Hybrid-Secondary Uncluttered (HSU) Induction Machine

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Abstract

A new hybrid-secondary uncluttered (HSU) induction machine is introduced. The hybrid secondary includes the effective-resistance, inverter, and magnetic switch options. The rotor current is magnetically coupled to the stator through an uncluttered rotating transformer. This machine can be used as a cost-effective slip-energy-controlled adjustable-speed induction motor that operates below synchronism and the wide-speed-range motor drives and generators that operate below and above the synchronous speed of the line frequency.

I. INTRODUCTION

An induction machine is normally viewed from its physical nature as a transformer with its stator as the primary and the rotor as secondary. This paper discusses the technology associated with its secondary circuit. The slip-ring induction motor, whose secondary winding is connected through a set of slip rings and brushes, has been known for decades. By changing the resistance connected to the brushes, the starting current and the speed of the motor can be changed; however, maintenance of a motor with slip rings and brushes is costly.

It is generally agreed that the major energy saving for electric motor drives comes from adjustable speed drives. The high cost of adjustable speed drives fed by an adjustable-frequency inverter discourages many potential users. There are many other known adjustable speed methods. For instance, even with its drawbacks the brushless doubly-fed motor (BDFM) is a good example [1] for lowering the initial cost of speed control for adjustable-speed. Pursuing the concept of slip-ring induction machines, this paper introduces a new induction machine [2] that has a significant potential to lower the cost of adjustable-speed drives. In addition to speed control below synchronism, this new machine has the potential to operate above synchronism.

The required adjustable speed range and the load torque versus speed curve dictate the rating of the slip power controller of an induction motor. Fan and pump loads represent two thirds of motor drives in industry. For a fan load without or with a backpressure, the required fan power may be proportional to the cube or to the square of speed, respectively. Assuming unity efficiency and power factor, the per-unit slip power for these two examples may be roughly estimated as.

$$\left(per\ unit\ slip\ \ power\right) \approx slip \cdot (1 - slip)^{3\ or\ 2} \qquad (1)$$

Based on stator rotating field	Per unit slip power	
	W/o back pressure	With back pressure
$slip$	$slip(1-slip)^3$	$slip(1-slip)^2$
-0.2	-0.346	-0.288
-0.1	-0.133	-0.121
0	0	0
0.01	0.0097	0.0098
0.1	0.0729	0.081
0.3	0.1029	0.147
0.5	0.0625	0.125
0.7	0.0189	0.063
0.9	0.0009	0.009
1.0	0	0

Table 1 Example of per-unit slip powers of fan loads

Table 1 shows that the rating of the positive slip power of a fan load is generally low for speeds below synchronism. Subsequently, even with consideration of the non-unity of

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power factor and efficiency, the required rating of the control for speed adjustment is low. This enables the use of a very small power electronics module or small adjustable resistors to control a motor with a high power rating. These energy absorption approaches can be characterized as an effective resistance approach.

In order to control the rotor slip energy of an induction motor that has no slip rings, the rotor current must be coupled to a stationary control circuit through a rotating transformer.

A rotating transformer that couples to the rotor bar currents in a conventional rotor and stator arrangement can be seen from many existing articles and patents [3-7] with various improvements. A typical arrangement is shown in Fig. 1. The secondary circuit of an induction machine can be affected by adding an additional core that accommodates the extension of the rotor winding or bars. This additional core is coupled to an additional stator core that is magnetically uncoupled to the original stator core. The additional rotor and stator cores are magnetically coupled.

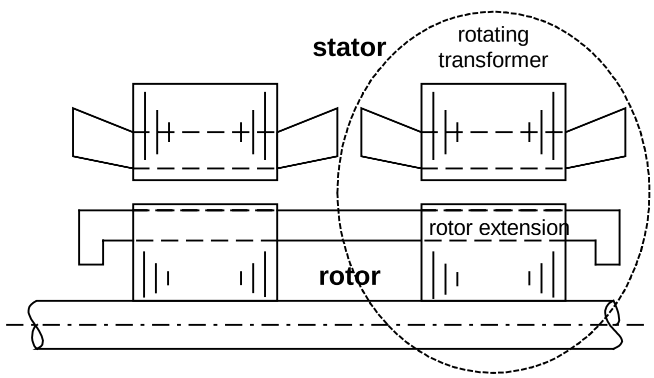

Fig. 1 Existing technology of cluttered coupling

A rotating transformer that transfers the rotor bar currents to stator through an additional rotor and stator arrangement as shown on the right in Fig. 1 is defined to be a *cluttered* coupling device. It is cluttered with two different energies associated with the rotor current frequency and the rotation, which are transformed together between the additional stator and rotor. The rotation energy is not wanted for the speed control, because it would produce a torque that weakens the shaft torque. Therefore, a critical requirement for the rotating transformer is that only the slip energy excluding the rotor rotation energy be transmitted to the stationary control circuit. A unique *uncluttered* coupling technology for power transfer is introduced in this paper.

II. PRINCIPLE OF HSU INDUCTION MACHINE

2.1 hybrid secondary:

The term *hybrid secondary* implies that several secondary circuits can be used in various combinations for different applications. The Hybrid Secondary Uncluttered (HSU) induction machine is associated with an effective variable resistance circuit, an inverter circuit for doubly fed operation, and a magnetic switch circuit. They will be discussed further.

2.2 Uncluttered Coupling:

Fig. 2 shows a peripherally wound stator coil that is magnetically coupled to a peripherally wound rotor coil. The latter one rotates and carries a slip-frequency current. Because the rotation does not change the total magnetic flux linking both the rotor and stator coils, no electromotive force (emf) is induced in the stator coil due to the rotation of the rotor coil. This *uncluttered* coupling allows only the slip energy power corresponding to the slip-frequency currents to be transferred between the rotor and stator coils.

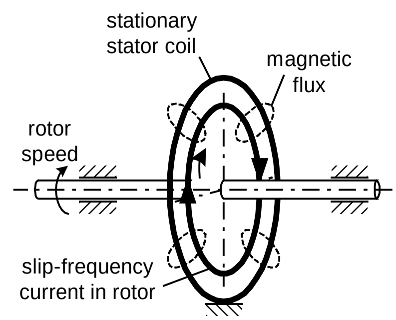

Fig. 2 Magnetic flux of an uncluttered coupling between stator and rotor coils

2.3 Example of an Uncluttered Coupling:

Fig. 3 shows an example of a two-phase uncluttered rotating transformer to transfer energy between the rotor and stator. Coils are wound peripherally in both the stator and rotor. Magnetically saturable cores, which will be explained in detail, are used.

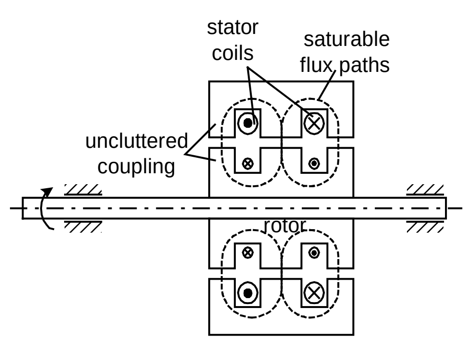

Fig. 3 Example of a 2-phase uncluttered coupling.

2.4 Variable Effective-Resistance Circuit:

The stator windings of the uncluttered rotating transformer can be connected to a variable resistance bank that absorbs the slip energy or to an energy recovery circuit that feeds the slip energy back to the power supply. Either approach is equivalent to connecting a variable resistance bank to the secondary circuit of the induction machine.

2.5 Inverter-Fed Circuit:

The capability of transferring energy that is not affected by the rotation of the transformer opens a door to feed the rotor with an inverter of adjustable frequency. The rotor speed and slip is defined according to the combination of both rotating fields generated by the rotor current and the stator current. The following relationship among angular velocities always holds true.

$$\omega_{rotor} + \omega_{rotor\ current} = \omega_{stator\ current} \quad , \qquad (2)$$

where

ω_{rotor} is the rotor angular velocity; $\omega_{rotor\ current}$ is a signed rotating field velocity generated by the rotor current (a positive sign means that the field rotates in the same direction as the rotor velocity); and $\omega_{stator\ current}$ is a signed rotating field generated by the stator current with the same sign convention.

2.6 Magnetic Switch Circuit:

When only the stator is fed and the rotor speed is approaching synchronism, the slip frequency is close to zero. At a low frequency the power-transfer capability of a rotating transformer is extremely low. In order to overcome this problem, a DC current can be introduced to the stator coils of the rotating transformer.

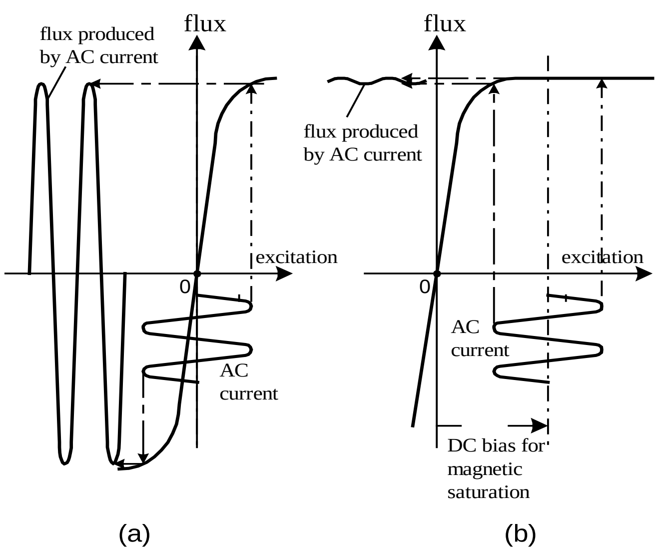

Fig. 4 Flux produced by AC current excitation. (a). without DC bias, (b) with DC bias.

Fig. 4 shows that a DC current can saturate the magnetic core of the rotating transformer. In Fig. 4a when there is no DC bias current, the flux produced by the rotor AC current in the core of the transformer is very high. Fig. 4b shows that with a DC bias current the alternating flux produced by the same AC current is negligible. Consequently, the rotor current sees small mutual and self inductances of the rotating transformer. This enables the induction motor to run as a conventional induction motor without a significant influence from the rotating transformer. Since the transformer has an uncluttered coupling, the DC flux produced by the DC bias current would not produce a braking torque. The power required to saturate the core is low, because the stator coils have low resistances and the DC voltage drop across the coils is very low. An example of a DC bias circuit is shown in Fig. 5.

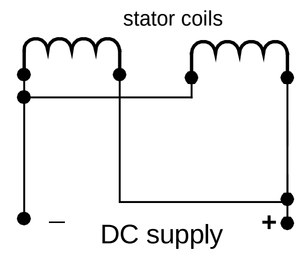

Fig. 5 Example of a DC bias circuit.

2.7 Equivalent Circuit:

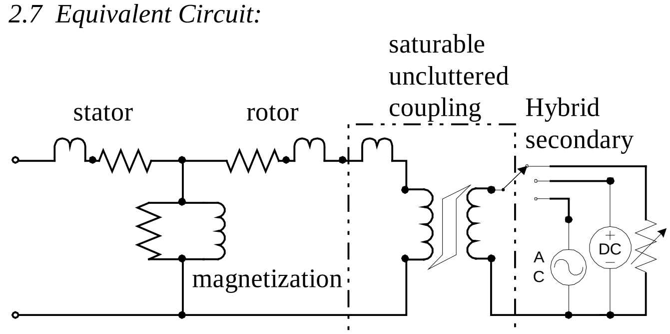

Fig. 6 Equivalent circuit of a HSU induction machine.

Fig. 6 shows the equivalent circuit of a slip-energy-controlled magnetically-switched adjustable-speed induction machine. The left-hand side of the circuit is a typical induction motor circuit with the stator, rotor, and magnetization impedances. A satuable uncluttered rotating transformer links the rotor current to the control circuit in the stator. It can be switched to a variable equivalent resistance that may convert the energy back to the system, or be switched to a DC power with a very low voltage that may saturate the core of the rotating transformer. The ratings of the variable equivalent resistance and the DC power are substantially lower than the rating of the motor at full load. Therefore, conversion of the slip energy that may otherwise be consumed in the variable resistance back to the power supply may not affect the package efficiency that much. The major energy saving comes from the lower power input to the motor at low speed.

III. PROTOTYPE FOR PROOF OF PRINCIPLE

3.1: Prototype:

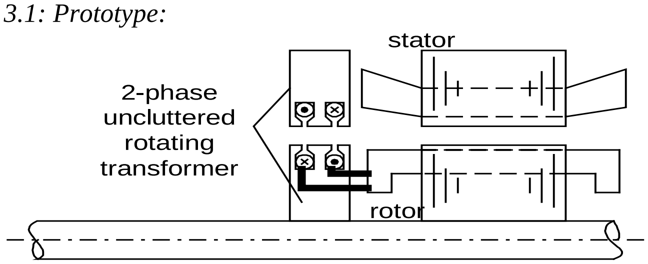

Fig. 7 Prototype of a 4-pole, HSU induction Machine.

Fig. 7 shows half of the side-view of a 4-pole, 10-hp prototype of a HSU induction machine. A stator core wound with a poly-phase winding is on the right-hand-side of the drawing. In this prototype the stator has a three-phase winding. A poly-phase (2-phase) rotor winding is in the rotor core. The number of phases can be different between the rotor and the stator. The reason to have a two-phase rotor winding is to have a two-phase uncluttered rotating transformer that is shown in the left-hand-side of the drawing. The rotor winding of the induction motor is connected to the rotor coils of the 2-phase uncluttered rotating transformer. The cores of the rotating transformer may be made of pressed powder [8]. However, the cost of the prototype was reduced by using slitted solid steel cores shown in the Appendix for the prototype stator and rotors of the rotating transformer to moderately reduce the core loss.

3.2 Photos of the Prototype HSU Induction Machine:

A stator photo of the prototype HSU induction machine is shown in Fig. 8. It clearly shows the peripheral arrangement of the uncluttered rotating transformer.

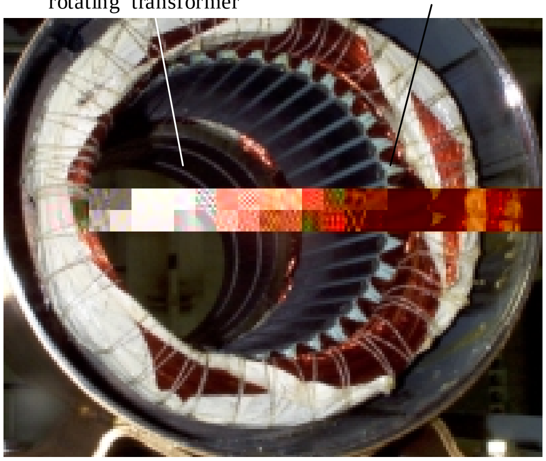

Fig. 8 Stators of an induction machine and an uncluttered rotating transformer of a HSU motor.

The peripheral arrangement of the uncluttered rotating transformer can also be seen in Fig. 9 from the rotor photo of the 10-hp HSU induction machine.

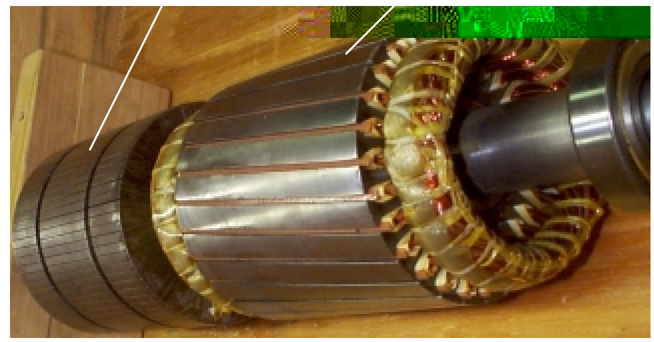

Fig. 9 Rotors of induction machine of a HSU motor.

3.3 *Test Results:*

Fig. 10 shows the prototype HSU induction machine mounted on a 10-hp blower for an actual load test.

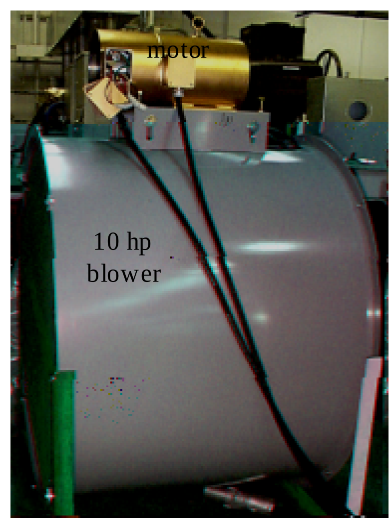

Fig. 10 Load test of a 10-hp HSU induction machine.

The slip energy coming from the uncluttered transformer is fed to a variable resistor through tapping. We will see that the slip energy is generally low. It is entirely possible to convert the slip energy back to the power system through a very small inverter. However, because the slip energy is small, it might not be practical to have an inverter. The slip energy is dissipated outside of the HSU motor to ensure that the motor runs cool. It is feasible to build a stepless variable resistor using power electronics devices with a low slip-energy power rating.

The control circuit for the prototype HSU motor is shown in Fig. 11. The circuit combines the resistors and the magnetic-switch circuits together for the speed control below the synchronous speed.

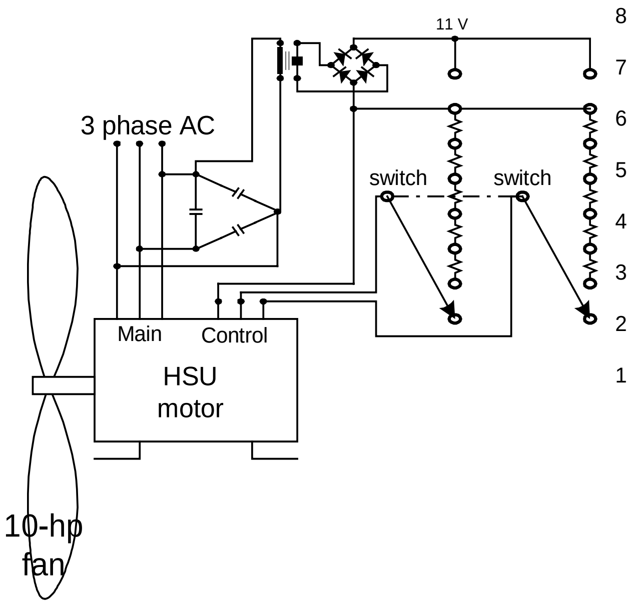

Fig. 11 Control circuit of a prototype HSU motor

Position	1	2	3	4	5	6	7	8
	Off	21 ohm	11 ohm	6 ohm	3 ohm	1 ohm	0 ohm	DC
Rpm	794	1160	1280	1387	1475	1569	1610	1703
Current [A]	7.0	9.3	10.5	11.7	13.1	14.3	15.7	15.6
Input KWatts	1.92	3.38	4.02	4.58	5.09	5.70	5.97	6.60
Power factor	0.61	0.81	0.85	0.87	0.86	0.89	0.84	0.93
Resistors loss [w]	0	404	446	418	320	139	0	0
DC power [w]	0	0	0	0	0	0	0	336
Phase 1 control [A]	0	3.1	4.5	5.9	7.3	8.5	9.3	12
Phase 2 control [A]	0	3.1	4.5	5.9	7.3	8.2	9.0	12

Table 2. 10-hp fan-load test data of a HSU motor at 260 V.

It is seen from Table 2 that the slip energy dissipated in the resistors is generally low. The low slip energy transferred indicates that there is no rotation energy transferred through the uncluttered rotating transformer. The DC power to control the magnetic switch is also low. The input KW at 1703 rpm is 6.6 KW. This indicates that the nominal 10-hp commercial fan at this speed consumes lower than 8.8 hp. The DC power to control the motor at high-speed is only 336 W. No sharp voltage spikes were observed when the slip energy was dissipated in the resistors.

The HSU induction machine was also tested at speeds above and below synchronous speed of the stator rotating field with the stator of the uncluttered rotating transformer fed by an adjustable-frequency inverter.

IV. CONCLUSIONS

- A hybrid-secondary uncluttered (HSU) induction machine is introduced.
- The hybrid secondary includes the options of effective-resistance, inverter, and magnetic switch.
- The rotor current is magnetically coupled to the stator through an uncluttered rotating transformer.
- The uncluttered coupling of the rotating transformer allows the slip energy to be transferred without a torque reduction penalty.
- Magnetic saturation is used at extremely low slip frequency for full-load operation. The power consumed by the magnetic switch is low.
- The slip-energy control power is significantly smaller than the full-load rating of the motor.
- Preliminary work has shown that this motor has a potential to be fed from both the stator of the induction motor and the stator of the rotating transformer for operation above synchronous speed. It also may be used as a wide-speed-range induction generator.
- The HSU induction machine can be used as a cost-effective slip-energy-controlled adjustable-speed subsynchronous induction motor.
- The HSU induction machine can also be used as a wide-speed-range motor drive and generator that can operate below and above the synchronous speed of the stator rotating field.
- No sharp voltage spikes were observed when the slip energy was dissipated in the resistors.
- Experimental results confirm the expectations.
- A paper on the cast HSU motor will be published soon.

V ACKNOWLEDGMENT

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VI. REFERENCES

[1] .Shibashis Bhowmik, et al., “Performance Optimization for Doubly-Fed Wind Power Generation Systems,” Conference Record of the 1998 IEEE Industry Applications Conference, Vol. 3 of 3, p.p. 2387-2394.

[2] John S. Hsu, "Hybrid-Secondary Uncluttered Induction Machine," Utility Patent Application Transmittal, Attorney Docket 610625.91647, Quarles & Brady, Dec. 30, 1999.
[3] Louis J. Hunt, "New Type of Induction Motor," March 19, 1907, Manchester, England.
[4] S. Beckwith, "Adjustable Torque Induction Motors," U.S. Patent 3,226,582, Dec. 28, 1965.
[5] R. Lee, "Single Phase Alternating Current Motor System," U.S. Patent 3,144,597, Aug. 11, 1964.
[6] Satake, "Variable Speed Controlled Induction Motor," U.S. Patent 4,785,213, Nov. 15, 1988, and U.S. Patent 4,945,296, Jul. 31, 1990.
[7] R. Lee, "Disc Rotor for Induction Motor," U.S. Patent 3,069,577, Nov. 4, 1959.
[8] R. F. Krause, J. H. Bularzik, H. R. Kokal, "High Density Metal Component Manufactured by Powder Metallurgy," United States Patent No. 5,594,186, January 14, 1997.

VII. APPENDIX

6.1 *Stator Core of an Uncluttered Rotating Transformer:*

The solid-steel stator Core of the HSU prototype uncluttered Rotating Transformer is shown in Fig. 12.

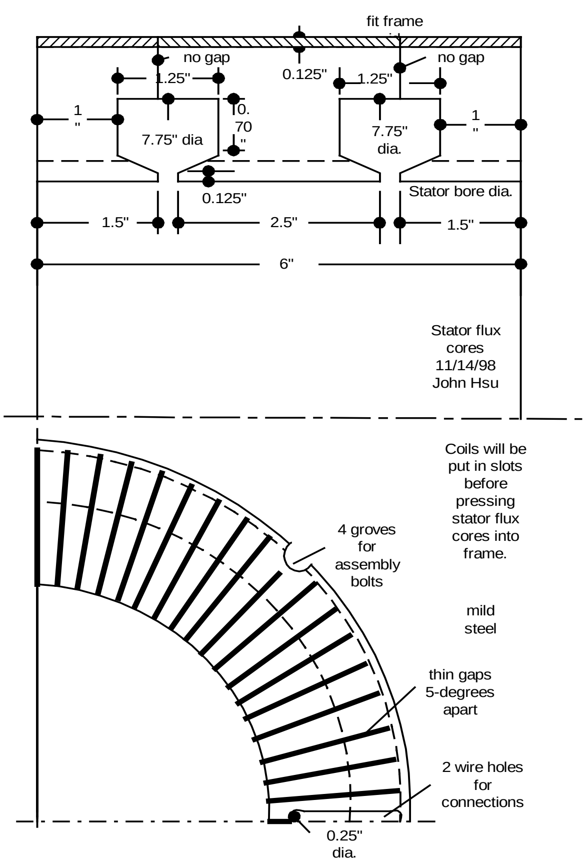

Fig. 12 Solid stator core with slits for a HSU prototype machine.

6.2 Rotor Core of an Uncluttered Rotating Transformer:

The solid-steel rotor Core of the HSU prototype uncluttered Rotating Transformer is shown in Fig. 13.

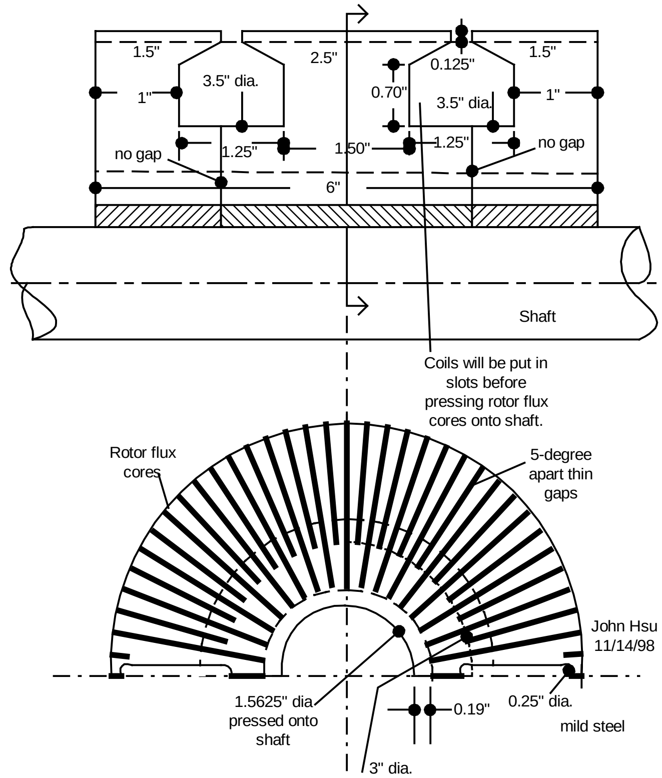

Fig. 13 Solid rotor core with slits for a HSU prototype machine.

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He worked in research and development areas for Newman Industry of England, Emerson Electric Company, and later for Westinghouse Electric Corporation. He served as head of the Rotating Machines and Power Electronics Program, Center for Energy Studies, the University of Texas at Austin for four years.

Presently, he is a lead scientist of the Power Electronics and Electric Machine Research Center, Oak Ridge National Laboratory. Dr. Hsu is the author or co-author of over one hundred technical papers and reports.