Abstract

Dead time is used to avoid the short circuit of DC link for the three phase pulse width modulation (PWM) voltage source inverters (VSI).But adding the dead time into the control signals causes severe distortion in phase current and also output voltage waveform. For that cases losses of the iron and the core and also torque ripple increases. Especially in low speeds the control performance and stability of the system will be degraded. The effect of dead time will be analyzed and will be investigated for both mosfet and igbt based VSI for various PMSMs. The proposed dead-time compensation method will be software based so will not require additional hardware and will not need precise current sampling especially in zero crossing regions. The method will be integrated to the PMSM drive which is controlled by FOC algorithm. The effectiveness of the proposed method will be verified by experimental results and spectrum analysis. The waveforms of a phase, id and iq currents will be compared with and without compensation in the steady state and dynamic process.

Introduction

The three phase pulse width modulation (PWM) voltage source inverters (VSI) are widely used in adjustable speed drive applications. To avoid DC-link short circuit, turn on delay time is added to the switches so that the leg switches never conduct at the same time. During dead-time both switches are remained in OFF position. The switches have also finite turn on and off delay times. Although these delay times are very short they cause voltage distortion on the output voltage of the inverter. The distortion of the waveform gets more severe when the switching frequency increases. There exist also inverse relationship between effects of the lag times and the frequency of the output voltage. As the frequency of the output voltage decreases, the distortion becomes more serious. So the worst case is high switching frequency, low output voltage frequency and also low output voltage magnitude. For that case losses of the iron and the core increases and also torque ripple increases. Especially in low speeds the control performance and stability of the system will be degraded because of these effects.

Literature

[8] uses eCAP module of the DSP to compensate the dead-time effect. eCAP module is used as a time stamper to measure elapsed time of Ton in a one switching period. The average inverter pole voltage is then calculated by assuming dc link is constant and no voltage on the inverter switches. The compensation method given in the paper does not need any of the phase current value. The desired reference voltage is known, the actual phase voltage is known (by using eCAP) the compensation is done after two sampling periods (comes from digital delay plus PWM update delay). To further improve this method PI regulator is used to zeroize difference of the voltages.

[15] compensates voltage distortion error by a graphical way. The method is applied to both mosfet- and igbt-based PWM-voltage source inverters while motors are in steady-state and also dynamic region. A current observer is used to handle time delay of phase current to get precise current (especially during zero-crossings of the current). By showing the waveforms of the gate signals of the one leg of switches and also showing the output voltage in an ideal and non-ideal cases, error voltage components are calculated in one switching time. In each switching period, voltage compensation method is applied to the reference duty cycles. The parameters of the inverter are measured in offline and error in the output voltage is done online.

[17] uses an adaptive dead-time compensation method by using PWM predictive control. To do this dead-time error voltages in d-q frame is obtained. Dead-time error voltages Ud\_dead and Uq\_dead is calculated in discrete time by using reference and feedback id\* and iq\* currents and as well as motor parameters. The proposed method does not rely on current polarities and valid for different motor speeds why they called it is adaptive. In simulation and experiment IGBT based PWM-VSI is used.

[19] in this paper, disturbance voltage is determined by using an observer which is based on harmonic analysis and kalman filter. The dynamic model of the PMSM synchronous motor is constructed in dq frame in state space model. The disturbance voltages are taken as a third state variable (id, iq & Vdead) by using dominant sixth harmonic component. Extended Kalman filter estimates the disturbance voltage by using the state equations which are in discrete time domain. The polarity of the compensation voltage is obtained from the estimated id and iq currents but not from the measured currents. So the risk of the faulty compensation around the zero crossings is reduced. The compensation method is applied in αβ domain rather than in dq frame due to Vαβ contains all required harmonic components not only the sixth harmonic.

[20] uses revised repetitive controller (RRC), to decrease distortion of the phase current which is caused by dead-time. RRC with moving average filter and an adaptive gain is added in series with current PI controller. The dead-time voltage error is given by using Tdead time and also the switch turn on/off delay time. Limitation of FOC is given by expressing the disturbance error transfer function. High frequency disturbances like dead-time voltage errors (dominant 5th and 7th harmonics in α-β frame, and 6th harmonics in d-q frame) cannot be reduced as expected by using only standard FOC PI controller. RRC includes three main blocks the delay function, FIR moving average filter and gain. Transfer function of these blocks are implemented and inserted in series with the current PI regulator. By using Vd and Vq voltage references in feedforward control, the DC component of dead-time voltage is also decreased. It is shown that low frequency gain is increased so better steady-state performance and dead-time related frequency gains are also increased to reduce dead-time induced current harmonics via bode diagrams of the open loop transfer function. During transients the proposed method is also tested and it is enabled and disabled without causing any overshoot or DC component change.

[23] a least mean square (LMS) based algorithm which is basis for artificial networks, is used to reduce current harmonics caused by dead-time in PMSM V/f control. The same formulation for dead-time voltage error in d-q frame is given in the paper with [20]. But for V/f control, voltage reference is constructed without using rotor position. From d-q frame a new orthogonal synchronous reference frame γ-δ is created to obtain voltage reference frame where δ is aligned with the voltage vector reference frame. The compensation is adapted both of γ-δ axes and generates the voltage reference frames. The algorithm does not depend on precise current sampling especially in zero-crossing region. The performance of the method is also tested in dynamic situations.

[28] uses an adaptive linear neuron based algorithm to reduce voltage distortion caused by dead-time effects. The voltage error is given by considering turn on/off time of the switches, the dead-time and also voltage drop of the switches and anti-parallel diodes. After frame transformations by using Park and Clarke transform and applying Fourier transform voltage distortion is expressed in d-q frame. Discrete time steady state PMSM equations is given by considering the distorted voltage components. Then after disturbance voltage is estimated by using ADALINE algorithm. The weights of the algorithm is modified by the least mean square. The paper states that the only needed information is d axis current and rotor position.

**Related\_topics**

* id &iq decoupling control strategy
  + [6]
    - to reduce the additional losses of the PMSM during the dynamic processes
      * The dynamic process of starting and braking is simulated, and the simulation results validate the effectiveness of the proposed approach in reducing additional loss.
  + [11]
    - coupling effects between two axes which may degrade current control performance
      * The proposed scheme is more robust to cross-coupling inductances and parameter errors, compared to conventional decoupling methods
* output voltage distortion, (due to o dead-time, switching time, delay time, voltage drops on semiconductors, freewheeling diode, parasitic capacitance, etc)
  + [8]
    - the dead-time results in the voltage distortion of the pole voltages which causes low order harmonic components in the output current of the inverter
      * the 5th and 7th harmonic currents are reduced
  + [15]
    - In model-based motor control techniques, voltage precision is crucial for control quality. Thus, a high precision voltage error compensation strategy is required.
      * The voltage distortion principles of MOSFET-based inverter and IGBT-based inverter were analyzed and compared. All voltage error factors were considered in the proposed voltage distortion compensation strategy. With the proposed graphical compensation strategy, the voltage error between reference voltage and output voltage is precisely compensated both in steady state and dynamic process. With current observer, inherent delay of phase current is overcome. The noise in phase currents is eliminated by using a lowpass filter. After voltage distortion compensation, the current total harmonic distortion (THD) is obviously lower.
  + [16]
    - paper strives to give full analysis for phase-current distortion and zero-current clamping phenomenon caused by parasitic capacitance of power devices and every power device is paralleled with additional capacitors of different values in the simulation and experiment
  + [17]
    - The performance of Predictive Current Control largely depends on the accuracy of the model.Many nonlinear factors such as dead time may cause a slight difference between the real model and the ideal model. This will lead to an error between real output voltage and reference voltage, which deteriorates the waveform and increases the THD of phase current, besides, oscillation also appears in torque and speed.
    - A novel adaptive dead-time compensation method based on PWM predictive control is proposed in this paper
      * The simulation and experimental results prove that this method is effective in the restraining of dead-time effect and polishing the phase current waveform, besides, it is with adaptivity.
  + [18]
    - the nonlinear behaviour of VSI is mainly due to dead-time of the switching signals, delay of the control unit, turn-on/off delays, and voltage drop of power switches. Main undesirable effect of nonlinearities is the voltage distortion, thus the loss of magnitude in the fundamental component and the increment of harmonics (especially 5th and 7th harmonics) . As result, the quality of motor current is degraded, mainly at the zero crossing, influencing flux and torque of the machine. Moreover, the control stability is especially endangered when the machine is operating at low speed-torque. At steady-state the VSI nonlinearity effects have a significant contribute in lowering the efficiency and in increasing the torque ripple of the electrical machine
      * In this paper, a nonlinearity compensation method for PCCbased VSI-fed electric drive has been proposed. The algorithm evaluates the voltage error and a suitable time shift for the switching pattern using only the error between the real current and the reference one
  + [19]
    - the processes of converting the command phase voltages into the resulting output voltages is not entirely accurate in practice. This error is given by non-ideal behavior of the switching elements during the switching cycle and overall design of the VSI. It causes distortion of the phase voltages which results in deformation of the phase currents, torque pulsation and overall affect the effectiveness of the control algorithm. Therefore, the error of phase voltages can not be ignored and must be compensated
      * In this paper, a novel adaptive compensation strategy for reduction of dead-time effects and nonlinearity of the VSI is presented. The observer that estimates the value of the voltage error by only one parameter is proposed based on the harmonic analysis and the Extended Kalman filter.
      * The adaptive observer which estimates the dq-currents and the value of the voltage error is designed based on the harmonic analysis and algorithm of the Extended Kalman filter
      * A better steady-state and dynamic performance of the PMSM drive is achieved through the suppression of the voltage distortion. The results of simulations and experiments show the effectiveness of the proposed compensation strategy
  + [20]
    - deadtime not only introduces load and frequency dependent distortion to the inverter output voltages, but also degrades stability and control performance especially at low speed operations
    - This paper proposes a dead-time compensation method based on RRC which is deployed in series with current PI controllers. A moving average FIR filter and an adaptive gain are inserted to assure stability. The RRC can be conveniently activated or bypassed without affecting motor’s operation.
      * It is shown that the proposed method significantly reduces the current THD and waveform distortion without depending on precise current sampling especially in the zero-crossing region. The proposed method is integrated to a 2.5 kW PMSM drive and requires 20% more instruction cycles in the digital signal processor (DSP) compared with traditional FOC algorithm.
  + [23]
    - the dead time and the switching device nonlinear characteristics produce errors at the output voltage and cause the current distortion. The current distortion can induce increased torque ripple and reduced efficiency.
      * This paper proposes a new LMS based dead-time compensation method which solves aforementioned issues. It can directly reduce the current harmonics caused by the dead time without depending on precise current sampling especially in the zero- crossing region. The LMS algorithm is the basis for artificial networks.
        + the proposed method is illustrated in the context of a V/f control scheme. In order to validate its fidelity, it is experimentally tested on a 2.5 kW PMSM VSI drive. The experimental results and spectrum analysis show that the current distortion is effectively reduced in both steady state and transient states.
        + In the steady state, the phase current THD can be reduced from 8.68% to 2.32% at 400 rpm under rated load when the proposed method is applied.
  + [28]
    - the dead-time effect is one of the most crucial nonlinearities that will result in serious distortion in the output voltage and phase current of the PWM controlled voltage-source-inverter (VSI) . The distorted output voltage likely will deteriorate the estimation accuracy of rotor position/speed so as to degrade the performance of the PMSM drive
      * This paper proposes a simple dead-time effect compensation strategy based on the ADALINE algorithm . Using the least mean square method, the proposed dead-time compensation method is capable of estimating the disturbance voltage Vdead online
        + Experimental results verify that the proposed dead-time compensation algorithm is capable of effectively suppressing the harmonics in the PMSM drive.
* The delay issues caused by calculation, filter and PWM generation, etc
  + [12]
    - for bandwidth improvement
      * the bandwidth for current, speed and position loops of servo drives can be significantly improved comparing to that using conventional methods

[1]: 5kVA output power single phase inverter by using enhancement mode GaN transistor at 50kHz switching frequency with the design of the output filter inductor based on a multilayer, high current PCB magnetics.

in this thesis three items are highlighted. First one is systematic approach is used to design the inverter. The losses of transistors are calculated by analytically with regarding modulation index. Second one pcb inductor design and last one is 5kVA single phase inverter which has not made up to now with GaN

[2] : This thesis develops a simplified finite-state predictive torque control (FS-PTC) algorithm based on selected prediction vectors (SPVs). The finite-state predictive torque control (FS-PTC) of motor drives is an MPC strategy. In FS-PTC, a finite number of possible control actions—voltage vectors in this study—are evaluated against control objectives (torque, flux and other system constraints) in an iterative prediction loop. After this, an optimum voltage vector is selected by minimising a predefined cost function and applied to the motor terminals via an inverter. The proposed SPVs strategy also assists reducing the average switching frequency for a two-level voltage source inverter fed induction motor (IM) drive. this thesis proposes to integrate the FS-PTC with a three-level neutral-point clamped (3L-NPC) inverter driven IM drive.

[3] : wide bandgap semiconductors (SiC, GaN), These components can switch much faster than their silicon counterpart, which can reduce converter losses and also decrease differential mode filter given the increase of switching frequency. However, such a fast commutation increases Electromagnetic

Interference (EMI) issues in the converter and loads connected to it. This paper investigate the trade-offs between losses and EMI issues of three-phaseinverters used in future aircraft applications. Given the voltageDC bus of 540V, SiC MOSFETs are investigated andexperimental results show the impact of these components onlosses and EMI for different parameters.

[4] : Silicon carbide (SiC) MOSFETs and gallium nitride (GaN) high-electron mobility transistors are perceived as future replacements for Si IGBTs and MOSFETs in medium- and low-voltage drives due to their low conduction and switching losses. However, it is widely believed that the already significant conducted common-mode (CM) electromagnetic interference (EMI) emission of motor drives will

be further exacerbated by the high-speed switching operation of these new devices. Hence, this paper investigates and quantifies the increase in the conducted CM EMI emission of a pulse width modulation inverter-based motor drive when SiC and GaN devices are adopted. Through an analytical approach, the results reveal that the influence of dv/dt on the conducted CM emission is generally limited. On the other hand, the influence of switching frequency is more significant.

[5] : This paper is an effort to put together all the potential applications of Wide Bandgap (WBG) devices in AC electric drives. Low inductance motors, high speed motors, and electric drives operating in a high temperature environment are the main application areas of WBG devices. Low voltage permanent magnet motors and slotless motors have a low inductance and require a stringent high-bandwidth currentregulation strategy to obtain an acceptable current ripple. Silicon(Si) devices cannot be used in this case due to their limitedswitching frequency. MW-level high speed motors have devicesoperating at high voltage and current levels and a highfundamental frequency (600-1200 Hz) that cause very highswitching losses in Si IGBT devices. SiC devices have enabled theuse of power electronic converters for MW-level high speedmotors. Integrated motor drives (IMDs) are also benefitted byWBG devices as they reduce the size of the power converter andallow operation at a high junction temperature. Therefore, theinverter can be mounted on the motor itself which can be asignificant heat source due to motor losses. Cooling requirementsin high temperature environment applications such as hybridElectric Vehicle (EV), ground vehicles in combat zones, andpower converters used in space technology like land rovers etc.,are greatly reduced due to low losses and high junctiontemperatures. Operation at high frequencies and hightemperatures reduces the size of electric drive significantly.

[6]:Additional loss is produced when the speed of the PMSM drive system is changed with the common id=0 control strategy. Hence, in this paper, a method based on the decoupling control strategy is proposed to reduce loss of permanent magnet synchronous machines (PMSMs) in dynamic state. The new decoupling control strategy could reduce the additional loss compared with the traditional method by holding the value of id near zero. The simulation results validate the effectiveness of the proposed decoupling strategy.

[7]: This paper presents a performance comparison of a cascodeGaN HEMT and a Si MOSFET rated at 600V which are used in a 1 kW three-phase inverter. The advantages and challenges of using GaN transistors in a motor drive application are discussed. Thermal simulations of a GaN and Si based inverter have been performed and experimental results of the switching performance and inverter efficiency using both device technologies are presented. The results show the high potential of GaN power devices in a motor drive application.

[8] : This paper presents a simple dead-time compensation method for a three phase PWM inverter based on the measured pole voltage using enhanced capture (eCAP) module usually embedded in a digital signal processor (DSP). The information of the inverter pole voltages can be employed to compensate the voltage difference between commanded voltage and actual output voltage of the PWM inverter. Because the method does not rely on any other information except for the measured switching instants of each phase of the inverter, it can be easily accommodated into the low cost drive system where accurate and instantaneous measurement of the phase current is not available. The difference can be added at the next sampling time of the switching period of the PWM and could be updated after one sampling period due to the digital sampling delay. These total two sampling periods delay would degrade the performance of the dead-time compensation. To enhance the performance, a PI regulator is employed to nullify the difference in controlled manner. The effectiveness of the proposed compensation methods has been verified through the experimental results. Through the proposed compensation method, the 5th and 7th harmonic currents are reduced by 85% and 70%, respectively.

[9] : GaN power devices offer great performance improvements compared to Si transistors. The lower conduction and switching losses of GaN transistors enable to build high efficiency power converters with high switching frequencies. An increase of the PWM frequency has many advantages in motor drive applications like reduced motor current ripple, lower motor losses and reduced filter size and cost. This paper presents the evaluation of a normally-off 650 V, 30 A GaN transistor in a motor drive application. The switching performance of the GaN HEMT is investigated by using a double pulse tester. Furthermore, design and experimental results of a high efficiency 1.5kW three-phase-inverter with sine-output filter and a PWM frequency of 100 kHz are shown. The GaN inverter with sine-output filter achieves 97% efficiency.

[10] : With the rapid development of wide bandgap power transistor technology, the latest gallium-nitride based power transistors are able to be used as the main switches in the high power (≥10 kW) conversion systems. In order to achieve the desired high efficiency and higher power density successfully, the entire GaN based power conversion system needs to take multiple considerations into the design stage. In this paper, a three-phase inverter is used as the example to explain those considerations in detail, including the critical component selection, the system physical layout, the cooling system design, the protection functions design and the EMI control. Based on the proposed design methodology, a 10 kW GaN-based three phase inverter is developed with 98.8% peak efficiency with 0.7 liter box volume.

[11] This paper proposes a decoupling control method for high-performance drive of permanent magnet synchronous motors (PMSMs). The conventional decoupling schemes proposed for removing coupling effects on d-q current regulation have the limited performance because the cross-coupling inductances caused by asymmetric structure and saturation are not considered. Those inductances may degrade the decoupling performance and even make the current control unstable by inducing the additional coupling voltages. Therefore, in this paper, a new voltage model including the cross-coupling inductances is developed and the compensation voltages for decoupling based on the model are calculated. The performance of the proposed decoupling method is verified by experimental results.

[12] : The controller design of servo drives for bandwidth improvement will presented in this paper. The delay issues caused by calculation, filter and PWM generation, etc. are addressed. The controllers of current loop, speed loop and position loop are designed considering the delay and phase margin. Experimental results show the bandwidth for current, speed and position loops of servo drives are significantly improved as compared to those using conventional methods. For the servo drives with switching frequency of 20 kHz, as compared to traditional design method, the achievable control bandwidth for the presented method of position control loop is improved from 20 Hz to 116 Hz.

[13] : Increased productivity in industrial processes can be achieved by dynamic and accurate positioning of servo drives. Therefore, improvement of servo drive dynamics using latest technologies in the key components such as inverter, control system and position measuring device are investigated. Using Gallium Nitride (GaN) or Silicon Carbide (SiC) semiconductors for motor inverters enables energy efficient operation up to pulse width modulation (PWM) frequencies of 500kHz. This allows motor filters with small component sizes. As a result, high motor efficiency, low torque ripple, high control bandwidth and almost ideal sinusoidal output voltages are achieved. Experiments on a 200kHz Gallium Nitride inverter with sine wave motor filter show a current control loop bandwidth of 3.2kHz and almost ideal sinusoidal phase voltages. The achieved bandwidths of the speed and position control loops are 318 Hz and 106Hz, respectively.

[14] : The medium power rating two-level three phase voltage source inverter is among the most popular power conversion systems. The typical switching frequency of the commercial medium power rating inverter, however, is limited to tens of kHz. By increasing the switching frequency and using emerging gallium-nitride devices, the size of the overall system can be greatly reduced. This paper begins by reviewing all commercially available GaN power transistors and their package technologies. The GS66516T device from GaN Systems is selected due to its suitable ratings and superior package performance. Then, a half-bridge structure is designed for this device to achieve low parasitic inductance and strong cooling capability at the same time. The dynamic characterization results of this 650V/60A Enhancement-mode GaN transistor are extracted with the proposed half-bridge structure. A gate drive circuit with comprehensive protection function is integrated. Based on the proposed phase-leg structure, a 10 kW three phase inverter prototype is built and the experimental waveform is shown at the end.

[15] : To achieve precise voltage value for modern model-based motor control strategies, an accurate voltage distortion compensation method for voltage source inverters is proposed in this paper. The voltage distortion principles of a mosfet-based inverter and an IGBT-based inverter are analyzed and compared. A graphical solution of compensating voltage error is proposed, all the voltage distortion factors are considered. A current observer is designed to overcome time delay, achieve precise current in each switching period for compensation. The proposed method is of high precision, intuitive, and easy to imple- ment. The effectiveness of the proposed method is verified byexperiments.

[16] : Insertion of dead time in space vector pulse width modulation (SVPWM) causes phase voltage and current distor- tion or even zero-current clamping phenomenon, degrading the control performance of ac induction motor. In addition, analysis of distortion becomes more complicated due to the existence of parasitic capacitance in power switching device of voltage source inverter (VSI). This paper tries to make clear that how the para- sitic capacitance influences VSI’s output independently. First, an equivalent circuit of VSI containing parasitic capacitance is con- structed. On that basis, mathematical expression of phase voltage distortion is derived fromKirchhoff’s voltage law, Kirchhoff’s cur- rent law, and charge and discharge characteristics of capacitance. Moreover, through the division of multiple zero-crossing regions in one phase current period, the difficulty of obtaining specific phase voltage error expressions is overcome. Second, to figure out the effect of parasitic capacitance, it is theoretically discussed in detail that howparasitic capacitances of different values affect phase volt- age, current distortion, and zero-current clamping phenomenon. At last, simulations and experiments are carried out in which VSI with different parasitic capacitances is constructed by paralleling additional capacitors and with phase voltage feedback methods, the theoretical analysis can be verified.

[17] : An adaptive dead-time compensation method is proposed on the basis of PWM predictive control in this paper. In order to eliminate the influence of dead-time, the dead-time error voltages in the d-q frame are acquired by reference current and feedback current as well as parameters of the motor. Then the dead-time error voltages are added to the predictive reference voltages. The proposed method is simple and with no requirement for the current polarity. Simulation and experimental results prove that the proposed method is effective in restraining the phase current harmonics. What’s more, it’s adaptive even under the variation of motor speed.

[18] :This paper presents a recursive nonideality compensation method for Voltage Source Inverter (VSI) controlled by Predictive Current Control (PCC) in the field of electrical drives. An accurate mathematical model of the effects of VSI nonlinearities, such as dead time and control delay, is here reported including the magnitude loss and the ripple distortion. For every sampling interval, the exact voltage error and ripple time-shift is calculated using only reference and real phase currents. As soon as a steady-state operation is detected, the voltage error of the entire fundamental period is stored in an array and then used to accurately compensate the VSI output voltage in the next fundamental period. The error array is renewed after every transient and a look-up-table is step-by- step built including the motor operating conditions and related voltage error. Experimental and numerical results validate the effectiveness of the proposed algorithm in reducing the VSI voltage and current distortions and their influence on the motor torque and efficiency

[19] : In this paper, a novel adaptive compensation strategy to reduce dead-time effects and nonlinearity of the VSI is presented. These undesirable properties of the inverter are nec- essary to compensate because they cause 5th and 7th harmonic distortion of the phase current, torque pulsation and generally reduce the effectiveness of control algorithm. The observer which estimates the dq-currents and the value of the voltage error by only one parameter is designed based on the harmonic analysis and algorithm of the Extended Kalman filter. Subsequently, the compensating voltages are determined from estimated voltage error and the polarity of the estimated currents. The results of simulations and real experiments demonstrate the effectiveness of the proposed approach.

[20] :This paper presents a new dead-time compensation method for voltage-source inverters (VSI) used in PMSM drives. The proposed method is developed based on the revised repetitive controller (RRC) to reduce current distortion caused by dead-time voltage errors at the inverter output. This method significantly suppresses the sixth order harmonics and it’s multiples in synchronous reference frame and reduces the current total harmonic distortion (THD). Unlike in most average value theory based compensations, the proposed method doesn’t require additional hardware for precise current sampling especially in the zero-crossing region. The algorithm is integrated to 2.5 kW PMSM drive controlled by FOC. It is quite immune robust to motor parameter variations due to the nature of repetitive control. Its effectiveness is validated by experimental results and spectrum analysis.

[21] :This paper discusses the effect of current measurement error in angle estimation of permanent magnet AC motor for position sensorless control based on motor back EMF. The current measurement errors due to non-ideal elements in the system are classified into the scaling error, the offset error, and the discretization error. Those errors have been represented in the estimated synchronous reference frame. The current measurement errors affect the sensorless observer input and the estimated angle. With these results, the effects of the current measurement errors on the estimated angle for the sensorless control are analyzed. Through the analysis, it has been figured out that the estimated angle for the sensorless control is directly affected by the current measurement. The analysis is verified by computer simulation and experimental results.

[22]This paper proposes an alternative strategy of finite-control-set model-predictive torque control (MPTC) to reduce the computational burden and the torque ripple and decouple the switching frequency from the controller sampling time. An improved discrete space-vector modulation (DSVM) technique is utilized to synthesize a large number of virtual voltage vectors. The deadbeat (DB) technique is used to optimize the voltage vector selection process, avoiding enumerating all the feasible voltage vectors. With this pro- posed method, only three voltage vectors are tested in each predictive step. Based on the improved DSVM method, the three candidate voltage vectors are calculated by using a novel algebraic way. This new strategy has the benefits of both the MPTC method and the DB method. The effectiveness of the proposed strategy is validated based on a test bench.

[23] This paper presents a new least-mean-square (LMS) based algorithm to suppress dead-time distortion in permanent-magnet synchronous motor (PMSM) V/f control schemes. The PMSM V/f control schemes are merited for their simple structure compared with sensorless field-oriented control (FOC) schemes. However, among the proposed ones, there isn’t any method developed specifically for dead-time compensation in V/f control schemes. In the proposed method, the LMS dead-time compensator can directly reduce the current harmonics induced by the dead time without depending on precise current sampling especially in the zero-crossing region. Unlike disturbance observer methods which are designed for FOC schemes, it can be applied to both FOC and V/f control schemes. It is also robust to parameter variations because of LMS algorithm’s online adaptation capability. This method is tested on a 2.5 kW PMSM drive controlled by a V/f scheme and requires negligible extra CPU bandwidth. The fidelity is validated by experimental results and spectrum analysis.

[24]: Due to the introduction of wide bandgap (WBG) devices such as silicon carbide and gallium nitride devices, the power inverters with ultra-low loss, high temperature, and compact size are made possible for various applications. However, the increased dv/dt and switching frequency of WBG devices also aggravate the common-mode (CM) voltage related issues of the PWM inverter based systems. In the past few years, the magnified CM EMI emission and ground leakage currents in WBG based inverter systems are starting to draw attentions and becoming a concern among researchers and engineers. In this paper, the four-leg topology is investigated as a potential solution to the CM voltage generation of WBG inverters. Detailed design and implantation considerations of a GaN-based four-leg inverter are presented, and the performance of the inverter is also evaluated.

[25]:This paper presents a high performance 12 kW motor drive system for an aerospace application. In order to achieve higher power density and reliability, the system uses a PMSM motor, SiC MOSFET inverter, high performance PWM control, and liquid cooling with phase change material. A power density of 33 KW/KG was achieved for the power inverter and control electronics excluding the cooling loop, and an overall power density of 0.75 kW/kg motor and drive system. An efficiency of 98% for the power inverter and 91% for the motor and drive system was achieved. Test results up to 10 kW are presented in the paper. The paper also presents challenges in the implementation of the inverters using SiC devices.

[26] High-performance current control is required to obtain a smooth output torque in permanent-magnet synchronous motor (PMSM) drives. In this manner, a new discrete-time robust predictive current controller is pre- sented for PMSM drives. Controller and current prediction schemes are designed based on the dead-beat structure. The dead-beat control has good transient response, but it suffers from parametric uncertainties and unmodeled dynamics. In order to provide robustness, a discrete-time integral term is added to the dead-beat current prediction. The stability analysis is carried out considering the predic- tion error dynamics, nonlinear uncertain model of PMSM, and the integral action as the states of the overall sys- tem. The designed robust predictive controller is tested through numerical simulations and experiments. The pro- posed controller is easy to implement and suitable for high-performance

[27] : Size and cost reduction are among the mainissues of electric motor design and fabrication. This pa- per proposes an original layout for an axial flux permanent- magnet motor with printed circuit board (PCB) winding. In contrast to other axial flux motors of the same type, which are generally made with a three-phase fractional slot wind- ing, the proposed motor has a two-phase wave winding printed on either side of the PCB. This configuration al- lows increasing the number of pole pairs and the supply frequency so to reduce the stator and rotor core widths. The winding is also characterized by a large copper per- centage on the board, which improves the torque density of the motor. The results of the mathematical analysis, of the numerical simulation and of the experiments are compared. A method for the computation of the phase inductances is also proposed and validated. The main dimensions of the magnets are optimized via the finite-element method. The experimental comparison shows the advantages of the pro- posed motor in comparison to the traditional shaded pole motor for household applications.

[28]:One of the commonly used approaches to avoid the short circuit of power devices for pulse-width-modulation (PWM) inverters is to add dead-time into the control signals. The drawback of this approach is that severe distortion in phase currents and output voltages may occur. This paper proposes an adaptive-linear-neuron based nonlinearity compensation strategy to cope with the disturbance voltage caused by dead-time effects. In particular, by minimizing the feedback d-axis current error, the amplitude of disturbance compensation voltage Vdead is self-tuned using the least mean square algorithm. The dead-time compensation method developed in this paper does not need any information about electric parameters and phase current polarity. Moreover, the proposed approach is also free of complex mathematical computations and additional hardware. Experimental results indicate that the proposed dead-time compensation approach is feasible.

[29] : This paper discusses a design methodology for high power density converter design. The ideas are applicable to any topology and any switching technology. Particular attention is paid to the DC-link capacitors, as they are a regular point of failure and take up a sizeable portion of the volume in converters. In moving to wide-bandgap devices, smaller and more reliable film capacitors can be used by switching faster, thereby increasing the power density. A prototype inverter capable of switching 30kW is built using the discussed ideas and low power experiments show good correlation between the estimated and measured efficiency. A power density of 34kW/L is achieved under rated conditions when switching at 100kHz.

[30] : High power density is a desirable feature of power electronics design, which prompts economic incentives for indus- trial applications. In this paper, a gallium nitride (GaN)-based 2-kVA single-phase inverter design was developed for the Google Little Box Challenge, which achieves a 102-W/in3 power density. First, the static and dynamic temperature-dependent character- istics of multiple SiC and enhancement-mode GaN FETs are investigated and compared. Based on the device testing results, several topologies of the inverter stage and different power decoupling solutions are compared with respect to the device volume, efficiency, and thermal requirements. Moreover, some design approaches for magnetic devices and the implementation of gate drives for GaN devices are discussed in this paper, which enable a compact and robust system. Finally, a dc notch filter and a hard switching full-bridge converter are combined as the proposed design for the prototype. A 2-kVA prototype is demonstrated, which meets the volume, efficiency, and thermal requirements. The performance of the prototype is verified by the experimental results.

[1] H. Meşe and I. Çadırcı, “Natural-air-cooled 5 kVA single-phase GaN inverter with paralleled multilayer PCB magnetics,” *J. Eng.*, 2017.

[2] M. Habibullah, “Simplified Finite-State Predictive Torque Control Strategies for Induction Motor Drives,” 2016.

[3] V. Dos Santos, B. Cougo, N. Roux, B. Sareni, B. Revol, and J. P. Carayon, “Trade-off between losses and EMI issues in three-phase SiC inverters for aircraft applications,” *IEEE Int. Symp. Electromagn. Compat.*, vol. 3, pp. 55–60, 2017.

[4] D. Han, S. Li, Y. Wu, W. Choi, and B. Sarlioglu, “Comparative Analysis on Conducted CM EMI Emission of Motor Drives: WBG Versus Si Devices,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 10, pp. 8353–8363, 2017.

[5] A. Morya, M. Moosavi, M. C. Gardner, and H. A. Toliyat, “Applications of Wide Bandgap (WBG) devices in AC electric drives: A technology status review,” *2017 IEEE Int. Electr. Mach. Drives Conf. IEMDC 2017*, 2017.

[6] S. Ding, M. Ding, J. Hang, Q. Wang, and P. Zhang, “Loss Reduction of Permanent Magnet Synchronous Machines based on Decoupling Control Strategy,” pp. 2–6, 2017.

[7] J. Lautner and B. Piepenbreier, “Performance Comparison of Cascode GaN HEMT and Si MOSFET based Inverter for Motor Drive Applications,” no. December, pp. 81–87, 2017.

[8] S. J. Chee, J. Kim, and S. K. Sul, “Dead-time compensation based on pole voltage measurement,” *2015 IEEE Energy Convers. Congr. Expo. ECCE 2015*, pp. 1549–1555, 2015.

[9] J. Lautner and B. Piepenbreier, “High Efficiency Three-Phase-Inverter with 650 V GaN HEMTs,” no. May, pp. 10–12, 2016.

[10] H. Li, X. Li, Z. Zhang, C. Yao, and J. Wang, “Design Consideration of High Power GaN Inverter,” pp. 23–29, 2016.

[11] K. Lee and J. I. Ha, “Dynamic decoupling control method for PMSM drive with cross-coupling inductances,” *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, pp. 563–569, 2017.

[12] M. H. Ho and Y. S. Lai, “Controller design of servo drives for bandwidth improvement,” *2017 IEEE 3rd Int. Futur. Energy Electron. Conf. ECCE Asia, IFEEC - ECCE Asia 2017*, pp. 52–56, 2017.

[13] F. Stubenrauch, J. Wittmann, A. Kiermayer, N. Seliger, R. Hagl, F. Programmable, G. Array, F. Gallium, and N. Gan, “FPGA-based High Dynamic Servo Drive Control with a 200 kHz Gallium Nitride Inverter Keywords Inverter with sine wave filter,” pp. 1–10.

[14] H. Li, X. Zhang, and Z. Zhang, “Design of a 10 kW GaN-Based High Power Density Three-Phase Inverter,” *Energy Convers. Congr. Expo.*, 2016.

[15] Y. Wang, S. Member, W. Xie, and X. Wang, “Strategy for Voltage Source Inverters,” vol. 65, no. 1, pp. 59–66, 2018.

[16] D. Wang, P. Zhang, Y. Jin, M. Wang, G. Liu, and M. Wang, “Influences on Output Distortion in Voltage Source Inverter Caused by Power Devices&#x2019; Parasitic Capacitance,” *IEEE Trans. Power Electron.*, vol. 33, no. 5, pp. 4261–4273, 2017.

[17] K. Yang, M. Yang, Z. Lang, and D. Xu, “An Adaptive Dead-time Compensation Method based on Predictive Current Control,” vol. 1, no. I, pp. 1–5, 2016.

[18] U. Abronzini, C. Attaianese, M. D’Arpino, M. Di Monaco, V. Nardi, and G. Tomasso, “Dead time and nonlinearities compensation for VSI feeding AC drives,” *IEEE Int. Symp. Ind. Electron.*, pp. 271–276, 2017.

[19] L. Buchta and L. Otava, “Adaptive compensation of inverter non-linearities based on the Kalman filter,” *IECON Proc. (Industrial Electron. Conf.*, pp. 4301–4306, 2016.

[20] Z. Tang and B. Akin, “Compensation of dead-time effects based on revised repetitive controller for PMSM drives,” *Conf. Proc. - IEEE Appl. Power Electron. Conf. Expo. - APEC*, vol. 32, no. 3, pp. 2730–2737, 2017.

[21] B. Kim and S. Sui, “li � , l J l l v â€TM li � , l J,” pp. 2171–2176, 2017.

[22] Y. Wang, X. Wang, W. Xie, F. Wang, M. Dou, R. M. Kennel, R. D. Lorenz, and Di. Gerling, “Deadbeat Model-Predictive Torque Control with Discrete Space-Vector Modulation for PMSM Drives,” *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3537–3547, 2017.

[23] Z. Tang, S. Member, B. Akin, and S. Mmeber, “A New LMS Based Algorithm to Suppress Dead- Time Effects in PMSM V / f Drives,” pp. 3156–3162, 2017.

[24] D. Han, S. Li, W. Choi, and B. Sarlioglu, “Design, implementation, and evaluation of a GaN-based four-leg inverter with minimal common mode voltage generation,” *2017 IEEE Energy Convers. Congr. Expo. ECCE 2017*, vol. 2017–Janua, pp. 5383–5388, 2017.

[25] S. Mir, J. Neely, and S. S.- Ieee, “High performance 12 kW motor and drive for modern aircrafts,” pp. 5453–5460, 2017.

[26] T. Turker, U. Buyukkeles, and A. F. Bakan, “A Robust Predictive Current Controller for PMSM Drives,” *IEEE Trans. Ind. Electron.*, vol. 63, no. 6, pp. 3906–3914, 2016.

[27] F. Marignetti, G. Volpe, C. Cecati, and S. M. Mirimani, “Electromagnetic Design and Modeling of a Two Phase Axial Flux Printed Circuit Board Motor,” *IEEE Trans. Ind. Electron.*, vol. 65, no. 1, pp. 67–76, 2017.

[28] Y. C. Pai, J. P. Chang, M. Y. Cheng, and T. J. Liang, “Dead-time effects compensation for PMSM drives - An adaptive linear neuron approach,” *2017 IEEE 3rd Int. Futur. Energy Electron. Conf. ECCE Asia, IFEEC - ECCE Asia 2017*, pp. 1025–1030, 2017.

[29] M. Eull, M. Preindl, and A. Emadi, “Analysis and Design of a High Efficiency, High Power Density Three-Phase Silicon Carbide Inverter,” *2016 IEEE Transp. Electrif. Conf. Expo*, pp. 1–6, 2016.

[30] S. Inverter, C. Zhao, S. Member, B. Trento, L. Jiang, S. Member, E. A. Jones, S. Member, B. Liu, S. Member, Z. Zhang, D. Costinett, F. F. Wang, L. M. Tolbert, J. F. Jansen, R. Kress, and R. Langley, “Design and Implementation of a GaN-Based, 100-kHz, 102-W/in3 Single-Phase Inverter,” vol. 4, no. 3, pp. 824–840, 2016.

[31] Y. Murai, T. Watanabe, and H. Iwasaki, “Waveform distortion and correction circuit for pwm inverters with switching lag-times,” *IEEE Trans. Ind. Appl.*, vol. IA-23, no. 5, pp. 881–886, 1987.