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SENSORLESS FRACTIONAL ORDER CONTROL OF PMSM BASED ON SYNERGETIC AND SLIDING MODE CONTROLLERS

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ABSTRACT: The field oriented control (FOC) strategy of the permanent magnet synchronous motor (PMSM) includes all the advantages deriving from the simplicity of using PI-type controllers, but inherently the control performances are limited due to the nonlinear model of the PMSM, the need for wide-range and high-dynamics speed and load torque control, but also due to the parametric uncertainties which occur especially as a result of the variation of the combined rotor-load moment of inertia, and of the load resistance. Based on the fractional calculus for the integration and differentiation operators, this article presents a number of fractional order (FO) controllers for the PMSM rotor speed control loops, and id and iq current control loops in the FOC-type control strategy. The main contribution consists of proposing a PMSM control structure, where the controller of the outer rotor speed control loop is of FO-sliding mode control (FO-SMC) type, and the controllers for the inner control loops of id and iq currents are of FO-synergetic type. Superior performances are obtained by using the control system proposed, even in the case of parametric variations. The performances of the proposed control system are validated both by numerical simulations and experimentally, through the real-time implementation in embedded systems.

Keywords: permanent magnet synchronous motor; fractional order control; synergetic control; sliding mode control

INTRODUCTION

The permanent magnet synchronous motor (PMSM) is widely used in industrial applications, the aerospace industry, electric vehicles, robotics, electric drives and computer peripherals. The popularity of using the PMSM for a very wide range of applications is due to a set of advantages such as efficiency, small size, high power and high torque density.

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Naturally, for the control of the PMSM, a numberof algorithms and control strategies have been developed, both in the range of the classic type of control, and also as through modern and unconventional approaches. The field oriented control (FOC) and direct torque control (DTC) [1–7] can be distinguished among the control strategies of the PMSM. The DTC strategy is characterized by a simpler structure in terms of controllers which are generally ON-OFF, but inherently the performance of the control system is affected by the occurrence of oscillations. The FOC strategy contains a cascade control structure, where the outer loop controls the PMSM rotor speed, and the inner control loops control currents id and iq. In the classical approach, the FOC strategy controllers are PI type. This approach includes all the advantages provided by the simplicity of using such controllers, but inherently the control performances are limited due to the nonlinear model of the PMSM, the need for wide-range and high-dynamics speed and load torque control, but also due to the parametric uncertainties which occur especially as a result of the variation of the combined rotor-load moment of inertia, and of the load resistance. Among the more complex control systems used to obtain superior performances we can mention the adaptive control [8–10], the predictive control [11–13], the robust control [14,15], the backstepping control [16], the sliding mode control (SMC) [17,18] and the synergetic control [19,20]. These types of control systems provide superior performance in terms of the response time, the overshoot and the parametric robustness, and the real-time implementation in embedded systems can be achieved with digital signal processors (DSP) with common performance, with a very good performance/price ratio. Among these control systems, due to their robustness to parametric variations, the SMC-type control systems have a special role, as well as the development of low-order controllers, with obvious advantages in the real-time implementation in embedded systems. To counter SMC's main disadvantage due to the occurrence of the chattering phenomenon, a series of techniques have been developed, among which we mention the use of a proportional-integral type of sliding surface plus integrator or a second-order SMC. Further, we recall that the synergetic control can be considered as a generalization of the SMC-type control, retaining the decoupling and model order reduction properties of this type of control

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and the advantages provided by this approach for the synthesis of the controller. We can mention the following intelligent control systems: fuzzy [21], neuro-fuzzy [22], artificial neural network (ANN) [23–25], particle swarm optimization (PSO) or genetic algorithms [26]. These types of control also provide superior performance, but in the real-time implementation in embedded systems it is necessary to use very fast DSPs, with relatively high costs, in addition to a number of specific software libraries of the control application development environments. Thus, the performance/price ratio does not recommend the widespread use of these types of controllers. Regarding the elimination of the speed sensors, in order to increase the reliability of the system, Luenberger [27], model reference adaptive system (MRAS) [28], and sliding mode observer (SMO) speed observers [29,30] are used for the deterministically described systems, and Kalman type observers [31] are used for the stochastic description of the system. Evidently, according to the performance-cost criterion, the deterministic observers are the most commonly used. Furthermore, a range of observers have been developed for the detection of faults, one of the most useful observers being used for the detection of faults in current sensors on the supply phases of the PMSM. One of the special applications of using the fractional calculus for integration and differentiation operators consists of obtaining the fractional order (FO) controllers [32–35], in order to obtain superior control performance. In this sense, the first approaches were obviously aimed at obtaining FO-PI-type controllers. Although the development of the FO-type controllers is very attractive due to the possibility for finer tuning of certain tuning parameters, which are traditionally integer and fixed parameters (for example the power of operator s in the structure of the PI or PID-type controller), the study of these controllers was greatly accelerated with the development of specialized toolboxes such as the fractional order modeling and control (FOMCON) integrated into the MATLAB/Simulink environment. Among the usual applications of the PMSM control systems we mention: maintaining the speed according to a profile set by a speed reference generator, but also master/slave type multi-motor applications where the coupling is rigid or flexible and it is necessary to maintain the same speed or maintain the torque developed by each engine in the narrowest range possible

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[36]. Furthermore, the electric vehicles drive control applications raise the problem of multi-motor speed control [37]. Applications such as the automatic control of the hydropower dam spillway require that the error accumulated in each drive chain corresponding to each engine be less than the set value [38]. These applications are generally achieved using the controllers described above, but of the integer order type. In this article we will focus on the fractional order controllers which provide superior control performance, but also on the increased difficulties regarding the implementation in embedded systems. This article compares the performances obtained using FO-PI, tilt integral derivatives (TID), FO-lead lag controller, and SMC speed controllers against the classic PI-type speed controller in an FOC-type control structure of the PMSM, under the conditions where the controller of the current loops is of PI type. It also presents the performances obtained by using the synergetic control for the control of currents id and iq, within an FOC-type control structure of the PMSM with PI speed controller. The main contribution consists of proposing a PMSM control structure, where the controller of the outer rotor speed control loop is of FO-SMC type, and the controllers for the inner control loops of id and iq currents are of FO-synergetic type. Superior performances are obtained by using the control system proposed, even in the case of parametric variations. The FO-SMC controller outputs the current reference iqref, while idref = 0 according to the FOC control strategy. The FO-synergetic-type controllers directly provide the control inputs ud and uq, and the control of the inverter is performed through the inverse Park and Clarke transformations from d-q reference frame system to abc reference frame system. The validation of the results presented is achieved by numerical simulations, but also by real-time implementation in embedded systems

LITERATURE REVIEW:

Eriksson, S. Design of Permanent-Magnet Linear Generators with Constant-Torque-Angle Control for Wave Power. ***Energies*** **2019,** ***12*****, 1312**
This paper presents a simulation method for direct-drive permanent-magnet linear generators designed for wave power. Analytical derivations of power and maximum damping force are performed based on Faraday’s law of induction and circuit equations for constant-torque-angle control. Knowledge of the machine

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reactance or the load angle is not needed. An aim of the simulation method is to simplify comparison of the maximum damping force, losses, and cost between different generator designs at an early design stage. A parameter study in MATLAB based on the derived equations is performed and the effect of changing different generator parameters is studied. The analytical calculations are verified with finite element method (FEM) simulations and experiments. An important conclusion is that the copper losses and the maximum damping force are mainly dependent on the rated current density and end winding length. The copper losses are inherently large in a slow-moving machine so special consideration should be taken to decrease the end winding length. It is concluded that the design of the generator becomes a trade-off between material cost versus high efficiency and high maximum damping force. Wave power has been studied for many years but there are still only a few realized commercial projects [1]. Many different types of wave energy converters exist and one of the most common is a point absorber. Alternative power take-off systems exist but a linear direct-drive permanent-magnet (PM) generator is a common solution and has previously been studied by different research teams, such as in [2,3,4,5]. At Uppsala University, a concept with a point-absorbing buoy and a direct-drive PM generator has been studied for 15 years [4]. Linear PM generators most commonly have magnets made of rare-earth metals [6], but generators with ferrite magnets have also been studied [7] and tested experimentally [8]. Advantages with PM generators are that you do not need to magnetize the rotor externally, through the magnetizing current in the stator or by directly magnetizing the rotor and therefore do not have any copper losses associated with the rotor. A disadvantage is that the magnetization is fixed and cannot be controlled. In this paper, the design of the moving part, commonly called translator, is not considered and it is only represented by a magnetic flux density amplitude in the generator airgap. Different generations of linear generators for wave power have been built by Uppsala University and a generator that has been designed, installed and tested is used as a reference design in this work [9,10]. There are a limited number of pervious papers on linear generator design optimization and design choices. A comparison of different design aspects was presented in 2006 [4] for the same generator concept as in this study. That

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study was performed with FEM simulations for diode rectification and therefore focused on different aspects than this study. A design optimization including a cost estimation of a slotless tubular linear generator with longitudinal flux can be found in [11]. Reference [12] presented an optimization study of a generator design for no-load operation but did not motivate how different design choices depend on each other. In [13], the performance of linear PM generators with different pole pitch is compared. In [14], constant-torque-angle (CTA) control is implemented for a wave energy converter with a rotating 248-pole generator. To the author's knowledge, no previous study has been performed on how to optimize the generator design for CTA control including a thorough investigation on how different parameters affect the performance. CTA control is a common choice for generators, and it is commonly implemented with PI-controllers and dq-transformation. CTA control has previously been implemented in wave energy converters. In [14] it is shown how CTA control can be implemented with PI regulators for a wave energy converter with rotating generator. In [15], a control system for an active rectifier with CTA control for a linear generator is simulated and verified experimentally. In [16], a different control system with active control of a PM linear generator is presented. Designing a generator is a task with many degrees of freedom and is therefore very complex and normally time-consuming. For a complete generator design, a full-physics simulation is always needed, usually performed by solving Maxwell's equations in a two-dimensional finite element method (FEM) simulation and taking important three-dimensional effects into account, as presented in [17]. However, to understand how different parameters affect each other a simpler approach may be used, as in this paper, where combining Faraday's law of induction and CTA control simplifies equations and makes it possible to draw some interesting conclusions regarding linear generator design without computationally heavy simulations. The main simplification in this comparative study is that no saturation is taken into account. This will especially influence results at high loading and lead to an overestimation of the maximum damping force. However, the approximation of the damping force can be used to compare different generator designs. The aim is of this study is, first, to present a fast computational method for comparing generator designs, where the generator design is adapted for a certain control strategy and, second, to gain increased understanding of how different design parameters influence the generator performance and to compare different generator designs. The evaluation is mainly performed based on three aspects; efficiency, maximum damping force, and relative material cost. Analytical derivations on generator performance and losses during CTA control, are presented. The equations have been implemented in MATLAB and the simulation method is verified through FEM simulations and experiments. A parameter study on linear generator design is performed and different generator designs are compared from different aspects.

Ouyang, P.R.; Tang, J.; Pano, V. Position domain nonlinear PD control for contour tracking of robotic manipulator. ***Robot. Comput. Integr. Manuf.*** **2018,** ***51*****, 14–24** Contouring control is most important in machining applications to ensure the quality of the final product. In this paper, the contouring control problem for a multi-dof robotic manipulator is studied, and a nonlinear PD (NPD) control law is proposed in position domain and applied to contour tracking control. To develop the position domain control system, the robotic motions are viewed as the combination of a master motion, controlled in time domain, and slave motions controlled in position domain. The master motion is used as a reference for the slave motions, and the slave motions are controlled by the developed NPD and synchronized with the master motion so that a good contour tracking performance can be achieved. Stability analysis is conducted based on the Lyapunov theory for the developed position domain NPD control. Linear and nonlinear contour tracking problems are simulated and compared with existed PD controllers. It is demonstrated that the position domain NPD control can achieve much better contour tracking performance compared with the counterparts in time domain and the linear PD-type position domain control. Furthermore, the proposed NPD controller is much efficient for nonlinear contour tracking problems.

Baek, S.W.; Lee, S.W. Design Optimization and Experimental Verification of Permanent Magnet Synchronous Motor Used in Electric Compressors in Electric Vehicles. ***Appl. Sci.*** **2020,** ***10*****, 3235** In this study, a shape design optimization method is proposed to improve the efficiency of a 3 kW permanent magnet synchronous motor (PMSM) used in an electric compressor

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intended for use in an electric vehicle. The proposed method improves the efficiency performance of the electric compressor by improving the torque characteristics of the initial PMSM model. The dimensions of the rotor were set as the design variables and were chosen to maximize efficiency and reduce cogging torque. During the determination of the design points with conventional Latin hypercube design, the experimental points may be closely related to each other. Therefore, the optimal Latin hypercube design was used to optimally distribute the experimental points evenly and improve the space filling characteristics. The Kriging model was used as an interpolation model to predict the optimal values of the design variables. This allowed the formulation of more accurate prediction models with multiple design variables, complex reactions, or nonlinearities. A genetic algorithm was used to identify the optimal solution for the design variables. It was used to satisfy the objective function and to determine the optimal design variables based on established constraints. The optimal design results obtained based on the proposed shape optimization method were confirmed by finite element analyses. For practical verification, the optimal model of the prototype PMSM of an electric compressor was manufactured, and a 1.5% improvement in its efficiency performance was confirmed based on an experimental dynamometer test. As the environmental pollution of internal combustion engine vehicles becomes serious, interest in eco-friendly vehicles and hybrid electric vehicles (HEVs) are increasing worldwide [1]. Among them, electric vehicles (EVs) are in the spotlight as pollution-free automobiles that reduce fuel efficiency [2] and have no harmful emissions because they use only electric energy in the system instead of the engine of an internal combustion engine [3]. Therefore, EV has been proposed as one of the methods to solve fossil fuel depletion and environmental problems, and research on it has been actively conducted worldwide [4]. Recently, the PMSM has been used in parts for electric vehicles because it has excellent efficiency characteristics compared with induction motors [5]. PMSM is a structure in which a permanent magnet is embedded in the iron core of the rotor, and the magnetic flux weakening operation area can be widened depending on the difference in inductance of the d-q axis [6]. Because of these advantages, it is widely used in EV or HEV where variable speed operation is required [7]. An electric compressor for air conditioning of electric

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vehicles has been developed, and by applying high-efficiency PMSM to the compressor, it has the advantage of increasing fuel efficiency regardless of the vehicle's driving speed [8]. Optimal design is essential to meet the various design requirements of PMSM. Optimal design is a method of finding the value of a design variable and obtaining an optimal solution within a limited design area [9]. The previous researches on the optimal design of PMSM can be divided into two categories. First, there are studies using the magnetic equivalent circuits (MEC) model [10,11]. In [10], it was proposed as a study on optimization using MEC model. It has been reported that the MEC optimization method combined with the optimization algorithm can optimize the volume and energy loss of PMSM. In addition, a novel MEC model of PMSM was developed to obtain maximum efficiency, minimum weight and price [11]. However, MEC-based design has a problem in that it is difficult to accurately consider the nonlinearity of parameters. Second, there are studies that combine numerical analysis methods of electrical devices such as finite element analysis (FEA) with optimal design algorithms [12,13]. FEA was performed to take into account the nonlinearity of permanent magnets and electrical steel sheets, which are difficult to consider in MEC. In [12], an optimal design of PMSM based on dynamic characteristics and finite element analysis of PMSM was performed. Design variables that influenced the efficiency characteristics of PMSM were selected and the efficiency and response characteristics were improved through experiments. In [13], the authors announced the optimization design process of PMSM for electric compressors of air conditioners applied to electric vehicles and hybrid vehicles. Research on the optimal design of PMSM using the response surface method has been carried out. In particular, the response surface method is often used in the optimization design of permanent magnet motors. The response surface method typically uses a second order polynomial regression model. However, it is difficult to accurately predict the optimum value because the response surface method becomes highly nonlinear and yields an unstable high-order prediction function. As a similar study related to PMSM, the rated efficiency was improved through the optimum design of 110 W small brushless direct current (BLDC) motor [14]. In addition, a study was conducted to improve the performance of the electric variable valve timing system

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for improving fuel efficiency and emission of automobiles [15]. Cogging torque is one of the most representative components of torque ripple in PMSM. This phenomenon can be a critical issue to automotive applications that need precision control of the PMSM and are sensitive to noise and vibration. Therefore, recently, studies to improve efficiency and reduce cogging torque have been actively conducted, and mainly focused on reducing the cogging effect by adjusting the combination of pole slot number, pole arc, and core shape [16,17]. Furthermore, the study of [18] performed multi-purpose shape optimization of PMSM based on FEA and particle swarm optimization algorithms. Unlike the existing methods, the proposed rule of start point selection takes an advantage of minimizing the search time. A study has been conducted on the multi-purpose optimized design PMSM of fractional slotted windings [19]. The optimization results demonstrated the accuracy of the proposed model with comparison to numerical models such as FEA, but with much faster computational performance which makes it much more suitable to be used in evolutionary optimization design approaches. Most of the previous studies were applied to the optimal design using metamodels created in one way [20,21]. In general, FEA's design of experiment (DOE) consists of a modeling process using CAD tools, an FEA analytical condition setting process, a FEA process, and a post-process for extracting and configuring results. A lot of DOE has to be done to get reliable and optimal design results. As a related study, Taguchi method was used to optimize the efficiency and cogging torque of BLDC motors used in automotive electric oil pumps. However, to obtain DOE results, 336 FE analyses for five design variables were required [22]. This study differs from previous studies given that five design variables were selected for the DOE and 54 experiments were performed. To improve the efficiency of the design variable distribution, the optimal Latin hypercube design (OLHD) [23,24] was used with an equal number of levels for all the design variables that has a better fill performance than Latin hypercube design (LHD) [25]. Numerous studies have been published on metamodeling conducted based on the application of a single method [26,27]. However, there are suitable metamodels for each optimal design problem. Correspondingly, the metamodels need to be written and compared in various ways. Given that the prediction performance of the metamodel

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affects the reliability of the optimal design, it is necessary to evaluate the accuracy of each metamodel. Therefore, we evaluated three representative metamodels, including Kriging [28], multilayer perceptron (MLP) [29], and ensemble of decision tree (EDT) [30], and compared the metamodeling results. The predicted performances of the metamodels were evaluated and compared based on the root-mean-square error (RMSE) test, the results, and Kriging was selected as the best metamodel. In this paper, Kriging model can evaluate models with many design variables, complex responses, or strong nonlinearities more accurately. The genetic algorithm (GA) [31] was used for the determination of the optimal design variables based on the objective functions and constraints set for the optimization. To verify the validity of the proposed optimization design results, the characteristics of the initial and the optimal models (back-electromotive force (EMF), cogging torque, and torque ripple) were evaluated based on finite element analyses, and the results were compared. To verify feasibility, the proposed optimization method was applied to the design of a 3 kW PMSM used in an electric compressor, and the method's performance was compared with the results obtained from the initial model with finite element analysis. Finally, prototype PMSMs were fabricated and dynamometer tests were performed to confirm the suitability of the proposed shape optimization design.

Reinforcement Learning for Process Control

Generally speaking, RL consists of learning the execution of a task by the host computer if it interacts dynamically with an unknown process. Without explicit programming of the task learning method, the learning process is based on a set of decisions that are made so as to achieve the maximum of the cumulative Reward, whose expression is set a priori. Figure 1 shows the schematic diagram for a RL scenario.

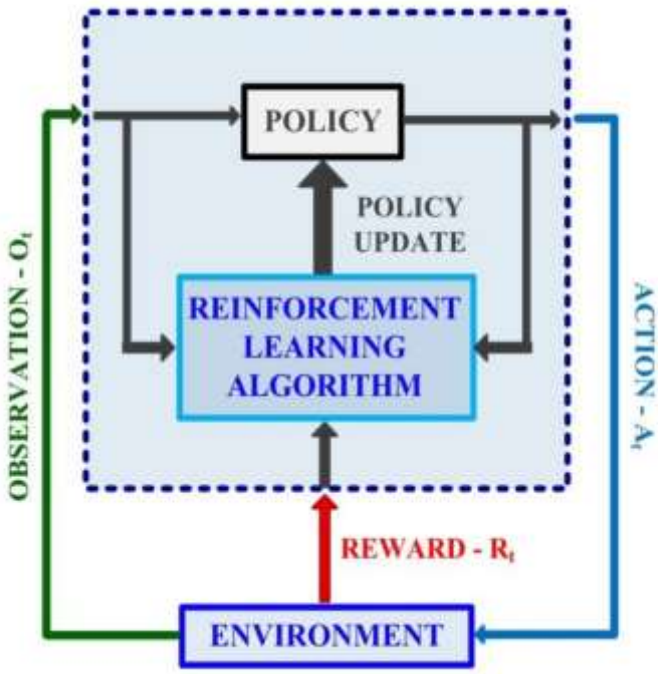

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Figure 1. Schematic diagram for a RL scenario.

The input signals to the agent are Observation and Reward. The Observation consists of a set of predefined signals characterizing the process, and the Reward is defined as a measure of the success based on the Action output signal. The Action is given by the control quantities of the controlled process. The Observations represents the signals visible for the agent and are found in the form of measured signals, their rate of change, and the related errors.

Usually, the Reward is created as part of the continuous actions in the form of a sum, such as the square of the error of the signals of interest and the square of past actions. These terms are given a weight determined by the final purpose of the problem. Usually, in the process control, the Reward is given by a function that implements the minimization of the steady-state error.

The agent contains a component called Policy, and also implements a learning algorithm. The Policy represents the way in which the actions are associated with the Observations of the process and is described by a function with adjustable parameters. In the case of the process control, the Policy is similar to the operating mode of a controller.

The learning algorithm is designed to find an optimal Policy by continuously updating the parameters of the function associated to the Policy based on the maximization of the cumulative Reward. The process (in the general case referred to as the environment) consists of a plant, reference signals and the associated errors, filters, disturbances, measurement noise, and analog-to-digital and digital-to-analog converters.

CONCLUSIONS

This paper presents the FOC-type control structure of a PMSM, which is improved in terms of performance by using a RL technique. Thus, the comparative results are presented for the case where the RL-TD3 agent is properly trained and provides correction signals that are added to the control signals u_d, u_q, and i_{qref}. The FOC-type control structure for the PMSM control based on an SMC speed controller and synergetic current controller is also presented. To improve the performance of the PMSM control system without using controllers having a more complicated mathematical description, the advantages provided by the RL on process control can also be used. This improvement is obtained using the correction signals provided by a trained RL-TD3 agent, which is added to the control signals u_d, u_q, and i_{qref}. A speed observer is also implemented for estimating the PMSM rotor speed. The parametric robustness of the proposed PMSM control system is proved by very good control performances achieved even when the uniformly distributed noise is added to the load torque T_L, and under high variations in the load torque T_L and the moment of inertia J. Numerical simulations are used to prove the superiority of the control system that uses the RL-TD3 agent.

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