Cost-Effective, High-Performing Motors without Neodymium Magnets - Part II

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In Part I we explored various motor technologies used today for industrial and traction motor design. Here in Part II we will explore another motor option: reluctance motors.

Although invented in the 1800s, the variable switched reluctance (VSR or SR) motor was re-discovered in the 1990s when the electronic power switches, FETs, IGBTs, became readily available on a commercial basis. In recent years the VSR has once again attracted a lot of attention as a cost-effective alternative to the permanent magnet (PM) motor.

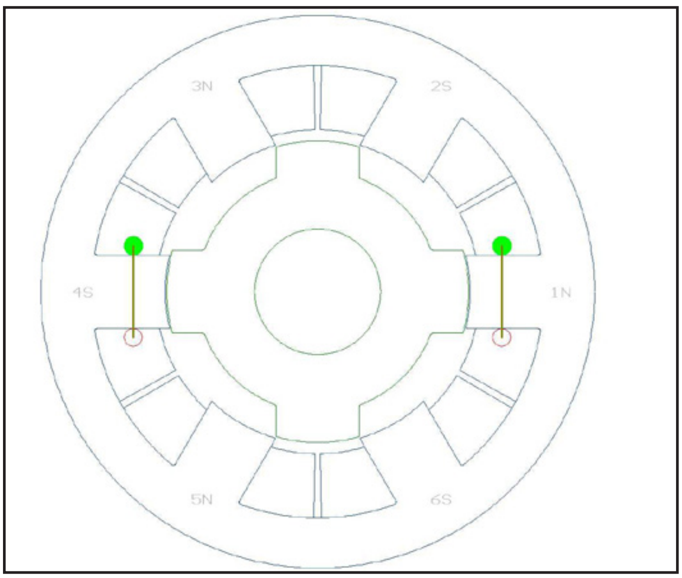

Figure 1 Basic lamination design of a VSR motor.

In Figure 1 we show the basic diagram of the VSR lamination. Other key parts of the VSR motor are shown in Figure 2. Finally, a picture of a production VSR motor is shown (Fig. 3).

The VSR has a number of rotor and stator teeth where the number of rotor teeth n_r is typically ±2 of the number of stator teeth n_s, and n_s is an integer multiple of 2 times the number of phases n_p. The VSR is characterized by its ratio of rotor-to-stator teeth and common ratios are 6:4 and 12:8 for a 3-phase motor and 8:6 for a 4-phase motor.

Unlike most other brushless motors, the coils are wound concentrically around a single stator tooth (Fig. 2) which reduces the end-turn length, copper weight and copper losses. It also reduces the cost to manufacture the VSR motor due to its simple winding patterns.

The VSR motor can be very efficient; for example, a 5 KW VSR motor can reach up to 95% efficiency. And a larger VSR motor can have even higher efficiency. The VSR delivers constant torque — from starting torque up to a "base" speed — and the constant power above up to 3× the base speed without a significant loss in efficiency. The speed/torque curve of a typical VSR motor is shown (Fig. 4).

An added advantage of the VSR is that it can be largely controlled by properly turning the phases "ON" and "OFF" at the correct times when running at a constant speed, and no additional current control will be required; this increases the drive efficiency and can reduce the controller cost.

Figure 2 Key components of the VSR motor.

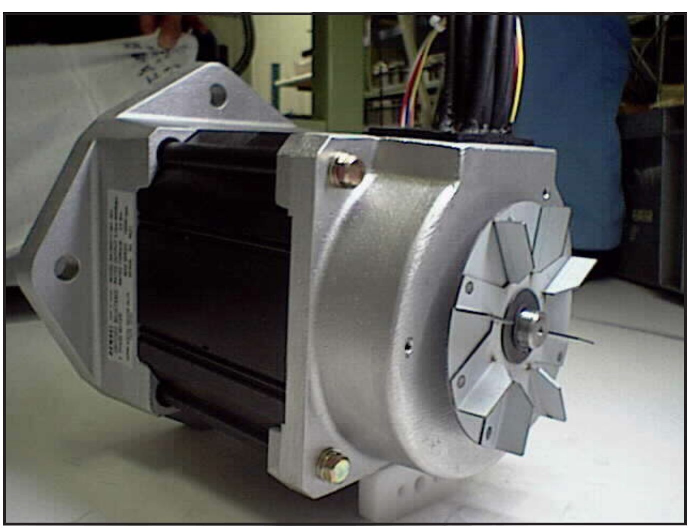

Figure 3 Full VSR motor.

The main drawback of the VSR motor is that each of its phases must be controlled independently — which requires two motor leads to be brought out from the motor to the controller for each phase — and the controller requires additional components, compared to a permanent magnet (PM) brushless motor (BL). In Figure 5 we show the flux pattern of a typical VSR lamination.

The VSR motor design requires high flux concentrations in the lamination steel for efficient operation and VSR motors typically operate at 1.8T–2.2T flux density, which is higher than those of similar PM BL motors. Due to the high flux densities in the steel, it is very important to minimize the back-iron and tooth width, which can result in a mechanically "weaker" lamination compared to that of a similar-sized PM or induction motor.

Also, the airgap of the VSR is small, i.e. 10–20 mils — which presents mechanical challenges — and it results in strong, radial magnetic forces acting on the rotor. These forces, coupled with the thin outer lamination ring, result in acoustical noise that is generated in the VSR motor; so they can be noisy unless additional design measures are taken.

An additional concern typically associated with VSR motors is the torque ripple, as shown in Figure 6.

The VSR motor is commonly considered "noisy," but many successful designs exist where the motor runs very quietly, i.e. — the Neptune washer VSR motor made by Emerson. We have also compared noise levels of a PM traction motor versus a properly designed VSR motor and found the noise measurements in the passenger compartment to be within ±3dB from each other, with neither motor being clearly quieter.

However, there is a second type of reluctance motor which, until recently, did not gain much attention, — the synchronous reluctance motor (SYR) — and it has only recently generated serious interest.

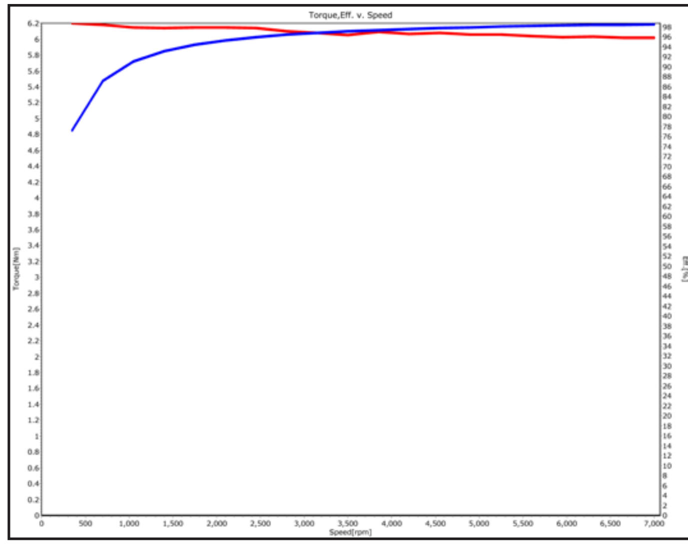

Figure 4 Speed/torque curve of a VSR motor.

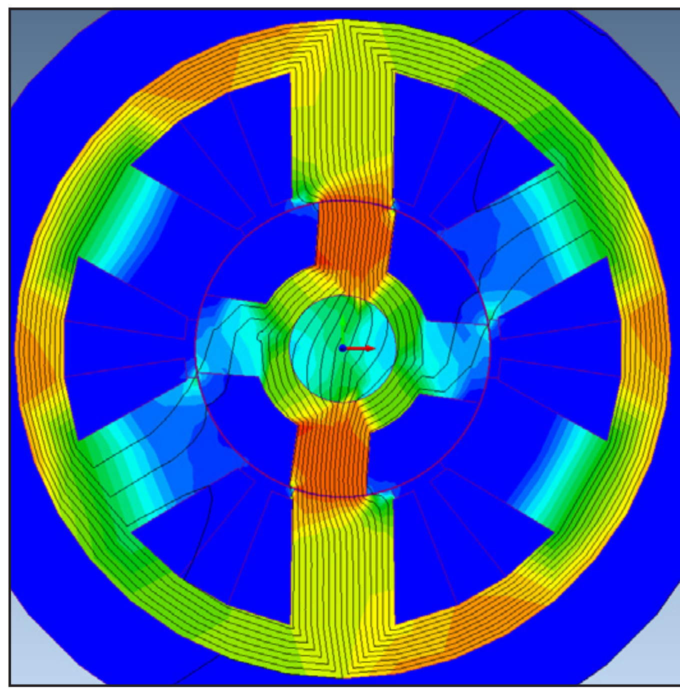

Figure 5 Flux distribution of a typical VSR motor.

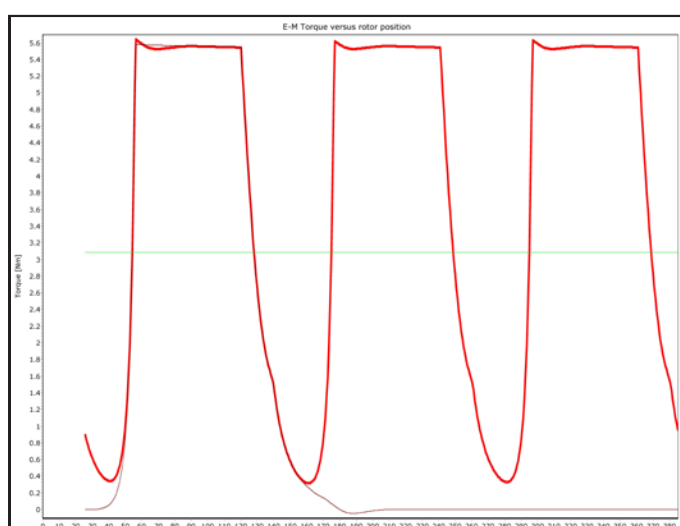

Figure 6 Torque ripple of the VSR motor.

Figure 7 shows the lamination design of a synchronous reluctance motor and Figure 8 shows the flux distribution in the SYR lamination; and in Figure 9 is a photo of a SYR motor.

In Figure 10 we show the speed/torque curve of a SYR motor.

The SYR delivers constant torque from stall (0 RPM) up to a "base" speed, and the constant power above the base speed. The SYR can be operated in this constant power region up to 3× the base speed without a significant loss in efficiency. Furthermore, the SYR can achieve very high operating efficiencies at high speed and we are designing a 3" diameter SYR motor with a 1.5" stack that can operate at 10 KW at 36,000 rpm, while maintaining above 93% motor operating efficiency.

The SYR has a distributed winding, just like the PM BL motor and the AC induction (ACI) motors, e.g. — the ABB SYR in Europe uses an existing AC stator and simply added a reluctance rotor. This ABB motor has become a very successful SYR motor product line, but most SYRs today are custom-designed specifically as SYR motors — especially in the U.S — which yield smaller and more efficient SYR motors.

The SYR can be manufactured with the same winding equipment and facilities as existing brushless and induction motors. No magnets need to be glued and/or retained, which further simplifies SYR manufacturing and results in cost savings.

Like the PM brushless and the ACI, the SYR requires one motor lead per phase and, with minor software changes, it can run with the same controller hardware as the PM brushless motor.

Because the stator backiron is generally thicker than that of the VSR motor, the SYR runs quieter. Testing on some motor comparisons has shown that the SYR has a noise signature that is comparable to that of a PM BL motor in specific applications.

The operating efficiencies of the SYR motor are slightly

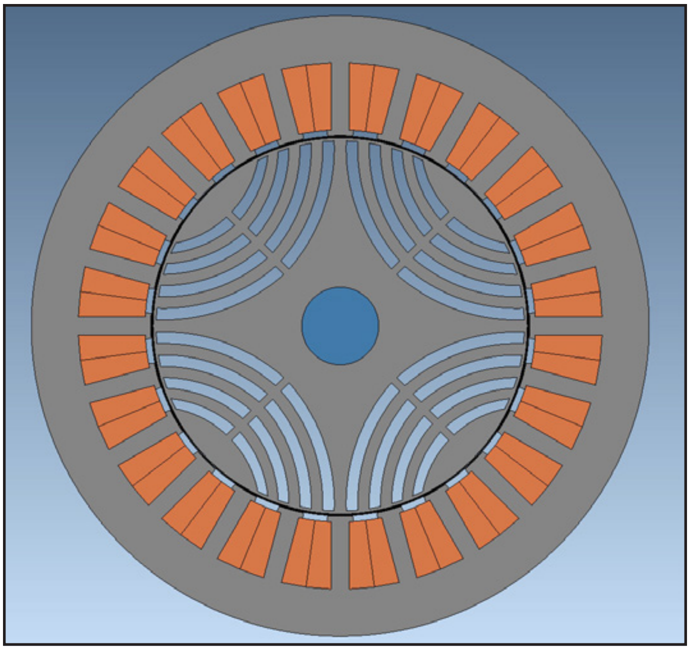

Figure 7 Lamination of the SYR motor.

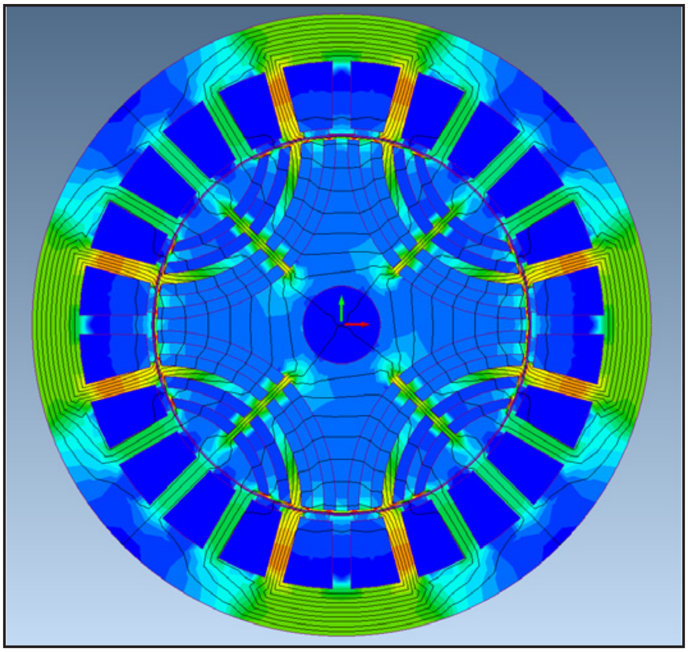

Figure 8 Flux distribution of typical SYR motor.

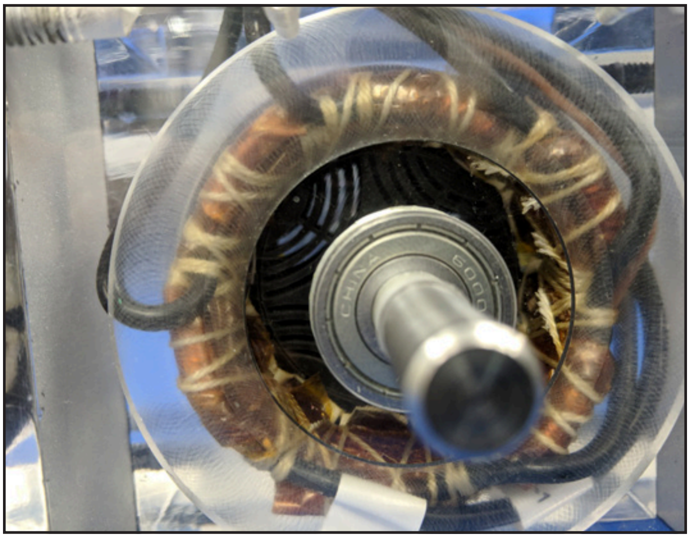

Figure 9 Synchronous reluctance test motor.

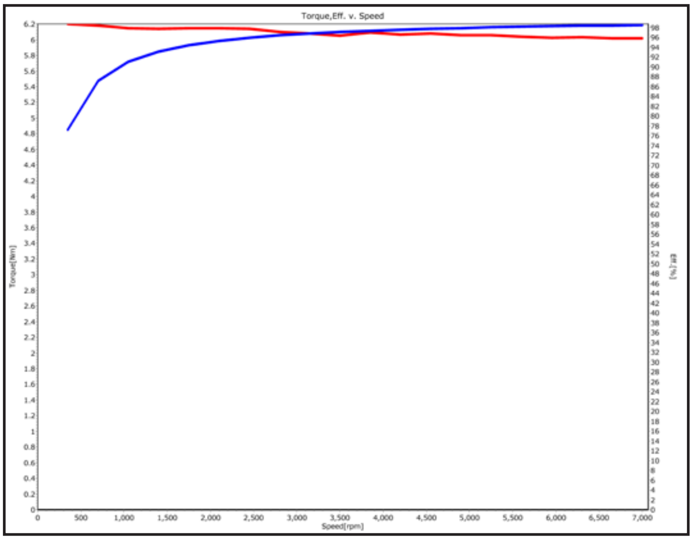

Figure 10 Speed torque of SYR motor.

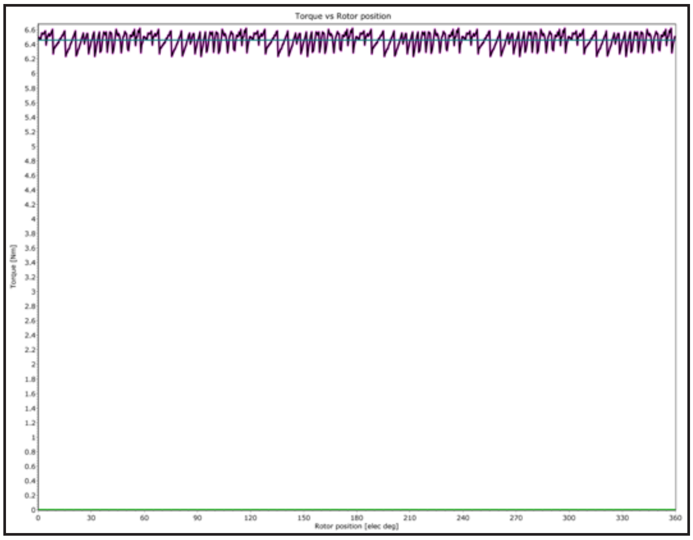

Figure 11 The torque ripple of a SYR motor.

less than those of a high-performance neodymium PM BL, but that is offset by a lower manufacturing cost compared to the brushless motor and a significantly lower controller cost compared to the VSR.

The SYR also has an almost constant torque. A typical torque ripple curve is shown in Figure 11; it shows only a small variation of the motor's torque as a function of its position.

Also, while the SYR will have its highest operating efficiencies when excited with sinusoidal waveforms (AC), the SYR will also perform very efficiently when energized with trapezoidal waveforms — just like the brushless DC motor. This allows for low-cost Hall sensors to be used for feedback. Both the VSR and SYR can be operated sensor-less, using proprietary sensorless controls for positioning and speed control of SYR motors without loss in performance for high-temperature automotive and military applications.

Also, since the SYR motor has no magnets, there is no risk of demagnetization during overload conditions and the motor can easily operate in higher ambient temperature environments — a key feature for some advanced automotive, downhole drilling and military applications.

In Table 1 we show a comparison of material weights: one

Table 1 Comparison of material weights.

	PM brushless	VSR	SYR
Laminations (lb)	0.48	0.53	0.42
Copper (lb)	0.22	0.28	0.16
Magnet (lb)			
Magnet Assembly	2.75	0.00	0.00
Shaft	1.50	1.50	1.50
Bearings	2.00	2.00	2.00
Endbells			
Housing			
Assembly			
Lamination $/lb	2.00	3.00	3.00
Copper $/lb	10.00	10.00	10.00
Magnet $/lb	5.60		
Total Cost	9.41	7.88	6.35

component in the cost comparison used when deciding which motor to use.

This comparison clearly favors the SYR in this specific example and, if the controller cost were taken into account, the SYR and the PM brushless will be the prime candidates.

Potential customers have been quite receptive, and working designs are under development to replace offshore PM BL motors with SYRs that can be cost-effectively produced domestically.

Next time you need a low-cost, high-performance motor, you should look beyond the PM BL motors and consider the reluctance motors — specifically the SYR — as an alternative to a lower-cost motor drive system. **PTE**

For more information.

Questions or comments regarding this paper? Contact the author at Rocky Mountain Technologies at 406-225-7120 or *info@RockyMountainTechnologies.com*.

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