Optimal rotor design of a synchronous reluctance motor suitable for pumping operation

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ABSTRACT: This paper presents the performance analysis of a synchronous reluctance motor (SRM) fed by a non-conventional energy resource used for pumping operation in agriculture. An optimal rotor design is proposed for the SRM, which ensures maximum flux density at q-axis and simultaneously maintains low torque ripple. Finite element analysis is used to determine the characteristic of the drive system even under saturation condition. Effect of number of flux barriers, their width and position on the performance is also studied. The machine is simulated in Quickfield software and simulation results show the effectiveness of the proposed rotor design.

India is a land of agriculture. Throughout the agricultural sector, pumps are used for land irrigation to draw water from tube wells or open wells. These motor-pump irrigation units are economical as well as clean and can be driven by wide varieties of power units but are dependable on source of electrical power.

Electrical energy has been found to be the most efficient, clean, and easy to use form of energy. Modern civilization cannot be even perceived in the absence of electrical energy and at the same time its application in agricultural sector is of utmost importance. With ever growing population, improvement in the living standard of the humanity, industrialization of developing countries, the global demand of energy is increasing at a high rate. Fossil fuels are the main sources of conventional energy along with hydro power and nuclear power which also fall under the same category but they are depleting at a fast rate. This has paved the way for non-conventional and renewable sources of energy like solar energy, wind energy and macro and micro hydro potential sources.

Energy conversion devices are required at both ends of an electrical system so as to be converted in useful form such as light, heat or mechanical energy. In the present study, the electrical energy of the drive system is converted into mechanical energy of the pumping unit, which is later used for irrigation. The use of SRM for pumping operation has been an exciting area of research.

Lawrenson *et al*. (1964 and 1967) proposed a purely segmental motor which had superior performance when compared to the conventional machine. The Honsinger (1971) did significant contribution for estimating and improving the performance of SRM motor. The application of a segmental-rotor synchronous reluctance motor in a variable-speed drive with current-regulated PWM control and the low-speed torque capabilities has been discussed by Miller (1991). The implementation of the PV energy sources for water pumping and irrigation applications based on dc motor was done by Veera (2000) and Rashad *et al*.(1999), an induction motor by Moussi *et al*. (2004) and Daud *et al*. (2005) and permanent magnet (PM) synchronous motor by Chenni et al. (2006) has been found a considerable interest from researchers. The design considerations of the PV array, suitable for driving a centrifugal pump are studied by Nabil *et al*. (2012).

An optimal design for rotor of SRM is proposed for improved performance suitable for pumping operation. Multiple flux barriers type rotor is taken into consideration and the slot width, position and numbers of barriers are optimized.

MATERIALS AND METHODS

With recent developments in power electronic devices, converters and control techniques, reluctance motors have emerged as high performance industrial drives for variable speed applications. The stator of such machines is similar to a standard polyphase AC motor with conventional winding. The modern reluctance motors are inverter driven and hence do not require starting cage windings which has given the designers a flexibility to optimize the magnetic circuit. A single phase SRM is shown in Figure 1. Here rotor is the main component for the model purposes. Almost all the important performance parameter of SRM depends on the synchronous ratio or saliency ratio. The main aim is to maximize saliency ratio so that a high torque and low loss/torque ratio can be obtained. The torque of a motor can be expressed as:

$$T_e = \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} \quad (1)$$

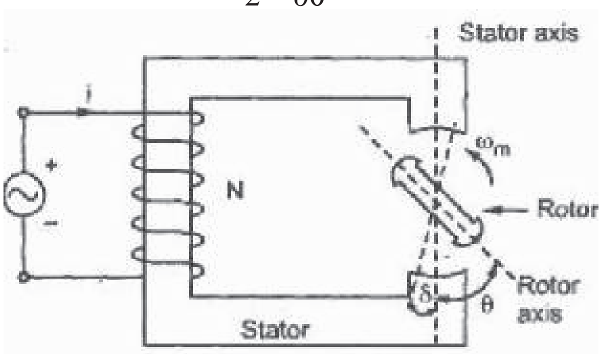

Fig. 1: Single phase reluctance motor

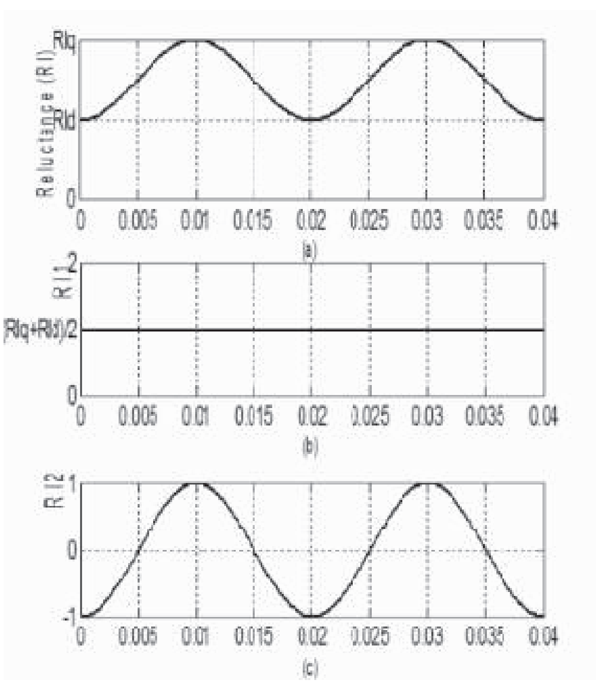

Fig. 2: Variation of reluctance with space phasor θ_r

The reluctance torque of the motor is shown in Figure 2 and can be expressed as:

$$T_e = \frac{1}{2} \varnothing^2 \frac{\partial Rl}{\partial \theta_r} \quad (2)$$

where, $Rl = RL_1 + Rl_2 = \frac{1}{2}\left(Rl_q + Rl_q\right) - \frac{1}{2}\left(Rl_q - Rl_q\right)\cos 2\theta_r$

$$T_e = \frac{1}{2} \varnothing^2 \left(Rl_q - Rl_q\right) \sin 2\theta_r \quad (3)$$

Let the instantaneous values of sinusoidal flux and space angle be written as:

$$\varnothing = \varnothing_{max} \cos \omega t$$
$$\theta_r = \left(\omega_r t - \delta\right) \quad (4)$$

where ω_r is the shaft angular velocity in rad/sec. Substituting the values of ϕ and θ_r gives the instantaneous values of torque as :

$$T_e = \frac{1}{2} \varnothing_{max}^2 \left(Rl_q - Rl_q\right) cos^2 \omega t \sin(2\omega_r t - 2\delta) \quad (5)$$

The average value of the torque can be obtained by finding the average value of the above equation over a complete cycle and can be written as:

$$T_{e(av)} = \frac{1}{8} \varnothing_{max}^2 \left(Rl_q - Rl_q\right) \sin 2\delta \quad (6)$$

It is clear that faster the inductance varies with θ, higher is the torque. A measure of inductance variation is the difference between the maximum and minimum inductances and their ratio.

The hydraulic output power of the pump can be characterized by Daud *et al*. (2005):

$$P_p = 2.725\, QH \quad (7)$$

The relation between the hydraulic output power (P_p) of the pump and the mechanical input power (Pm) can be defined as the pump efficiency given by Arrouf and Ghabrour (2007):

$$\eta_p = \frac{P_p}{P_m} \quad (8)$$

The load torque of the centrifugal pump is given by Alghuwainem (1992):

$$T_L = T_0 + C w_r^{1.8} \quad (9)$$

where To and C are constants.

RESULTS AND DISCUSSION

In the present study, an optimized rotor design in proposed. The FEM uses a non linear and a magneto-static solver to analyze the different SRM rotor designs. The stator has 24 slots, 4 poles, and 57 mm inner diameter and hence the slot pitch is 15 mechanical degrees. The

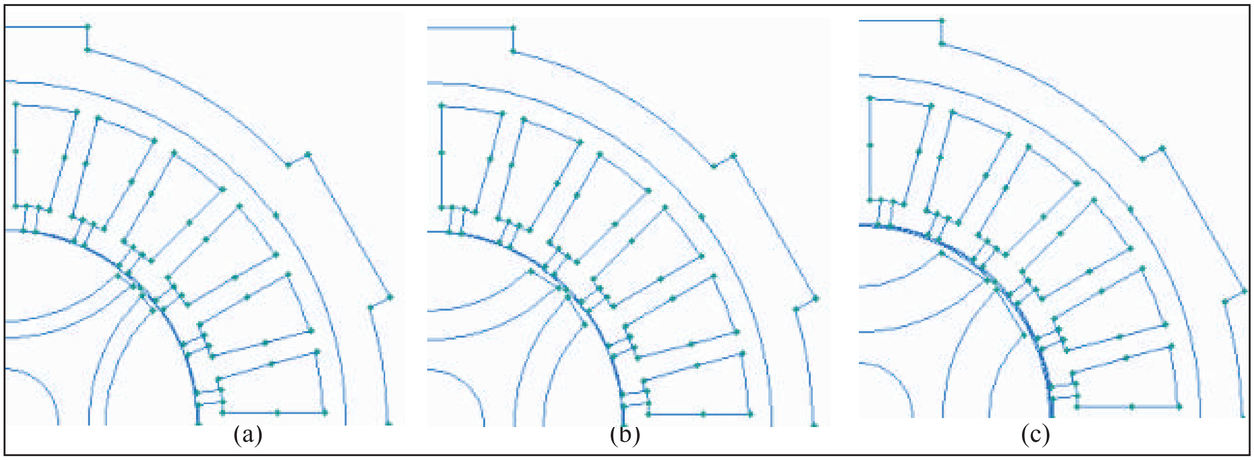

Fig. 3: Modification of flux barrier width (a) 2mm (b) 4mm (c) 6mm.

effect of air-gap length and width of flux barrier is studied. The drive system is simulated under different operating conditions.

Effect of the single flux barrier width

The effect of a single flux barrier width has been investigated by changing the width of the barrier as it is shown in Figure 3. At each step, the flux barrier width is increased by 2 mm.

Variation of motor torque with respect to the rotor angle is plotted as shown in Figure 4.

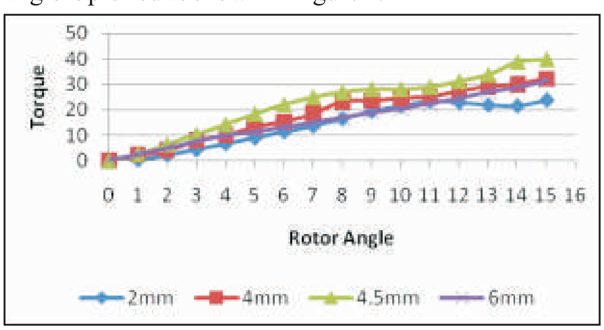

Fig. 4: Torque of a single flux barrier rotor as a function of the rotor angle with different barrier width.

Effect of the air-gap length

The air-gap length affects the direct axis inductance, the stator leakage flux inductance, the iron losses and the mechanical loss values. Decreasing the air-gap length increases effectively the d-axis inductance. Figure 5 illustrates the effect of the air-gap length on the output torque which can be inferred as an effect on d-axis self-inductance. It can be concluded that 0.3mm air gap provides better motor torque as compared to 0.5mm air gap and is taken during the course of study. Table 1 summarizes the design data for the proposed SRM.

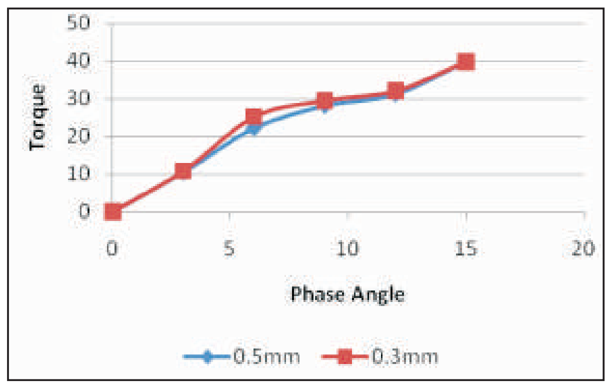

Fig. 5: Behavior of output torque as a function of the rotor angle with different air gap.

Table 1: Summary of Design data

Stator		**Rotor**	
Lamination outer diameter, mm	112.0	Outer diameter, mm	56.4
Lamination inner diameter, mm	57.0	Shaft diameter, mm	16.0
No. of Slots	24	Number of flux barriers	3
Tooth Width, mm	3.1	**Stator Winding**	
Slot opening, mm	2.2	Number of poles	4
Slot area, mm^2	102.055	Number of turns per phase	140

CONCLUSION

In the present study, a multiple-flux carrier rotor for SRM is modeled for suitable operation in pumping application. An optimized rotor design is built by taking into consideration the barrier width and effect of air-gap on the performance of designed machine. By simulating the model, values of self and mutual inductance were obtained and with the help of dq0 equations, the values of the leakage inductance, constant magnetizing inductance and sinusoidally varying magnetizing inductance were determined.

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