Guest Editorial Special Issue on Integrated Control and Modulation for Electric Drives

GREEN energies and electric mobility are considered exciting solutions to help reduce the emissions of greenhouse gases into the atmosphere. This scenario has significantly promoted the use of electric drives; consequently, higher technical requirements are assumed as mandatory. Focusing on the required high-performance electric drives, the direct control of power converters and the use of integrated modulators, namely, control techniques that avoid the pulse-width modulation stage, can be an attractive alternative to conventional linear controllers. For example, Model Predictive Control (MPC) presents inherent flexibility in defining control objectives, while Direct Torque Control (DTC) provides a fast dynamic response. Unfortunately, unacceptable harmonic distortion can appear in the system if single control action is applied per control cycle. This scenario promotes a higher current ripple in three-phase electric drives when a control scheme using a standard integrated modulator is implemented. The situation is even worse when multiphase drives are used since several orthogonal subspaces need to be regulated with a single control action. In addition, the characteristic low value of the equivalent impedance of the secondary subspaces may lead to enormous harmonic currents. Considering the previous scenario, although the dynamic response is very fast in direct controllers (control scheme based on integrated modulators), these control strategies could be discarded due to their high harmonic distortion. Fortunately, the disadvantages of direct control strategies can be mitigated by using enhanced integrated modulators, such as multi-vector solutions as control actions. On the other hand, as these control techniques' performance is founded on the nature of the available voltage vectors, the use of some specific electric drives, such as symmetrical six-phase machines, can allow taking advantage of their desirable skills.

This Special Issue presents and encourages the dissemination of new research achievements within the design and experimental testing of new modulation strategies for direct controllers applied to power electronic converters in electric motor drive systems. Topics of interest included in this special were:

1) Modulation strategies for the direct controllers in electric drive systems.
2) Theoretical study of voltage vector production in power electronic converters.
3) Application of direct control in power electronic converters.
4) Comparison of MPC with other direct control techniques.
5) Design of direct controls for different electric machine topologies.

In response to the call for papers, 30 manuscripts were received, and 15 articles were finally selected for publication. The manuscripts were submitted from several countries worldwide, such as Belgium, Brazil, Chile, China, Finland, Germany, Iran, the United States of America, the United Kingdom, and Spain. The 15 articles in this Special Issue cover various aspects of the selected Special Topic. In the following, each article will be briefly discussed.

An attractive direct MPC scheme for asymmetric six-phase Permanent Magnet Synchronous Machines (PMSMs), which combines control and modulation in one computation interval, is proposed in [A1] by Wu et al. By emulating the switching pattern of Space Vector Modulation (SVM), the MPC problem is formulated as a 4-D current control problem, where the switching sequences and instants are computed and directly applied to the inverters. This implicit modulation addresses the well-known issues of direct MPC methods, namely a variable switching frequency and spread harmonic spectra.

In [A2], a Modulated Model Predictive Torque and Flux Control (M2PTFC) method with low complexity for a two-level voltage source inverter-fed PMSM is proposed by Nasr et al. to reduce the computation burden and simplify the control implementation of the conventional M2PTFC scheme. Then, the number of candidate voltage vectors at every control sample is reduced to the minimum, and the elimination of the weighting factor of the cost function and its corresponding tuning procedures are presented.

In [A3], an adjacent-vector-based MPC (AVB-MPC) combining the finite-control-set MPC (FCS-MPC) and the multiple-vector-based-MPC is proposed by Chen and Qiu to reduce the current ripples while keeping the merits of fast dynamic responsiveness and inherent overmodulation ability. In addition, a full model estimation method is proposed so that the knowledge of the machine parameters is not required.

In [A4], a cascaded finite set predictive control based on model-free predictive zero-sequence current (ZSC) control for the dual inverter-fed open-end-winding induction-motor (OEW-IM) is proposed by Mousavi et al. The proposal can reduce the computational burden using the two-stage cascaded structure. First, the predictive algorithm is performed for the voltage vectors (VVs) with zero common mode voltage to detect the optimum zone of the space vector locations. In the second stage, the proposed model-free predictive control (MFPC) is implemented with the VVs of the selected zone, and the optimum VV is achieved.

In [A5], a computationally efficient predictive current control (PCC) combined with an extension of the finite set using

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current derivative projection to solve the challenges experienced by FCS-MPC is proposed by Xie et al. A reformulated objective function using current derivative projection with Least-Squares (LS) optimization in PCC is presented, and PCC is geometrically described as a quadratic programming problem. The objective function is rearranged as the quadratic Euclidean norm of the derivative deviation to minimize the deviation between the selected and desired current derivative. A preselection principle avoids the exhaustive search in the optimization stage. Based on the above, the optimal stator current derivatives in the consecutive sampling intervals combined with their duty cycles are optimized by the LS method.

In [A6], an accurate model of current dynamics that captures the computational delay and pulse-width modulator (PWM) characteristics in the discrete-time domain is developed by Wang et al. This analysis helps eliminate the cross-coupling effects in PMSM drive systems. A new structure for controlling the current in the discrete-time domain is proposed targeting the complete compensation of cross-coupling effects of the synchronous reference frame (SRF) while improving dynamic stiffness at low sampling to fundamental (S2F) frequencies ratios.

In [A7], a FCS current controller for grid-tied converters, specifically tailored to meet the characteristics of AC ship microgrids in all-electric ships, is proposed by Pérez-Estévez et al. While the design based on PWM often employs an *LCL* filter, the proposed scheme can meet applicable harmonic regulations using an L filter with the same total inductance as the *LCL* filter and the same switching frequency required by PWM-based solutions. Moreover, the proposed design provides a low sensitivity in a wide frequency range from dc to the switching frequency of the power converter. This low sensitivity permits quickly attenuating low-order disturbances.

In [A8], an improved flux-weakening method with excitation current distribution is proposed by Xu et al. for the hybridly excited asymmetric stator pole doubly salient machine to solve the problem of poor torque capability during the high-speed operation range.

In [A9], a reconfigurable topology of a five-leg inverter for the OEW-PMSM driving system after the device fault condition is presented by Wei et al. Due to the asymmetric structure and common dc bus of the reconfigured fault-tolerant five-leg inverter, the zero-sequence current generated by the dead-time effect and inherent third harmonic voltage of the open-end winding will deteriorate the output torque and the efficiency of the driving system. Therefore, an integrated control method with the closed-loop of zero-sequence current and the compensation of dead-time effect and third harmonic voltage is employed to suppress the distortion current for the low current THD of the OEW-PMSM.

In [A10], a novel reference current slope-based model-free predictive control with modulation strategy is proposed by Ma et al., to address the issues of high current ripple and the model parameter dependence in conventional model-based predictive current control (MBPCC). In the proposed method, the slope of the reference current is used to reduce the active voltage vectors straightforwardly, thus avoiding the enumeration operation of the conventional MBPCC. To reduce the current ripples, a two-vector modulation strategy is introduced to the proposed method. In addition, the current slopes for the possible voltage vectors are obtained in a model-free manner based on online measured data only to reduce the influence of parameter uncertainties on the controller. Here, starting from the principles of the two-vector modulation, the variation of the current with the input voltage vectors in two sampling periods is used to estimate the current slopes for all the voltage vectors. As a result, even though two voltage vectors with variable time durations are applied in each control period, the current slope information can be refreshed every half-control period, thus guaranteeing the reliability and accuracy of current predictions.

In [A11], a model predictive control with duty cycle optimization for a variable-speed wind turbine with a six-switch converter connected to the grid and a squirrel-cage induction generator is developed by Guazzelli et al. The proposed controller improved the steady-state performance of the system, with lower torque ripples, active power ripples, and current total harmonic distortion. Calculations are performed through a virtual null voltage vector adequately applied to the system.

In [A12], a model-free PCC (MFPCC) based on an ultra-local model and an extended state observer is proposed by Agoro and Husain for an asymmetrical dual three-phase (ADTP) PMSM. The MFPCC method provides superior current regulation compared to the standard MBPCC approach under uncertain parameter conditions. Furthermore, the harmonic currents and the current ripple in the ADTP PMSM drive have been regulated to near-zero values using optimized voltage vectors comprised of virtual and null vectors. A generalized center-aligned PWM scheme is presented to facilitate the synthesis of the optimal virtual voltage vectors for implementation on a low-cost digital signal processing platform.

Since FCS-MPC of multiphase drives can use an extra number of inverter configurations compared with the three-phase case, it requires more computing power for the optimization phase. The application time of each selected voltage vector is then increased, which can result in increased harmonic content. Reducing the allowed voltage vectors can speed up the computations, thus ameliorating the current tracking/regulation in the different orthogonal sub-spaces. However, the flexibility offered by the reduced set of voltage vectors is less than that of the full set. Furthermore, a lower sampling time can increase the switching frequency, especially for some speed-load combinations. Therefore, in [A13], a hybrid scheme is proposed by Arahal et al. where the set of allowed voltage vectors is not fixed but instead selected online according to the actual speed and load.

In [A14], a nonlinear variable-horizon predictive functional control (NVHPFC) is proposed by Wang et al. for the speed controller of variable speed PMSM drive system. By analyzing the relationship between the prediction horizon and the electromagnetic torque, a nonlinear variable predictive horizon strategy is presented, which replaces the fixed predictive horizon in classical PFC. Aiming to improve the prediction accuracy and anti-disturbance performance of NVHPFC, a discrete prediction error compensation strategy is incorporated into the NVHPFC. Meanwhile, the stability of the proposed method is verified by the Lyapunov function in the discrete domain.

In [A15], the synchronous optimal PWM (SOPWM) with continuous switching-to-fundamental frequency ratio is proposed by He et al. to reduce the current harmonics. For that purpose, first, the deduction of the traditional pulse patterns is introduced based on the symmetry of the voltage pulse waveform. Then, the principle of the proposed strategy is illustrated in detail, and an overall comparison with traditional SOPWM is given theoretically. With the proposed technique, a considerable reduction in the current THD is achieved over almost the whole high-speed range, and the losses and efficiency of the system are analyzed by the finite-element method (FEM).

In conclusion, the editorial team hopes this Special Issue will provide readers with new research inspirations and encourage them to progress further in high-performance integrated controllers for electric drives and related topics. The editorial team believes that, in the long term, the extensive research in this challenging field will push innovation forward and accelerate the industrial uptake of promising control strategies.

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APPENDIX: RELATED ARTICLES

[A1] Y. Wu et al., “A direct model predictive control strategy with an implicit modulator for six-phase PMSMs,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Apr. 26, 2022, doi: 10.1109/JESTPE.2022.3170847.

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[A3] Z. Chen and J. Qiu, “Adjacent-vector-based model predictive control for permanent magnet synchronous motors with full model estimation,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, May 4, 2022, doi: 10.1109/JESTPE.2022.3172714.

[A4] M. S. Mousavi, S. A. Davari, V. Nekoukar, C. Garcia, and J. Rodriguez, “Computationally efficient model-free predictive control of zero-sequence current in dual inverter fed induction motor,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, May 12, 2022, doi: 10.1109/JESTPE.2022.3174733.

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[A10] C. Ma, J. Rodriguez, C. Garcia, and F. De Belie, “Integration of reference current slope based model-free predictive control in modulated PMSM drives,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Mar. 14, 2022, doi: 10.1109/JESTPE.2022.3159586.

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[A12] S. Agoro and I. Husain, “Model-free predictive current and disturbance rejection control of dual three-phase PMSM drives using optimal virtual vector modulation,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Apr. 28, 2022, doi: 10.1109/JESTPE.2022.3171166.

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[A14] T. Wang, G. Luo, C. Liu, Z. Chen, and W. Tu, “Speed control for variable speed PMSM drive system using nonlinear variable-horizon predictive functional control,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, May 30, 2022, doi: 10.1109/JESTPE.2022.3179386.

[A15] K. He, J. Li, Y. Lu, L. Xiao, L. H. Wu, and H. Chen, “Synchronous optimal PWM with continuous switching-to-fundamental frequency ratio,” *IEEE J. Emerg. Sel. Topics Power Electron.*, early access, Mar. 28, 2022, doi: 10.1109/JESTPE.2022.3162715.

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