphase motor control methods are proposed by researchers all around the world. Evolved from the Field-oriented control (FOC) design for three-phase IMs, FOC for the six-phase (dual three-phase) IM was proposed by researchers from *T. A. Lipo*'s group in the University of Wisconsin-Madison [16]. Moreover, the mathematical model of the six-phase IM under open-circuited faults were analyzed and fault-tolerant FOC was proposed in Ref. [17]. *H. A. Toliyat* found that toque density of the multiphase machine can be improved by the adoption of concentrated stator windings [18], and proposed resilient current control methods for the fault-tolerant operation of five-phase IMs [19]. The research group lead by *E. Levi* from Liverpool John Moores University spent much effort on the Pulse Width Modulation (PWM) techniques of multiphase converters [20], and proposed novel PWM methods with advanced characteristics, such as the improvement of the DC bus utilization [21], the suppression of the Common Mode Voltage (CMV) [22], etc. *L. Parsa* and her co-investigators from Rensselaer Polytechnic Institute concentrated on the fault-tolerant control of multiphase permanent magnet synchronous motors (PMSMs) under both open-circuit and short-circuit faults, and put forward a global fault-tolerant control strategy with notable simplicity and flexibility [23]. Open-end winding five-phase PMSM was preferred by *E. Semail* and his team members, which can be simply handled by the reconfiguration of converter legs when short-circuit faults occur [24]. A group of Spanish researchers led by *F .Barrero* and *M. J. Duran* proposed Model Predictive Control (MPC) strategies for the variable-speed drive of multiphase machines [25], which was further extended to fault-tolerant operation with open-circuit or IGBT failure faults [26].

Multiphase drive has also attracted great research interest in China. The Naval University of Engineering (NUE) explored the mathematical model [27] and short-circuit characteristics [28] of the three-&twelve-phase synchronous generators with both AC and DC output, analyzed the steady-state performance of a 15-phase IM under non-sinusoidal power supply[29], and derived the parameter variation of the 15-phase IM with faulty-phases [30]. In recent years, researchers from NEU proposed some novel multiphase machine topologies, such as the dual nine-phase energy storage machine [31] and the six-phase block feeding cylindrical linear IM [32]. Harbin Institute of Technology focused on the five- and six-phase PMSMs, and conducted extensive study on the machine designing [33], harmonic injection [34] or suppression [35], Space Vector PWM (SVPWM) [36] and fault-tolerant control strategies [37]. Researchers from Zhejiang University proposed a winding function-based parameter estimation method for multiphase machines[38], and conducted detailed study on the non-sinusoidal power supply for concentrated-winding considering the effects of both air-gap and yoke flux densities [39]. The research group led by *M. Cheng* in Southeast University contributed a lot on the fault-tolerant control of multiphase motors fed by neutral-point-clamping (NPC) converters, including the diode-clamping-type [40] and T-type [41] ones. They also proposed novel multiphase machine topologies with enhanced fault-tolerant ability, such as the flux switching PMSM [42]. Tsinghua University applied the tandem fifteen-phase IMs in a ship propulsion experimental system [11]. China Shipbuilding Industry has developed mature industrial-class multiphase converters, and has released the product of 10 MW multiphase drive system for the first time in China.

III. MULTIPHASE MOTOR DRIVE CONTROL

The principle of drive control for multiphase machines is similar to the three-phase counterpart. However, the redundancy of stator phases calls for controllers on additional 2-D planes, so that current in each of the stator phase can be regulated, including the phase position, amplitude and harmonics. Sophisticated control algorithms in existing literatures can be broadly divided into three categories: Field-oriented control (FOC), Direct torque control (DTC), and Model predictive control (MPC).

A. FOC

The FOC for traditional three-phase motors usually employs an orthogonal transformation matrix to map the control variables in the a-b-c coordinates to those in the d-q-0 coordinates. Therefore, the flux and the torque can be decoupled by regulating current components on the d- or q- axis, respectively. Though similar to the three-phase counterparts, the orthogonal transformation matrix is different in the FOC for the multiphase motors. As shown in Fig.1, when an $m*m$ orthogonal transformation matrix is applied to an m-phase motor, m independent control variables can be obtained. It should be noted that if the m-phase motor has n connected neutral points, the number of independent control variables would be (m-n). Currents on the d1-q1 plane contribute most of the electromechanical energy conversion in multiphase machines, especially for those with sinusoidal distributed windings. Consequently, the d1-q1 plane is called the fundamental plane, and i_{d1} and i_{q1} are regulated as the flux and torque components. Other d-q planes are called harmonic planes, and currents on these planes are regulated to specific values or suppressed to zero.

1) Harmonic Injection

In multiphase machines with concentrated full-pitch windings, currents on the harmonic planes could contribute a part of electromechanical energy conversion. Therefore, low-order current harmonics can be injected to increase the toque density.

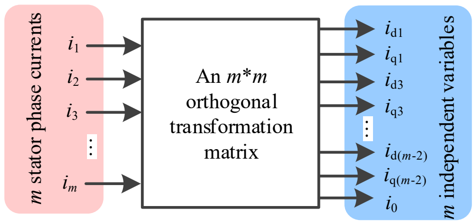

Fig. 1. The decoupling transformation of phase currents for multiphase machines.

To improve the iron utilization, minimum peak value of air-gap MMF is selected as the criterion [43], which determines the phase and magnitude relation between fundamental and harmonic currents. Recent study in [39] declared that both air-gap and yoke flux densities should be considered when determining injected harmonics ratio, otherwise the yoke iron saturation might decrease the torque density. Moreover, the power sharing among several phase groups could be achieved by injecting appropriate currents at the fundamental frequency in the harmonic planes without affecting the flux and average torque [44].

2) Harmonic Suppression

In multiphase machines with sinusoidal distributed windings, currents on the harmonic planes barely contribute flux or torque, but result in copper loss in the stator windings. To reduce the copper loss, PI controllers in synchronous frames or resonant controllers tuned at the harmonics are employed to suppress the current harmonics [45]. Additionally, the suppression of spatial current harmonics can help to keep the balance among different phase currents [46].

B. DTC

Conventional DTC was extended to multiphase occasions for the first time in [47] , where five-phase DTC was applied. The number of voltage space vectors is 2^5 in a five-phase machine fed by two-level inverters, which is much higher than 2^3 in the three-phase counterparts. The redundancy of space vectors provides higher DOFs in selecting inverter switching states, accomplishing a more precise control of the stator flux and torque, and thus achieving a fast toque response with low ripple. DTC extended directly from three-phase to multiphase occasions focuses only on toque and flux in the fundamental plane, which unavoidably results in uncontrollable currents in the harmonic planes. The 32 voltage vectors for a five-phase PMSM are mapped on both fundamental and harmonic planes in [48]. Effects on both planes were considered when selecting voltage vectors, and thus low-distorted phase currents could be reduced along with precisely adjusted stator flux and torque.

However, two drawbacks hinder the application of DTC. One is that the look-up-table in DTC leads to variable switching frequency, which is not suitable for high-power applications. The other drawback is that the number of switching states grows exponentially with the increase of phase number, which makes it quite complicated to implement DTC for multiphase machines with large phase number.

C. MPC

Though the computation cost is the highest, MPC achieves a faster response than FOC, and has higher DOFs than DTC. Extended from three-phase MPC, multiphase MPC can be designed as shown in Fig. 2. However, different from three-phase cases, injection or suppression of current harmonics should be added to the cost function. Experimental results on a five-phase IM in [25] declares that though the computational time of MPC is 1.5 times more than that of DTC, the ripples of electrical torque can be reduced and the switching frequency could be decreased under MPC.

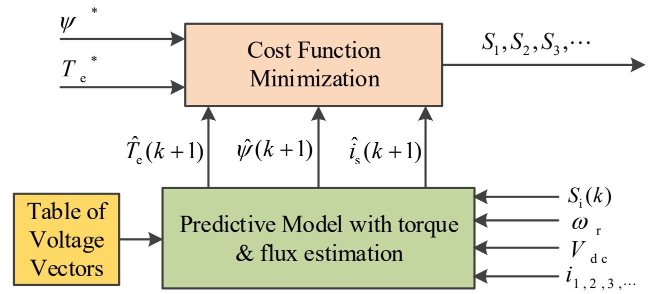

Fig. 2. The block diagram of MPC.

To improve the fault-tolerant performance of multiphase machines, MPC was adopted in the current control loops of FOC [25], as shown in Fig. 3. When open-circuit or IGBT gating-failure faults [26] occur, the faulty switches would be identified and the table of voltage vectors would be updated. Thus, the most suitable voltage vector of the fault-tolerant converter can be selected by tracking the reference currents.

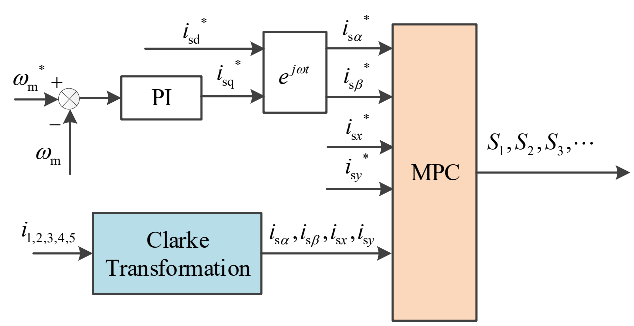

Fig. 3. MPC in current control loops.

However, the size of the table of voltage vectors increase exponentially as the phase number increases. To the best of our knowledge, MPC was applied in the multiphase drive applications with only five or six stator phases.

IV. Fault-Tolerant Control

Due to the outstanding fault-tolerant ability, multiphase machines are gaining increasing popularity in safety-critical motor drive occasions, such as more-electric aircraft [12] and spacecraft [13]. Various kinds of faults may occur in the motor drive system, while the power switching devices and the machine windings are the most vulnerable. According to [12], the possibility of faults on switching devices is much higher than that on machine windings, and more than 70% of the faults would finally turn to open-circuit or IGBT gating-failure faults.

Therefore, most of the fault-tolerant research concentrate on faults of these two types, as shown in Fig. 4.

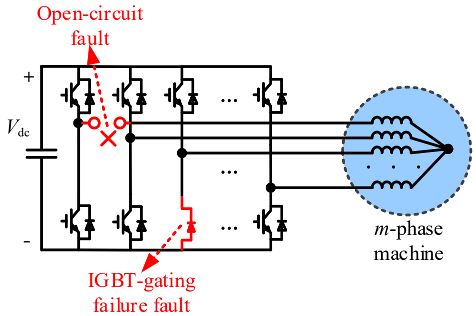

Fig. 4. Open-circuit fault and IGBT-gating failure fault of the multiphase converter.

One or more faulty phases lead to the asymmetry of power supply, which would affect the rotating trajectory of air-gap MMF and finally result in serious torque oscillations. Therefore, fault-tolerant strategies are required to suppress the torque ripples by utilizing the redundant DOFs. There are mainly three types of fault-tolerant strategies in existing literatures.

The first type is the vector space decomposition (VSD) method, which was first proposed in [17]. An orthogonal reduced-order transformation matrix was applied to a six-phase IM with one open-circuit phase, so the number of remaining healthy phases equals to the number of control variables. However, this matrix results in complicated asymmetrical machine models with time-varying parameters. Though the non-orthogonal reduced-order matrix proposed in [49] could lead to the same machine model as the healthy case, it is only for the faulty case with one open-circuit phase. In other words, when faulty case changes, the reduced-order matrix would also change.

The second type is optimal current control (OCC) strategy, first suggested in [50]. This strategy aims to generate a smooth rotating air-gap MMF, which requires the compensation of supply asymmetry by properly regulating the currents in the remaining healthy phases. Meanwhile, redundant DOFs could be utilized to optimize the current references. The optimization goals could be the minimization of stator copper losses [51], the maximization of the output torque [52], or the uniformity of stator copper loss distribution [53]. To compensate the faulty phase currents, the remaining healthy phase currents are usually asymmetrical in amplitudes and phase angles. The tracking of the irregular current references can be achieved by hysteresis controllers, Proportional Resonant (PR) controllers, dual-PI controllers or MPC. Because the transformation matrix and the machine model remain, OCC is easier to extend to different faulty conditions than VSD. However, the optimal current reference values still rely heavily on the specific faulty conditions.

The third type is to apply robust controllers in the speed and/or current control loops for the multiphase machines. Actually, the failure of stator phases can be regarded as the variation of machine parameters. Fortunately, the robust controllers, such as the Fuzzy Logic Controller (FLC), are able to adapt to the variation of parameters. Therefore, the fault-tolerant ability can be enhanced by robust controllers in various kinds of faulty conditions even without fault detection [54].

V. Topology of Multiphase Converters

Research on multiphase converters in the past decades leads to various kinds of topologies. Based on the types of power sources, converters are divided into Voltage Source Converters (VSC) and Current Source Converters (CSC). Due to much wider application of VSC, all the converters discussed in this paper belong to this type.

The existing multiphase converter topologies can be classified in Fig. 5. On one hand, according to the power conversion process, multiphase topologies can be divided into AC-DC-AC and AC-AC modes. The AC-AC converters are also called matrix converters, which contain direct and indirect types. On the other hand, according to the connection of neutral points, multiphase topologies can be divided into the open-winding and single-sided modes. Without neutral point connection, the two ends of open-winding topologies can be fed by one or two independent DC sources. Additionally, the single-sided topologies may contain one or multi neutral points.

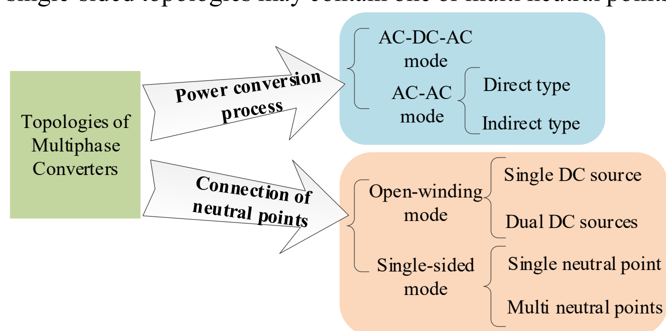

Fig. 5. Classification of multiphase converter topologies.

A. AD-DC-AC mode

In this mode of topology, the AC power supplies are rectified into DC power, and then DC power is inverted into multiphase AC power, which finally feeds the multiphase machines. The DC bus decouples the AC input and output, which facilitates the decoupling control of rectification and inversion. Furthermore, this topology mode is easy to be extended to the multilevel topology, such as multiphase NPC converters [40].

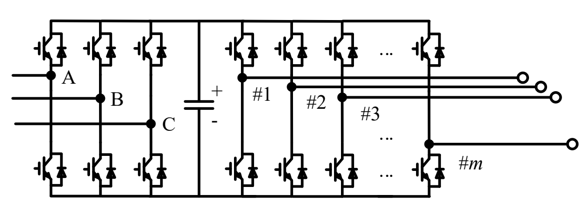

Fig. 6. The topology of AC-DC-AC multiphase converters.

B. AC-AC mode

The AC-AC converters are also called matrix converters, which achieve power conversion from AC to AC without intermediate DC links. Direct matrix converters perform voltage and current conversion in one single stage [55], which is shown in Fig.7. The indirect matrix converters, shown in Fig. 8, act like the AC-DC-AC converters, which perform voltage and current conversion in separate stages, but the virtual DC-link has no intermediate energy storage elements [56]. Although DC-link with energy storage was saved and the volume of the converter was reduced, the number of switching devices is largely increased, and the PWM modulation is rather complicated when phase number is high [57]. Consequently, multiphase matrix converters have until now only achieved very low industrial penetration.

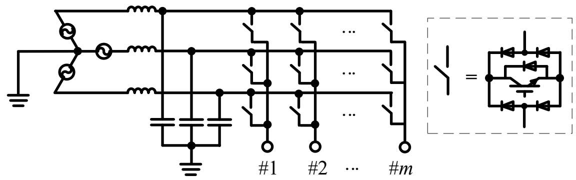

Fig. 7. The topology of direct matrix multiphase converters.

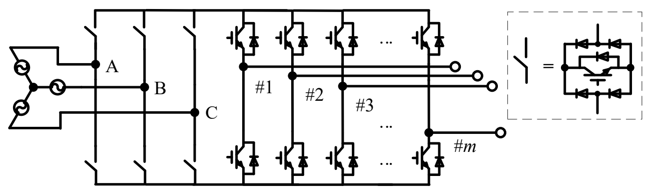

Fig. 8. The topology of indirect matrix multiphase converters.

C. Open-winding mode

Open-winding topology means that both ends of the stator winding are accessible and connected to the converter phase legs. Conventional open-winding topology is the H-bridge type, which can be further classified by the number of isolated DC sources shown in Figs. 9 and 10.

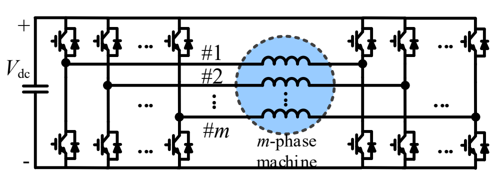

Fig. 9. The topology of open-winding multiphase converters with one DC voltage source.

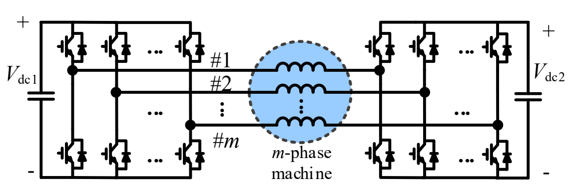

Fig. 10. The topology of open-winding multiphase converters with two DC voltage sources.

Compared with the single-sided mode, the open-winding mode has many advantages: 1) The DC bus utilization is doubled. 2) Output voltage levels are increased. 3) Voltage across each phase is determined by its H-bridge and independent from other phase voltages, which facilitates the implementation of more flexible PWM methods. 4) When the fault occurs on certain phase leg or stator winding, other phase legs and corresponding phase voltages would not be affected. However, the open-end topology requires at least four switching devices per phase, and the high cost hinders its wide application. Until now, this topology has been mainly adopted in high-power occasions [58], such as the electric ship propulsion system [59].

It should be noted that in the single DC source topology shown in Fig. 9, zero-sequence current could be very large even with very low CMV, which leads to additional copper loss in the machine windings. Therefore, many modified PWM methods are proposed to suppress the zero-sequence current. However, these methods usually reduce the utilization of DC bus [22], while difficult to be extended to other multiphase cases with different phase number [60].

The dual DC topology in Fig. 10 requires two isolated power sources, which further increases the cost but blocks the circulation of zero-sequence current. Additionally, two DC voltages can be set at different voltage levels, such as 2:1, to produce four-level output voltage [61].

D. Single-sided mode

In the sing-sided topologies, only one end of the stator winding is fed by the converter while the other end is usually connected to one or more points. Compared with the open-winding mode, the single-sided mode deteriorates in control flexibility and fault-tolerant ability. Additionally, the CMV on the neutral point produced by the PWM could lead to harmful bearing currents [62], and bring about EMI problems [63]. However, the half-bridge based configuration saves hardware cost and simplifies control computation. Consequently, the single-sided topology is widely used in multiphase applications, ranging from several kilowatts to hundreds of kilowatts [64, 65].

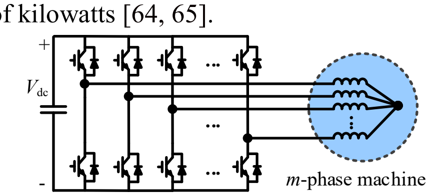

Fig. 11. The topology of one-sided multiphase converters with one neutral point.

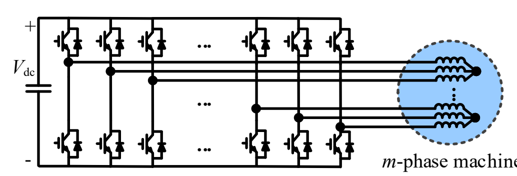

Fig. 12. The topology of one-sided multiphase converters with multiple neutral points.

The single-sided topologies can be further classified into two types shown in Figs. 11 and 12. The single-end converter with single neutral point is shown in Fig. 11, where all the stator windings are connected to one neutral point. This type is the most popular multiphase topology due to the redundant DOFs and simple configuration. Different groups of stator windings can be separately connected to several neutral points, shown in Fig.12. A six-phase example is given in Ref [66], where two groups of three-phase windings are separately connected. The modular property of the multi-neutral-point topology enables the isolation of different stator winding groups and phase legs. Therefore, when fault occurs on one phase, variable-frequency power supply for windings in the other groups would not be effected. However, compared with the single-neutral-point topology, the multi-neutral-point type reduces the DC bus utilization and decreases the number of available voltage space vectors in PWM. Moreover, it is not practical to split the neutral point of symmetrical multiphase machines with odd phase number.

VI. PWM Techniques for Multiphase Inverters

Similar to the three-phase cases, there are two categories of PWM techniques for multiphase inverters, which are Space Vector PWM (SVPWM) and Career-based PWM (CPWM).

A. SVPWM

In the multiphase inverters, the number of switching states grows exponentially with the increase of the phase number, so does the number of Space Vectors (SVs). Taking the three-level inverters as an example, the number of SVs in the three-phase case is only 3^3 (27), but turns to be 3^5 (243) in the five-phase case and 3^{15} (14,348,907) in the fifteen-phase case. Therefore, it would be a rather complicated task to analyze and select proper SVs, when the phase number is high.

Initially, three-phase SVPWM was simply extended to multiphase cases. To maximize the DC bus utilization, only the largest SVs on the α-β plane are employed [67]. For a five-phase two-level inverter, the non-zero SVs are shown in Fig. 13. When only the 10 largest SVs on the α-β plane are employed, voltages on the x-y plane would be uncontrollable, which could lead to undesirable harmonics in the phase currents. As the phase number increases, the output voltage waveform produced by the largest SVs modulation gets closer to a trapezoidal wave.

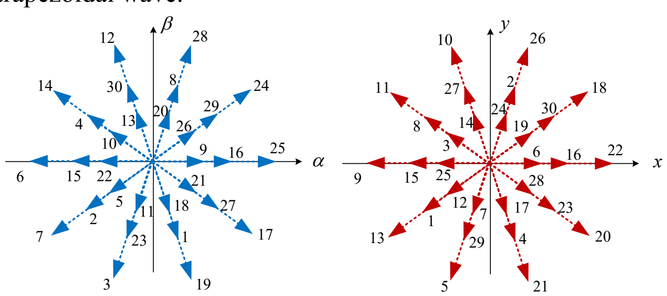

Fig. 13. The space voltage vectors in the α–β and x-y planes.

To eliminate the phase current harmonics, a vector space decomposition based SVPWM was proposed in Ref. [16]. When selecting SVs, all the SVs are candidates including those largest ones. Combination of selected SVs should synthesize the d-q voltage vectors to satisfy the machine's torque control requirements, and, at the same time, to maintain the average volt-seconds on the harmonic planes to be zero during every sampling interval. However, the duration of each selected vector needs to be determined online, which leads to a heavy computation burden. Moreover, multiple switch transitions could occur within one switching cycle, which increases the switching loss and jeopardizes the safety of switching devices. To reduce the computation cost, modified SVPWM technique is proposed in [68] for a five-phase inverter, where only the nearest four SVs are employed to track the reference voltage. However, the simplification unavoidably deteriorates the distortion of the output voltage.

Some researchers managed to extend the multiphase SVPWM technique to five-phase and seven-phase three-level inverters [22, 69]. But the very involved offline procedure of the algorithms lead them to the conclusion that CPWM, rather than SVPWM, will always be the first choice for practical implementation of multiphase inverters [20].

Based on the multiple d-q spaces concept, a modified SVPWM technique was proposed in [70], which can realize non-sinusoidal power supply in a five-phase inverter to improve the DC bus utilization. Considering the effects of SVs on fundamental and three harmonic planes, a non-sinusoidal SVPWM is developed for a nine-phase inverter to improve the torque density of a nine-phase IM with concentrated windings [71] .

B. CPWM

In CPWM, the output voltage pulses of each phase leg are generated by comparing its modulating wave to the carrier wave. For each phase, its CPWM procedure is independent from other phases. Therefore, the computation cost of CPWM increases linearly as the phase number increases, which facilitates the extension of CPWM to multiphase inverters with any phase number.

Tough the DC bus utilization of CPWM is usually lower than that of SVPWM, this drawback can be overcome by the injection of zero-sequence component into the modulating wave [72]. A detailed comparison of CPWM and SVPWM in five-phase three-level inverters was conducted in Ref [20]. The conclusion is that the proper injection of zero-sequence component enables the CPWM to achieve the same performances in utilization of DC bus, suppression of harmonics and elimination of CMV. Obviously, CPWM outweighs SVPWM in simpler implementation and easier extension.

Moreover, converters' performances with improved characteristics can be generated by changing the injected zero-sequence component. The min-max injection could achieve the maximum DC bus utilization, while the min or max injection could reduce the switching loss of inverter phase legs [73]. When the loads for different phases are unbalanced, zero-sequence components could be set at different values according to respective loads, so that all the phase currents would be balanced [74].

Except for the zero-sequence signals, the carrier waves could also be adjusted to achieve modified PWM outputs. In the open-winding drive system, there are two triangle carriers for each phase. A comparison of Phase Shifted PWM (PSPWM) and Level Shifted PWM (LSPWM) was conducted in [75], which declares that LSPWM give better results in terms of voltage and current THDs. Furthermore, carrier waves in different phases can be set in different phase positions. In the symmetrical six-phase machine, which consists of two groups of three-phase windings, the phase angle between the two carrier waves for the two three-phase groups would affect the loss of the machine. Moreover, there exists an optimal phase shift angle that can minimize the overall loss [76], while the optimal value varies depending on the modulation index and machine parameters. To reduce the CMV produced by the multiphase inverters, phase angle shifts of triangle carrier waves in different phases are suggested to be evenly distributed [77]. Additionally, even the shape of carrier wave can be modified to improve the CPWM. Mirror-symmetrical sawtooth carriers are adopted in an asymmetrical six-phase drive system, which leads to the reduction of CMV in both amplitude and changing frequency [78].

To simplify the PWM procedures in multiphase AC-AC converters, the CPWM techniques, which can be easily implemented on low-cost embedded controllers, are proposed for three-to-five-phase [79] and three-to-nine-phase [80] matrix converters. But the DC bus utilization is limited, and the maximum voltage transfer ratio is less than 79%.

VII. Conclusions

This paper reviews the drive and control techniques for multiphase machines. Based on the review, we can make the following predictions.

1) With the increasing demand for high-power drive system, the number of phases and voltage levels would increase. Because the number of SVs increases exponentially with the growth of phase number, the computation cost of DTC and MPC, which are based on the selection of space vectors, would be too high to be implemented in practice. On the contrary, the FOC combined with CPWM concentrates on the current control in the fundamental and harmonic planes, so the computation cost of this algorithm increases linearly with the phase number. Therefore, FOC would outweigh DTC and MPC in the future multiphase applications with large phase number.

2) Tough many fault-tolerant control strategies have been proposed, most of these algorithms apply in the open-phase fault conditions. Improved fault-tolerant algorithms, which also apply in short circuit and IGBT gating failure conditions, are still lacking. Additionally, the fast, accurate and robust fault diagnosis methods are needed, which are the preconditions of high-performance fault-tolerant operation.

3) Taking into account of desired power rating, DC bus utilization, reliability and hardware cost, the best topology can be chosen from various types of multiphase converter topologies. Besides the existing topologies, a large number of improved and novel topologies would emerge in applications such as multiphase multilevel converters, multiphase fault-tolerant converters, charging and discharging multiphase EV converters, etc.

4) The additional DOFs of multiphase PWM in both zero-sequence signals and carrier waves can be further utilized to optimize the drive system in suppressing CMV, reducing overall loss and saving hardware cost like DC capacitors.

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