Optimization of Single Pulse Control based on Design of Experiments for Switched Reluctance Machines

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Owing to the robust structure of switched reluctance machines, high-speed operations are preferred to achieve higher power densities. Generally, at high speeds, single pulse control is applied. However, its control parameter set is not unique. This paper proposes an algorithm based on design of experiments that simultaneously allows the calculation of optimal control parameters for an operating area and the minimization of the total machine losses. The designed experiments are finite-element analyses (FEAs) considering both iron and copper losses. A Pareto search algorithm solves the proposed multi-objective optimization problem. The results for different response surfaces are compared considering the errors in torque production and machine loss prediction. A reduced response surface based on 15 FE-runs shows a mean error of 1.9%, whereas the maximum error is 6.3% for machine losses within the validation operating area.

Keywords: design of experiment, single pulse control, switched reluctance machine, response surface

1. Introduction

Due to the simple geometrical structure, switched reluctance machines (SRMs) are mainly operated at high speeds allowing higher power densities⁽¹⁾. With higher speeds the back-emf increases reducing the capability of an active phase current control. Instead, single pulse control (SPC) aims to magnetize and demagnetize each phase such that a reference average torque is provided. However, the current waveforms have a pulsating nature with high current slopes. This, in turn, does not only lead to higher iron losses but also to distinctive copper ac losses in the windings. The combinations of the control parameters are not unique for a considered operating point. Different sets of turn-on θ_{on} , turn-off angles θ_{off} and freewheeling duration $\Delta\theta_{fw}$ provide the same torque at the same speed. Nevertheless, the current waveform differs and, thus, both the iron and copper losses are different. The considered control parameters are depicted in Fig. 1.

This paper presents a method based on design of experiments (DOE) to find the optimal control parameters for SRMs controlled by SPC with minimized iron and copper losses. This paper's objective is to statistically map the input parameters shown in Fig. 1 and the machine speed to outputs

Fig. 1. Current waveform of SRG with SPC

of interests. The copper, iron and mechanical losses are used as output values in order to find the minimal losses. Especially, the eddy-current losses within the windings are speed dependent. Therefore, not only the control parameters of SPC are considered, but the machine speed n is also considered as an independent input variable for the optimization problem. Furthermore, the provided torque is considered as an output variable in order to set a specific operating point.

2. Optimal Single Pulse Control

This paper concentrates on control optimization for switched reluctance generators (SRGs). In this work, an asymmetric half-bridges inverter is considered. Furthermore, only the generator mode is investigated. Thus, the SRM driven by the inverter is also referred as SRG within this work. Fig. 1 shows the phase current i_{ph} and the unaligned and aligned phase inductance L_{un} and L_a . At the turn-on angle θ_{on} a machine phase is magnetized by applying the positive dc-link voltage V_{dc} to one phase. During the freewheeling phase $\Delta\theta_{fw}$ one of the switches in the asymmetric half-bridge is closed. Therefore, no voltage is applied to the phase. Eventually, applying the negative dc-link voltage $-V_{dc}$ at the turn-off angle θ_{off} demagnetizes the phase allowing the

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phase current i_{ph} decreases to 0 A.

In (2), optimal control angles θ_{on} and θ_{off} are calculated to maximize machine efficiency. Furthermore, (3) investigated the efficiency improvements with the freewheeling period $\Delta\theta_{fw}$. However, both investigations do not consider eddy-currents in the coils. Especially, for SRGs with high-speed operation high eddy-current losses occur depending on the current waveform, the electrical frequency and the coil geometry. In (1), an empirical model of the eddy-current losses based on finite element analysis (FEA) was derived to adjust the freewheeling angle for machine losses minimization. This paper proposes a DOE approach to cope with all control parameters at the same time. In addition, no physical equation for the machine losses is derived or fitted. Instead, a statistical model based on FEA experimental runs is used for optimization of the control parameters. Hence, both the iron losses and the dc and ac losses in the copper coils can be considered with the precision of FEAs.

3. Methods

3.1 Design of Experiments The objective of DOE is to generate a relation between in- and output parameters. The challenge of an efficient response surface (RS) design is the generation of a minimal experimental set, which is still able to accurately represent the in- and output behavior. In this work, central composite design (CCD) ⁽⁴⁾ is applied, which is suitable to fit a full quadratic model and to run sequential experiments. CCD applies three different methods for generating sample points for an experimental run. Fig. 2 shows the sample points for two design variables. Firstly, each design variable has two levels (+1 and -1) based on full factorial design. The factorial points (black dots) allow an estimation of first-order and interaction terms. In addition, for each design variable the median is considered. Eventually, additional points above and below the median values represent axial points, which allow an estimation of squared terms. For the circumscribed CCD type, the red stars depict axial points with sequential replacement of each design variable by $\pm\alpha$ from the center point. Hence, these points are outside the hypercube spanned by factorial design. Instead, the inscribed CCD type can be obtained by dividing all factor levels by α . The total number of experiments with CCD is calculated by

$$N_{CCD} = 2^k + 2k + cp, \dots \dots \dots (1)$$

with the number of design variables k , and the number of replicates of the center points cp . The total number of axial points is $2k$. The number of factorial runs is calculated by 2^k .

Fig. 2. Circumscribed and inscribed CCDs

In order to minimize the number of experiments, it is sufficient to consider one replicate, i.e. $cp = 1$. The distance α is obtained by (4)

$$\alpha = [2^k]^{\frac{1}{4}} \dots \dots \dots (2)$$

For circumscribed CCD the axial points are outside the defined parameters limits. Thus, in the following inscribed CCD is considered, since it keeps the predefined parameter limits.

3.2 Loss Calculation

Besides the objective to accurately set the machine to a defined operating point, determined by the reference machine speed n^* and the torque T^* , the control parameter set also needs to minimize the machine's total losses. Generally, iron losses occur in the components of an electrical machine consisting of steel sheets. Not only do these losses depend on the injected current waveforms, but also on the machine's geometry and material. Hence, this paper utilizes FEAs for the calculation of iron losses, that consists of hysteresis and eddy-current losses

$$P_{Fe} = P_{Hys} + P_{Eddy}, \dots \dots \dots (3)$$

where the hysteresis losses are calculated from the time series data of local magnetic flux densities B_k of the k -th loop for each direction in each finite element volume V_e ⁽⁵⁾

$$P_{Hys} = \sum_{n=1}^{n_{elem}} \left[f \cdot \sum_{m=1}^{n_{loop}} a(B_k) \cdot V_e \right] \dots \dots \dots (4)$$

n_{elem} is the number of elements, n_{loop} the number of loops, f the base frequency, and $a(B_k)$ is obtained by frequency separation method ⁽⁵⁾. The FEA considers the thickness of the steel sheets by performing a one-dimensional magnetic field analysis in the lamination direction for each volume element. With the electric resistivity of the steel sheets, the FEA calculates the eddy-current loss P_{eddy} . In this paper, the material NO10 with a thickness of 0.1 mm is considered ⁽⁶⁾.

In (7), SRMs show high copper losses in the coils near the air gap. The injected currents not only cause dc ohmic losses, but they also cause additional losses in the windings due to the skin- and proximity effect. Hence, the copper losses do not only depend on the geometrical form and placement of the windings, but they also depend on the injected current waveforms. In Fig. 3 the current displacement in the windings is depicted.

Fig. 3. A quarter of an 8/4-SRM with current density distribution in coils in Amm^{-2} for nominal operating point

Table 1. Parameter limits for DOE

Parameter	Limits		Unit
	Min	Max	
θ_{on}	100	190	el
θ_{off}	230	300	el
$\Delta\theta_{fw}$	10	40	el
n_{SRG}	20000	30000	rpm

Eventually, electrical machines also generate mechanical losses due to friction. In (8), an empirical model estimates the windage losses for salient pole machines

$$P_{Wdg} = K_{sal} \cdot \pi \cdot C_d \cdot \rho_{air} \cdot \omega_r^3 \cdot R_{rotor}^4 \cdot L_{stk}, \dots (5)$$

with the skin friction coefficient C_d , the air density ρ_{air} , the rotational speed ω_r in rad s^{-1} , the rotor radius R_{rotor} and the stack length L_{stk} . In this paper, the SRM is assumed to have shrouds on both sides. Generally, rotor shrouds impede axial air flow and, thus, reduce the windage losses⁽⁸⁾. Hence, the saliency factor is set to $K_{sal} = \frac{3}{2}$. Finally, the sum of all losses represents the total machine losses

$$P_{Loss} = P_{Cu} + P_{Fe} + P_{Wdg}, \dots (6)$$

where the iron losses P_{Fe} and copper losses P_{Cu} are calculated with FEAs, while the windage losses P_{Wdg} are analytically calculated.

3.3 Generation of Response Surfaces The objective of the response surface (RS) is to generate an analytical representation between the control input parameters and defined output parameters. In total, three control parameters and the machine speed can be considered as independent variables with the limits in Table 1. Since the total objective is both an accurate torque generation and a minimization of the total losses of the SRM, the resulting torque $T_{m,RS}$ and machine losses P_{RS} are defined as outputs. Note that a larger interval for each design variable also leads to a wider range of possible torque and machine loss outputs. This may lead to non relevant or even unfeasible operating points, which again decreases the accuracy of the RS. Here, the nominal speed of 25 krpm is also the center of the speed interval.

In this paper, a second-order RS given by

$$f_{RS}(\mathbf{x}) = \beta_0 + \sum_{i=1}^{N_D} \sum_{j \geq i}^{N_D} \beta_{i,j} \cdot x_i x_j + \epsilon, \dots (7)$$

approximates the relationship between the independent variables in Table 1 and the depended variables namely the torque $T_{m,RS}$, the copper losses $P_{Cu,RS}$, the iron losses $P_{Fe,RS}$ and the windage losses $P_{Wdg,RS}$. N_D indicates the number of design variables and ϵ the error term. In order to evaluate the error of the RS, two measures are considered. The root mean squared error (RMSE) and the R^2 are described by the evaluation of the RS $f_{i,RS}$ for the i -th experiment f_i , the outputs from the corresponding FEA results y_i and the mean value $\bar{y}$

$$RMSE = \sqrt{\frac{1}{N_D} \sum_{i=1}^{N_D} (y_i - f_{i,RS})^2} \dots (8)$$

$$R^2 = 1 - \frac{\sum_{i=1}^{N_D} (y_i - f_{i,RS})^2}{\sum_{i=1}^{N_D} (f_{i,RS} - \bar{y})^2} \dots (9)$$

3.4 Multi-Objective Optimization The objective is not only to find optimal control parameters to minimize the machine losses, but also the error to a desired operating point. A reference operating point is defined by the machine speed n^* and the machine average torque T^* . The optimization problem for the multiple-objective optimization (MOO) is defined as

$$\min f_{Loss}(\mathbf{x}_{ctrl}) + f_{OP}(\mathbf{x}_{ctrl}) \dots (10)$$

$$\text{subject to } x_{i,lb} \leq x_{i,ctrl} \leq x_{i,ub} \text{ for } i = 1, \dots, N_D - 1 \dots (11)$$

$$n_{SRG} = n^* \dots (12)$$

The lower and upper bounds $x_{i,lb}$ and $x_{i,ub}$, respectively, are the minimum and maximum values from Table 1. Note that the machine speed n_{SRG} is set equal to the reference speed n^* . Consequently, this allows a fixation of one operating point value. The first objective function in the cost function represents the total machine losses with a weighting factor w_{Loss} and a scaling factor $\hat{P}_{Loss}$:

$$f_{Loss}(\mathbf{x}_{ctrl}) = w_{Loss} \cdot \frac{P_{Loss,RS}(\mathbf{x}_{ctrl})}{\hat{P}_{Loss}} \dots (13)$$

Note that $P_{Loss,RS}$ is composed of individual RSs for every loss component

$$P_{Loss,RS}(\mathbf{x}_{ctrl}) = P_{Cu,RS}(\mathbf{x}_{ctrl}) + P_{Fe,RS}(\mathbf{x}_{ctrl}) + P_{Wdg,RS}(\mathbf{x}_{ctrl}). \dots (14)$$

The second objective function gives the absolute difference between the reference average torque and the average torque calculated by the RS

$$f_{OP}(\mathbf{x}_{ctrl}) = w_{OP} \cdot \frac{|T^* - T_{m,RS}(\mathbf{x}_{ctrl})|}{\hat{T}_m} \dots (15)$$

with a weighting factor w_{OP} and a scaling factor $\hat{T}_m$. This objective function aims to set the machine average torque equal to the desired torque T^* . The weighting factors are set to $w_{OP} = w_{Loss} = 1$ in order to equally minimize the total machine losses and the torque error.

3.5 Workflow The complete workflow is summarized in Fig. 4. The first step is to select the independent input variables of interests and to define their appropriate limits. Note that the selection of the limits impacts the quality of the RS. Next, the current waveforms of each SRG phase are generated with MATLAB Simulink®⁽⁹⁾ and serve as inputs in JMAG®⁽¹⁰⁾ for the FEA of each set of control parameters. For each output parameter a RS according to Eq. (7) is generated with the resulting torques and machine losses from the FEAs. Finally, the RSs for the total machine loss (Eq. (13)) and the torque error (Eq. (15)) outputs are both minimized with Eq. (10). The optimization can be performed by a particle swarm optimization (PSO) or a Pareto search algorithm. In order to investigate the error of the response surface and validate the optimal parameter sets, the two measures in Eq. (8) are applied.

4. Simulation Results

The investigated electrical machine is a two-phase SRG for

Fig. 4. Overview of applied workflow

Table 2. SRM Properties

Parameter	Value
Diameter	150 mm
Length	200 mm
Number of windings	40
Wire diameter	1.9 mm
Lamination thickness	0.1 mm
Lamination resistivity	52 $\mu\Omega$ cm
Dc-link voltage	800 V
Nominal speed	25 krpm
Nominal power	90 kW

a gas turbine application⁽¹¹⁾. The electrical machine is mainly operated in generator mode. The active component of the machine consists of 8 stator teeth and 4 rotor teeth. Due to symmetry, a quarter of the machine is sufficient for the FEA as shown in Fig. 3. The asymmetrical rotor geometry allows a torque generation at standstill in order to start a gas turbine. The machine properties are shown in Table 2.

4.1 Goodness of Response Surfaces Two different design parameter sets are investigated. Each parameter set has a different number of design variables. The first set has four design parameters and also considers the machine speed n_{SRG} . Thus, an arbitrary operating point (n^*/T^*) can be considered in the MOO. The second set only consists of the three design parameters. The turn-off angle is set constant to $\theta_{off} = 280^\circ$ el for the complete loss calculation process. Generally, a different constant turn-off angle can be set. In this work, a constant value within the interval in Table 1 is selected. The two parameter sets mainly differ in the number of design parameters, which allows an investigation of the accuracy of the different RSs. While the first parameter set represents the maximum degree of freedom for selecting the optimal control parameters, the second one is a reduced and practical one, where either the turn-on or turn-off angle are assumed to be constant. Thus, the first set allows a greater solution space with more combinations of control parameters with minimum losses. However, more FEA calculations

Table 3. RMSE, R^2 and number of FEA runs for different parameter sets

Parameter Set	RMSE/ R^2 in %			FEA Runs N_{CCD}
	T	P_{Fe}	P_{Cu}	
1. $\theta_{on}, \theta_{off}, \Delta\theta_{fw}, n_{SRG}$	1.38 99.6	3.33 99.9	113 99.6	25
2. $\theta_{on}, \Delta\theta_{fw}, n_{SRG}$	0.667 99.9	3.76 99.9	71.2 99.9	15

are necessary compared to the second set. An overview of the sets and the corresponding measures of error are shown in Table 3. The RMSE of the average torque between the RS and the FEA data set obtained by CCD decreases with less number of design variables. This indicates a lower prediction accuracy of the average torque for four design variables. However, the RMSE for the iron losses P_{Fe} increases, whereas the error for the copper losses P_{Cu} decreases for a lower number of design variables. Generally, the second-order RSs (see Eq. (7)) show high goodness for all sets. More than 99% of total variation can be described by the RSs. In the following, the set of RSs generated with four and three design variables are denoted as RS1 and RS2, respectively. Note that RSs representing windage losses are also generated. Due to their analytical calculation and their only dependency on the machine speed (see Eq. (5)), the R^2 values of the RSs are close to 100%.

4.2 Validation of Optimized Design Parameters In this chapter, the precision of RS1 and RS2 are investigated. Thus, a validation operating area for the SRG is defined. The objective is to find control parameters for each operating point with minimized losses. Subsequently, additional FEAs validate the loss predictions from the RSs. One result of the MOO is depicted in Fig. 5. The optimal set of control parameters is located at the cross section of the Pareto front and the x -axis. Here, the difference of torque production and the reference torque is minimized (see Eq. (15)). Fig. 6 depicts the optimal control parameters for different reference speeds from 20 krpm to 27.5 krpm and powers from 18 kW to 90 kW. The start of each bar denotes the turn-on angle θ_{on} , whereas the end represents the turn-off angle θ_{off} . The change of colors indicates the position of the freewheeling operation. Firstly, the RS1 including the machine speed is investigated (see on the left in Fig. 6). Intuitively, one would expect a smooth transition for all control angles in case of a constant operating speed and varying power outputs. However, the defined limits (see Table 1) cause discontinuities along varying power outputs. Another cause is the fact, that the control sets with three degrees of freedom for a specific torque output are not unique. In contrast, with RS2 the turn-on angle θ_{on} gradually increases with lower power generation for constant speed (see on the right in Fig. 6). In addition, the freewheeling duration $\Delta\theta_{fw}$ slightly decreases for higher speeds.

Fig. 7 depicts the average torque output of the RS (blue), which is also the expected operating torque T^* , and the corresponding value obtained with FEA (orange). Note that the reference torque T^* is given by the relation $P^* = 2\pi \cdot n^*/60 \cdot T^*$. Higher absolute torque errors ΔT occur for the reference power $P^* = 90$ kW. The highest error occurs at 90 kW and 20 krpm with an error of 3.75 Nm. Here, the RS overestimates the average machine torque. The lowest error in torque can be observed around the operating point

Fig. 5. Pareto front

 Fig. 6. Optimized SPC control parameters with RS1 on the left and RS2 on the right with const. $\theta_{\text{off}} = 280^\circ$

 Fig. 7. Top: Average torque output $T_{m,RS} = T^*$ (blue) with RS1 and of torque $T_{m,Val}$ (orange) from FEA, Bottom: Absolute error

54 kW and 25 krpm. Fig. 8 shows the total machine losses approximated by the RSs (blue) and calculated by FEAs (orange). The maximum relative error of 6.47% is at the speed of 18 krpm. Here, higher deviations in the approximation of the iron and copper losses occur. The total losses in the nominal operating point is $P_{\text{Loss}} = 3.7$ kW and the error is

 Fig. 8. Top: Total machine loss output P_{RS} (blue) with RS1 and loss P_{Val} (orange) from FEA, Bottom: Relative error

 Fig. 9. Top: Average torque output $T_{m,RS} = T^*$ (blue) with RS2 and of torque $T_{m,Val}$ (orange) from FEA, Bottom: Absolute error

0.0423%. However, due to the absolute error in torque of $\Delta T = 1.13$ Nm the FEA for validation calculates a generating power of $P_{Val} = 87.01$ kW. Fig. 9 summarizes the torque output with RS2. Here, the turn-off angle θ_{off} is constant. Therefore, the RS is only a function of the machine speed n_{SRG} , the turn-on angle θ_{on} and the freewheeling length $\Delta\theta_{fw}$.

Due to the smaller solution space, the absolute torque error is generally reduced compared to Fig. 7. The highest error in torque of 1.26 Nm occurs at a speed of 20 krpm and at the desired generating power of 36 kW. For the nominal operating point, the validation FEA calculates the total machine loss of $P_{Val} = 3.82$ kW (see Fig. 10). This is a relative error of 1.05% compared to the predicted total loss $P_{RS} = 3.86$ kW obtained by RS2. The maximum error with three design variables is 6.3% for the operating point with 18 kW and 22.5 krpm. The mean error for all considered operating points is 1.9%. In total, the mean error is smaller compared to RS1 (see Fig. 8)

Fig. 10. Top: Total machine loss output P_{RS} (blue) with RS2 and loss P_{Val} (orange) from FEA, Bottom: Relative error

Fig. 11. Phase current with optimized parameter from RS1 (discontinuous) and from RS2 (continuous lines) at the power $P_N = 90$ kW and $60\% \cdot P_N$ for speed $n_{nom} = 25$ krpm

with a mean error of 2.18%. In Fig. 11, the current waveforms for the two reference generation power 54 kW and 90 kW at a constant speed of $n_{nom} = 25$ krpm are shown. For each generation power, two current waveforms with different control angles are given. Fig. 6 provides the corresponding control parameters. For RS1 the turn-on angles and the freewheeling duration are smaller compared to RS2. As a result, the control based on RS1 leads to higher currents during the phase magnetization and lower currents as soon as freewheeling is active. The current waveforms show that the MOO results based on different RS lead to different optimal parameters. The error analyses show, that both RS1 and RS2 are able to predict the torque generation of an SRG and its total machine losses in a particular operating point. However, it also demonstrates the rather high torque deviations for RS1 with four degrees of freedom. The interactions between all four design variables cannot be completely represented in the RS $T_{m,RS}$ for average torque prediction. The assumption of a constant turn-off angle θ_{off} leads to better torque predictions with RS2, which is also consistent with the RMSE in Table 3. Furthermore, the RMSE and R^2 indicates that with four variables a lower accuracy is achieved compared to three variables regarding the copper loss prediction. The difference

in prediction accuracy is also observed for different operating points, because the copper losses significantly impact the total machine losses at high speed operation. Consequently, loss predictions with RS2 have a lower total error. In general, RSs statistically approximate the SRG regarding torque production and loss generation. However, if the data set generated by DOE covers the relevant operating points for a considered application, low errors in torque and a maximum error of 6.3% can be achieved.

Not only is the selection of the design variables important, but also the selection of their intervals for DOE. Within this work, a non-continuous decreasing turn-on angle for increasing machine power is observed for RS1 (see Fig. 6). Hence, for ensuring machine stability the reduced parameter set RS2 should be considered. Eventually, different approaches compared to CCD with more experiments can improve the data set. Consequently, higher order linear regression models can also improve the input and output relation.

5. Conclusion

This paper presents an algorithm based on design of experiments and multi-objective optimization in order to find optimized control parameters for high-speed switched reluctance machines. An inscribed central composite design generates a data set based on the turn-on angle, turn-off angle and the freewheeling duration for single pulse control of an SRG. Furthermore, consideration of the machine speed as another design variable allows a torque and loss prediction over a wide operating area around the nominal speed. Not only are the resulting control parameters able to reach the operating points with a maximum torque error of 1.26 Nm for the reduced response surface, but they also keep the losses minimal with a mean error of 1.9% for the considered operating points.

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