A Novel Switched Reluctance Motor Drive with Optical Graphical Programming Technology

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***Abstract*—Due to magnetic nonlinearities, switched reluctance motor (SRM) drive control is complicated and normally requires a microprocessor or a digital signal processor. This paper presents a simple and reliable SRM drive using an innovative encoder based on optical graphical programming technology. There is no microprocessor in the drive, no A/D or D/A circuitry, with a drive system that matches the simplicity of the motor construction. It features a simple and effective control capability. Current waveform optimization for the encoder is carried out offline, for high efficiency, and programmed directly into the encoder. Experimental results validate the concept.**

***Index Terms*—Current waveform optimization, encoder, switched reluctance motor.**

I. INTRODUCTION

THE switched reluctance motor (SRM) has advantages of simple and robust structure, high thermal capability, and high speed potential [1]–[3]. Commercial products based on SRMs are making their way into the market place. The operational principles of the SRM are straightforward, but the proper control of the SRM is complicated.

A conventional control method is given in [4], where an encoder is used for position measurement and a microprocessor used to implement the control algorithms. At low speed, current chopping is used to adjust the current level and, hence, to control the torque. At high speed, angle control is used so that a desired current level can be obtained. An optimal angle control is quite complicated since the motor has highly nonlinear characteristics depending on both the rotor position and phase current. The angle control can be used to optimize efficiency or reduce output torque ripple. Similar approaches to [4] are given in [5] and [6].

To achieve high efficiency, the turn-on and turn-off angles can be calculated offline for different speeds and different loads. These variables are stored in the computer memory. The CPU decides on the correct angles based on the operational condition. For high-grade control, such as high efficiency and/or low torque ripple control, current shaping is necessary. The optimum current waveforms for high efficiency and/or smooth torque at different speeds and different loads are precalculated and stored in memory [7], [8]. Another way to achieve high-grade control is to calculate the optimal current online [9], [10]. This requires complicated algorithms and high computational power. In recent years, new control theories have been applied to SRM drives, such as neural networks, fuzzy logic, self-tuning control, etc. However, the complicated algorithms needed and hardware requirements undermine the simple, low-cost, and robust [11], [12]characteristics of the SRM drives in comparison to other motor drives.

This paper presents a simple and reliable SRM drive using an innovative encoder. The new encoder uses optical graphical programming technology. Instead of multiple control parameters like turn-on angle, turn-off angle, current-chopping level, or current-shaping waveforms embedded in a microprocessor, this drive has only an encoder and the power electronics stage. There is no microprocessor in the drive, no A/D or D/A circuitry, with a drive system that matches the simplicity of the motor construction.

II. ROTOR POSITION SENSOR

Rotor position information is essential in SRM drives. The position information may be attained from sensors or detection algorithms. Research is continuing on position-detection algorithms, while commercial products still use sensors for position detection and commutation. Two types of position sensors are generally used for SRM drives: the optical encoder and the Hall-effect sensor. There are two types of optical encoders that are generally used: the absolute encoder and the incremental encoder. An absolute encoder can provide absolute position information which is necessary for an SRM drive, and its resolution can be very high. A 12-b absolute encoder can provide a resolution of 0.088 mechanical degrees. The drawback is that the absolute encoder is expensive. An incremental encoder is less expensive, and the resolution can be very high. The disadvantage is that it does not provide absolute position information. If an incremental encoder is used in an SRM drive, some other measures must be taken to determine the absolute position information. A Hall-effect sensor with an interrupting-type disk is a low-cost way to measure position, but it is difficult to achieve high resolution, which is important in an SRM drive.

Some serious efforts have been made to eliminate the position sensor in the SRM drives, but this has not yet been commercialized. The optical encoder, either absolute or incremental, outputs digital signals, which makes it problematic for many domestic and commercial applications. In addition, usually, their size and attachment are cumbersome, costly, and error prone. In this paper, a new optical encoder is used for the SRM drive. It is

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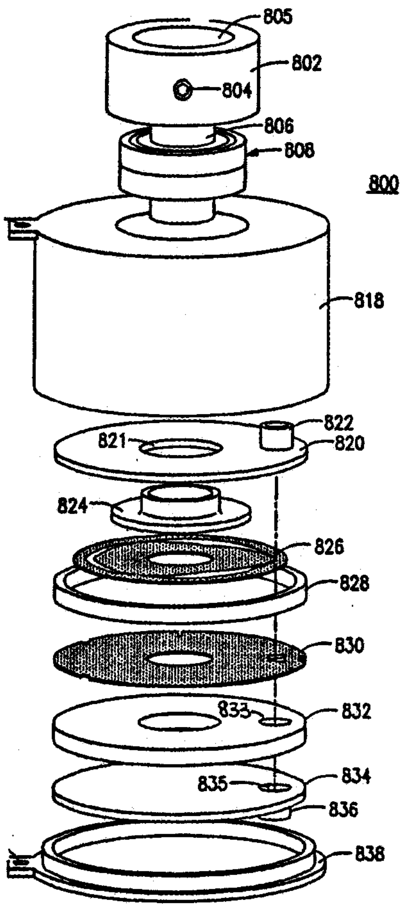

Fig. 1. Structure of the new encoder.

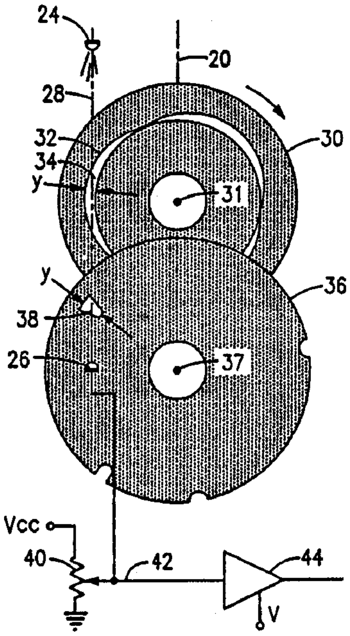

Fig. 2. Operation principle of the encoder.

fabricated based on the patented "Optical Programming Technology." It is compact and has a low-cost method of attachment. It outputs analog signals with prewritten desired waveforms. The structure is shown in Fig. 1.

As seen in Fig. 1, parts 805, 802, 804, 806, and 808 are hollow-end shaft assemblies. 818 is the housing for the encoder. 822 is the light-source housing. 824 and 826 are the moving disc assembly. A precalculated waveform has been written into disk 826. Parts 828, 830, and 832 constitute the fixed mask assembly. A preselected shape slot is on 830. The light detector is on 836. 838 is the end cover for the encoder.

The principle of operation is shown in Fig. 2. Part 24 is the light source and part 26 is the light detector. Parts 40 and 44 are the accessory electronics to amplify the signal. The light source, light detector, and the accessory electronics are all fixed to the encoder housing. Part 30 is the moving disk which rotates with the shaft. A precalculated waveform is written onto the disk. Part 36 is the fixed mask (static to the housing). Slot 38 in the fixed mask lets light go through. Differently shaped slots can be chosen to obtain desired waveforms. As the moving disk rotates with the shaft, the desired waveform is produced on the output of the amplifier. The conventional optical encoder has simple lines or blocks in the moving disc and slotted fixed mask, so it outputs a digital signal, i.e., either "1" or "0." The new encoder has precalculated waveforms in both the moving disk and the mask, so the output signal is an analog signal instead of a digital signal, but, more importantly, any desired waveform vector or algorithm can be generated as the shaft rotates. For different applications, different waveforms can be written into the encoder to obtain the desired output. The resolution of the waveform can be very high (greater than 12 b), and its design and construction make it much smaller and lower in cost than standard optical encoders.

In Section III, a procedure for calculating the desired waveform for the SRM drive is presented, and in Section IV, the principles of the new drive are described.

III. SRM CURRENT WAVEFORM OPTIMIZATION

Normally, there are two objectives for current waveform optimization in SRM drives: high efficiency and smooth torque. In applications like fans and pumps, efficiency is of a higher concern and the torque ripple is less important (as long as it can start). In this paper, the application is for a fan for heating, ventilating, and air conditioning (HVAC) systems. The optimization is based on minimizing the I^2R loss for a required average torque. Since there is a current limit for both the inverter and the motor, there is a maximum current constraint in this optimization. The motor used in this paper is a 1/2-hp three-phase 12/8 SRM, with a maximum current of 14 A. The optimization is carried out at the rated speed and rated torque which are 1800 r/min and 2 N·m, respectively. The measured torque and flux linkage are shown in Fig. 3.

Since the flux linkage and torque are nonlinear functions of both rotor position and phase current, it is not possible to find a closed-form expression for the optimal current waveform. A numerical method has to be used. For each phase, a period is 45 mechanical degrees. The current is represented with 1° resolution, as $i(0), i(1), \ldots i(44)$, i.e., 45 discrete points. It is assumed

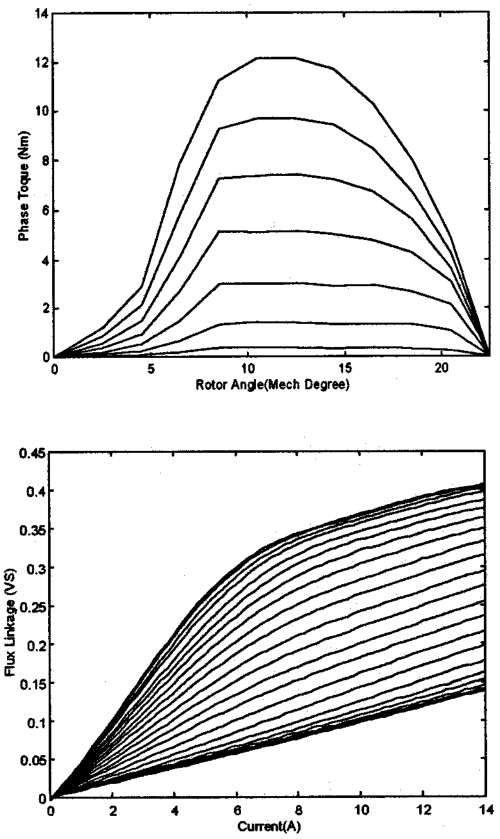

Fig. 3. Measured torque and flux linkage of the test motor.

that the phases are symmetrical, so only one phase current is optimized here.

To optimize the current for 2 N·m average torque, the numerical representation is minimize $f = \sum_{k=0}^{44} i^2(k)$ with the constraints of

$$0 \leq i(k) \leq 14 \tag{1}$$

$$\frac{\sum_{k=0}^{44} T(k)}{45} * 3 = 2 \tag{2}$$

$$\left| \frac{d\psi}{dt} + i * R \right| \leq 160 \tag{3}$$

where $k = 0, 1, 2, \ldots, 44$, and 160 is the dc-bus voltage.

Equation (1) is the maximum current limit, (2) requires the average torque to be 2 N·m, and (3) constrains the required voltage to be within the supply voltage. The flux-linkage and torque data were measured directly for even-spaced angles and currents, and stored in tables. Two–dimensional (2-D) interpolation is used to obtain flux linkage and torques at arbitrary intermediate points from the lookup table.

The optimization result for the current is shown in Fig. 4. The positive torque production region is 0–22.5 mechanical degrees, with the highest torque/ampere region in the middle. The optimized current waveform takes full use of the high torque/ampere region. Due to the high EMF at rated speed and the limited dc-bus voltage, the rising edge of the current cannot be very steep and from 7° to 16° the current is dropping, even with full dc-bus voltage applied. After 16°, the current waveform is a turn-off transient. The current tail in the negative torque region is cut off for higher efficiency at low speed. At rated speed, the current will go into the negative torque region, but it is still the optimized value due to the limited voltage. As the speed reduces, the current tail in the negative torque region gets shorter, so we will see higher efficiency.

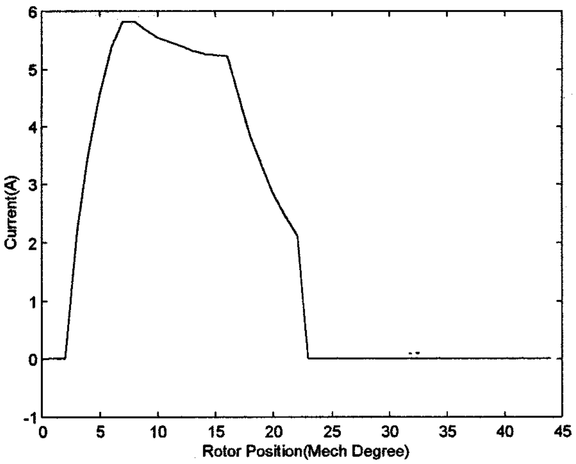

Fig. 4. Optimized waveform for the encoder.

IV. The New SRM Drive

With this encoder and the optimization theory, the new SRM drive is shown in Fig. 5. The main idea in this drive is that the "intelligence" of the drive is embedded directly into the encoder which is directly driven by the motor and is responsible for creating the reference waveform for the power electronics and tracking the position. The torque command is the scaling factor of the current reference waveform. The encoder for this drive has three output channels, one for each phase. Each channel outputs a voltage signal as shown in Fig. 4. There are 8 electrical cycles per revolution for each channel and there is a 15° phase shift between phases, for the 12/8 SRM. As seen in Fig. 5, the encoder outputs are multiplied by T^* which is the torque command. Then, the actual waveform signals from the encoder are used as references for the current controller. Current sensors are used to close the current control loop. T^* is the scaling factor for the current reference, so it controls the magnitude of the stator currents and, hence, the output torque directly.

V. Experimental Results

The encoder with the optimized waveform was fabricated using the optical programming technology; the new drive built using standard electronics components and the test platform with a dc dynamometer as the load was set up. The system is shown in Fig. 6. The motor is in the middle of the picture with the encoder on the right-side shaft. The power electronics are to the right of the encoder. The coupling and the dynamometer are to the left.

The experimental results are given in Fig. 7 for the steady-state results. Increasing the magnitude of the torque command increases the current reference and, hence, the actual current. The operating speed is where the generated torque equals the

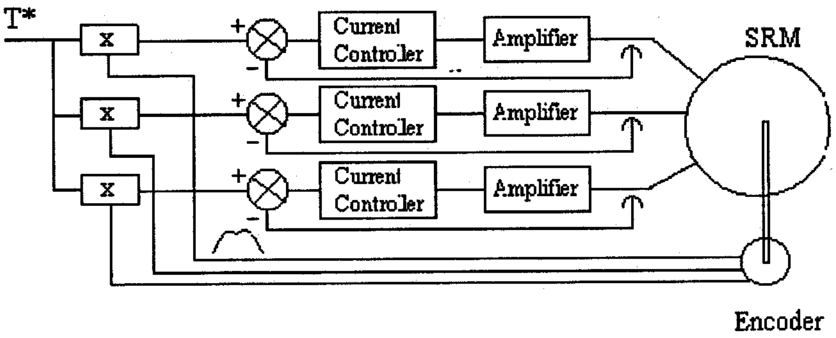

Fig. 5. Block diagram for the new SRM drive.

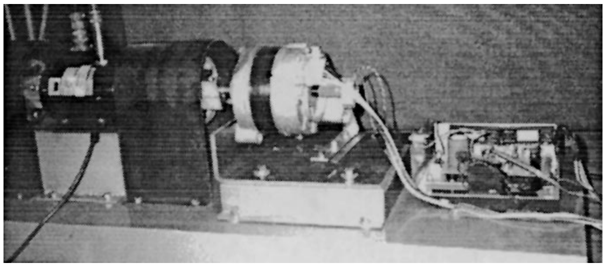

Fig. 6. SRM drive test system.

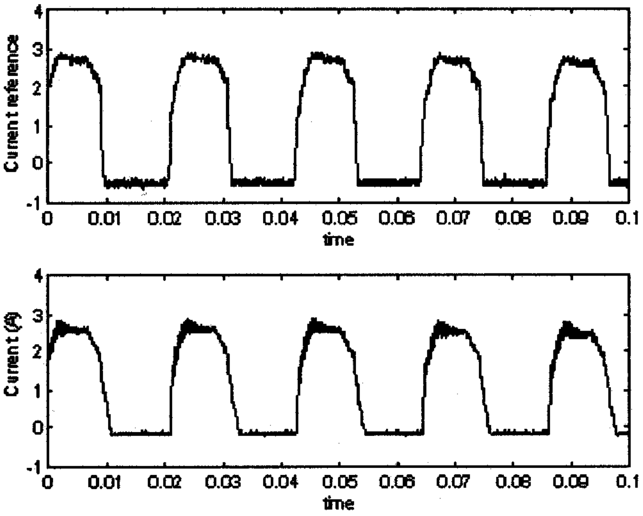

Fig. 7. Experimental results.

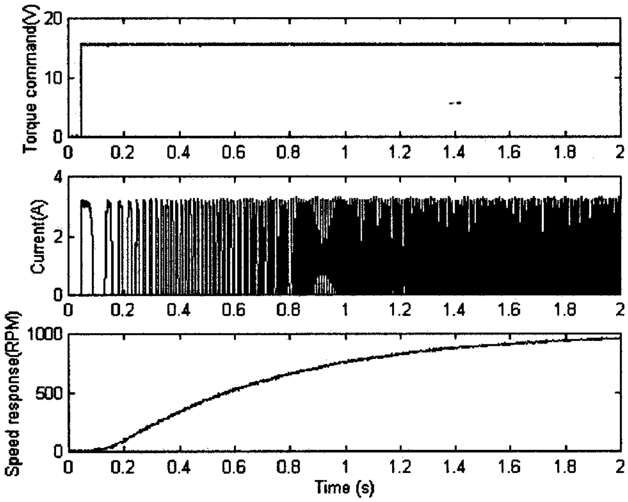

Fig. 8. Dynamic response of the SRM drive.

load torque. There are no complicated algorithms or intensive computation needed for online control. The current reference waveform (top trace) and the motor current (bottom trace) for one phase are shown in Fig. 7. The reference voltage is zero when the phase is off in Fig. 4. Three current controllers and loops allow individual phase current control (i.e., one main and two followers or any combination). However, it is also possible to use this encoder technology in a less expensive open current loop drive, under voltage control. Also, the encoder waveforms do not have to be the same. Each could be modulated in shape and size as a function of the poles, phases, nonlinear loads, torque ripple, etc. The dynamic response of the SRM drive of a step torque command is shown in Fig. 8. The torque command, a phase current, and the measured speed are shown in the figure. The speed reaches the steady state after about 2 s, because of the high inertia represented by the dynamometer.

It can be seen from the operating principles of this drive, a simple drive structure is achieved at the expense of losing the flexibility as in the microprocessor-based drive. Only one waveform can be programmed into the encoder, which is optimized at the rated condition. At a different load and operating speed, the optimized waveform is different. The output torque and the current command do not have a ideal linear relationship. For the microprocessor-controlled drive, the turn-on angle can be advanced for higher speed operation, while in this drive the turn-on angle cannot be controlled so a steeper torque drop will be seen after the rated speed. In general, analog current control is more susceptible to noise than is digital current control in a microprocessor-based drive. Therefore, a more careful layout of the circuit board is needed in this drive.

VI. CONCLUSIONS

A new SRM drive using a patented optical graphical programming technology has been presented in this paper. It features a simple and effective control capability without the use of a microprocessor and associated hardware. Current waveform optimization for the encoder is carried out offline for high efficiency at rated condition and programmed directly into the encoder. Experimental results validate the concept.

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