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A Review on Multiphase Permanent Magnet Synchronous Motor Drive

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ABSTRACT: This paper gives a peer review on multiphase permanent magnet synchronous motor drive system. In particular the paper deals with the Superiority of PMSM motor.In addition we add Simulink model of Six phase PMSM drive in order to show that the model is able to operate at rated speed and torque even with there is sudden change of load torque. This is already carried out by different researchers

KEYWORDS: Multiphase, Permanent magnet synchronous motor (PMSM), Drive system, PWM,Vector control

I. INTRODUCTION

Multiphase variable speed drive has received growing interest since the second half of the 1990s. Although oldest records concerning this topic dates back to the second half of the 1960s. Historical technical reasons that required adopting the multiphase drive solution instead of three-phase are listed below [1, 2, 3]:-

1) Multiphase variable speed drive reduces the stator current per phase, for a given motor output power.
2) The use of more than three phases offers an improved reliability.
3) Multiphase machines present reduced pulsating toques produced by time harmonic components in the excitation waveform.
4) Fault tolerant drives

The main application areas of multiphase machines specially motor drives are ship propulsion, traction (including Electric and hybrid electric vehicles) and the concept of More-electric "aircraft. Other suitable applications are Locomotive traction, aerospace and high power Applications.

II. THREE PHASE DRIVES VS. SIX PHASE DRIVES

As stated above at point no.1, the use of multiphase drive instead of the three-phase helped to overcome the problems related to high-power applications with current limited devices. For a given motor power, an increase in phase number determines a reduction in Power per phase, enabling the use of smaller power electronic devices in each inverter leg, without increasing the voltage per phase.

This is still a solution adopted for high-power applications, such as transport and ship-propulsion drives. In fact, large multiphase machines for ship propulsion have already been prototyped industrially, and are currently undergoing commercial evaluation.

The improved reliability features of multiphase drives, listed at point no.2, enable their use also in faulty conditions; in fact if one phase of a multiphase machine becomes open circuit, the machine is able to self-start and to run with only a de-rating, which depends on post-fault control strategy and in the number of the phases. In the three-phase case, the loss of one phase determines an important de-rating of the machine while it is running. Furthermore the machine is not self-starting and, for this purpose, it requires an external mean.

Finally, the advantages derived from statement at point no.3 were very important in the 60s, when three-phase inverter-fed ac drives operate with six-step mode. Time-harmonic of voltages and currents introduced by this operation-mode produced low frequency torque ripple, leading to difficulties on speed control and noise production. Since in a n-phase machine torque pulsations are caused by supply time-harmonics of the order $2n\pm1$, which result in torque ripple harmonic $2n$ times higher than the supply frequency, an increase in the number of phases seem the best solution to the problem. This aspect of multiphase drives has lost importance since the discover of PWM of VSI, which allows the control of inverter output voltage harmonic content.

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As stated at point no.4.The increased number of phases in multiphase drives offers considerable benefits because of the capability to continue operation when a single or multiple phase loss occurs.[1,2,3]

Three-phase drive is sensitive to different kinds of faults, both in motor phase and in inverter leg. When one of these faults does occur in one phase, the drive operation has to be stopped for a non-programmed maintenance schedule. The motor in faulty conditions is able to run but it is not still self-starting. The cost of this schedule can be high, thus justifying the development of fault tolerant motor drive systems. On the contrary, multiphase machines in post-fault condition can continue to be operated with an asymmetrical winding structure and unbalanced excitation, producing a higher fraction of their rated torques with little pulsations when compared to the three phase machines

III. HISTORY

1. Superiority of PMSM motor over Other motors [4-10]

There are a variety of ac servo drives on the market competing with both the DC brush Machines and AC servo drives. Two types of permanent-magnet ac motor drives are available in the drives industry. These are Permanent Magnet Synchronous Motor (PMSM) drives with sinusoidal flux distribution and the brushless DC Motor (BLDC) drive with trapezoidal flux distribution [1-2]. Recent availability of high energy-density permanent magnet (PM) materials at competitive prices, continuing breakthroughs and reduction in cost of powerful fast, digital signal processors and micro-controllers combined with the remarkable advances in semiconductor switches and modern control technologies have opened up new possibilities for permanent magnet /brushless motor drives in order to meet competitive worldwide market demands. In addition to this PMSM have several advantages over the DC brush motor and induction motor for low power application. (Listed below)

PMSM have the following advantages over DC Motors:-
Less audible noise, longer life, Spark less (no fire hazard)
Higher speed, higher power density and smaller size, Better heat transfer [4-10]
PMSM have the following advantages over Induction Motors:-
Higher efficiency, Higher power factor, Higher power density for lower than 10 KW applications, resulting in smaller size,Better heat transfer [4-10]
The above comparison shows that the PMSM are superior to the induction motor /DC motor for low power applications.

2. Previous worked that has been carried out already

In the year 1980 T.A. Lipo derived a d-q model for a six phase induction machine , In particular the slot leakage coupling between three phase groups is incorporated into the model, when the equations are specialized to sinusoidal steady state, it is shown that the usual per phase equivalent circuit results. In this paper it is shown that the simplest practical six phase connection using split phase belt result in a penalty of increased stator leakage inductance and consequently increased inverter commutation voltage. [11]

In 1995 (Fig::1) T.A.Lipo again presented a paper on the technique of vector space decomposition control of voltage source inverter fed dual three phase induction machine. In this paper by vector control decomposition, the analytical modeling an control of machine are accomplished in three two dimensional orthogonal subspace an the dynamics of the electromechanical energy conversion related and the non electromechanical energy conversion related machine variables are thereby totally decoupled. A space vector PWM is also developed to limit the 5^{th}, 7^{th}, 17th, 19^{th}…….harmonics currents.[12]

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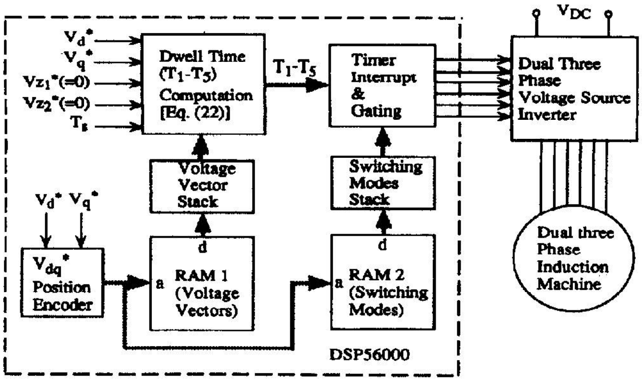

Fig: 1 Block Diagram

In the next paper by T.A.Lipo in 1996, a unified approach to the modeling and field-oriented control of dual three phase induction machine with one phase open is presented. Using the concept of vector space decomposition, the proposed technique is established on the basis of the asymmetrical winding structure directly, and thus provides a precise, physically insightful tool to the modeling and control of induction machines with structural unbalance.[13]
Again by T.A.Lipo in the year 2001, describes a technique of injecting third Harmonic zero sequence current components in the phase currents (Fig:2), which greatly improves the machine torque density. Analytical, finite element and experimental results were presented to show the system operation and to demonstrate the Improvement on the torque density. [14]

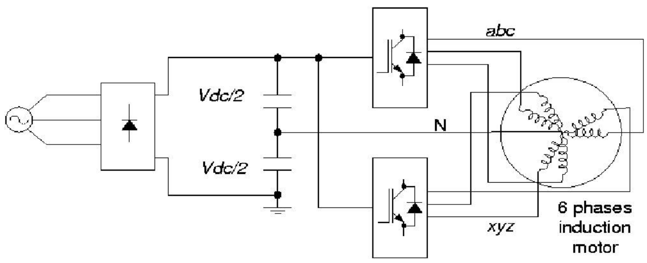

Fig:2 Six-phase machine drive system.

In 2001 Ho-Yong Choi, Sun Jung Park, Young Kyung Kong and Jae Goo Bin, gave, a design proposal of permanent magnet Synchronous motor for ship propulsion. The Appropriate number of poles and slots are selected and the cogging torque is minimized in order to reduce noise and vibrations. To perform high efficiency and reliability, the inverter system consists of multiple modules and the stator coil has multi phases and groups. Because of the modular structure, the motor can be operated with some damaged inverters. In order to maintain high efficiency at low speed operation, same phase coils of different group are connected in series and excited by the half number of inverters than at high speed operation. A MW-class motor is designed and the performances with the proposed inverter control method are calculated.[15]
In 2002, Mingzhong Qiao, Xiaofeng Zhang, Xiuming Ren presented Mathematical models of p-pair poles N-phase sine wave permanent static reference frame and d-q rotating reference frame were established. The maximum transient short-circuit current circuit of the motor was deducted. Experiment showed that the mathematical models established and short circuit current expressions deducted were correct[16].
In 2003 Bojan ˇStumberger,, Gorazd ˇStumberger,Anton Hamler, Malden Trlep, Marko Jesenik, and Viktor Goriˇcan, presented a finite-element method-based analysis of output power capability improvement in a six-phase flux-weakened permanent magnet synchronous motor with a third harmonic current injection. It was shown that the flux-weakened permanent magnet synchronous motor with the third harmonic current injection is capable of producing more output torque per root mean square current flowing through the windings than the same motor supplied with sinusoidal currents. The results of the analysis were partially verified with measurements [17].

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In 2003 Leila Parsa Hamid A. Toliyat Gave a paper, a new five-phase brushless permanent magnet motor, the proposed motor has concentrated windings so the produced back-EMF is almost trapezoidal. The motor is supplied with the combined sinusoidal plus third harmonic of currents. For presenting the superior performance of the proposed five-phase motor, its three and five-phase. Counterparts were also analyzed. By changing the number of turns and slot width, the amount of copper and iron are kept constant in all motors so that the copper and core losses are almost the same. Finite element method was used for studying the flux density and calculating the developed static torque. Also, the developed Torque was obtained using the mathematical model in d-q frame. The average torque and the torque ripple all cases are presented and compared.[18]
In 2005 Narayanaswamy. P.R. Iyer Dr. Jiangsu Zhu described, modeling of a six step discontinuous current mode inverter fed PMSM drive using SIMULINK (Fig: 3). The dq-axis voltage-current and torque relation in terms of machine parameters were used to develop the simulink model. A six step 120 degree mode inverter model was newly developed using simulink [19].

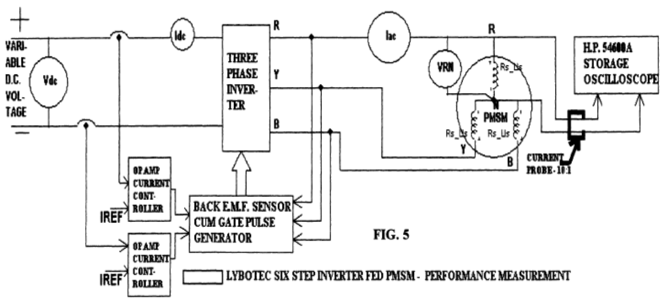

Fig: 3 block diagram

A. R. C. Sekhar Babu1, K. R. Rajagopal, and P. R. Upadhyay in 2006 presented the effects of no uniformity of the air gap on various performance characteristics of a multiphase doubly salient permanent magnet motor (DSPM). A 6/4 DSPM configuration is analyzed with the help of two-dimensional finite element analysis to predict the effects of three important air gap no uniformities viz. 1) relative eccentricity between the stator and rotor axes; 2) concentricity Error on one half of the rotor; and 3) an elliptical rotor. It was observed that a relative eccentricity up to 20% of air gap has no appreciable effect on the static torque characteristics of the DSPM, above which the permanent magnet torque increases due to reduced air gap, thereby increasing the unbalanced magnetic pull. Therefore, about 20% tolerance in air gap can be allowed for relative eccentricity errors. In case of the concentricity error on one half of the rotor, this tolerance is from 10% to +15% of the air gap, whereas the corresponding limits in the elliptical rotor case are 15% of the air gap.[20]
In 2006 G.Q. Bao, J.K.Wang, D.Zhang and J.Z. Jiang presented a topology Based on the characteristics of transverse flux permanent magnet machine (TFPM), a novel multi-pole and multi-phase TFPM topology with assembled stator and concentrated flux rotor. The associated electromagnetic fields of the prototype were investigated by means of three dimension equivalent magnetic network method (3DEMNM)[21].
In the same year Leila Parsa Taehyung Kim multi-phase interior permanent magnet motors with fractional-slot stator and double layer winding distribution were studied. It was shown that despite other IPM Machines; the introduced multi-phase IPM machines have a very low torque pulsation. Seven and nine-phase IPM machines have been designed using the same method. The approach can be extended to the machines with any number of phases. For comparison purposes, IPM machines with common configuration are also considered. It was shown that the torque pulsation of the proposed IPM machines was significantly lower than the conventional ones. Nonlinear finite element method was used to analyze different machine configuration [22].
In 2008, Zitao Wang gave a new topology a six-phase Permanent magnet synchronous machine (PMSM) system AC-DC control. A hybrid control method was s developed based on this topology. The six-phase system was divided into two three-phase systems. One three-phase system, as a master
System, operates through a three-phase active boost rectifier, which controls Vdc voltage and output current; the other Three-phase system, as a salve system, operates through airee-phase diode rectifier, whose output current is Controlled by a DC-DC boost chopper and is sent on the same DC-bus with the master system. The system space vector control is

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realized through controlling the master system by measuring the six-phase currents and Vdc voltage. The simulation results were used to verify this new control method [23].

Same year 2008 Sándor Halász gave different continuous PWM strategies of multi-phase inverter-fed ac motors were investigated from point of view of ac motor harmonic losses. It is shown that for phase number over seven the natural or regular sinusoidal PWM of multi-phase system gives the best solution both from the point of view of the simplicity of realization and the value of harmonic losses. However, these losses were higher than those in case of three-phase system. The theoretical results were checked by simulation [24].

In 2008 Hongyang Zhang , Renyuan Tang gave a paper Characteristics and application of multi-phase space vector PWM (SVPWM) technology (Fig:4) based on multi- phase permanent magnet synchronous motor (PMSM) variable speed system with high performance, and experimental performances for motor and inverter were evaluated[25].

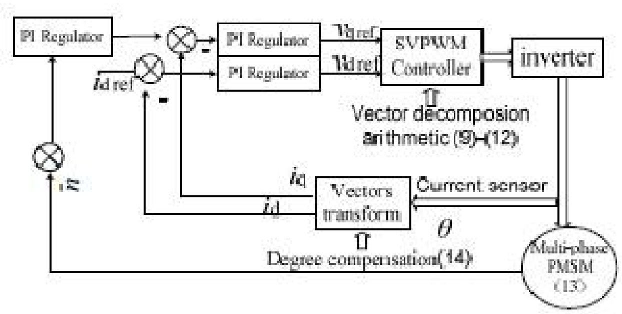

Fig: 4 The basic schematic diagram of FOC for multi-phase PMSM

In Same year Jianguang Zhu, Hongyang Zhang, Renyuan Tang the general methods of analysis and study for Multi-phase permanent magnet synchronous motor (PMSM) Variety speed system based on the vector space decompositionmtheory was discussed in this paper. Furthermore, the reliability of the system was discussed and a fault-tolerant compensation strategy purposed forming the revolving magnetic field in order to solve the system occurred familiar faults was also introduced, thereby improve consumedly the ability of fault-tolerant [26].

In 2009 F. Baudart, F. Labrique, E. Matagne, D. Telteu, P. AlexandreThis paper deals with the control of multiphase Surface mounted permanent magnet (SMPM) synchronous machines with mechanically and magnetically decoupled phases. As this type of machines is well suited for fault tolerant drives in critical applications as aerospace applications, the paper focuses on the power architecture and torque control strategies allowing to produce an almost ripple free torque both under normal and fault operation. The cases of a five-phase machine and of a six phase machine are considered [27].

In the same year T.J.E. Miller and M.I. McGilp, presents the complete steady-state analysis of the PM synchronous machine with multiplex windings, suitable for driving by multiple independent inverters. Machines with 4, 6 and 9 phases are covered in detail. Particular attention is given to the magnetic interactions not only between individual phases, but between channels or groups of phases. This is of interest not only for determining performance and designing control systems, but also for analysing fault tolerance. It is shown how to calculate the necessary self- and mutual inductances and how to reduce them to a compact dq-axis model without loss of detail.[28]

Advance techniques such as neural network and fuzzy logic control has also been used by the researcher like in 2011 Faa-Jeng Lin, Ying-Chih HungA Takagi-Sugeno-Kang type fuzzy neural network with asymmetric membership function (TSKFNNAMF) was proposed in this study for the fault tolerant control of a six-phase permanent magnet synchronous motor(PMSM) drive system. First, the dynamics of the six-phase PMSM drive system is described in detail. Then, the fault detection and operating decision method were briefly introduced. Moreover, to achieve the required control performance and to maintain the stability of six-phase PMSM drive system under faulty condition, the TSKFNNAMF control, which combines the advantages of Takagi- Sugeno-Kang (TSK) type fuzzy logic system (FLS) and asymmetric membership function (AMF), is developed. The network structure, online learning algorithm using delta

Adaptation law and convergence analysis of the TSKFNNAMF are described in detail. Furthermore, to enhance the control performance of the proposed intelligent fault tolerant control, a 32-bit floating-point digital signal processor (DSP) TMS320F28335, is adopted for the implementation of the proposed fault tolerant control system. Finally, some

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experimental results are illustrated to show the validity of the proposed TSKFNN-AMF fault tolerant control for the six-phase PMSM drive system [29].

In 2011, Marco Fei, Roberto Zanasi and Federica GrossiThis paper deals with the modeling of multi-phase permanent magnet synchronous motors under open-phase fault condition. In this paper the model of a multi phase PM machine in the case of open phase fault condition is proposed. The model is suitable for faults occurring at any phases: the faults can happen on one single phase or more than one phase (both adjacent and not adjacent phases). Moreover the model holds for any shape of the rotor flux and for a generic odd number of phases [30].

In 2011M. Villani M. Tursini G. Fabri L. Castellini. The present paper recalls the basic concepts of multi-phase fault-tolerant design and illustrates their adoption in the development of two different systems for aircraft application such as a flap actuator and a cart lift system. Design details will be presented. Reports of analyses and tests carried out on the drives prototypes will be included to confirm the fault-tolerance capabilities with respect to the lack of one or two phases [31].

In 2011Yi Guo, Xuekui yan A new matrix converter topology has been designed for the dual-three-phase PMSM in this paper. This topology has six phase input and overcomes the

Standard matrix converter disadvantage. Some control methodologies have also been researched on. By simulation and experiment, Designed matrix converter and control method are feasible and have high efficiency [32].

In 2011 R. Zanasi, F. Grossi, M. Fei presented two power-invariant real and complex state space transformations for modeling multi-phase electrical machines in a compact and general form. In particular the paper deals with the modeling of multi-phase permanent magnet synchronous machines with an arbitrary number of phases and an arbitrary shape of the rotor flux. The dynamic model of the motor was obtained using a Lagrangian approach and in the frame of the Power-Oriented Graphs technique. The obtained models are equivalent from a mathematical point of view and can be directly implemented in Simulink. The complex transformed model is quite compact and uses a reduced order state vector [33].

In 2012, ZHANG Fan, ZHU Jingwei and LIU Dongxing,In order to improve the control performance of the six-phase fault tolerant permanent magnet (FTPM) motor drive (Fig:5) in healthy and faulty conditions, the vector control technique for this motor drive is studied in this paper. Based on the analysis of the structure and operating principle, the mathematical models in the rotational coordinate system and the simulation model of vector control system using SVPWM technique for this motor drive are established. The simulation results shows that the designed vector control system for six-phase FTPM motor drive can quickly track the required speed and output torque. After one-phase open-circuit fault, through properly increasing the current in healthy windings, the motor drive can still provide the same output torque as in healthy operation and the torque ripple is not increased obviously[34].

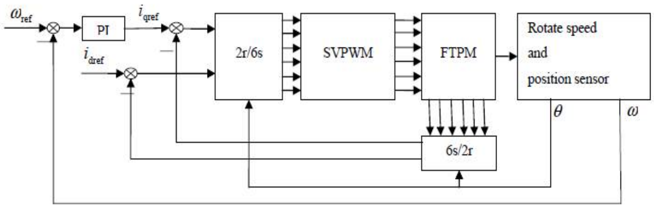

Fig:5 vector control scheme

In 2012 , J. Karttunen, S. Kallio, P. Peltoniemi, P. Silventoinen, and O. PyrhonenThis paper investigates a dual three-phase Permanent magnet synchronous machine supplied by two Independent three-phase voltage source inverters (VSIs). Dual three-phase machines have many important advantages compared with their conventional three-phase counterparts. Instead of six-phase converters and special vector controls, it would be a very interesting alternative to supply these machines by two conventional three-phase VSIs since they are readily commercially available. This paper shows that the proposed supply method can be used successfully although it suffers from a decrease in the dynamic performance and an error in the estimation of torque. On the other hand, two independent VSIs do not cause low-frequency current harmonics and guarantee balanced current sharing between the winding sets thus avoiding the two most common problems with dual three phase machines. Experimental results are provided to verify the conclusions. The results suggest that the simple supply method of two conventional VSIs could be a feasible alternative for many industrial applications [35].

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In 2013 A.S. Tomer and S P Dubey presents a complete modeling and performance analysis of six phase Permanent Magnet Synchronous Motor (PMSM) drive system supplied by two voltage source inverters. The Six phase PMSM drive system is reliable, reduces the stator current per phase, and posses high degree of freedom as compared to conventional three phase drives. Vector control technique is used with two Pulse width modulated (PWM) inverters (fig:6). The proposed model is simulated under various load conditions such as no load, steady load and dynamic load. Computer simulations obtained under various operating conditions have been presented and found satisfactory.[36]

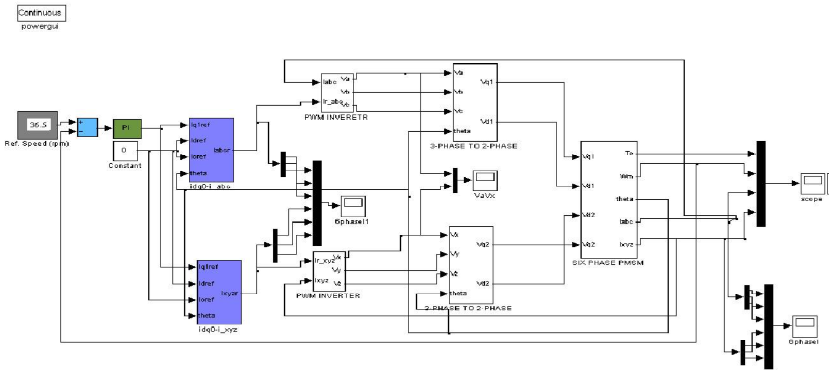

Fig:6 Simulink model of Six phase PMSM drive

In 2014 S.A.KH. Mozaffari Niapour, GH. Shokri Garjan, M. Shafiei, M. R. Feyzi, S. Danyali, M. Bahrami Kouhshahi Brushless DC (BLDC) motors and their drives have been increasingly considered in a broad range of applications due to their significant features. The implementation of these motors is possible thanks to firstly, the progress of permanent-magnet (PM) technologies which provide high efficiency, power density, and torque for these motors. Secondly, the structure and special features of these motors have prepared a basis for simpler control and smaller size compared to those with the same power. In this paper, the basic drives of BLDC motors have been reviewed in order to provide a useful reference for primary research in conventional methods of these types of motors. To present a proper insight to various drive techniques in these motors a systematic classification to control strategies with principles of these techniques has been made. In addition, computer simulations have been utilized in order to achieve a more accurate evaluation, provide the possibility of comparative analysis between various strategies, and place emphasis on the constraints and features of each method. Apart from the comparison of different methods of each strategy, a general comparison among the different methods of various strategies has been made based on the torque ripple, analysis of frequency, and losses of the BLDC motor drive as well as various applications of the different controlling methods. Moreover, considering the importance of electric vehicles (EVs) in industry, selection of the best controlling method for this type of applications together with energy regeneration has been discussed[37].

IV. CONCLUSION

Nowadays,multiphase drives exhibit excellent feature, especially for the industrial sector. Multiphase drives have large number of degrees of freedom if compared to the classic three-phase system. This enables enable the implementation of new and promising drive structure, such as the so called
multi-motor multiphase drive. Multiphase machines with special design can be connected in series and then independently controlled with a single multiphase inverter, resulting in a more compact structure, with less inverter legs than the three-phase counterpart. Furthermore, the centralized control of such a structure reflects in a high performance drive. Though the multiphase drive concept is not new, it has attracted the attention of the research community since the 90s. and with the advancement of technology in terms of neural network controller, Fuzzy logic controller, wavelets, FEM analysis, new features have been developed, such as the drive power capability enhancement, fault-tolerant characteristics And, last but not least, the multi-motor drive configuration.

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