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Driven to Excel

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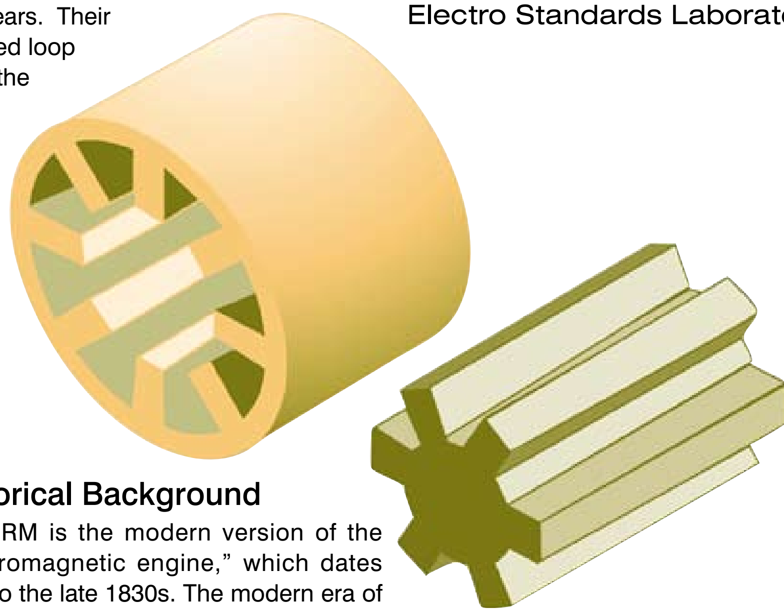
Switched reluctance motors (SRMs) have attracted considerable attention in industry over the past few years. Their unique capabilities (e.g., robustness, ease to closed loop control, low–cost manufacturing, etc.) are among the determining factors for this renewed interest.

Today, SRM drives are among the main players for important automotive applications (e.g., electrically assisted power steering, integrated starter alternators, and pumps). You'll observe the same trend in other sectors of industry (for example, home appliances, aerospace, and heavy–duty mining equipment). The ongoing worldwide research and devel-opment on various aspects of SRM drives has resulted in substantial advancements.

We've developed a variety of innovative solutions for this emerging technology. These include advanced magnetic design and novel configurations, self–tuning and adaptive control to enhance efficiency, specific control solutions to mitigate torque pulsation and radial vibration, and position sensorless control over the entire speed range. What follows is an attempt to underline SRM technology's capabilities and to introduce related applications–ready technical solutions.

SRM drives are relatively new entrants in the rapidly developing variable speed drives (VSDs) market. They are inherently VSDs featuring simple construction, a wide speed range, good energy efficiency, and high ratios of torque to inertia and torque to power density. The SRM's simple structure will likely make it less expensive than other VSDs in mass production. It flexibly operates as a four–quadrant drive, independently controlling both speed and torque over wide ranges. This in turn eliminates the need for expensive and troublesome mechanical gears and transmissions.



1 A 3–D view of an 8/6 SRM.

Historical Background

The SRM is the modern version of the "electromagnetic engine," which dates back to the late 1830s. The modern era of SRM development began in 1972 with Bedford's patents.[1, 2] SRMs received considerable attention following exemplary work at the Universities of Leeds and Nottingham in the 1980s. This spurred a series of global research activities, especially in Europe and in the U.S., resulting in several publications, patents, and applications. However, despite almost 30 years of research into the SRM (perhaps among the simplest of all machines), some critical issues need further study.

Switched reluctance motor drives provide new solutions to high–performance, adjustable–speed applications.

[1]Bedford, "Compatible permanent magnet or reluctance brushless motors and controlled switch circuits," U.S. Patent No. 3,678,352, July 1972.

[2] Bedford, "Compatible brushless reluctance motors and controlled switch circuits," U.S. Patent No. 3,679,953, July 1972

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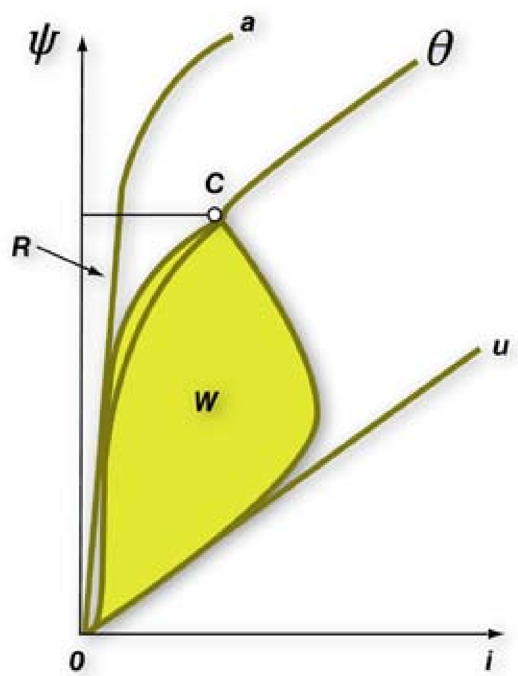
Basics of Operation

Figure 1 (p.1) shows a four–phase SRM with eight stator and six rotor magnetic poles. This SRM consists of a doubly salient structure, singly excited motor in which the rotor carries no magnetic source. Electromagnetic torque results from continuously changing magnetic reluctance. Each stator phase is excited sequentially with pulses of active current while in the positive inductance slope region to provide motoring operation. Hence, stator phase excitation must be properly positioned with respect to rotor location.

An SRM's electromagnetic torque develops via the magnetic circuit's tendency to settle in the minimum reluctance configuration. This can be expressed analytically as:

$$T(i,\theta) = \frac{\partial}{\partial\theta}\int_0^i \psi(i,\theta)di \qquad (1)$$



2 Electromechanical energy conversion in an SRM drive.

REGION	PHASE VOLTAGE EQUATION
Region I	$V = Ri + (L^* + i\frac{dL^*}{di})\frac{di}{dt}$
Region II	$V = Ri + (L(\theta) + i\frac{dL}{di})\frac{di}{dt}$
Region III	$V = (R + \omega\frac{dL}{d\theta})i + (L(\theta) + i\frac{dL}{di})\frac{di}{dt}$
Region IV	$V = (R + \omega\frac{dL}{d\theta})i + L(\theta)\frac{di}{dt}$
Region V	$V = \omega\frac{dL}{d\theta}i + L(\theta)\frac{di}{dt} + \sum M_j\frac{di_j}{dt}$

Table 1 The dynamic behavior of SRM drives varies across operational regions.

where T, i, ψ and θ stand for electromagnetic torque, phase current, flux linkage, and rotor position, respectively.

Figure 2 graphically interprets electromechanical energy conversion in an SRM drive. The shaded area, W, shows electromagnetic energy converted into mechanical form. By tuning the current trajectory, we can optimize the drive's torque generation capability. This in turn illustrates the impact of machine design and control strategies on drive performance. Thus, obtaining an optimal solution requires considering the coupled nature of machine design and control strategy.

Remember that, ideally, each SRM phase can be considered as a decoupled magnetic circuit with dynamics given by the phase differential equation:

$$V = ri + \frac{\partial\psi}{\partial\theta}\omega + \frac{\partial\psi}{\partial i}\frac{di}{dt} \qquad (2)$$

in which V, r, and ω denote phase voltage, stator phase resistance, and angular speed, respectively. It's also important to recall that flux linkage is described as:

$$\psi(i,\theta) = L(i,\theta)i \qquad (3)$$

where $L(i,\theta)$ represents the stator phase winding's gross self–inductance. The differential equation governing an SRM drive's phase winding dynamic is:

$$V = (R + \omega\frac{\partial L}{\partial\theta})i + (L(\theta) + i\frac{\partial L}{\partial i})\frac{di}{dt}$$

or equivalently:

$$V = R_{eq}i + L_{eq}\frac{di}{dt} \qquad (4)$$

$$R < R_{eq} < R + \omega\frac{L_{\max} - L_{\min}}{\min(\alpha_s,\alpha_r)}$$

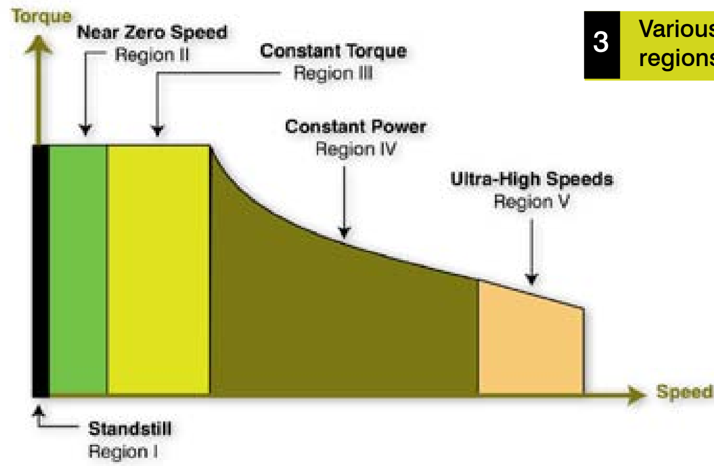
$$L_{\min} < L_{eq} < L_{\max}$$

where V, R, i, L, ω, α_s, α_r, and θ denote phase voltage, winding resistance, phase inductance, angular speed, stator arc, rotor arc, and rotor position, respectively, and mutual inductance effects are neglected. Due to spatial distribution of the magnetic field and saturation effects, this equation's coefficients represent a time–variant, nonlinear function. This in turn contributes to the systems' complexity. Furthermore, the electrical frequency of excitation for consecutive SRM phases is:

$$f_e = \frac{\omega[rad/\sec]N_sN_r}{2\pi(N_s - N_r)} \qquad (5)$$

where N_r and N_s signify the respective number of rotor and stator poles. This shows that the available time for computation in control reduces as speed increases. Table 1 summarizes an SRM drive's dynamic behavior in various operating regions (Figure 3).

SRM dynamics undergo a significant behavioral change as drive speed increases. This stems from 1) the minor role of motional back–EMF at very low speed, 2) unsaturated operation, along with the significant contribution of mutual inductances, at very high speed,and 3) the nonlinear effects of saturation in the constant torque region (Region III). This can be interpreted as a highly dynamic system with a variable structure that in turn affects the SRM's operational characteristics.



3 Various operational regions in an SRM.

Design and Development of SRM Drives

The machine design process involves finding suitable machine dimension variables to satisfy a set of performance requirements, taking into account minimization of cost, weight, etc. The SR machine's simple structure disguises the complex nature of its required design proce-dure. The inherent nonlinear nature of both the SRM and its converter circuits makes this procedure difficult. Basic design parameters include the number of rotor poles, number of phases, pole arc to pole pitch ratio, and winding connections, among others. Factors such as switching –frequency, core losses, and flux dis-tribution also play an important role in SRM drive design. In addition, due to the control strategies' inherent dependency on the machine's magnetic design, we need an integrated design and control simulation tool.

To achieve this, we've developed user–friendly programs in a Mathlab environment that take the design specification (in terms of geometry constraints, supply characteristics, and required dynamic performance) and generate optimal machine geometry. This approach combines the results obtained from a modified magnetic equivalent circuit method with a dynamic simulator, in which various converter topologies and control strategies can be programmed. This allows us to perform a timely and efficient optimization while accessing the SRM drive's detailed performance.

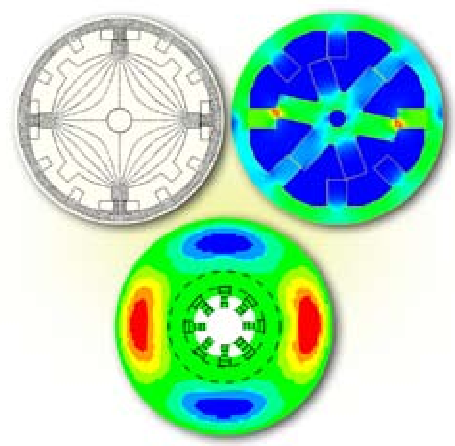
We also incorporate finite element techniques to compute the final candidate's precise magnetic, structural, and acoustic performance. This lets us perform fine adjustments on the design, thereby improving both its compactness and quietness while providing more room for developing efficient control strategies. Figure 4 shows some sample results obtained from finite element analysis of magnetic and acoustic fields in an SRM drive.

After finalizing the designs of the motor, power electronics converter, and supporting electronics, we'll need to examine the prototype's performance in the context of a specific application. In the past, we've designed, manufactured, and engineered final motor drive solutions for a number of applications. The development's application–specific stage demands considerable expertise on various drive system aspects. Creating smart control solutions is a significant part of that.

This is important: Optimize the drive within the context of its application. Optimizing performance in isolation won't suffice when the drive is later integrated into a specific product. Thus, it's vital to both engineer and integrate the best solution the appli-cation demands.

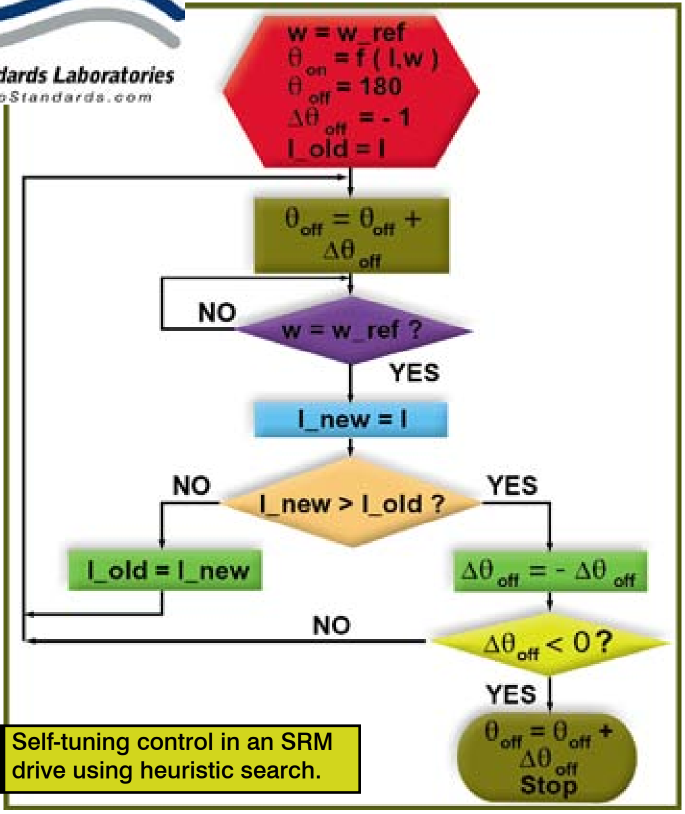
Self-tuning Control

Manufacturing imperfections can alter an SRM's characteristics significantly. This can result in performance deterioration of mass–produced volumes. Moreover, aging effects can intensify this problem greatly. Squeezing maximum performance from a motor with relaxed manufacturing tolerances means employing advanced adaptive and robust control methodologies. For SRMs, closed–loop control is simple enough that we can use it effectively to implement such control schemes.

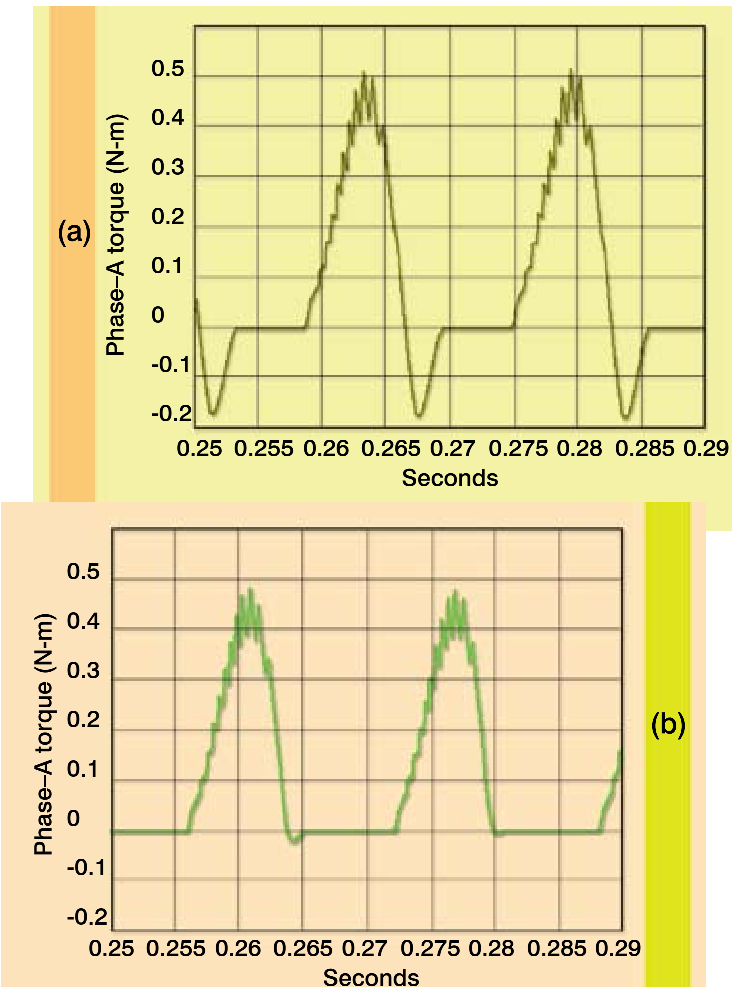


4 Distribution of magnetic and acoustic fields in an SRM drive.

Therefore, to enhance SRM drives' reliability and cost, we've developed advanced control technologies that can optimize performance under parameter variations. Consequently, we get a robust control scheme that compensates for imperfections (e.g., eccentricity, partial motor phase failure, etc.), thus reducing labor expenses with almost no extra hardware. A flow chart (Figure 5, p.4) explains the online self–tuning control algorithm we apply to optimize the torque / ampere of SRM drives.



5 Self-tuning control in an SRM drive using heuristic search.



6 An SRM drive's torque productivty (a) improves after self-tuning (b).

To illustrate the technology's effectiveness, Figure 6 shows the results for electromagnetic torque generated by an individual SRM phase both before and after tuning. You'll note that adjusting the commutation instants removed a significant portion of negative torque. This translates into low–cost manufacturing, superior compactness, and less vulnerability to aging effects.

Sensorless Operation

Rotor position sensing is integral to SRM control because of the nature of torque production. A shaft position sensor is usually employed to determine the rotor position. However, these discrete devices not only add complexity and cost to the system but also tend to reduce the drive system's reliability. Also, there are certain applications, such as compressors, where the ambient conditions don't allow using external position sensors. So it makes perfect commercial—as well as engineering—sense to equip SRM drives with position sensorless technologies.

Figure 7 summarizes available sensorless technologies for SRM drives. Ideally, it's desirable to have a sensorless scheme. Such setups use only terminal measurements, don't require additional hardware or memory, and operate reliably over the entire speed / torque range with high resolution and accuracy. Recent advances in developing low–cost, digital signal processor–based microcontrollers have paved the way for fulfilling this objective.

These techniques arise from the fact that an SRM drive's mechanical time constant is much larger than its electrical time constant. Moreover, due to its salient structure, the SRM's magnetic status is a function of its rotor position. Therefore, we can recover the encoded position information that's stored in the form of flux linkage, inductance, back–EMF, etc., by solving the voltage equation in either an active or idle phase. The following phase voltage equation incorporates those terms, which contain position information.

$$v_j = Ri_j + \frac{d}{dt}\sum_{k=1}^{m}\psi_{kj}$$

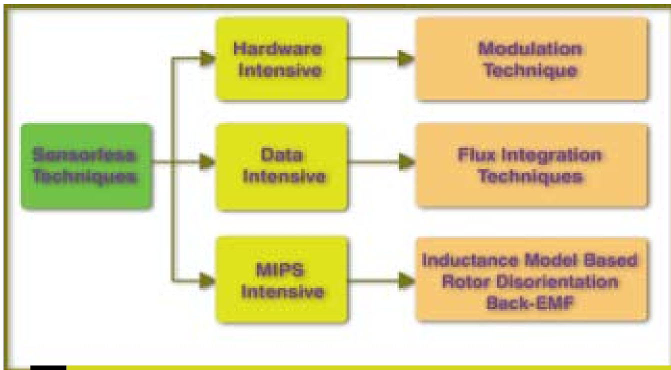
$$v_j = Ri_j + \frac{d}{dt}\sum_{k=1}^{m} L_{kj}(i_k,\theta)\, i_k \qquad (6)$$

$$v_j = Ri_j + \sum_{k=1}^{m}\left\{ i_k \frac{\partial L_{kj}}{\partial i_k}\frac{di_k}{dt} + L_{kj}\frac{di_k}{dt} + i_k\frac{\partial L_{kj}}{\partial \theta}\,\omega \right\}$$

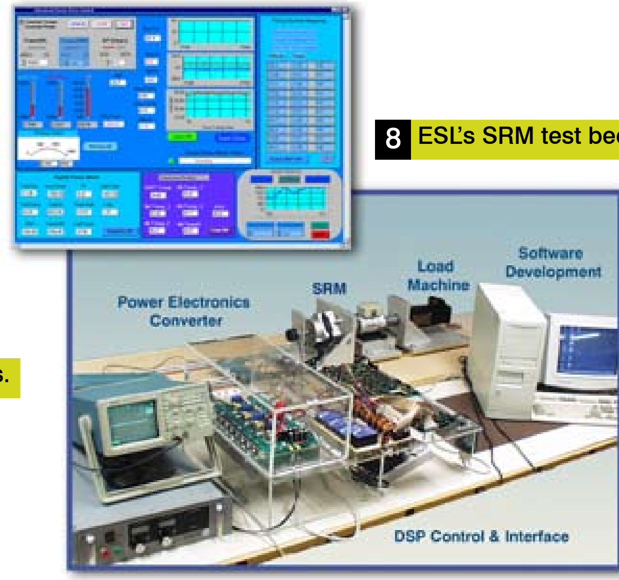
Embedded Position

where, ψ_{kj} and L_{kj} stand for flux linkage and inductance caused by the k^{th} phase in phase *j*, respectively.

We've created an experimental test bed (Figure 8) to develop sensorless position methods. We use a four–phase (8 / 6) SRM drive rated at 2.1 kW / 48 volts for this investigation. We control



7 Categorizing existing sensorless technologies in SRM drives.

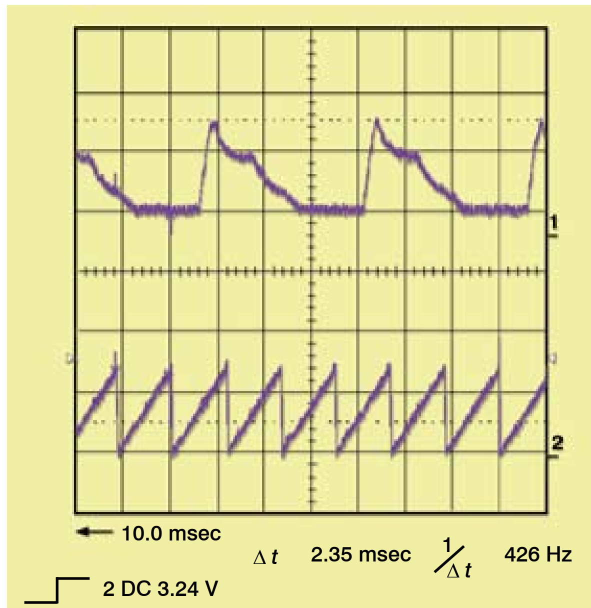


8 ESL's SRM test bed.

the motor with a two–switch–per–phase converter with paralleled MosFet switches. This machine is loaded by a progammable brushless DC drive over its entire speed range (0–6,000 rpm). In addition, we use an in–line torque–meter device with appropriate characteristics for measurement purposes. Finally, we use a TMS320F240 processor for drive control.

Figure 9 depicts the experimental results we obtained from this approach at 4,260 rpm. Notably, this sensorless technique operates precisely over the entire speed range starting from standstill. This method can be easily adapted to another machine over a wide range of speed and torque. Lack of any extra hardware or memory makes this technology a superior can-didate in terms of cost, size, and reliability.

Switched reluctance motor drives are vivid examples of replacing complex machine geometries with smart control strategies. Recent advances in developing high–speed microcontrollers and high–frequency semiconductor switches have brought renewed attention to this emerging technology. Different sectors of indus-try are considering SRM drives as viable candi-dates for important applications. Unique attributes of SRM drives (e.g., super high–speed operation, reliability, and robustness) qualifies them for demanding applications such as the aerospace and automotive industries. More than 20 years of research and development in adjustable–speed SRM drives has resulted in advanced technologies such as sensorless control and self–tuning. These mature technologies are ready for application over a wide range of speed and torque.



9 Experimental current waveform along with internally generated position at 4,260 rpm.

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