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Optimization of a Permanent Magnet Synchronous Motor

Szilard Jagasics, Prof. Dr. Istvan Vajda
Obuda University, Institute of Automation
Obuda University, Institute of Automation
Corresponding author: Szilard Jagasics

ABSTRACT

Permanent magnet synchronous motors are widely used due to their high power to volume ratio and performance. Every application has its own requirements for the motor. Therefore, their design optimization process is getting more complex. It is recommended to think over the parameters at the beginning of optimization. Too much parameters may result in a too complex solution but if one of the important ones is left out the process is incomplete. The main task of an optimization is to find the parameters which mainly influence the properties of the product.

KEYWORDS - *cogging torque, optimization, sizing, pmsm*

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I. INTRODUCTION

Permanent magnet synchronous motors (PMSM) are widely used due to their high performance and good power to volume ratio. Besides efficiency, there are many specification parameters for electrical machines such as torque, power density, volume, weight, torque quality, thermal behavior, etc. The priority of requirements depends on the application: efficiency is first priority for a continuous operational motor but for an actuator which is used only periodically efficiency is less important.

The sizing of a motor starts with the analyzation and deep understanding of the task and the boundaries of the application. If the main decisions are made, comes the optimizing process. There is a number of papers about optimizing strategies [1,2], but it is a usual problem which parameter of the motor should be modified. Unfortunately if one property is improved in most cases one or several other parameter may get worse.

II. OPTIMIZING METHOD AND ASPECTS

The multi-objective optimization model can be expressed as "equation 1-3":

$$min: \{f_1(x), f_2(x), \dots, f_p(x)\} \quad (1)$$

$$s.t.\, g_j(x) \leq 0, j = 1,2, \dots, m \quad (2)$$

$$x_l \leq x \leq x_u \quad (3)$$

where x, f, g are the design parameter vector, objectives and constraints, x_l and x_u the lower and upper boundaries. The usual objectives are maximizing efficiency or torque, minimizing weight, volume, etc. The optimal solution is a compromise between the objectives. Constraints are supply voltage, volume, temperature rise, etc. Optimization parameters are mainly materials, dimensions of stator or rotor, number of turns.

Fig.1. shows the difference between deterministic and robust optimization methods. Deterministic method finds the global optimum (point A) which is sensitive for parameter variations. The roboustness of Design B is much better.

The importance of optimizing an application mainly depends on the cost level and quantity. The piece count of an electric power steering (EPS) application is usually very high and the price should also be kept low. The load of a steering system is a main input data for the sizing. The steering maneuvers and the gear ratio in the mechanics define the torque-speed graph of the motor which is usually mounted in the engine compartment. The boundaries are defined by the available power source and the area of installation. Power level of a typical EPS is around 500-800W on 12V, top speed is about 5000 RPM, ambient temperature range is -40..100°C. The temperature rise of a motor is limited by the properties of the insulating materials and the magnets. The motor is operated only by steering, so first the required maneuvers should be checked and the most problematic load-profile has to be chosen for thermal simulations.

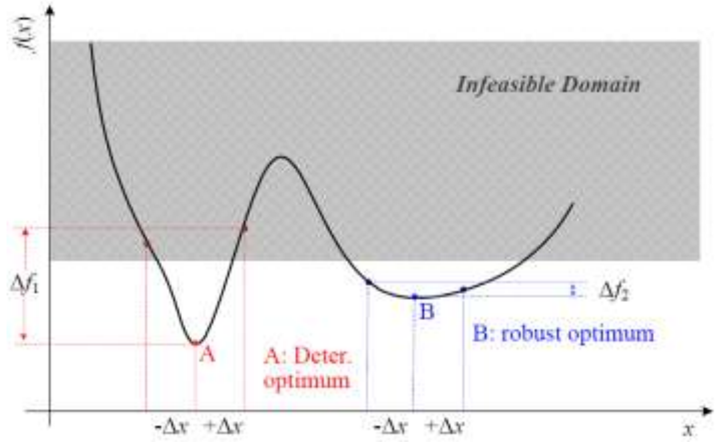

Fig.1. Deterministic and robust optimum.

An EPS is a very special application, the load of the system depends on the speed of the vehicle. If the vehicle is stopped, the turning of the wheels needs very high power. If the vehicle starts moving steering needs much less power. The main requirement of an EPS is to provide a good steering feel, which means easy steering and very smooth torque on the steering wheel. That is, the peak torque required from the driver is limited to a peak value and pulsating torque on steering wheel is also limited.

Pulsating torque of a PMSM has two main components: cogging torque and ripple torque. Ripple torque is mainly the function of the loading level of the motor. Cogging torque is a magneto static effect which arises by the interaction of the stator slots and rotor magnets, it is independent of the loading of the motor.

If the speed of the vehicle is higher, the load for the motor is lower. Cogging torque can be felt as a kind of torque noise, the steering wheel stucks periodically. A typical situation is driving on a highway. The load for EPS is low, the driver mainly steers to define the position of the car in the track. If steering wheel jumps periodically due to cogging torque, only defined positions can be set on steering wheel which may result in driving in zigzag which is unpleasant for most of passengers so cogging torque has to be kept in a low, acceptable level which is set to 0.5% of rated torque. This is a very strict requirement, cogging torque is not specified for most of applications like pumps or conveyors, etc.

III. OVERVIEW OF APPLICABLE CONSTRUCTION POSSIBILITIES

Sizing should be started by identifying the priority order of the requirements and choosing a concept for the motor like pole number, slot number, magnet material, winding and stator lamination technology. If the concept is worked out, the slot shape, magnet pole shape, other parameters can be fine tuned as optimization. The torque to volume ratio can be maximized by using high energy density neodinium magnets.

The temperature rise of the motor is limited due to high ambient temperature so losses of the motor should be kept as low as possible. The phase current is high and the size of the motor is low which results high current density in the windings so the phase resistance should be minimized. If tooth-winding technology is used, the length of end-winding is minimized, the further aim is to maximize the slot fill factor. There are two main winding techiques which influences not only the slot fill factor but also cogging torque level of the motor.

The slot opening size is defined by the applied stator winding and stator stack manufacturing technology [3]. If the lamination is not segmented, in most cases needle winding is used. Needle winding can not use parallel wires, so the slot opening size is defined by the wire diameter and the size of the needle. Also, the slot area where the needle travels is not available for winding. If the stator lamination can be segmented, the slot opening can be much lower and also the slot fill factor can be higher which improves efficiency. It also has to be taken into account that the joining surface of stator segments should be very accurate otherwise the additional air gap at joining surfaces is also a cogging torque source.

Magnet pole skewing on the rotor is another commonly used cogging torque reducing method [4]. Cogging torque can be effectively reduced but the rated torque of the machine decreases as well. Magnet pole shaping or modifying magnet width may be also used but this method is effective for a small number of slot number and pole number combinations and may cause additional ripple torque.

Dummy slot can be applied for segmented and not segmented stators and it is an effective cogging torque reducing method [5]. The dummy slot increases the effective air gap so the rated torque decreases as well.

The manufacturing misalignments like magnet positioning error or air gap eccentricity is a common cogging torque source [6]. The stator is usually mounted in the housing by heat-shrinking. The housing is usually made of aluminum, the stator lamination is a kind of electrical steel. The housing is heated up, stator stack may be on environmental temperature or cooled down. In this situation due to thermal expansion the stator stack can be dropped into the housing. If the cooling down of the mounted stator and housing is asymmetrical, the housing and the air gap of the stator may get oval. This is only two of the most common air gap eccentricity sources, which is a common difficulty for the designing of manufacturing process.

Fig. 2. shows results of a comprehensive simulation about cogging torque range for different pole number and slot number configurations and sensitivity for air gap eccentricity. The 4p9s case means a four pole nine slot PMSM. The outer diameter of the analyzed motors is 150mm, stator stack length is 100mm.

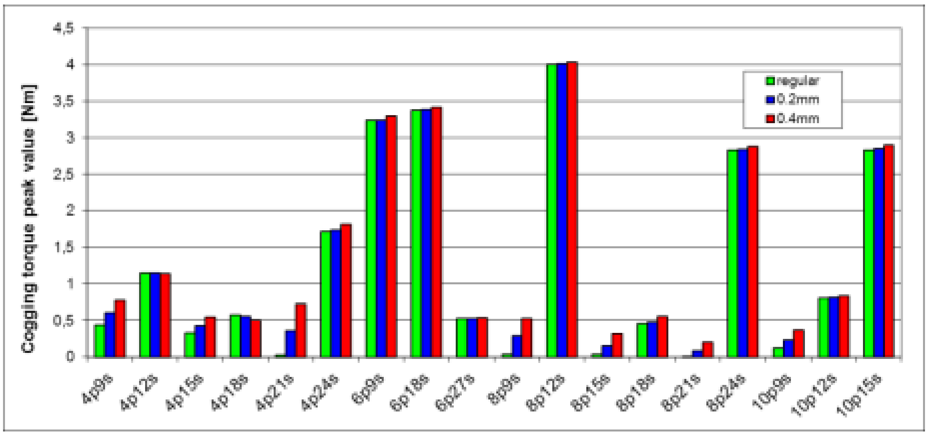

Fig. 2. Sensitivity of cogging torque for air gap eccentricity for different pole number-slot number cases [3].

Different mechanical misalignment cases can be simulated by finite element method (FEM) but usually these simulations take quite long time. Several different motor model has to be built up and has to be solved. Unfortunately there is no analytical method for such simulations.

IV. SIMULATION METHODS

An effective tool can speed up the optimizing process if several geometry variants should be calculated. There are many analytical cogging torque calculating methods presented in papers which are compared in [7]. Their accuracy depends on the geometry and they are capable only for ideal geometry. Finite element analysis (FEM) is an accurate tool for computation but time consumption is much higher.

The advantages of the different calculating methods were checked and a new simulation technique was worked out in [8]. The cogging torque wave of the motor can be decomposed to several elemental curves. The elemental cogging torque, $f_c(x)$ wave for one slot and magnet pole interaction is calculated by FEM. The precision of this curve has key importance. Later on, the summation of the elemental curves is made in such a way that the air gap eccentricity and the magnet positioning error can be taken into account.

The new simulation method is applicable not only for cogging torque calculation for an ideal motor but also for ones with defined mechanical misalignments as air gap eccentricity or magnet positioning error. The calculation time takes about one minute so the designer can check the range for permissible manufacturing tolerances in a short time.

The main steps of the method are the following. The cogging wave for one slot can be created by the summition of the $f_c(x)$ wave with mechanical angle of α which is the pole pitch of the rotor and if magnet positioning error is present, it can be taken into account by φ_k. The result wave, $f_{slot}(x)$ is in (4) the cogging torque for one slot for a complete rotor revolution.

$$f_{slot}(x) = \sum_{k=1}^{n} f_c(x + k\alpha + \varphi_k) \qquad (4)$$

$$f_{cogg}(x) = \sum_{k=1}^{z} c_z \cdot f_{slot}(x + k\beta) \qquad (5)$$

$$\alpha = \frac{360^\circ}{2p} \qquad \beta = \frac{360^\circ}{LKT(2p, Z)} \qquad \gamma = \frac{360^\circ}{Z} \qquad (6)$$

The summing of $f_{slot}(x)$ waves for all slots results the cogging torque wave for the complete motor (5), where α is the rotor magnet pole pitch, p is pole number, Z is slot number, LKT is least common multiple, γ is the slot pitch. All variables in (6) are defined by the motor deign. The c_z factor (Fig.3.) has special importance about air gap eccentricity. The amplitude of elemental cogging torque, $f_c(x)$ changes if air gap is different of the rated value, the shape remains the same. If air gap eccentricity is present, mechanical air gap is different for each slot which can be calculated. The $f_{slot}(x)$ waves can be rescaled by the c_z factor.

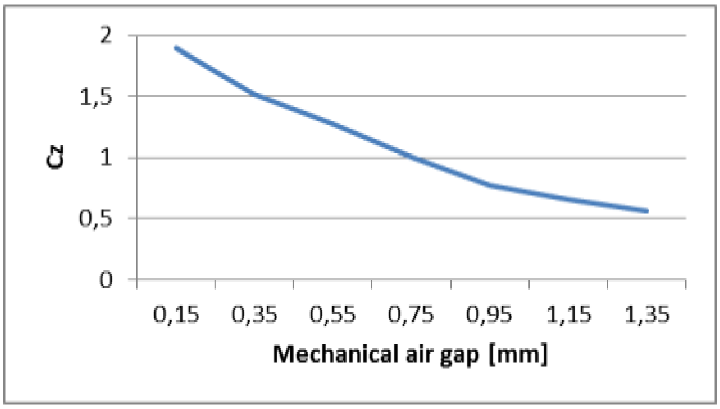

Fig.3. The c_z factor for air gap eccentricity.

If the pole number and slot number configuration has common divider, some of the $f_{slot}(x)$ waves will be in the same phase. For example, at the case of 10 pole 12 slot machine $f_{slot}(x)$ for slot 1-7, 2-8 etc will be in the same phase. If eccentricity is present, slot 1-7, 2-8 are slot pairs being on the opposite side of the motor, one is on the lower and the other is on the higher air gap side. On Fig.3, rated air gap is 0.75mm and c_z is 1. If eccentricity is 0.1mm air gap length for slot 1-7 air gap is 0.65 and 0.85mm respectively, the summed $f_{slot}(x)$ can more or less compensate the effect of air gap eccentricity depending on the magnetic circuit. This effect can also be checked on Fig.2. Motor variants having common multiplier are less sensitive for air gap eccentricity.

This tool can be effectively used in sizing phase. The calculating time for a pole number, slot number and mechanical misalignment case takes less than a minute. Modifying of parameters takes similar time. The cogging torque level, sensitivity for manufacturing tolerances can be checked at the early phase and helps to find a potential pole number and slot number combination which can be further optimized.

Optimal design means optimal solution for a specified task with an efficient calculating method. The most software company has many solutions for each area. Let's see the product palette of Altair: for fast precalculations for motor design they offer Fluxmotor: it can provide performance graph, efficiency and loss maps, etc. The model of Fluxmotor can be exported to Flux for more detailed FEM analyzation. They have an optimization tool, Got it, which can scale parameters between defined boundaries and run Flux automatically. It is an effective tool if the needed time and hardware is available. For the calculation about sensitivity for manufacturing tolerances is more effective with the method mentioned in [8].

The performance graph, protection mode and cooling mode, magnet and lamination properties usually defines the size of the motor. The speed range limits the pole number possibilities due to iron losses. The winding technology, stator manufacturing technology and the wire diameter defines the slot opening size which mainly defines the cogging torque level. The expectable air gap eccentricity is the result of the motor part manufacturing and assembly technology. All these data has to be taken into account for the choosing of the pole number and slot number of the motor.

It is worth to check the sensitivity of cogging torque for air gap eccentricity before the optimizing of the design. Cogging torque level of the machine is defined not only by the stator and rotor geometry but also by the manufacturing technology and tolerances. It is important to have the feeling which parameters will mainly determine the behavior of the motor and also the priority of the parameters. If some of the parameter variants, which may be manufacturing tolerance, material quality tolerance etc. are too wide and the design is an optimum like design A on Fig.1., the ratio of motors that has higher cogging torque than the limit defined in requirements may be too much. If this sensitivity comes to light at production integration or testing phase, it is too late or very costly to modify the design. The potential higher scrap ratio and more complex testing of products result also higher manufacturing cost.

V. DESIGN DECISIONS

Optimal design means optimal solution for a specified task with an efficient calculating method. The most software company has many solutions for each area. Let's see the product palette of Altair: for fast precalculations for motor design they offer Fluxmotor: it can provide performance graph, efficiency and loss maps, etc. The model of Fluxmotor can be exported to Flux for more detailed FEM analyzation. They have an optimization tool, Got it, which can scale parameters between defined boundaries and run Flux automatically. It is an effective tool if the needed time and hardware is available. For the calculation about sensitivity for manufacturing tolerances is more effective with the method mentioned in [8].

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VI. CONCLUSION

The designing of an optimal product is a very complex task. The applications which have special requirements like smooth torque, usually need some additional attention at sizing phase. The specification may be fulfilled by several electric motor design variants. The main construction related decisions are made at the sizing phase like choosing of pole number and slot number, manufacturing technology, material grades. Final optimization can be the fine tuning of the shape of the slots, magnet poles, using of additional cogging torque reducing methods, modifying material grades. This phase can be automated by software using parametrized FEM simulations but the main design decisions still need highly qualified experienced engineers.

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Prof. Dr Istvan Vajda (CSc, PhD, DSc, dr. habil) is with Obuda University, director of the R&D Center of Electrical Energy Conversion. Graduated from Budapest University of Technology and Economics (BME) in 1976 as electrical engineer. 37 years he used to work with BME. In the years 2014-1017 he was the dean of Kando Kalman Faculty of Electrical Engineering, and in 2012-2017 he was the director of Institute of Automation. He is the leader of the Doctoral School Materials Science and Technology.

He is an internationally acknowledged scientist and expert in the fields of Large scale applications of superconductivity, Theory and design of electrical machines, particularly for Electrical Vehicles. Other research fields: Electrical Energy Storage, Diagnostics of Electrical Energy Converters and Storage, Engineering problem solving. Nonconventional energy conversion.

In 2007-2013 he was a doctor representative and in 2009-2014 the president of the Electrotechnical Committee of the Hungarian Academy of Sciences. He is an international expert in evaluating EU projects.
He has 287 scientific publications, 322 independent citations; number of PhD students defended is seven. He used to be the leader of numerous national and international projects. Examples are Pilot plant of a current limiting transformer, Development of 1–10 MW PM Synchronous Motors for Ship Propulsion, Development of 0.5–1 MW Inverter Fed Induction Motor Series, Development of Hybrid and Electrical Vehicles. Presently he is the scientific leader of the eMobility FIEK program in Gyor University. He has played relevant role in establishing and operating the coordinated collaboration of universities and companies in the field of electrical energy conversion.

Szilard Jagasics is with Obuda University at Institute of Automation. Graduated from Budapest University of Technology and Economics (BME) in 2006 as electrical engineer. He is instructor at Obuda University (known as Kando) in 2006-2018. Meanwhile from 2013 he works as motor designer on electric power steering applications.

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