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TRANSIENT PERFORMANCE OPTIMISATION OF LINE-START PERMANENT MAGNET SYNCHRONOUS MOTORS USING TAGUCHI BASED REGRESSION RATE METHOD

AJ Sorgdrager*, **R-J Wang*** **and AJ Grobler**†

* *Department of Electrical and Electronic Engineering, Stellenbosch University, Stellenbosch, South Africa. E-mail: ajsorgdrager@gmail.com, rwang@sun.ac.za*

† *School of Electrical, Electronic and Computer Engineering, North-West University, Potchefstroom, South Africa. E-mail: Andre.Grobler@nwu.ac.za*

Abstract: In this paper the Taguchi method based regression rate method is proposed for optimising the transient performance of line-start permanent magnet synchronous machines (LS-PMSM). To enable the fast evaluation of the synchronisation capability of a design during the optimisation process, an analytical LS-PMSM synchronisation model is used to determine the critical inertia. It shows that the proposed method is a viable optimisation tool for the design of LS-PMSMs.

Key words: Line-start motor, permanent magnet machine, synchronisation, analytical modelling, Taguchi method, transient performance, design optimisation

1. INTRODUCTION

Line-start permanent magnet synchronous motors (LS-PMSM) are well suitable for fixed speed applications such as fans, compressors and pumps systems. Unlike conventional permanent magnet (PM) motors, an LS-PMSM has a hybrid rotor containing both a squirrel cage and PM array, which provides self-starting capability and enables synchronous operation at steady-state. When designing an LS-PMSM, both steady-state and transient operations need to be considered. Traditionally, the design of an LS-PMSM starts at steady-state performance optimisation followed by a synchronisation capability check using transient finite element (FE) modelling. The design is considered a success if it passes the synchronisation check, otherwise, another design iteration is necessary. Because of the high computational expenses of transient FE modelling, it is not viable to fully incorporate it into an optimisation procedure.

The transient state of an LS-PMSM is rather complex as the behaviour of the machine is determined by a number of torque components as illustrated in Fig. 1, namely, the cage torque, the braking torque (due to PMs) and the load torque. Once synchronised the steady-state torque is dominated by the PM torque and the reluctance torque components. Apart from the load torque, the moment of inertia (J) also significantly influence transient synchronisation performance of an LS-PMSM [2, 3]. In [4], the critical inertia (J_{cr}) or maximum synchronisable load inertia of an LS-PMSM was proposed as a synchronisation capability factor. This is based on an analytical synchronisation energy criteria and has been developed and applied in the design of LS-PMSMs [1, 5].

The use of Taguchi method [6], a variant of design of experiments (DOE) method, in electrical machine design has seen increased interest [7]. In [3, 8, 9], the Taguchi method has been used together with FE analysis to improve

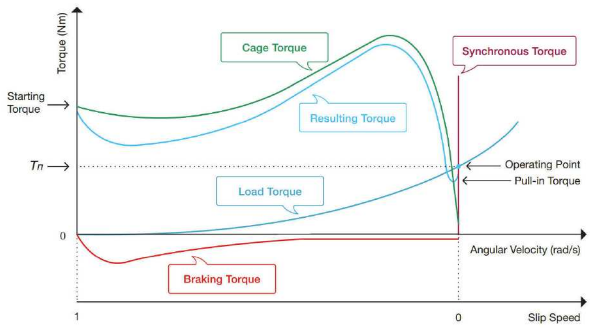

Figure 1: LS-PMSM torque components as a function of slip [1]

transient and steady-state performance of an LS-PMSM. However, using the Taguchi method in a fully automated iterative optimisation framework would require (i) the exclusion of designer intervention during the process, and (ii) a method to adjust the range of a design parameter. Weng's approach [10–13], originally used for antenna array optimisation, may be used to address these issues.

In this paper, the viability of Weng's Taguchi based optimisation method for the transient performance optimisation of LS-PMSMs is investigated. An analytical time-domain synchronisation model developed in [1] is used to determine the critical inertia. The Taguchi method based regression rate (TBRR) and the analytical synchronisation criteria are described in Sections 2 and 3, respectively. The implementation of the optimisation framework and optimisation results are presented in Sections 4 and 5. Relevant conclusions are presented in Section 6.

2. TAGUCHI BASED REGRESSION RATE METHOD

The use of Taguchi method in electrical machine design is relatively new. The perceived advantages of using the Taguchi method as part of an iterative

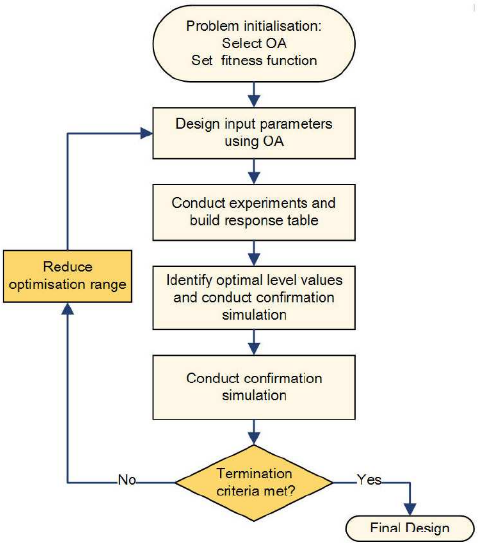

Figure 2: Taguchi based regression rate framework [10]

optimisation framework include: less sensitivity to initial conditions, reduced parameter complexity to the optimisation problem, reduced effort in determining the subsequent conditions of the parameters in an iterative process. This is largely due to the fact that the Taguchi method [6] analyses the results over a region rather than searching for a definite point in the domain as with more common optimisation methods.

Figure 2 shows the design optimisation framework proposed by Weng [10], in which the two highlighted blocks provide an automated decision-making functionality in the optimisation process. This is done by including a fitness function as an Overall Evaluation Criteria (OEC), quantitative termination criteria and a standardised method to adjust each parameter's range for the subsequent iteration. Since each iteration follows the same procedure, only the first iteration is explained in detail here. The blocks in Fig. 2 function as follows:

• *Problem initialisation*: The optimisation procedure starts with the problem initialisation including: parameter selection, parameter range identification, selecting a suited orthogonal array (OA) and formulation of a fitness function. The range of a parameter is very important as all the trial machine designs (as specified by the OA) must be a viable design for performance calculation. The selection of an OA mainly depends on the number of parameters. The fitness function is devised according to the optimisation objective and is either maximised or minimised depending on the objective.

• *OA input parameter allocation*: For an iteration the numerical values for each level of an parameter must be determined in order to conduct the trials. For the first iteration (if a 3-level parameter OA is used) the maximum (Pn_{max}) and minimum (Pn_{min}) range value of a parameter is allocated to level-1 and level-3, respectively, thus, level-2 will be the mid-range value between the two boundaries. The distance between any two levels is known as the level difference (LDn_i) of the i^{th} iteration. For the first iteration, LDn_1 is determined by the following equation:

$$\mathrm{LDn}_1 = \frac{Pn_{max} - Pn_{min}}{\text{number of levels} + 1} \tag{1}$$

For the subsequent iterations, LDn_i is reduced after each iteration if the termination criteria are not met. By reducing the level difference between two levels the parameter's range is also reduced.

• *Conducting experiments and result analysis*: Once all the OA's trials have been compiled and conducted the relative information must be obtained for the fitness function of each trial. The fitness function performance of a given trial is used to build the Analysis of Mean's (ANOM) response table. For this method the Analysis of Variance (ANOVA) is not required. The ANOM's respond table is formulated using the Signal-to-Noise (S/N) ratio values of the fitness function.

• *Optimal level identification and confirmation experiment*: As the S/N ratio analysis is used, the optimum condition for each parameter is identified by the largest S/N ratio value. Using each of the optimum level conditions, a confirmation trial is done under the same conditions as the main OA trials. This is done to determine the fitness value of the current iteration.

• *Check the termination criteria*: The optimisation is terminated when one or both goals have been achieved. The first and most basic termination criterion is when the fitness function has converged over several iterations. The second termination criterion involves the ratio between the first and current level difference value. As the number of iterations increase the overall level difference decreases. If the LD ratio is larger than the Converged Value (CV) set by the designer during the problem initialisation, another iteration is required. The following equation may be used as a termination criterion for the optimisation procedure:

$$\frac{\mathrm{LDn}_i}{\mathrm{LDn}_1} < \mathrm{CV} \tag{2}$$

with CV selected between 0.001 and 0.01. As the parameter level values move closer to each other the current fitness value should be close to the previous value thus converging around the optimum point.

• *Reduce the optimisation range*: If another iteration is required due to the termination criterion/criteria not being met, the current parameter range for each parameter must be reduced. To reduce a parameter's range for the next iteration, the current LD is multiplied with a regression rate (RR) factor as follow:

$$\mathrm{LDn}_{i+1} = \mathrm{RR}\,.\,\mathrm{LD}_i \tag{3}$$

The *RR* is set by the designer between 0.5 and 0.99 during the initialisation. A RR closer to 0.99 will results in a slower LD convergence, thus, a higher number of iterations before termination. For the next iteration the current optimum value is placed in Level-2 slot. Level-1 and Level-3 are calculated using the new LD determined with (3). It is necessary to check if the new level values are still within the original range of the parameter as it is possible that it may fall out of bounds. This is especially true when LD is still large and the optimum level is near or equal to the boundary value. Therefore, a process of checking the new level values is necessary in order to ensure that all level values are within the parameter range.

From the above implementation steps, it is clear that the level difference regression framework can easily be implemented on a wide spectrum of machine design problems.

3. ANALYTICAL SYNCHRONISATION CRITERIA

Using the analytical time-domain approach as proposed in [1], the speed versus time characteristics of a non-linear partial differential equation system can be used to study the synchronisation capability of the LS-PMSM for a given load equation with an inertia value of J_l. Synchronisation is determined by applying two simple rules:

- an LS-PMSM is considered synchronised when the mean value of the speed and its 1st order derivative at the last part of the time interval equals to synchronous speed and zero respectively;

- an LS-PMSM is considered un-synchronised when its speed oscillates below synchronous speed.

As the load equation is assumed to be the same for all the Taguchi trial machines, the maximum J_l value that a trial machine can successfully synchronise needs to be determined. A normalised machine critical inertia value (x_{cr}) is defined as:

$$x_{cr} = \frac{J_{lmax}}{J_{rotor}} \tag{4}$$

with J_{rotor} the approximate rotor inertia for all trial machines and J_{lmax} the maximum load inertia of the trial machine. Using synchronisation verifier, J_{lmax} is determined by rewriting (4) to determine x_{cr}:

$$J_{lmax} = x_{cr} J_{rotor} \tag{5}$$

Instead of incrementing x up to a point that synchronisation fails, a range based search method is employed to reduce the number of iteration needed to find x_{cr} as presented in Fig. 3. As shown in the figure, x_{min} is initially set to 1 and x_{max} is set by the designer. From literature and machine manufacturers' data sheets, is known that LS-PMSMs have poorer load synchronisation capabilities than induction machines (IM) with similar power levels. Thus an IM's J_{cr} can be used as a reference value.

The search method's functionality is: Once a trial machine's required parameters have been obtained, synchronisation is firstly checked at x_{min}. If synchronisation

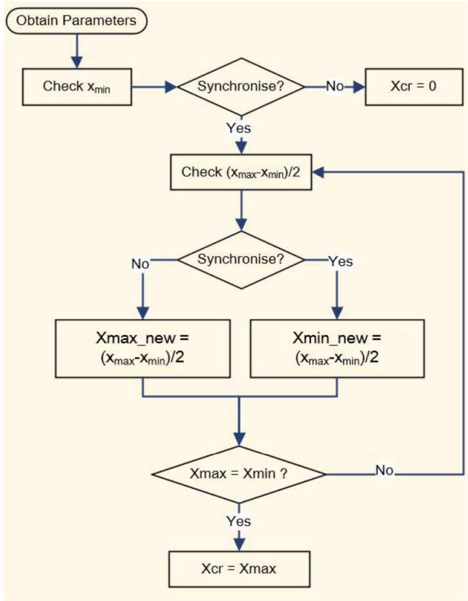

Figure 3: Improved method to obtain critical inertia value for a trial machine

Table 1: Key LS-PMSM design specifications

Description	Stator	Rotor
Outer diameter (mm)	160	99.4
Inner diameter (mm)	100	26
Stack length (mm)	120	120
Winding type	Lap	Cage
Number of slots	36	28
Core material	M400-50A	M400-50A
Magnet type	-	N48H
Rotor bars	-	1050 alloy
Moment of inertia (kg.m^2)	-	0.009

is not achieved, $x_{cr} = 0$ and no further checks are done. If synchronisation is achieved, the next check is done at the midway point of x's range. In the case that synchronisation is again obtained, the lower half of the region is discarded and x_{minnew} is set to the midway point, otherwise, the top half of the region is discarded and x_{maxnew} is set to the midway point. This process is repeated until $x_{min} = x_{max}$ at which point x_{cr} is equal to the current x_{max}. For each iteration of the synchronisation validation the remaining region of x is halved.

4. IMPLEMENTATION OF THE OPTIMISATION FRAMEWORK

In this section the TBRR framework is implemented for the rotor design of an retrofit LS-PMSM. The selected base machine is a 4-pole, 2.2 kW, premium efficiency induction machine. The stator is star configured with a line-to-line voltage of 525 V. The basic design specifications of LS-PMSMs are summarised in Table 1.

To simplify the design and to ensure equal representation when calculating the current LD, the Taguchi framework incorporates per unit (PU) parameter values. An L9 (9 trial machines) and an L4 (4 variations in the main trials) OAs

Table 2: Selected topologies' parameters

	Spoke	Radial	V-type	U-type	Rotor Slot
P1	D1	D1	O2	O2	D1
P2	Rib	Rib	Rib	Rib	H1
P3	PMt	PMt	PMt	PMt	H2
P4	PMw	PMw	PMw	PMw	B1/B2

are used for the main and the outer noise OAs, respectively. By including an outer noise OA, a robust optimum rather than the global optimum will be realised. A total of 40 design analyses per iteration are required, of which 36 (L9×L4) are main trials and 4 (1×L4) are optimum trials. To obtain the necessary machine parameters the same analysis approach as described in [1, 14] is used.

Essentially, an optimally designed LS-PMSM is realised by searching an optimum trade-off between the PM array and cage winding designs. To evaluate their separate influence to the transient performance, the following two design steps are studied:

- *Step 1: PM duct optimisation* - four common PM duct topologies shown in Fig. 4 are used along with a fixed cage design (Fig. 5(a)). By fixing the cage design, only the influence of the PM duct design on the critical inertia will be evaluated.

- *Step 2: Rotor cage optimisation* - A parallel tooth slot shape is selected as shown in Fig. 5(b). The PM duct dimensions are parametrised in such a manner that as *D1* is adjusted the PM duct design is changed according to its optimum PU value from Step 1. For Step 2, it will be investigated whether the critical inertia can be further increased by optimising the cage design.

The selected design parameters for each topology are provided in Table 2. The L9 OA has a limit of four variables per optimisation. In Step 1, *D1* is included in the optimisation of the Spoke and Radial flux topologies whereas for the V- and U-type it is fixed.

To ensure that the TBRR framework realises a robust design, the outer noise factors need to have direct influence on the synchronisation capabilities of the machine. Per definition these factors must be known to the designer, but also be uncontrollable (manufacturing tolerances, ambient conditions) [6]. For this study the conductivity of the rotor bar material, the PM remanent flux density and the rotor diameter are chosen as noise factors because (i) they all affect the synchronisation of the machine, (ii) their variation ranges are known but uncontrollable.

To determine if the proposed TBRR optimisation method is viable for LS-PMSM design, three different RR values (i.e., 0.5, 0.75 and 0.95) are used for each topology case. Thus, a total of 12 optimisations are needed for each of Step 1 and Step 2. According to [10, 11, 13], a successful implementation of the TRBB method exhibits the following attributes:

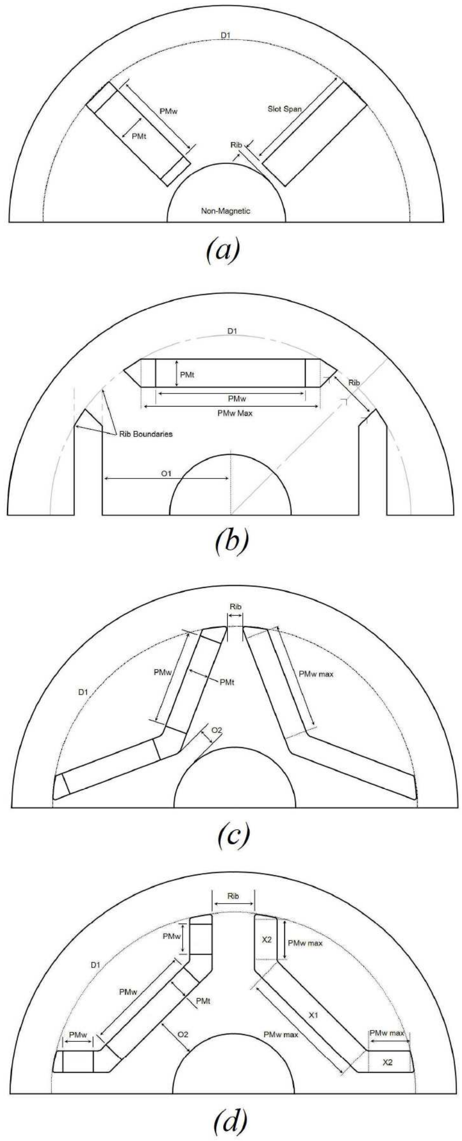

Figure 4: Selected PM duct topologies: a) Spoke-type b) Radial flux c) V-type d) U-type

- The number of iterations increases with the RR value.
- The performance results using different RR values should show a clear convergence or close correlation.
- A stable performance point should be identifiable before the the termination of an optimisation.
- The TBRR optimisation should demonstrate the ability to recover if the OEC drops off an optimum region.

For the optimisation, the OEC is formulated to maximise the normalised critical inertia, i.e. OEC $= \mathrm{MAX}(x_{cr})$. An ideal fan load equation, $T_l(s) = T_{rated}(1-s)^2$, is included in the analytical synchronisation solver with s representing the slip. The parameters required by the analytical synchronisation method were determined using a steady-state analytical model. For each relative optimum x_{cr}, efficiency (η) and power factor (PF) are also calculated.

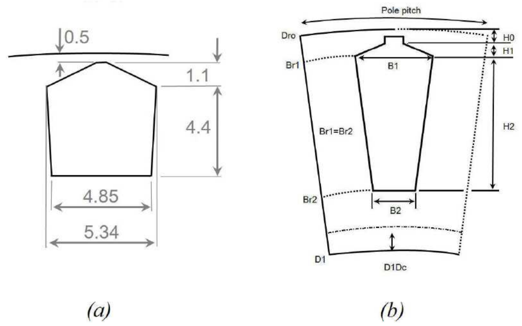

Figure 5: Selected rotor slot shape for (a) fixed slot with dimensions (Step 1)(b) parallel slot with parameters

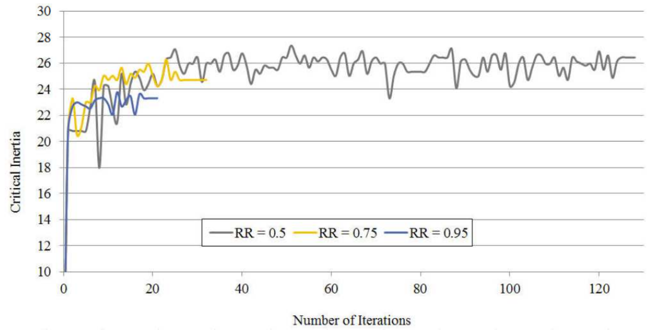

Figure 7: Regression rate performance comparison: Step 2 of Radial flux topology (relatively poor correlation)

Table 3: TBRR machine performance results

	Step 1			Step 2				
	x_{cr}	PF	η	x_{cr}	PF	η	RR	n
Spoke	19	0.89	90.44	27	0.90	91.83	0.95	130
	18	0.84	90.83	26	0.89	91.12	0.75	32
	18	0.84	90.85	26	0.89	91.23	0.50	19
Radial	21	0.87	90.22	26	0.88	91.19	0.95	130
	21	0.87	90.21	25	0.89	91.15	0.75	32
	20	0.88	90.97	22	0.77	88.83	0.50	19
V-type	20	0.90	91.26	27	0.78	89.24	0.95	96
	20	0.91	91.29	27	0.79	89.36	0.75	26
	20	0.88	90.97	22	0.77	88.83	0.50	17
U-type	20	0.85	90.21	26	0.89	91.29	0.95	98
	21	0.88	90.96	25	0.89	91.36	0.75	26
	20	0.83	90.60	25	0.89	91.22	0.50	17

5. OPTIMISATION RESULTS

Table 3 contains the optimisation results and the number of iterations (n) needed for each case. Note that x_{cr} was rounded to the nearest integer after the optimisation was terminated.

Fig. 4 displays the OEC performance results for the radial flux topology for all three RR values of Step 1. Similar OEC performance characteristics were observed for the remaining three topologies. From the results of Table 3 and the OEC performance curves it is found that the TBRR method satisfies all the criteria.

For Step 2, only two of the four topologies showed good correlation between results. Both the Spoke and U-type had similar OEC plots as found in Step 1. In Fig. 4 the OEC plots for the Radial flux topology show relatively poor correlation, in which two RR values (0.95 and 0.75) realised machine designs with the higher x_{cr} than that of RR= 0.5. A smaller RR value may result in reduced iterations but also less accuracy. This agrees with the information in literature. Care must be taken when selecting a RR value for an unknown optimisation. A lower RR value can initially be used to investigate possible optimisation outcomes before using a higher RR for the final optimisation.

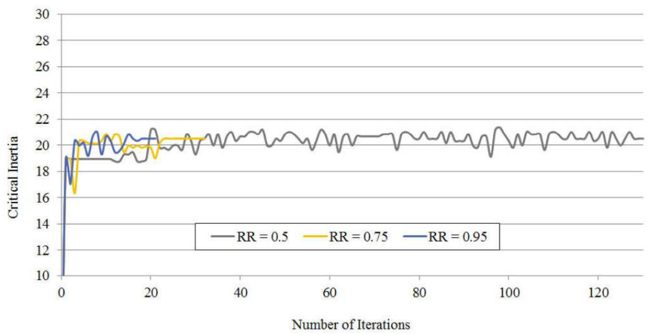

Figure 6: Regression rate performance comparison: Step 1 of Radial flux topology (good correlation)

Although the optimisation objective is to maximise x_{cr}, the realised machines in all cases still have satisfactory steady-state performance. In all cases the steady-state performance can satisfy IE3 standard. It appears that by maximising x_{cr}, steady-state performance is not significantly altered.

For all four PM duct topologies an increase in x_{cr} can be obtained when optimising the cage slot. This is evident in Fig. 8 and Table 3. In Fig. 9 the realised rotor designs for all four topologies from Step 1 and Step 2 are presented, in which a RR value of 0.75 was used. From Step 1 to 2 a noticeable increase in rotor bar material can be seen with little change in PM volume. This highlights the fact that rotor cage optimisation is required to ensure a good synchronisation capability. Furthermore it was found that the synchronisation capabilities of an LS-PMSM is not solely influenced by the cage design but also by the PM duct topology.

6. CONCLUSION

In this paper the TBRR optimisation method has been proposed for LS-PMSM design. It shows that both the accuracy and optimisation time of the TBRR method are dependant on the selected RR value. A lower RR leads to shorter computational time than that of a higher RR. However, it may somewhat result in a loss of accuracy.

The maximum synchronising capability of all the topologies for both design steps are relatively close with each other. The use of x_{cr} as an optimisation objective to

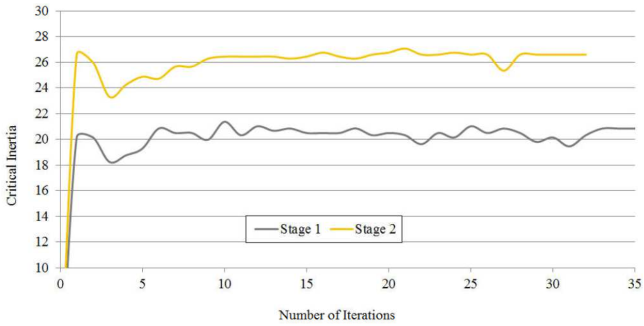

Figure 8: OEC result comparison between Step 1 and Step 2 for Spoke type topology (RR= 0.75).

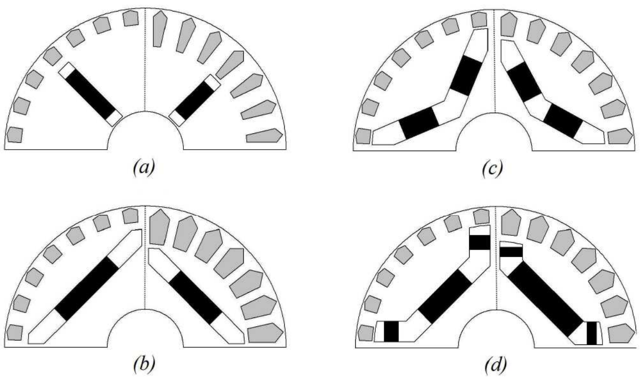

Figure 9: TBRR's machine design comparison between Step 1 and 2 (RR= 0.75).

improve the transient performance of an LS-PMSM can be seen as viable. It is shown that by using the TBRR method along with an analytical synchronisation model a machine design could be realised with both improved synchronisation capabilities and satisfactory steady-state performance.

From the optimisation results, it has been shown that the implemented TBRR optimisation method works in the same manner as described in literature. Thus, it is a viable optimisation tool in the LS-PMSM design. Further improvements of the method can be made by refining the way of determining, selecting or adjusting the RR value.

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