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PRINCIPLE OF DESIGN OF FOUR–PHASE LOW–POWER SWITCHED RELUCTANCE MACHINE AIMED TO THE MAXIMUM TORQUE PRODUCTION

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This paper deals with the design of a low-power four-phase SRM optimized to maximum torque performance. The design is made from the point of view of the space available for motor location. The outer dimensions such as outer stator diameter and effective length of iron are input values. The influence of operational parameters as well as the rest of geometrical dimensions upon motor performance is discussed. Some of the geometrical topologies of this SRM type are investigated by various speeds. The moment of switching is aimed to maximum torque production. The operation of the motor as well as motor converter and control strategy are described.

K e y w o r d s: SRM design, torque production, one-pulse operation, chopping operation

1 INTRODUCTION

The concept of a switched reluctance motor (SRM) was established in 1838 [1] but the motor could not be fully realized until the era of modern power electronic started. Since the 1960s began its quick development and therefore in only last decades SRM is applied practically. The first commercial application of SRM in Europe and the US is described in [1, 2].

Following works also deal with the design of SRM with some various approaches. A procedure for the design of SRM based on output equations similar to those of conventional AC machines is described in [3]. There is given a selection of values and their verification, and a criterion to evaluate the operational limit is developed. An electromagnetic design for the high voltage and power SRM (5 MW, 9000 V) including losses, efficiency and temperature computation was made in [4]. In [5] optimization of motor performances is carried out according to pole tooth width change. The system of 5 hp fuel-lube pump with SRM is described in [6]. It contains the design of the machine, power inverter, control circuit with both hardware and software part. In [7] a high torque density and high efficiency SRM is designed and built for vehicle propulsion. For optimization of the magnetic circuit for high density, the finite element method (FEM) was carried out. Much attention was paid to lowering the acoustic noise and increasing the overload capability.

This paper deals with the design of a low power 4 phase SRM. The aim is to replace a universal motor used in home appliances by a SRM with the same outer dimensions. Therefore the design is made from the point of view of the space that is available for motor location. The outer dimensions such as outer stator diameter and effective length of iron are given values and the influence of operational parameters upon motor performance is observed.

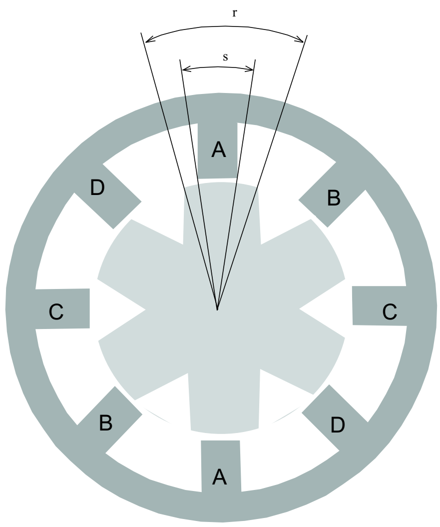

Fig. 1. Arcs of the stator β_s and rotor β_r poles

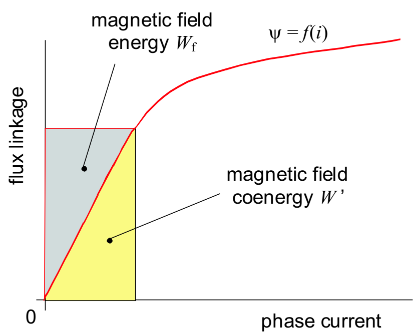

Fig. 2. Display of magnetic field energy and coenergy

The motor has salient poles both on the rotor and the stator. The field winding is on the stator and there is no winding on the rotor. The whole developed torque is reluctance only. SRM works with rotor position feedback

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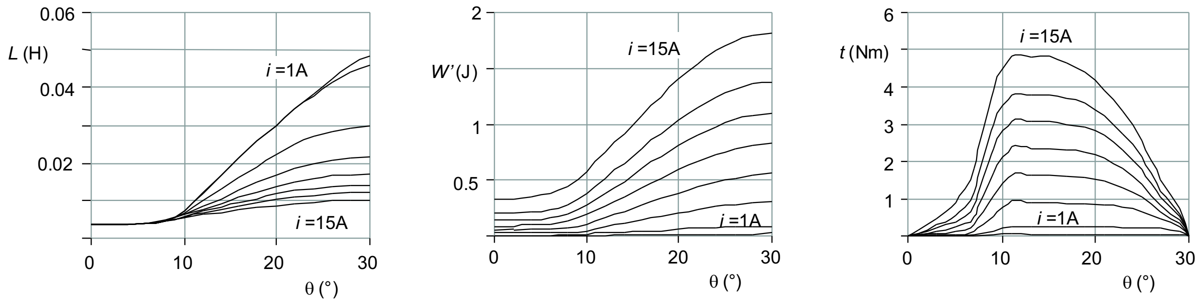

Fig. 3. Phase inductance, coenergy and static torque *vs* rotor position of SRM with $\beta_s/\beta_r = 20°/20°$ by various current

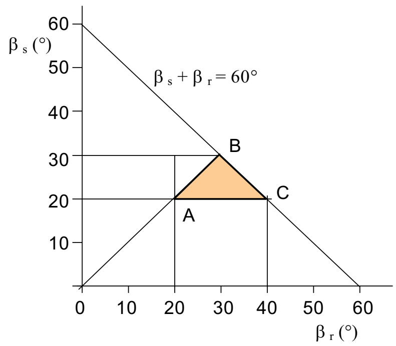

Fig. 4. Feasible triangle for 4-phase 8/6 SRM

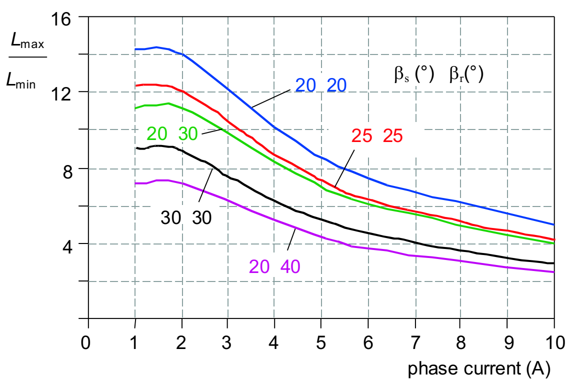

Fig. 5. $L_{\max}/L_{\min}$ for various pole measurements

and on continuous status. Rotor position sensing can be made by some optical sensor or electronically. The comparison of electronic position sensing and direct sensing is in [6]. In the next chapter some needed terms of SRM operation will be explained that will be used in this paper.

2 IMPORTANT TERMS

Aligned position: When any pair of rotor poles is exactly aligned with the stator poles of the given phase, then the phase is said to be in the aligned position (in Fig. 1 it is the phase marked with A). The phase inductance is on maximum ($L_{\max}$) and the phase produces no torque until it is displaced to either of sides.

Unaligned position: When interpolar axis of the rotor is aligned with the stator poles of phase, the phase is in unaligned position (phase C in Fig. 1). The phase inductance is on minimum ($L_{\min}$) and when it is displaced to either side, there appears a torque that tends to displace it towards the next aligned position.

Effective torque zone: It is the angle through which one phase can produce torque comparable to the rated torque. It is also comparable to the lesser pole arc of two overlapping poles.

Pole arcs: These are the widths of stator or rotor poles marked as β_s and β_r (Fig. 1 and Fig. 3).

3 TORQUE PRODUCTION AND COMPUTATION

The torque in each of motor phases is created towards growing inductance. The poles of the rotor try to get aligned position. Each of the phase currents must be switched in line with areas of growing inductance (see Fig. 8). According to Fig. 2, the magnetic field coenergy W' can be expressed as follows:

$$W' = \int_0^{i_1} \psi di \tag{1}$$

where ψ is the flux linkage of one phase. Then the instantaneous value of torque produced by one phase t is as follows:

$$t = \left[\frac{\partial W}{\partial \theta}\right]_{i=\text{const}} \tag{2}$$

where θ is the rotor position. Phase inductance, coenergy and the torque have been computed by the finite element method (FEM). They have been carried out as two-dimensional tables of static values L, W' and t that are depending on the current as well as on rotor position. These values are graphically expressed for one of the investigated SRM in Fig. 3.

Then the dynamic simulation in Matlab application has been performed to find the phase current as follows:

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \left[U_{dc} - \left(R + \frac{\mathrm{d}L}{\mathrm{d}\theta}\omega\right)i\right]\frac{1}{L} \tag{3}$$

where U_{dc} is the supply voltage, R and L is phase resistance and inductance, respectively, and ω is the angular speed of the rotor. The instantaneous value of inductance has been determined by two-dimensional interpolation from the mentioned two-dimensional table of inductance values for a known current i as well as rotor position θ. Therefore, besides i a new value of L is determined in each step of simulation. Similarly as L also the instantaneous value of torque produced by one phase has been determined from the two-dimensional table of static torque values. The overall produced torque has been given as an average value of the sum of all phase torques. When the number of phases and the outer dimensions of motor are given, the torque value depends on:

- rotor diameter,
- supply voltage

and the parameters typical in SRM as follows:

- pole size,
- turn-on and turn-off angle.

The influence of all these parameters on the torque production will be discussed in next chapter.

4 DESIGN OF GEOMETRICAL DIMENSIONS

In this chapter the reasons for choosing the geometrical dimensions is shown and the influence of their variation is roughly given.

Outer dimensions: The outer diameter of the stator and the effective length of iron has been chosen as 90 mm and 44 mm, respectively, because these are dimensions of a universal motor produced for some home applications, such as vacuum cleaners.

Number of stator and rotor poles: In general, the stator has two or more poles per phase in order to balance the radial forces produced by each phase [2]. The most suitable type of four-phase SRM is topology 8/6 that means the motor winding. Two stator poles of one phase are located in opposite sides of stator and their windings are connected in series (it can be in parallel too).

Rotor diameter: It is known that the torque rises with rotor diameter but enough space for phase winding on stator poles must be kept. According to [1] when saturation of the magnetic circuit is negligible, the torque produced by one phase can be simplified as follows:

$$t = \frac{1}{2} i^2 \frac{\mathrm{d}L}{\mathrm{d}\theta} \,. \tag{4}$$

The condition that saturation of the magnetic circuit is negligible is sufficiently valid at higher speeds of the motor. According to (4) it can be said that the saliency ratio of aligned and unaligned inductances ($L_{\max}/L_{\min}$) is proportional to the developed torque. The rotor diameter has been chosen to 56 mm (Fig. 1), which is the biggest value that still makes possible to put the appropriate phase winding on the stator pole. It has been found by means of the above-mentioned method of torque computation that by decreasing the rotor diameter from 56 mm to 48 mm the ratio $L_{\max}/L_{\min}$ decreases by 14.9 % and, hence, the average torque decreases, too. Similarly, if the number of rotor poles were higher than 6 at the same number of stator poles, the poles would be narrower and $L_{\max}$ and, hence, ($L_{\max}/L_{\min}$) would me smaller.

Number of turns and wire cross-section: The cross-section of wire has been chosen to $0.45\,\mathrm{mm}^2$. Then the maximum number of turns we can put into the given stator interpolar space is 100. That means 200 turns of each phase. The number of turns is adequate to the magnetomotive force and then also the torque produced by the phase. A higher number of turns means a smaller wire cross-section and then lower current loading. Therefore, these values should be chosen according to requirements of the used application. The value 100 turns per pole has been roughly chosen according to the mentioned universal motor. The phase resistance is $1.32\,\Omega$ at temperature $75\,^{\circ}\mathrm{C}$.

Length of air gap δ: This value should be chosen as small as possible because the whole magnetic circuit is magnetized from the stator side. That is why every increase of δ contributes to reduction of the efficiency of electromagnetic energy conversion. A higher δ brings about a lower phase inductance and, hence, impedance, and the motor draws a considerably higher magnetizing current and more input power from the power supply. The δ has been chosen to 0.2 mm, which is a sufficiently small value, but it is difficult to manufacture. It has been found that by rising of δ the change of torque is only negligible or the torque slowly decreases but the winding losses rapidly increase because of a higher magnetizing current.

The width of stator and rotor arcs: The width of poles β_s and β_r can be chosen according to "feasible triangle" (Lawrenson, 1980), which is shown in Fig. 4. By means of FEM, the static parameters for one phase have been established for five combinations of β_s and β_r and the influence of these pole sizes on the developed torque was explored.

In Fig. 5 there is shown the ratio $L_{\max}/L_{\min}$ *vs* current for these β_s and β_r combinations. Figure 6 shows the phase inductance for SRM with $\beta_s/\beta_r = 20^\circ/20^\circ$ (which equals to point A in Fig. 4) in dependence on current and rotor position. In this picture the remarkable effect is seen of saturation on rising the current in aligned rotor position (see values of L at $\theta = 30^\circ$).

In this way all geometrical dimensions are determined and now our interest will be focused on the converter topology and control strategy.

5 THE CONVERTER TOPOLOGY AND CONTROL STRATEGY

There are many converter topologies for SRM operation, which are analyzed in [2], and it depends on specific application which topology will be used. An asymmetric converter circuit (Fig. 7) has been used to control the

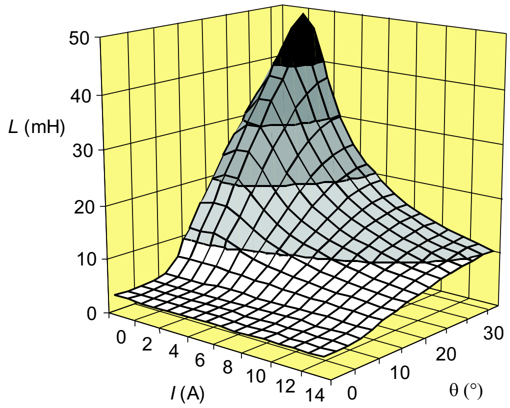

Fig. 6. Phase inductance variation of SRM

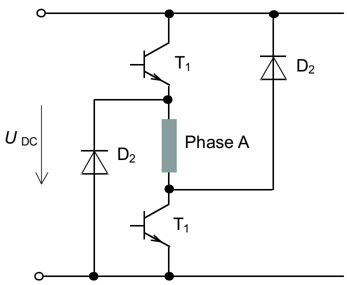

Fig. 7. Asymmetric power converter for SRM phase

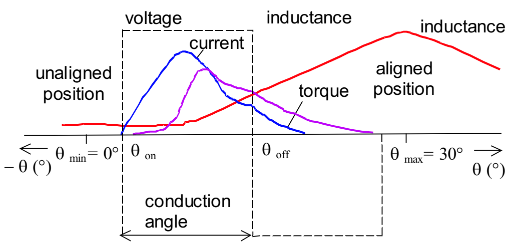

Fig. 8. Schematic waveforms of 4 phase 8/6 SRM

phase supply because of its simple topology. The influence of control strategy upon the developed torque can be investigated.

Converter operation: When the rotor of given phase reaches *turn-on angle* θ_{on}, the power switches T_1 and T_2 are on. At this moment the supply voltage U_{dc} is applied to the phase as it is seen in Fig. 8. When the operating speed is high enough, the growing back-EMF causes that the current will start to decrease. By reaching *turn-off angle* θ_{off} the switches are off and the freewheel diodes D_1 and D_2 take the phase current, which quickly decreases because the phase voltage is $-U_{dc}$. In that condition the motor is supplied by $+U_{dc}$ along the whole conduction angle ($\theta_{on} \div \theta_{off}$) and this mode is called *one-pulse operation* (see Fig. 9b).

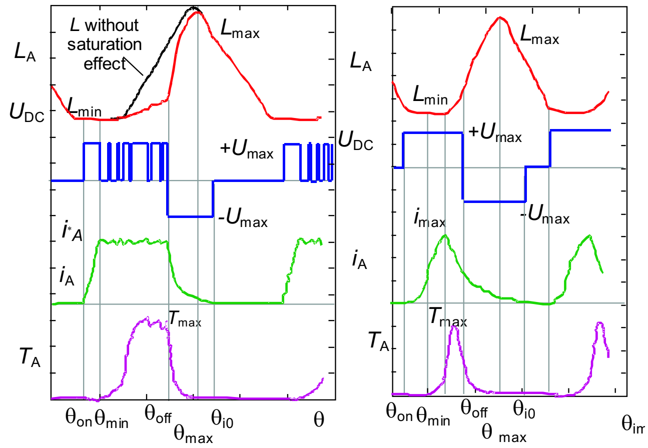

Fig. 9. Simulated operational waveforms of one from SRM phases ($\beta_s = \beta_r = 20°$, a) by chopping at 5000 rpm, b) by one-pulse operation at 20000 rpm

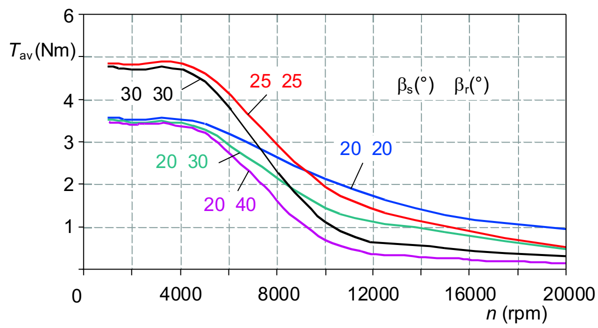

Fig. 10. Average developed torque of all motor phases

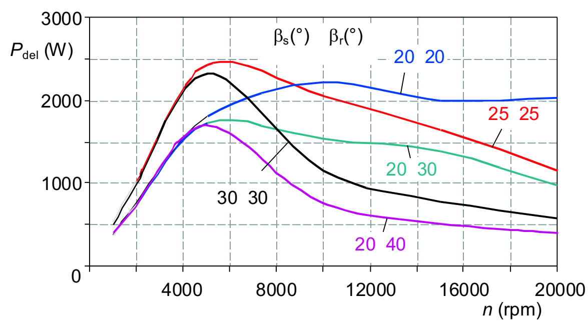

Fig. 11. Power transferred from stator to rotor through air gap

If the current achieves the value that is set as a required (reference) value i_A^* (see Fig. 9a), one from the power switches is left on and another is switched off or on with some hysteresis according to whether the current is greater or less than i_A^*. The phase voltage is 0 or $+U_{dc}$. This mode is called *chopping — current regulation*.

At a higher operating speed it is not possible to achieve i_A^* current because of high back-EMF. Both operations, chopping — current regulation as well as one-pulse operation, have been used in simulations depending on motor parameters and speed.

The task of control strategy is to define θ_{on} and θ_{off} angles with aim of developing the maximum torque. This is the topic of the next sub-chapters. This control strategy is applied to computation of all the next waveforms (Figs.9, 10, 11).

5.1 The choice of conduction angles by chopping operation

In Fig. 9a some simulated phase waveforms can be seen: inductance, current, voltage and developed torque for SRM with $\beta_s = \beta_r = 20°$ and speed 5000 rpm. These conditions represent chopping converter operation. The choice of θ_{on} determines the profile and values of current and developed torque. It is important to choose the θ_{on} in such a way that the *current should have a maximum value in the beginning of the torque zone, which is an unaligned position*. Then the voltage must be applied to phase at θ_{on} in time before the unaligned rotor position ?min. It is said that the motor works with advanced conduction angle and θ_{on} has negative polarity (see Tab. 2). At SRM 8/6 with 6 poles on the rotor, the angle between two of pole axes is $360/6 = 60°$, which is also the value of *period of phase current*. Therefore the angle between aligned and next unaligned rotor position is $60/2 = 30°$. When the value of $\theta_{\min}$ angle is marked as 0○, the value of $\theta_{\max}$ is $30°$ as it is seen in Fig. 8.

The θ_{off} angle should be chosen as follows: At the angle of maximum inductance θ_{max} the current should have a minimum value compared with the reference current. From the observations it can be said: *Motoring torque developed at the phase current fall-down* ($\theta_{off} \div \theta_{\max}$) *must be higher than the total generating torque* ($\theta_{\max} \div \theta_{i0}$ *and* $\theta_{on} \div \theta_{\min}$). Generating torque appears at some periods of rotor position and its value is only negligible in comparison with the motoring torque.

By this operation, SRM is able to obtain a multiple torque than a similar asynchronous or synchronous motor, but the following must be kept:

- Sufficient cooling is supported because of high winding losses.
- Motor works in interrupted operation and should not work in permanent operation.
- Reference current is limited to the value with which the coil temperature does not exceed the allowed value.

Table 1. Maximum average torque (Nm) for various SRM and operating speed

β_s, β_r	$n = 1000$ rpm	2000	5000	10000	15000	20000
20, 20	3.571	3.538	3.42	2.107	1.262	0.962
25, 25	4.874	4.838	4.619	1.751	1.041	0.544
20, 30	3.523	3.46	3.28	1.457	0.88	0.465
30, 30	4.749	4.68	4.399	1.091	0.492	0.2715
20, 40	3.52	3.45	3.22	0.543	0.331	0.184

Table 2. θ_{on} angle (°) corresponding to the torque values in Tab. 1

β_s, β_r	$n = 1000$ rpm	2000	5000	10000	15000	20000
20, 20	0	0	0	−7	−14	−14
25, 25	−1	−2	−6	−10	−15	−14
20, 30	−1	−2	−5	−10	−15	−14
30, 30	−1	−2	−7	−12	−14	−14
20, 40	−1	−2	−9	−10	−14	−14

Table 3. θ_{off} angle (°) corresponding to the torque values in Tab. 1

β_s, β_r	$n = 1000$ rpm	2000	5000	10000	15000	20000
20, 20	29	28	25	22	17	15
25, 25	28	27	25	20	15	15
20, 30	27	24	25	20	15	15
30, 30	27	26	25	18	15	15
20, 40	20	20	20	16	15	15

5.2 The choice of conduction angles by one-pulse operation

This operation occurs when the current does not achieve the reference value i_A^* because of high speed (Fig. 9b), because the back-EMF has a higher value than the supply voltage. This will happen in every SRM above a certain speed (which is called base speed in [1]). The current waveform depends only on U_{DC} value, magnetic circuit and conduction angle.

In general, the same rules are valid at θ_{on} and θ_{off} angles optimization as by chopping. The advanced angle should be bigger to get a higher current while the inductance is small enough. In one period of phase current the supply voltage achieves 3 specific values as it is seen in Fig. 9b:

1. $+U_{DC}$ in interval of conduction angle ($\theta_{on} \div \theta_{off}$)
2. $-U_{DC}$ in interval when the current is carried by freewheeling diodes ($\theta_{off} \div \theta_{i0}$)
3. 0, when the stored energy is quite exhausted and there is no current in the phase ($\theta_{i0} \div \theta_{on}$)

By optimization of angles it has been found that *the conduction angle and the interval of leading of freewheeling diodes occupies the whole period of phase current while the width of interval* ($\theta_{i0} \div \theta_{on}$) *is as small as possible*. This interval is intentionally enlarged in Fig. 9b to make the picture more instructive. The waveform of the supply voltage is nearly square with values from $+U_{DC}$ to $-U_{DC}$.

6 RESULTS

Motor operation has been investigated for speeds from 1000 to 20000 rpm for SRM with various pole arcs as it is seen in Tabs. 1 to 3. The supply voltage U_{dc} has been chosen to 240 V dc and the reference current has been limited to 10 A. The 240 V is a chosen value in the range from 207.5 to 325 V. These voltages mean the lowest and the highest value of typical rectified 1 phase ac voltage from a main supply 230 V/50 Hz respectively. The load value has a negative and the capacity of the filtering capacitor has a positive influence on the value of average dc-bus voltage U_{dc}. There is shown the developed torque and θ_{on} and θ_{off} optimized to get a maximum torque in Tabs. 1 to 3. In the tables the values printed in bold letters mean one-pulse operation. In Figs. 10 and 11 there are graphically demonstrated the results of torque as well as proportional air-gap power $P_\delta = \omega T_{av}$. It can be seen in Tab. 2 that almost all θ_{on} angles are in advanced angle because of their negative signs.

6.1 Low speed operation

As it is seen from the results in Fig. 10, in the range from 0 to 5000 rpm, the torque of the investigated magnetic circuit topologies is limited by the motor current and its value is constant. The current is limited by chopping of dc voltage by means of presented control strategy. It is clear form Fig. 10 that the SRM 8/6 topologies with larger effective torque zone ($\beta_s/\beta_r = 25/25°$ and $30/30°$) produce the torque 4.8 Nm that is 37 % higher value than in other cases. Therefore the topologies with larger effective torque zone produce higher torque because they have widest conduction angle and draw more input power from power supply. These two topologies have the value of effective torque zone according to [2] 25° and 30°, respectively, while the others have it in value 20°.

6.2 High speed operation

The situation is changed in high-speed operation. The motor topology, which is still working in chopping operation, can produce more torque. The most favourable topology seems to be that with $\beta_s/\beta_r = 20/20°$ (Fig. 10). This one works roughly with a constant output power in speed range from 6000 to 20000 rpm. This topology can draw one works roughly with a constant output power in speed range from 6000 to 20000 rpm. This topology can draw more current also in one-pulse operation because of lower phase inductance and lower produced back-EMF.

7 CONCLUSION

For a maximum developed torque, an unsuitable type of SRM is that with $\beta_s/\beta_r = 20/40°$ which produces a high back-EMF and has also a low torque zone. Other topologies can be more or less applicable. From Fig. 10 it is obvious that one with $\beta_s/\beta_r = 25°/25°$ can achieve the highest torque at low speeds and $\beta_s/\beta_r = 20°/20°$ at higher speeds and it is a question of application where the motor should be used. Some increase of the output power can be possible by additional filtering and then by increasing the U_{dc} voltagwhich would lead to an increase of the drive size and cost.

It must be noted that various converter types or control strategies can have some influence on the whole drive performances and the design of SRM should deal with other practical performances such as motor losses and efficiency and torque ripple. These have not been discussed in this paper but must be observed so that the motor could be really used in practice and replace other types of motors.

Acknowledgement

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