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OPTIMAL EFFICIENCY DESIGN OF SWITCHED RELUCTANCE MOTOR-DRIVE

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Abstract – Design of Switched Reluctance Motor (SRM) for adjustable speed drive applications is fundamentally coupled to associated converter configuration and its mode of control. This paper describes a SRM design optimization algorithm based upon employed mode of control and associated converter configuration, considering total efficiency of motor-drive as objective function constrained by torque ripple limitation. The paper best employes total-torque/winding-number/chopping-current curves obtained from finite element analysis of constructed SRMs in order to found the basis of optimization algorithm. Then, the algorithm is applied to design of 4000 W, 1500 rpm, 8/6 SRM.

I. INTRODUCTION

Switched Reluctance Motor (SRMs) unlike Induction Motor (IM) and Synchronous Motor (SM) is not capable to operate without its converter and direct or indirect sense of rotor position. The rotor position data is directly or indirectly required to determine which phase should be excited at time. The converter which plays the role of current commutator like that of DC Motor (DCM), connects the proper phase to input dc supply. On the other hand, the performance characteristics of SRM such as efficiency, torque ripple, mechanical noise or thermal distribution is dependent upon phase current waveform supplied by converter and commanded by mode and strategy of control. Therefore, the optimal designs of SRM for different configurations of converter and different modes of control are fundamentally different.
The mode of controls for SRM, can be divided to two main categories: current based mode of control and voltage based mode of control. If control variables of these modes of control come to zero, they will converge together and to single pulse mode of control in which the phase current waveform is only governed by phase turn on and turn off angles.
This paper presents a SRM design optimization algorithm based upon the current PWM (chopping) mode of control and half-bridge converter [1], considering total efficiency of motor-drive as objective function constrained by torque ripple limitation. However, the optimization algorithm can be suitably changed to apply for other modes of control and converter configurations.
Although the basic rules of SRM design are known [2,3], because of the highly saturated doubly salient pole structure of SRM, there is no suitable analytical formula to predict output torque or other performance indices of SRM. Many attempts have been done by recent literatures to clarify the relationship between these performance indices and design parameters of SRM [4-6]. The paper employes total-torque/winding-number/chopping-current curves at constant current density, obtained from constructed SRMs, in order to found the basis of optimization algorithm.

II. SRM SYNTHESIS

The synthesis is a procedure to produce a feasible motor design, on the basis of a set of values for all design parameters associated to motor and the motor specifications. This procedure searches for achieving to the condition of working point without any optimization of motor performance characteristics [7]. The SRM design parameters consist of two groups. One group of parameters are constantly determined by designer and another group, so called design variables, will be optimized in design optimization algorithm.
In the synthesis of SRM, the design variables include independent and dependent variables. The dependent variables are changed in order to meet the synthesis constraints which are defined by the condition of working point. Here, the independent design variables are external stator diameter, D_o ,rotor bore diameter, D_r, stator pole arc, β_s, rotor pole arc, β_r, stator yoke thickness, w_s, rotor yoke thickness, w_r, rotor stack length, l_{stk}, and current density, J . Also, the dependent design variables are number of winding turns per stator pole, N , and cross section of copper wire, a_{cu} . Since the efficiency is objective function in optimization algorithm, the design variables should include current density and cross section of copper wire which have direct effect on copper loss of motor. The parameters of the mode of control, here current PWM (chopping) mode of control, are turn on angle, θ_{on} , turn off angle, θ_{off} , and current chopping level, I_{chop} . The independent design variables also include turn on and turn off angles. The current chopping level, as a dependent variable, changes to meet synthesis constraints in current PWM (chopping) mode of control.

All other design parameters are assumed to be known. The synthesis constraints are output power, P_{out}, or corresponding output torque, T_{out}, and demanded current density that is entered as independent design variable of J. The values of dependent design variables at first of synthesis can be initially determined as following:

$$a_{cu} = \frac{P_{out}}{UJ\sqrt{N_{ph}}} \tag{1}$$

$$N = \frac{N_{ph}U\pi}{2N_s k_1 k_2 B l_{stk} D_r \omega_m} \tag{2}$$

where N_{ph}, N_s, ω_m, U and B are respectively number of phases, number of stator poles, mechanical rotor angular velocity, input voltage and maximum flux density at the stator pole. The coefficients of k_1 and k_2 are also respectively $\pi/4$ and 0.75 [8].

The synthesis of SRM has two different procedures in terms of associated mode of control which is described as following.

A. *SRM synthesis in single pulse mode of control*

Figure 1 shows the variations of total output torque, rms value of phase current and cross section area of copper wire versus number of winding turns per stator pole for a well-designed 8/6 SRM at constant current density of 5 A/mm^2 in single pulse mode of control. The trend of these variations is also same for other studied SRMs. As a result, the increase of the number of phase winding turns yields the decrease of output torque. The flowchart of SRM synthesis in single pulse mode of control can be founded on this result as shown in Figure 2. After analysing the motor, if the calculated torque is greater than the demanded value, the number of winding turns should be increased. Hence, slot fill factor should be checked for this increase. If it exceeds the maximum specified value, the design can not achieve required torque and the mode of control should be changed into current chopping mode. Adversely, if the calculated torque is lower than the demanded value, the number of winding turns should be decreased. Achieving the required torque value, if the current density fails to be equal to its desired value, the cross section area of copper wire should be suitably changed. Figure 3 shows the variations of current density versus cross section area of copper wire for mentioned SRM at constant total torque of 30 Nm in single pulse mode of control. At a given total torque, the current density decreases with increasing the cross section area of copper wire. Therefore, in flowchart of Figure 2, if the current density is lower than its desired value, the cross section area of copper wire should be increased and if the current density is greater than its desired value, vice versa.

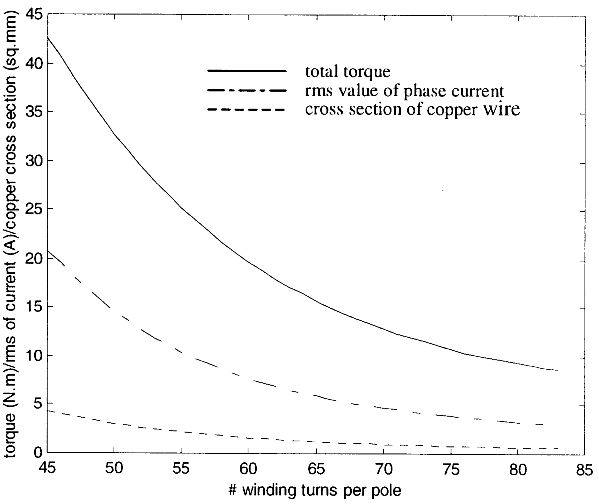

Fig. 1. Total torque, rms value of phase current, cross section area of copper wire vs. number of winding turns per pole at constant current density in single pulse mode of control.

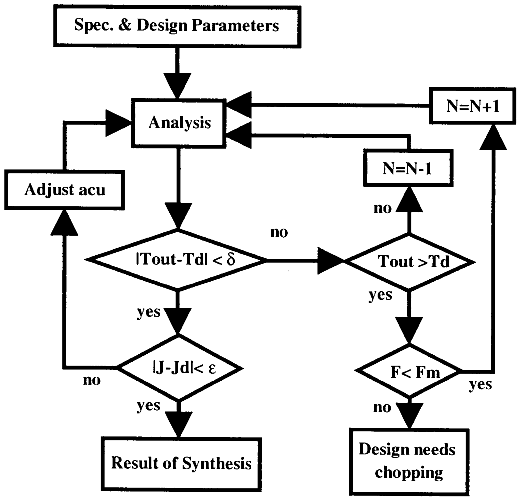

Fig. 2. Flowchart of SRM synthesis in single pulse mode of control.

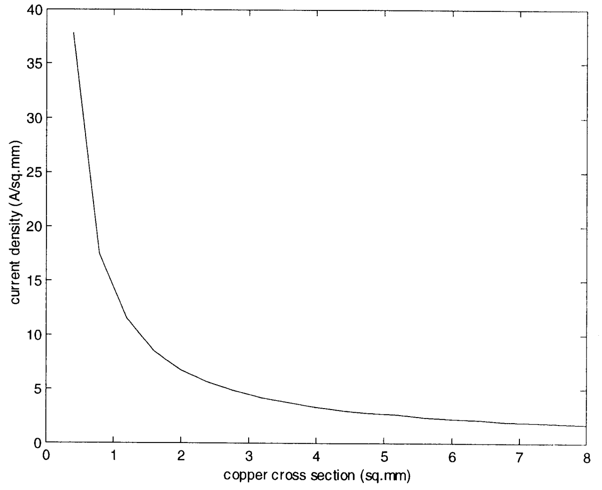

Fig. 3. Current density vs. cross section area of copper wire at constant total torque in single pulse mode of control.

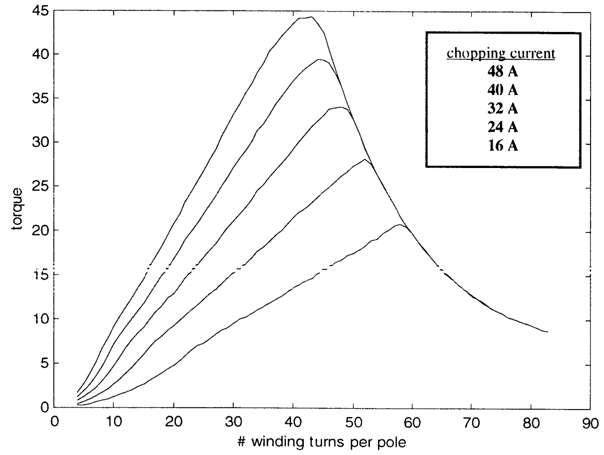

Fig. 4. Total torque vs. number of winding turns per pole at constant current density in current PWM mode of control.

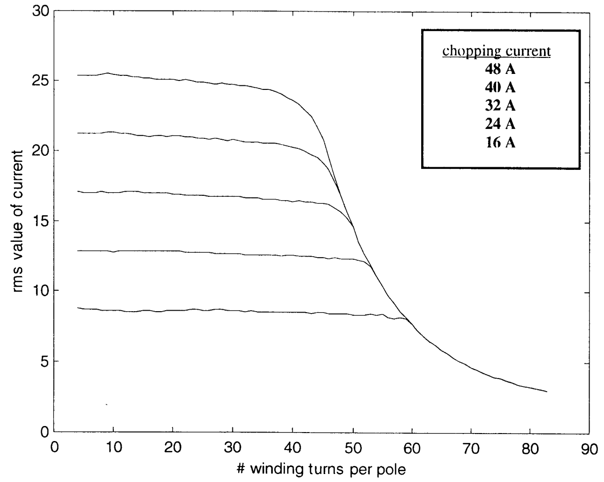

Fig. 5. The rms value of phase current vs. number of winding turns per pole at constant current density in current PWM mode of control.

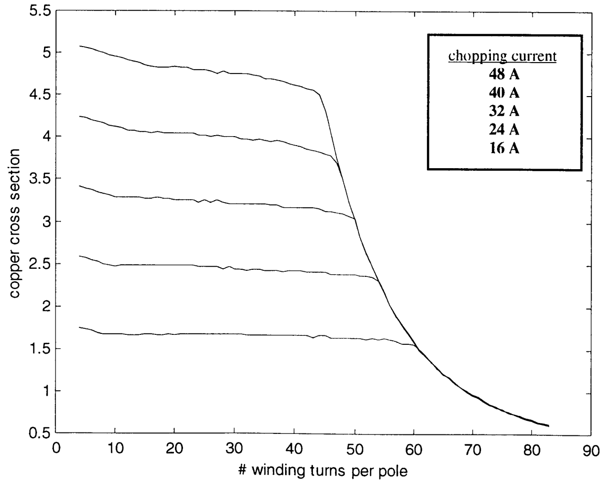

Fig. 6. Cross section area of copper wire vs. number of winding turns per pole at constant current density in current PWM mode of control.

B. SRM synthesis in current PWM (chopping) mode of control

Figures 4 to 6 respectively show the variations of total output torque, rms value of phase current and cross section area of copper wire versus number of winding turns per pole for the mentioned 8/6 SRM at constant current density of 5 A/mm^2 in current PWM mode of control. As a result, the increase of the number of phase winding turns yields the increase of output torque, because the decreasing parts of these curves again belong to single pulse mode of control. Also, the higher current chopping level increases motor capability to produce higher output torque. The flowchart of SRM synthesis in current PWM mode of control is shown in Figure 7. Since the optimization algorithm will consider SRM synthesis in current PWM mode of control after its synthesis in single pulse mode of control, some useful points have been used in this flowchart. In order to attain a specified output torque with an arbitrary current chopping level capable to produce the required torque for the constant value of current density, only two values of number of winding turns can be obtained ,as Figure 4. One of these values involves in single pulse mode of control which is already obtained by the corresponding synthesis in that mode. This value is maximum number of winding turns per pole meeting the required torque for the specified constant current density at selected current level. So, SRM synthesis in current PWM mode of control should search for less value of number of winding turns at same current chopping level. In other words, this synthesis should look for the value of current chopping level which produce the required torque for each value of number of winding turns less than this maximum. For this purpose, the gradual decrease of number of winding turns will be done in optimization algorithm and the synthesis just looks for the value of the current chopping level which produces the required torque. Before the SRM synthesis starts, the initial value of current chopping level is set to maximum value of phase current obtained from SRM synthesis in single pulse mode of control. If the single pulse mode of control is not capable to produce required torque, SP will be set to 1. In this case, since the value of the computed torque is greater than the required value, the current chopping level should be initially decreased to meet the required torque at the maximum possible number of winding turns limited by slot space. Then, SP is changed to 0 and search goes on for less values of number of winding turns. This is shown in Figure 7. If SRM synthesis can produce the required torque (SP = 0), the current chopping level will be varied in the direction as resulted from Figure 4. After meeting the required torque, the cross section area of copper wire should be adjusted to conduct the specified current density. The trend of the variation of current density versus cross section area of copper wire in current PWM mode of control is same as that of single pulse mode of control as Figure 3.

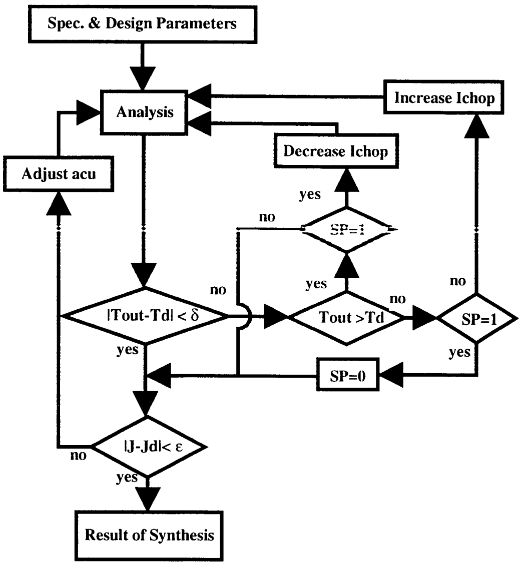

Fig. 7. Flowchart of SRM synthesis in current PWM mode of control

III. DESIGN OPTIMIZATION ALGORITHM

The flowchart of SRM design optimization algorithm is shown in Figure 8. The motor specifications and constant design parameters are the input of algorithm. The optimal routin used in the algorithm for independent design variables is univariate method [9]. Here, the asterisk sign means optimal value. In the loop on θ_{on} and θ_{off} , after the SRM synthesis in single pulse mode of control and determination of SP, if the torque ripple is lower than its demanded limit, the efficiency will be stored as optimal value. Otherwise, the optimal value is set to zero. In addition, the maximum value of phase current is selected as initial value of current chopping level. Then, the number of winding turns per pole decreases as a loop in order to obtain optimal value of current chopping level in chopping mode of control. The SRM synthesis in current PWM mode of control searches for this current chopping level producing the required torque at each value of number of winding turns per pole. If three successive iterations result in no change in optimal value, this loop will be terminated. This optimal value yields the SRM design with maximum efficiency of motor-drive and limited torque ripple.

IV. EXAMPLE OF OPTIMAL DESIGN

The optimization algorithm has been applied to design of a 4000 W, 1500 rpm, 8/6 SRM. The analysis and prediction of the electromagnetic characteristics of every design throughout the optimization algorithm has been done by using a magnetic equivalent circuit [10]. For a torque ripple less than 8%, optimal efficiency has been obtained 93.2%.

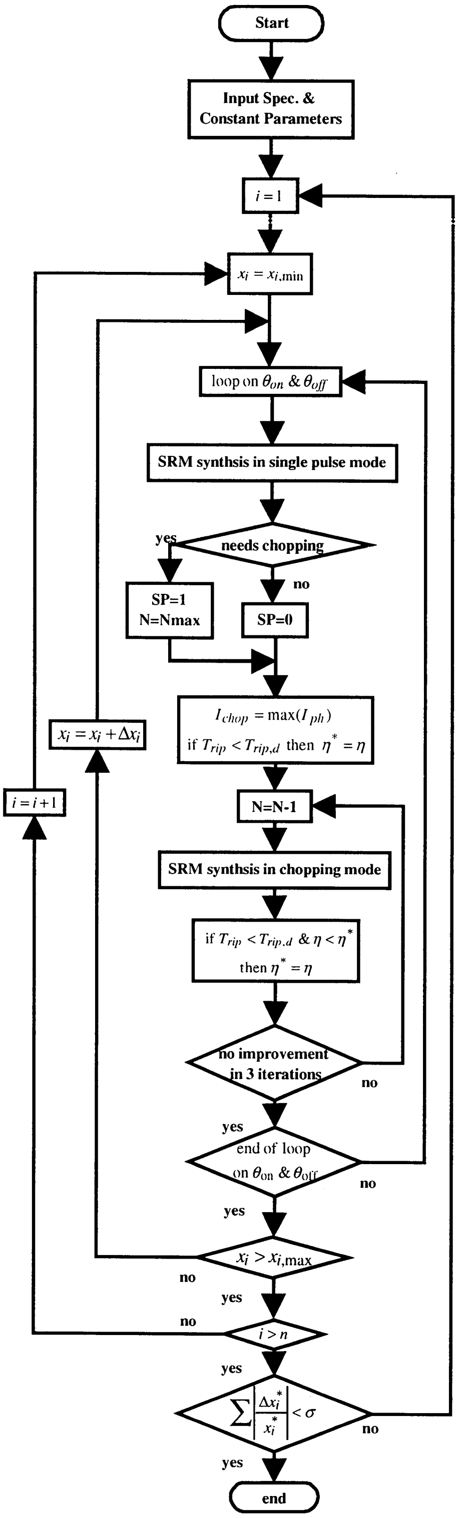

Fig. 8. Flowchart of the SRM design optimization algorithm

Figure 9 shows the predicted total torque of the designed SRM in terms of p.u. based on the nominal torque of the machine. The optimal design has been obtained in single pulse mode of control. But if the torque ripple is considered more limited, optimum design will occur in current PWM mode of control, sacrificing the efficiency.

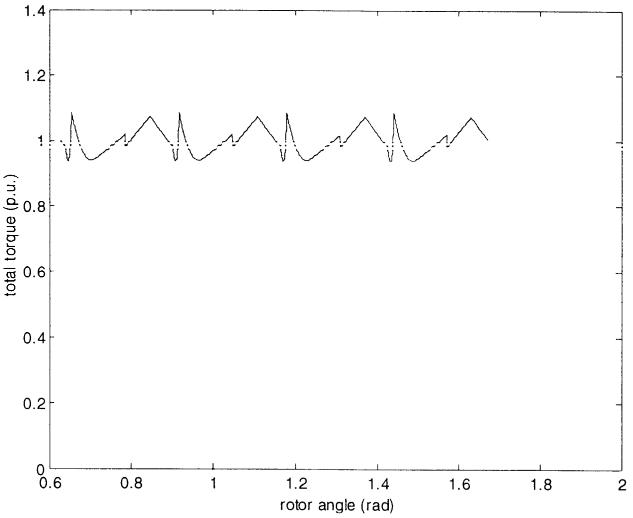

Fig. 9. Total torque of the optimal designed SRM based upon the presented design optimization algorithm

IV. CONCLUSION

The design of SRM is fundamentally coupled to associated converter configuration and applied mode of control. The paper has presented a systematic SRM design optimization algorithm based upon the current PWM mode of control and the configuration of a mostly used half-bridge converter, considering total efficiency of motor-drive as objective function constrained by torque ripple limitation. But the methodology can be applied to other modes of control and other converter configurations. The design procedure includes the synthesis of SRM in single pulse mode of control as well as the synthesis in current PWM mode of control. The total-torque/winding–number/chopping-current curves at constant current density and current density/cross section area of copper wire curve at constant total torque, obtained from the finite element analysis of constructed SRMs, have been best employed to found the basis of the synthesis procedures and design optimization algorithm. The presented design optimization algorithm has been applied to a 4000 W, 1500 rpm, 8/6 SRM. The resulting optimal efficiency is 93.2% for a limited torque ripple of 8%. Although the obtained optimal design for this example is in single pulse mode of control, a more limited torque ripple shifts the optimal design to current PWM mode of control, sacrificing the efficiency.

V. REFERENCES

[1] M. Barnes, C. Pollock, "Power electronic converters for switched reluctance drives", *IEEE Trans. on Power Electronics,* vol. 13, No. 6, Nov. 1998, pp.1100-1111.

[2] P.J. Lawrenson, J.M. Stephenson, P.T. Blenkinsop, J. Corda, N.N. Fulton, "Variable-speed switched reluctance motors", *IEE Proceedings Pt. B,* vol. 127, No. 4, July 1980, pp. 253-265.

[3] T.J.E. Miller, Switched reluctance motors and their control, Oxford, Magna Physics Publishing and Clarendon Press, 1993.

[4] J. Faiz, J.W. Finch, "Aspects of design optimization for switched reluctance motors", *IEEE Trans. on Energy Conversion,* vol. 8, No. 4, Dec. 1993, pp.704-713.

[5] A.V. Radun, "Design considerations for the switched reluctance motor", *IEEE Trans. on Industry Applications,* vol. 31, No. 5, Sept./Oct. 1995, pp. 1079-1087.

[6] Y. Ohdachi, Y. Kawase, Y. Miura, Y. Hayashi, "Optimum design of switched reluctance motors using dynamic finite element analysis", *IEEE Trans. on Magnetics,* vol. 33, No. 2, March 1997, pp. 2033-2036.

[7] M. Nurdin, M. Poloujadoff, A. Faure, "Synthesis of squirrel cage motors: a key optimization", *IEEE Trans. on Energy Conversion,* vol. 6, No. 2, 1991, pp. 327-333.

[8] R. Krishnan, R. Arumugam, J. Lindsay, "Design procedure for switched reluctance motors", *IEEE Trans. on Industry Applications,* vol. 24, No. 3, May/June 1988, pp. 456-461.

[9] R.L. Fox, Optimization methods for engineering design, Addison-Wesley, 1971.

[10] M. Moallem, G.E. Dawson, "An improved magnetic equivalent circuit method for predicting the characteristics of highly saturated electromagnetic devices", *IEEE Trans. on Magnetics,* vol. 34, No. 5, Sept. 1998, pp. 3632-3635.