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Efficiency Improvement of Permanent-Split Capacitor Motors in HVAC Applications Using a Two-Phase Asymmetrical Inverter

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***Abstract*—Permanent Split Capacitor motors are widely used in HVAC fan and pump applications less than 5 hp. These motors operate at efficiencies from 20% to 65%. These efficiencies can be increased if the motor is operated from a variable-frequency, variable voltage supply. However, application of power electronic controllers to realize the benefits of variable speed operation of these motors has generally been impeded due to a perceived lack of cost advantage. This paper presents a novel power converter based variable speed drive topology for the PSC motor, with appropriate dynamic efficiency control and a detailed evaluation of efficiency improvements. Simulation results that compare prior art in line-operated efficiency, and drive-operated efficiency are presented, illustrating that the proposed approach can result in efficiencies from 65% to 75%. The paper presenta hardware demonstrations and simuation results.**

I. INTRODUCTION

Variable speed operation of HVAC pumps can save a significant amount of energy [1]. This is not only true for three-phase pump motors of significant size, but also true for PSC motors in HVAC applications. It is estimated that 100 million Permanent Split Capacitor (PSC) motors are currently installed in HVAC applications in the United States, operating at nominal efficiencies near 50% [1]. With a conservative estimate of saving about 10W per motor, over 1GW of power throughput can be saved by installing higher efficiency controllers onto these motors. This will represent a significant environmental benefit, whether expressed in equivalent pounds of carbon emission savings, US dollars saved per year, or other metrics.

PSC motors have been manufactured since capacitors transitioned from glass-based condenser technology to oil-filled capacitor technology. PSC motors employ a capacitor in series with their auxiliary winding, shown in Figure 1. In this schematic, the main winding has multiple taps to vary the speed of the motor at discrete speeds. The permanently installed capacitor trades off starting torque capability at standstill with ripple torque reduction at running speed. Due to the high VA rating of the capacitor, capacitors are often selected to meet the minimum starting performance requirements, resulting in poor running efficiency.

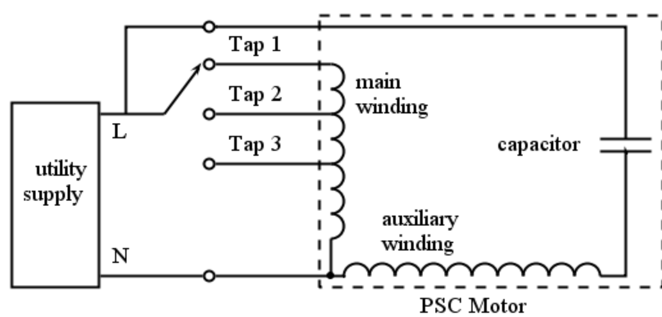

Figure 1. Schematic of PSC motor with multiple taps on the main windings for multiple speed operation

The main winding in a PSC motor is traditionally designed to meet a specified breakdown torque performance. The auxiliary winding is designed for a specific range of values of capacitors to limit inrush current that meet single-phase utility connection requirements, to provide adequate starting performance, and to meet the physical constraint of fitting the conductors in the slot area. The balancing of these tradeoffs does not lead to the best machine efficiency, particularly at small power ratings. Consequently, small size wire and inexpensive materials are used, resulting in significant winding resistances and core losses. Normalized machine parameters for an example ¾ hp PSC motor are summarized in Table 1 and Figure 2, and are compared to typical scaling laws for three-phase induction motors. It may be observed that for the base quantities chosen, the PSC motor exhibits significantly higher resistance than the three-phase machine, and significantly lower reactance values than the three-phase machine.

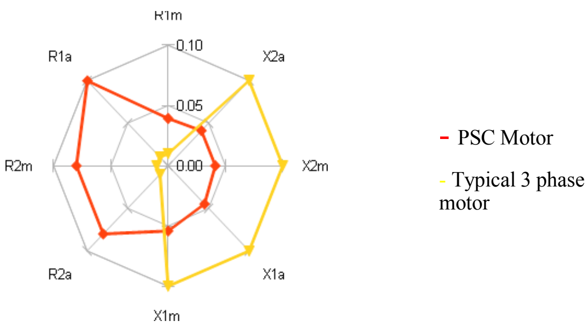

Figure 2. Graphical comparison of PSC motor resistance and leakage reactance to typical three-phase motors in p.u.

TABLE I. COMPARISON OF MACHINE PARAMETERS OF A PSC MOTOR TO THAT OF A TYPICAL 3 PHASE MOTOR IN P.U.

Motor Parameter	Classical 3 phase motor	Typical PSC motor
R_{1m}	0.01	0.04
$(N_m/N_a)^2R_{1a}$	0.01	0.1
X_{1m}	0.1	0.05
$(N_m/N_a)^2X_{1a}$	0.1	0.04
X_m	3	1.3
X_2	0.1	0.04
R_2	0.01	0.010

At this juncture one may choose to abandon the PSC motor technology and adopt a three phase machine, possibly with permanent magnet excitation for the HVAC application to realize a variable speed system. In such cases, a single rectifier followed by a three phase inverter would be used as the choice topology. However, such an approach requires the replacement of the motor and the introduction of a power electronic system to realize the upgrade. This approach leads to a prohibitive cost in such applications, particularly with respect to target payback periods. In order to establish a criterion for cost-effective application of power electronics in HVAC applications, a payback period may be defined on the basis of previous studies, illustrated in Figure 3 [2].

It may be observed that payback periods of 1-2 years are required to realize significant market penetration in residential applications. Thus historically, it has been prohibitively costly to install a full scale three phase variable speed drive with a motor in HVAC applications. All but the simplest use of power electronics (e.g., TRIAC's and SCR's) has been dismissed as infeasible [3].

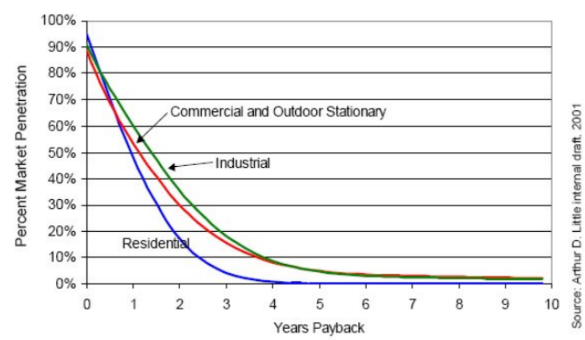

Figure 3. Summary of the market penetration of an efficiency upgrade product as a function of payback period [2].

Relatively simple approaches to improve the efficiency of PSC motors, several techniques have been proposed. In [4], a field upgrade of the permanent capacitance value is proposed. This has the effect of improving the efficiency, but it cannot eliminate the ripple torque. In order to eliminate the ripple torque, the capacitance and auxiliary winding must be controlled, or the two winding voltages must be directly controlled [5,6]. Figure 4 shows the effect that varying the fixed capacitance has on efficiency for the example ¾ hp motor described above. It may be observed that while an efficiency improvement can be realized for particular operating taps, application tradeoffs preclude cost-effective solutions that improve efficiency at all settings.

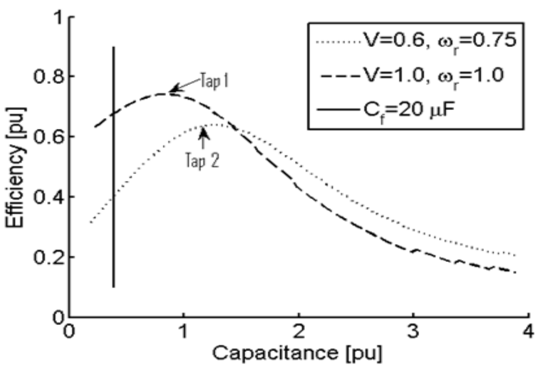

Figure 4. The effect that varying the fixed capacitance under fixed frequency has on operating efficiency for a two-speed motor.

In [3], Mademlis et al. use a TRIAC to reduce the effective voltage applied to the motor and capacitor combination. There are penalties to the performance of this approach, such as line harmonics, motor current harmonics, the lack of variable speed, and the inflexibility that comes with tuning the controller off line. This approach may be cost effective to save energy if the application demands the motor operates for considerable time at or near full speed.

On the other hand, the approach studied further in this paper is a retrofit to the system by utilizing the existing motor and the system controller, and replacing the capacitor with a suitable power electronic converter optimized for the motor topology, particularly, taking advantage of decreasing cost of power semiconductors, and machine designs optimized over a century.

Since the PSC motor is an asymmetric motor, and the utilization of silicon should also be asymmetric. For example, the return current through the motor's neutral connection carries up to 1.4 times the current in the main winding or the auxiliary winding. The inverter should not be sized so that the three pole currents are uniform in rating. In addition, the voltage applied to the main winding need not be more than the utility supply voltage, but the voltage applied across the auxiliary winding needs to supply the voltage sufficient to balance the machine's MMF. Applying more voltage than these can result in partial discharge events and resulting damage to the winding. This paper further presents an asymmetric inverter topology to realize the increase in efficiency.

II. Efficiency Control of the PSC Motor

In order to improve efficiency when operating an induction motor from a programmable supply, the flux level should be set appropriate to the motor's load. This paper considers the HVAC pump/fan load line, where torque is proportional to square of the speed.

It is anticipated that the most efficient way to set the flux level in an induction machine for this load is to adjust the flux proportional to rotor speed, or equivalently, to set the machine voltage squared proportional to rotor speed. This section explores popular methods to arrive at an optimum and identifies the principle tradeoffs in doing so.

Mademlis et al. identify a straight-forward approach to operate the motor at optimum efficiency for fixed frequency operation in [3]. When this concept is applied to variable frequency, two observations are made: 1) the flux level should be set to match the load requirements, and 2) the current ratio between the auxiliary and main winding and ripple torque trade off should be rationalized.

In order to identify the appropriate flux level in an induction motor, [7] showed how a search controller can be used to dynamically perform on-line tuning for optimal efficiency. This approach is useful for loads that do not require high bandwidth, and HVAC systems share this characteristic.

The tradeoff between ripple torque and efficiency dominates the difference between a traditional open-loop controller and a closed-loop efficiency controller. The authors think ripple torque reduction is important, and therefore the approach we take is to choose the flux level with an efficiency controller, and set the current ratio to balance the MMF. The comparison between line operation at rated frequency, balanced current ratio, and optimal efficiency current ratio is shown in Figure 5.

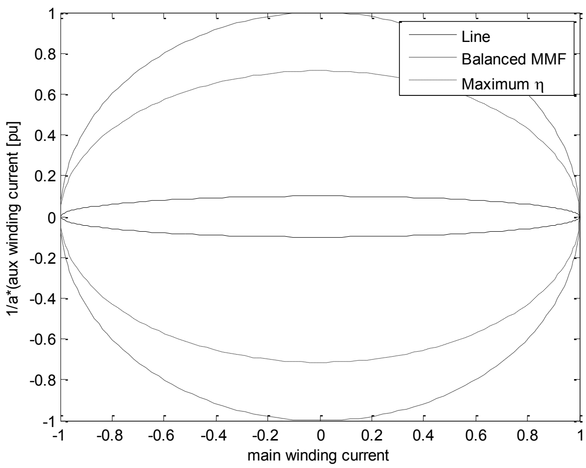

Figure 5. Currents under line operation, balanced MMF operation, and optimal efficiency operation of a PSC motor. The maximum efficiency operating point lies between line operation and balanced operation.

III. Power Converter Topology

There have been several approaches presented for driving a PSC motor using inverters [8]. The topology illustrated in Figure 6(a) uses a half bridge topology to drive each of the motor windings, while the neutral terminals are connected to the mid point of a split capacitor bank. This topology suffers from large capacitor ripple currents and would lead to a DC bus voltage greater then about 3 times the peak value of the rated voltage of the motor increasing the risk of partial discharge and resulting winding failure on standard motors.

On the other hand, the topology illustrated in Figure 6(b) uses a third half bridge inverter leg connected to the neutral point of the motor, such that the neutral potential may be clamped to either of the DC rails. In this case, the DC bus voltage would be greater than about 1.5-2 times the peak value of the rated voltage of the motor, still posing a risk of partial discharge, etc.

To overcome the voltage stress limitation, an asymmetric inverter is proposed to drive the auxiliary winding and the main winding with different voltage capabilities as illustrated in Figure 7.

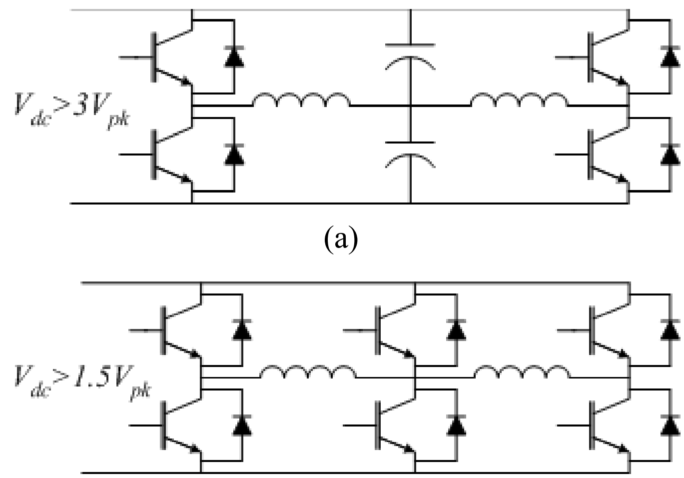

Figure 6. PSC drives using (a) Half bridge inverter with nuetral at mid point of DC bus (b) Half bridge inverter neutral clamped at DC rails

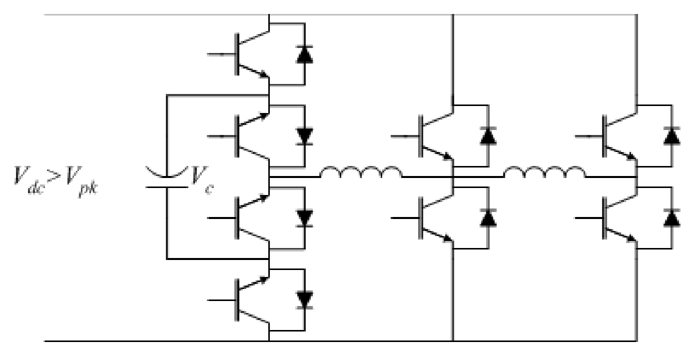

Figure 7. Topology for the proposed asymmetric inverter employing a boost leg to drive the auxiilary winding

The voltage vectors and resulting voltage capability envelope for the three inverters are illustrated in Figure 8. It may be observed that the inverter of Figure 6(a) with a significant boost front end can achieve the voltage required to operate the PSC motor's main winding at rated voltage and frequency. On the other hand, the inverter of Figure 6(b) may realize the full voltage requirement for the auxiliary winding, only at the cost of increased voltage stress on the main winding. On the other hand, the proposed asymmetric inverter illustrated in

Figure 7, realizes full voltage for the auxiliary winding without any additional stress. Although the machine windings in this case are coupled together at the neutral, which is modulated in unison, the resulting torque waveforms are shown to be acceptable in the forthcoming section.

The converter VA ratings (which represent the semiconductor cost) are summarized in Table 2. At a first glance, the asymmetric inverter appears to be more costly than the symmetric inverter. However, the switches do not all conduct the same amount of current, and do not all block the same amount of voltage. As shown in the table, the VA ratings of the asymmetric inverter can be competitive with the symmetric three-leg inverter.

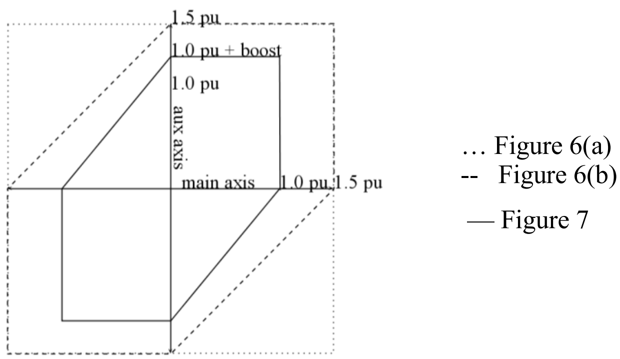

Figure 8. Comparison of voltage capability envelope of the various inverter topologies

TABLE II. COMPARISON OF VA RATINGS OF SYMMETRIC AND ASYMMETRIC TOPOLOGIES

Converter Parameter	Figure 6(b)	Figure 7
Blocking Voltage	6.0	6.8
Switch Current	8.46	6.82
Capacitance	1.41	1.8
Total Semiconductor VA	50.75	46.37
Total VA	52.1	48.7

IV. MODELING AND SIMULATION

A D-Q model for the single phase machine is used to develop a detailed model for studying the operation of the proposed converter. The machine model included the asymmetries and the effect of saturation [10]. The model is used to study the dynamic and steady state performance of the system including pulsating torque magnitude predicted by [11].

Analytical investigations of the PSC induction motor using the model shows some key results as they relate to efficiency: 1) appropriately setting the machine flux level is important to obtaining good efficiency, 2) balancing stator current results in low torque ripple, but not the optimum efficiency, 3) manipulating the stator current ratio is a key variable in manipulating motor efficiency [3]. Key results are illustrated in Figure 9.

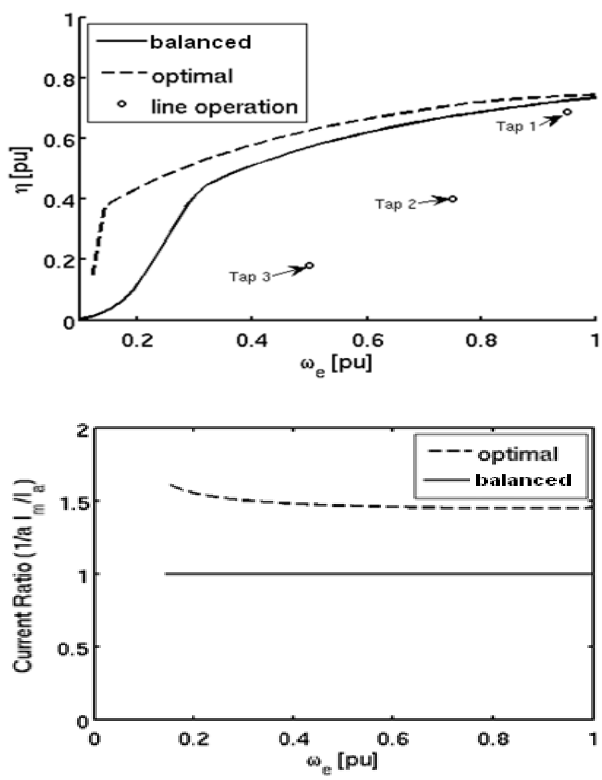

Figure 9. Summary of the efficiency of inverter operated PSC motor compared to line operated PSC motor.

When manipulating the ratio of stator winding currents (N_mI_m/N_aI_a), care must be taken to avoid motor overload. Normally, the ratio of stator current is large when the auxiliary winding is operated with a capacitor (Figure 5). As the current ratio decreases and current is moved from the main winding to the auxiliary winding, the motor temperature protection mechanism needs to be managed appropriately to avoid overloading the motor. This effect is further illustrated in Figure 10.

A block diagram of a control method for the converter is illustrated in Figure 11. The converter is operated in a voltage control mode, with the caveat that it manipulates the auxiliary voltage in steady state to control the auxiliary stator current's phase angle. Results from the time domain simulation of the system is illustrated in Figure 12. Detailed dynamic analysis of the controller and modulator for the asymmetrical inverter is beyond the scope of this paper, and will be presented in a forthcoming publication.

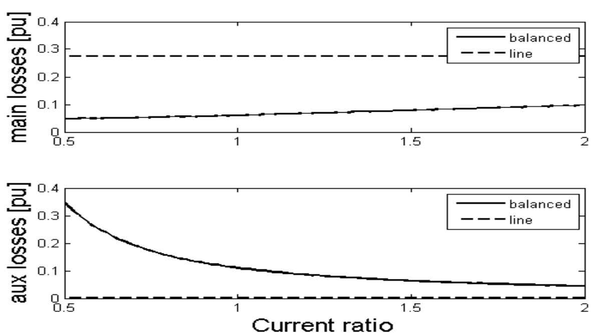

Figure 10. Illustration of the segregation of main- and auxiliary-losses in the PSC motor.

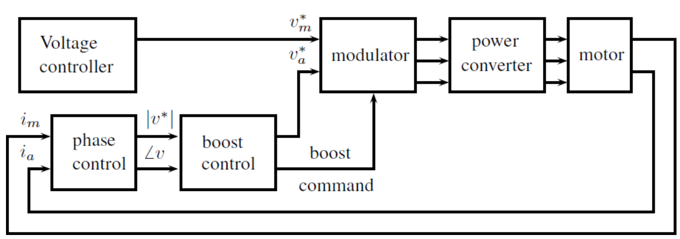

Figure 11. Block diagram

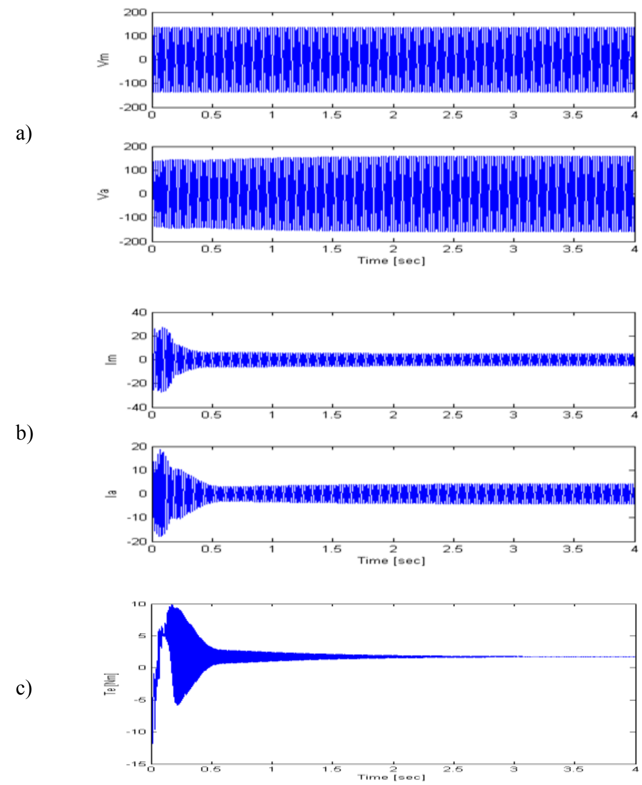

Figure 12. Simulation results. a) simulated applied stator voltages. b) simulated stator currents. c) simulated electromagnetc torque. The current controller does an adequate job of maniplating auxiliary-winding current for HVAC loads.

V. Experimental Results

A prototype inverter was constructed to demonstrate the operation of the proposed inverter topology and compare to a range of line-operated conditions driving a motor with a fan load . A photograph of the prototype is shown in Figure 13. This prototype uses an IRAM power module and a discrete four-transistor boost leg (illustrated in Figure 6a). The controller is realized using a TI TMS320F28335 microcontroller.

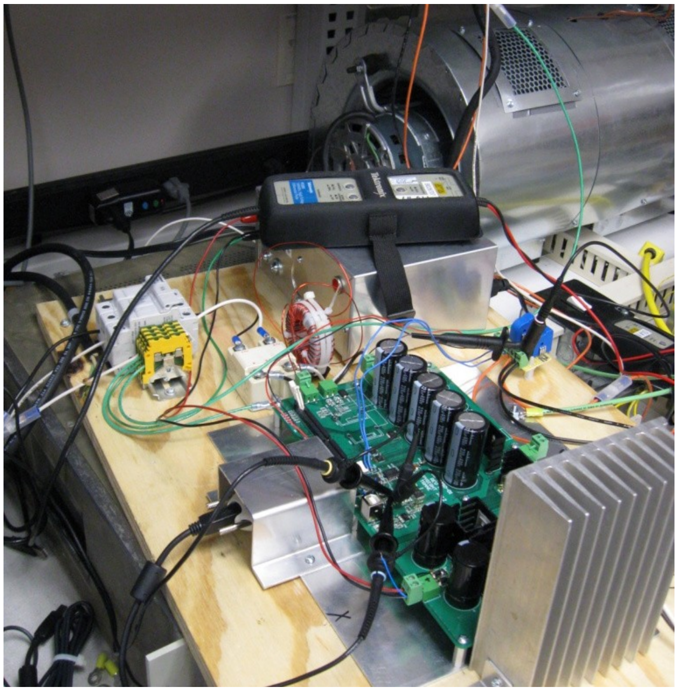

Figure 13. Photograph

In order to compare inverter operation, a 1/6 hp PSC motor is baselined under capacitor operation. The motor nameplate characteristics are summarized in Table 3. Variation of the efficiency for different value of capacitors is plotted in Figure 14.

The efficiency improvement of the inverter operated PSC motor is shown in Figure 15. In comparison to line-fed operation with a capacitor in the auxiliary winding, operation with a two-phase supply using the inverter increases the machine's torque capability. The inverter is therefore able to dramatically reduce the applied voltage (e.g., reduce the machine flux level) from that used under capacitor operation, and a large benefit in efficiency is achieved.

The selection of the optimum machine flux level may be optimized for a given application and can be dynamically tuned by estimating rotor speed in real time.

TABLE III. SUMMARY OF MOTOR NAMEPLATE PARAMETERS

Motor Parameter	Quantity
Nameplate Voltage	115 V
Nameplate Current	1.90 A
Nameplate Capacitance	20.0 uF
Nameplate speed	1075 RPM
Nameplate Power	1/6 HP

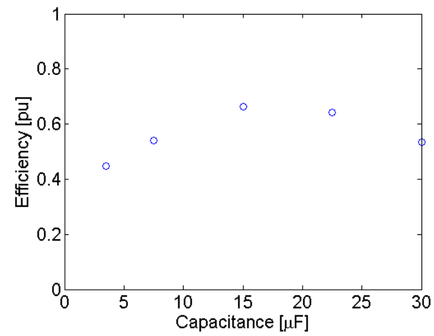

Figure 14. Efficiency map as auxiliary winding capacitance varies. Test motor: 1/6 hp, 1070 rpm, 115 VAC.

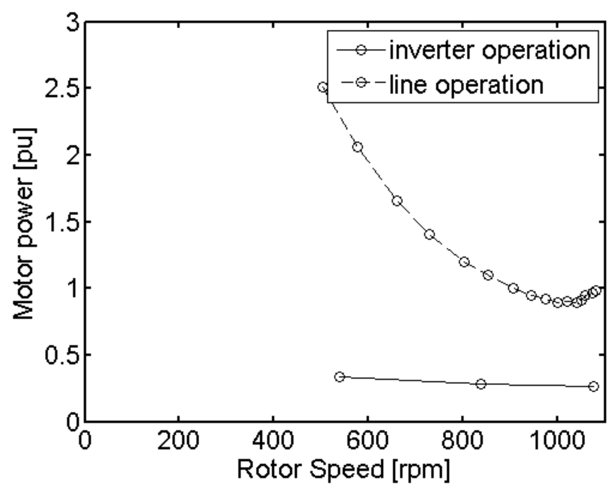

Figure 15. Comparison of line-operated (capacitor) motor power with inverter-operated motor power of a PSC motor. The motor power was normalized to line-operated rated condition, and was derated at reduced speed against a fan curve for power comparison at reduced speed. Efficiency was not shown here since the exact load power was not known.

VI. Conclusions

There is currently a large quantity of PSC motors installed in HVAC applications. By improving how these motors are operated, a very large amount of electricity can be saved each year.

Due to the large variability involved with PSC motor design and application, it is difficult to generalize the operating features that lead to optimal efficiency of a PSC motor under variable speed operation. Nevertheless, the dominant factors that influence PSC motor efficiency have been summarized.

An inverter topology that can attain the majority of these benefits while reducing winding stress (compared to the options currently available in the literature) has been introduced.

In order to achieve the efficiency benefit of PSC motors under variable speed, the machine flux level needs to be set an optimal level. This can be performed through laboratory characterization or by estimating speed at run time (and dynamically optimizing output power). This selection is an application decision that trades off motor parameter repeatability due to manufacturing tolerances as well as microcontroller performance cost.

By appropriately managing the application trade offs, the approach presented in this paper can improve PSC motor torque ripple, improve machine performance, and save energy. When these benefits are scaled to the magnitudes of the PSC motors that are in service in HVAC applications, a large benefit to society can be realized.

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