

System solution to improve energy efficiency of HVAC systems

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Abstract. According to recent surveys, heating and air conditioning systems account for over 45% of the total energy usage in US households. Three main types of HVAC systems are available to homeowners: (1) fixed-speed systems, where the compressor cycles on and off to match the cooling load; (2) multi-speed (typically, two-speed) systems, where the compressor can operate at multiple cooling capacities, leading to reduced cycling; and (3) variable-speed systems, where the compressor speed is adjusted to match the cooling load of the household, thereby providing higher efficiency and comfort levels through better temperature and humidity control. While energy consumption could reduce significantly by adopting variable-speed compressor systems, the market penetration has been limited to less than 10% of the total HVAC units and a vast majority of systems installed in new construction remains single speed. A few reasons may explain this phenomenon such as the complexity of the electronic circuitry required to vary compressor speed as well as the associated system cost. This paper outlines a system solution to boost the Seasonal Energy Efficiency Rating (SEER) of a traditional single-speed unit through using a low power electronic converter that allows the compressor to operate at multiple low capacity settings and is disabled at high compressor speeds.

1. HVAC system overview and component characteristics

Vapor compression air conditioning and heat pumping systems used in US residential habitations typically comprise the following elements: an evaporator coil with a fan, a condensing coil with a fan, a compressor, and an expansion device. These systems are used in conjunction with a thermostat that regulates operation in order to maintain the requested temperature.

The following sections will outline the key characteristics of single-speed systems, that represent the vast majority of residential installations, and variable-speed systems.



2. Single-speed system overview and characteristics

Single-speed systems use a fixed-speed compressor. When the HVAC unit is designed to operate on single-phase power, the compressor motor is generally a Permanent Split Capacitor (PSC). When the HVAC system is designed to operate on three-phase power, the compressor motor is typically a three-phase induction motor.

In US residential applications, systems traditionally range from smaller units providing two tons (6.7 kW) of cooling capacity to larger units providing up to five tons (17 kW) of cooling, depending on the size of the habitation. These systems are run with single-phase power.

2.1 Performance of PSC motors

A PSC motor is a two-phase induction motor that can run on single-phase power. The motor comprises two sets of windings, a main winding and a start winding. In order for a PSC to operate on single-phase power, the start winding of the motor is connected in series with a run capacitor. This series connection creates an out of phase voltage with respect to the main winding voltage that allows the motor to accelerate from standstill to full load without the use of power electronics circuitry.

Figure 1 below depicts the torque characteristics and machine current for a PSC from standstill to no load.

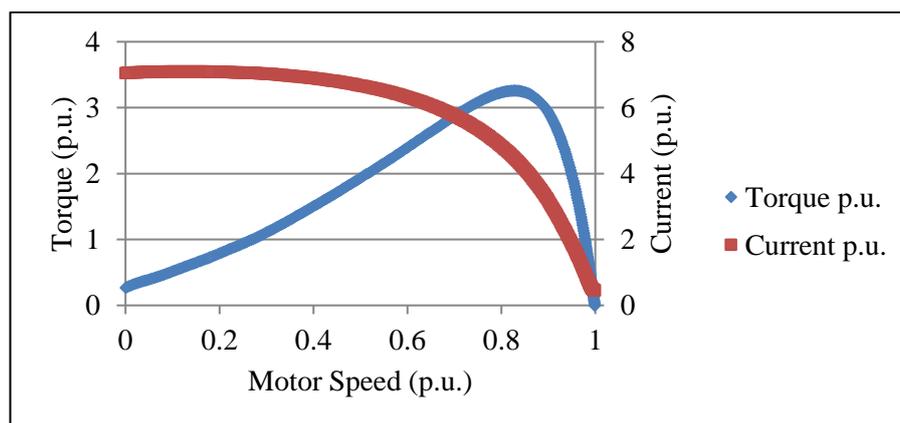


Figure 1. PSC torque and current versus speed.

As can be seen on Figure 2, a PSC motor has very limited starting torque and high inrush current when coming up to speed from standstill. As a result, single-stage systems need protection mechanisms against locked rotor currents that can reach up to ten times normal operating currents.

Figure 2 describes a typical efficiency curve for a PSC motor. As can be seen, the motor peak efficiency is achieved at a particular load point, typically the full-load operating point of the system, and both slight increases and decreases in load negatively affect motor performance. Additionally, it can be seen that operation at lower speeds, also called high motor slip operation, dramatically reduces efficiency.

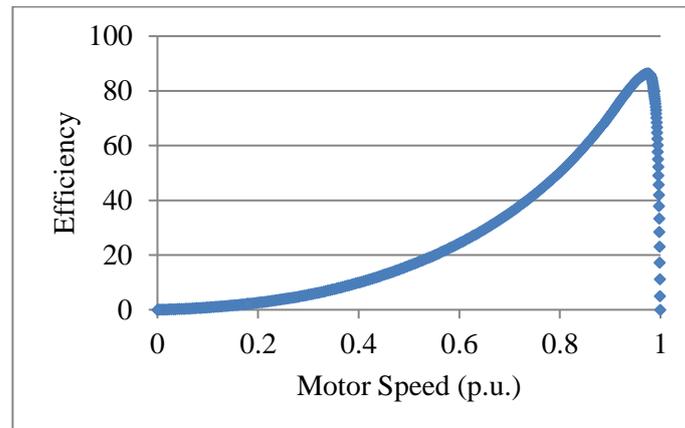


Figure 2. PSC efficiency versus speed.

2.2 Single-speed system operation

For single-speed systems, the thermostat controls the power to the compressor motor. The compressor motor is cycled according to the temperature setting of the thermostat.

Cycling is necessary because the compressor operates at single-speed and the system always provides high cooling capacity. While high cooling capacity is necessary and useful on warm and humid days, for example in the summer, it is excessive on milder days, and the system needs to stay powered only for short bursts of time to avoid excessive cooling of the habitation.

However, there exist constraints on the cycling ability of single-stage systems. Indeed, because of the limited starting torque of the PSC motor, the duty cycle for cycling operation has to be limited. When the HVAC unit is operating, the system refrigerant is compressed and a pressure differential is created between the suction and discharge ports of the compressor. This pressure differential subsists and slowly decays when the compressor turns off. The pressure differential immediately upon compressor shut off exceeds the maximum starting torque of the PSC. Under such conditions, the PSC compressor would be unable to restart, and would enter a locked rotor condition. As a consequence, single-speed systems have built in features, also called interlock mechanisms, that prevent successive and immediate restarts of the compressor.

Cyclical operation of the HVAC system prevents tight regulation of the temperature inside habitations and also negatively affects indoor air dehumidification.

2.3 Efficiency rating for single-speed systems

In the US, the energy efficiency of an HVAC system in cooling mode is measured through its Energy Efficiency Ratio (EER) and Seasonal Energy Efficiency Ratio (SEER). The EER is calculated by taking the ratio between the cooling capacity the system is able to deliver in Btu/hr with the total electrical power consumed in W. The total electrical power consumed comprises the indoor blower input power, the outdoor condenser fan input power, and the compressor motor input power.

The SEER for a single-speed system is calculated according to the ANSI/AHRI Standard 210/240 for the Performance Rating of Unitary Air-Conditioning and Air-Source Heat Pump Equipment [1]. The standard defines required and optional tests at various indoor and outdoor air temperatures. Some of the tests are performed during continuous operation of the unit while others are performed under cyclical operation. The cyclic tests allow to determine the cyclic degradation coefficient C_d . Table 1 below outlines the tests for a single-speed unit.

Table 1. Single-speed system test points. 80.0°F / 67.0°F indoor air.

Test condition	Outdoor air temperature °F	Compressor Speed	Cooling air volume rate
A (steady)	95.0/75.0	Max.	Max.
B (steady)	82.0/65.0	Max.	Max.
C (steady)	82.0/-	Max.	Max.
D (cyclic)	82.0/-	Max.	Max.

Once the tests in Table 1 are completed, the SEER rating is calculated according to Equation (1) below.

$$\text{SEER}_{\text{single speed}} = \text{EER}_B \times (1 - 0.5 \times C_d) \quad (1)$$

3. Variable speed system overview and characteristics

Variable speed HVAC systems achieve higher SEER rating than single-speed systems through using high efficiency variable-speed motors for the compressor, the indoor blower and the outdoor fan, that can adjust their speed of operation to match the load. Additionally, these systems may use an Electronic Expansion Valve (EEV) to achieve greater controllability of the refrigerant cycle.

3.1 Performance of motors used in variable-speed systems

To achieve best in class efficiency, variable-speed systems typically use brushless permanent magnet motors mated with electronic controllers. Brushless permanent magnet motors, also known as Brushless Direct Current motors (BLDC) can achieve higher power densities and efficiencies compared to PSC motors as there are no rotor losses during operation. Figure 3 below contrasts efficiency and operating area between BLDC and PSC.

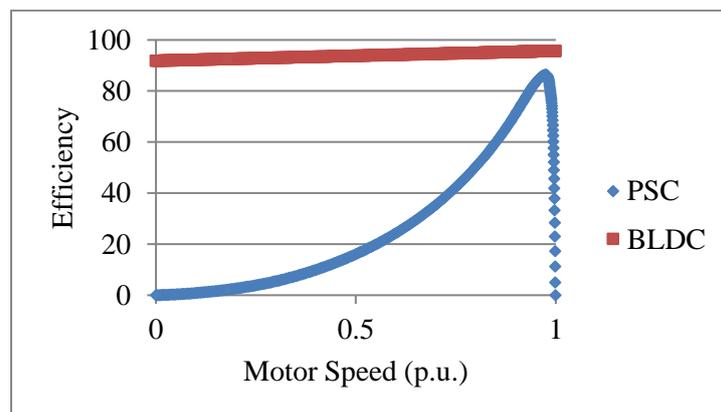


Figure 3. PSC and BLDC efficiency versus speed.

3.2 Electronic circuitry required to run variable speed motors

Variable speed operation of a BLDC motor is accomplished by using an electronic drive. The role of the electronic drive is to convert the fixed voltage and frequency of the utility power source into a source of variable voltage and variable frequency. Figure 4 details the traditional elements of a variable speed drive.

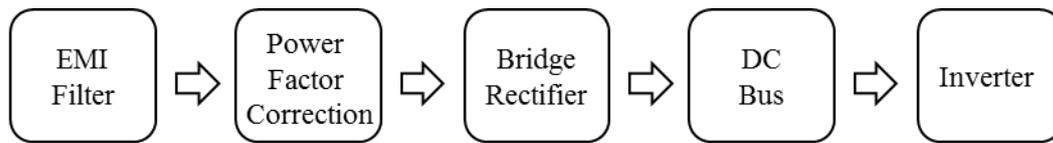


Figure 4. Block diagram of a variable speed drive.

The electronic drive transforms the AC voltage from the utility power source into a DC voltage. The energy is stored by large electrolytic capacitors. An inverter stage composed of power electronic switches transforms the DC voltage into AC voltages with amplitudes and frequencies adjusted using Pulse Width Modulation (PWM) techniques.

The electronic drive also contains a power factor correction (PFC) unit to condition the current drawn from the utility source into a sinusoid. Input power factor represents the ability to extract optimal power from the source. The power factor of a PSC motor under load typically reaches above 90%. An electronic drive without a power factor correction unit on the other hand is generally limited to 60%. Under these conditions, a PSC compressor consuming 4 kW would draw 18 Amps from the source when a BLDC compressor consuming 4 kW would draw 28 Amps. Due to limitations in available currents in residential habitations, it is therefore necessary for variable-speed systems to include PFC units to run the compressors at full power.

The power electronic switches in the PFC stage and in the inverter stage introduce losses from conduction and switching of electric current, as well as Electro Magnetic Interference (EMI). Therefore, to compare system efficiency between PSC and BLDC system, it is necessary to take into account the efficiency of the electronic drive. Typically, for HVAC units ranging from two tons (6.7 kW) to five tons (17 kW) of cooling, the efficiency of electronic drives reaches 92 to 93%. Finally, the losses in power electronic components generate heat that needs to be dissipated outside the drive, and present cooling challenges, especially when the HVAC system operates at high power and high ambient. Under high ambient conditions, the thermal management of the electronic drive sometimes requires derating and reduction of compressor speed, thereby reducing the total available cooling capacity when it is most needed.

3.3 Variable-speed system operation

In a typical variable speed system, a thermostat sends digital information regarding the ambient temperature and the set point selected by the user. Based on the temperature difference between commanded and measured temperatures, as well as other specific modes of operation, the thermostat sends a cooling request to the system controller of the HVAC unit. The system controller then selects the optimum operating speed for the compressor, the indoor fan and the outdoor fan based on the thermostat request and the information measured from multiple sensors such as refrigerant pressure or temperature sensors.

Figure 5 shows a typical operating profile for the system cooling stage following a thermostat cooling call. Figure 6 illustrates the effectiveness of temperature regulation between single-speed and variable-speed systems.

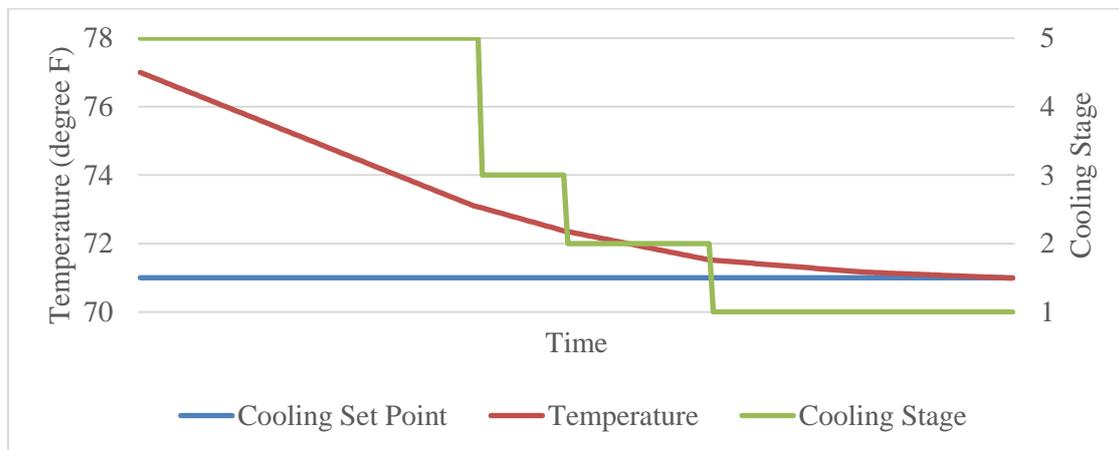


Figure 5. Typical cooling operating profile.

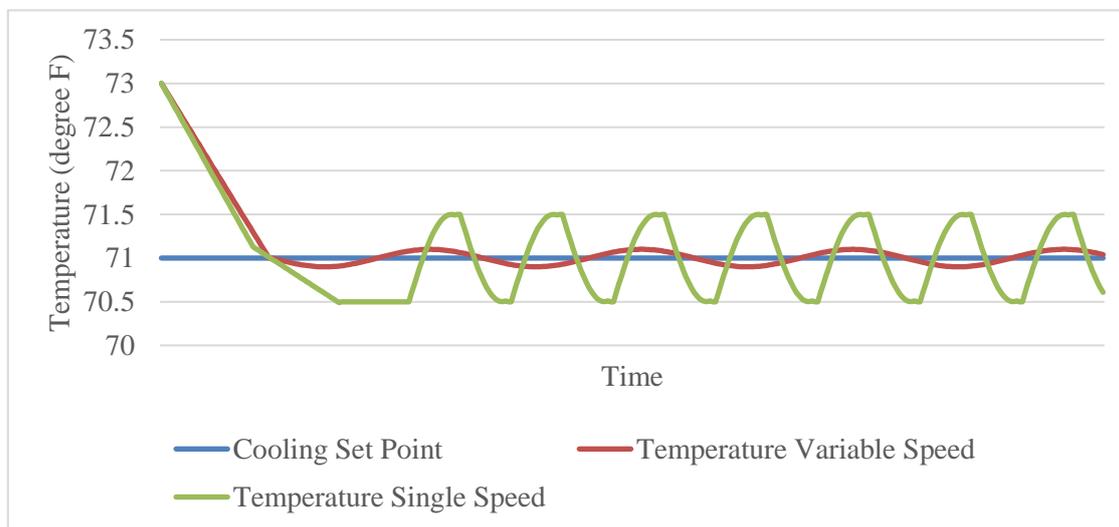


Figure 6. Temperature control of single stage and variable speed units.

As can be seen in Figures 5 and 6, the compressor runs at high speed and the HVAC system delivers high cooling under high temperature differential. As the measured temperature approaches the user set point, the system controller reduces compressor speed to match the cooling load of the building, thereby reducing cycling requirements and optimizing temperature regulation and ultimately user comfort. Typically, variable speed compressors operate in a 900 to 1200rpm range for cooling stage 1, up to a 3600 to 4200rpm range for cooling stage 5. The operating speeds between stages 1 and 5 are generally evenly spaced, yet other speed distributions are possible depending on the programming of the HVAC system controller.

3.4 Efficiency rating for variable speed system

As for single-speed systems, the SEER for variable-speed systems is calculated according to the ANSI/AHRI Standard 210/240. Table 2 below summarizes the tests to calculate the SEER for variable-speed systems.

Table 2. Variable-speed system test points. 80.0°F / 67.0°F indoor air.

Test condition	Outdoor air temperature °F	Compressor Speed	Cooling air volume rate
A ₂ (steady)	95.0/75.0	Max.	Max.
B ₂ (steady)	82.0/65.0	Max.	Max.
E _v (steady)	87.0/69.0	Intermediate	Intermediate
B ₁ (steady)	82.0/65.0	Min.	Min
F ₁ (steady)	67.0/53.5	Min.	Min
G ₁ (steady)	67.0/-	Min.	Min
I ₁ (cyclic)	67.0/-	Min.	-

For variable-speed systems, it is necessary to perform tests at three distinct compressor speeds. The relationship between compressor speeds follows Equation (2).

$$\text{Speed}_{\text{intermediate}} = \text{Speed}_{\text{min}} + \frac{\text{Speed}_{\text{max}} - \text{Speed}_{\text{min}}}{3} \quad (2)$$

In addition to varying the compressor speed, it is possible to vary the indoor and outdoor fan speeds to further adjust the cooling capacity of the system.

4. Proposed system solution: combination of single speed and variable speed components

One of the key elements to improve the SEER of HVAC units is to adjust the compressor speed to match the cooling capacity to the cooling load. However, the use of an electronic drive may be detrimental to efficiency and lead to thermal management challenges at full load operation. To address some of these drawbacks, a system solution using a standard single-speed compressor and an electronic drive is proposed.

4.1 System overview and benefits

The proposed system solution resides in the combination of a single-speed PSC compressor with an electronic drive. The system will operate on the inverter drive when the cooling demand and cooling load are reduced, and run directly from utility power at high load. A block diagram for this solution can be seen in Figure 7 below.

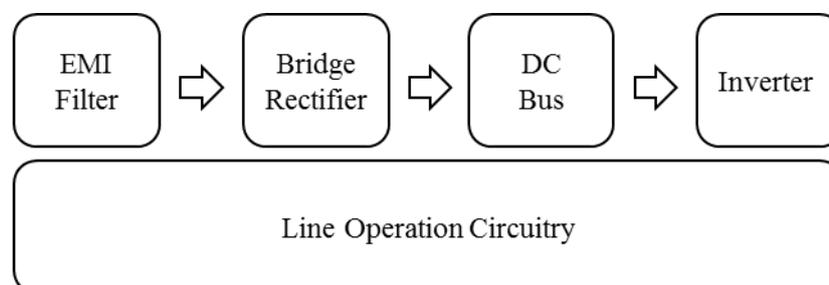


Figure 7. System solution to convert fixed-speed system into variable speed.

The proposed combination provides substantial benefits over traditional single-speed systems and variable-speed systems altogether. First, the ability for the compressor to operate directly from the utility source at high power solves several challenges encountered with variable-speed systems. Indeed, as the electronic drive is disabled at high loads, there is no concern for power factor or EMI compatibility, and

there are no losses associated with power electronics, so the full load electrical efficiency of the proposed solution is comparable to the one of variable speed compressors burdened by their electronic losses. Additionally, as the drive is only used at reduced output power, the size and thermal management of electronics is simplified. However, a few limitations exist compared to fully variable speed systems. First, as the standard PSC compressor operates on utility power at full load, the maximum achievable compressor speed remains unchanged. Second, at lower operating speeds, the combination of a PSC on an electronic drive remains less efficient when compared to the efficiency of a BLDC on an electronic drive.

Adding an electronic drive to a PSC compressor also yields significant benefit over single-speed systems. First, the cooling capacity can be modulated to match the cooling load, resulting in higher comfort for the user through improved temperature control and dehumidification. Moreover, the PSC motor used in conjunction with the electronic drive can achieve substantially higher starting torque, removing the need for time delays between successive restarts of the compressor. Finally, the electronic drive allows precise acceleration of the compressor resulting in lower inrush current and audible noise when the air conditioner starts.

4.2 Psychrometric chamber results for a five tons HVAC unit

The proposed system solution combining a production standard PSC compressor from a single-speed system with an electronic drive has been tested using a five tons (17 kW) split-system air conditioning unit in two side-by-side psychrometric chambers. Test procedures have followed the standard testing outlined in ANSI/AHRI 210/240.

Tables 3 and 4 summarize the findings for a system using a 5-tons (17 kW) scroll compressor.

Table 3. Single-speed system test points. PSC Scroll Compressor.

Test condition	EER	SEER
A (steady)	12.08	14 @ $C_d = 0.11$
B (steady)	14.81	

Table 4. Variable-speed test points. PSC Scroll compressor.

Test condition	EER	Compressor speed (RPM)	SEER
A ₂ (steady)	12.08	3525	15.37 @ $C_d = 0.11$
B ₂ (steady)	14.81	3525	
E _v (steady)	14.20	2445	
B ₁ (steady)	15.73	1905	
F ₁ (steady)	20.55	1905	

Tables 5 and 6 summarize the findings using a 4.5 tons (15.3 kW) PSC rotary compressor.

Table 5. Single-speed system test points. PSC Rotary compressor.

Test condition	EER	SEER
A (steady)	11.50	13.08 @ $C_d = 0.11$
B (steady)	13.84	

Table 6. Variable speed test points. PSC Rotary Compressor.

Test condition	EER	Compressor speed (RPM)	SEER
A ₂ (steady)	11.50	3525	
B ₂ (steady)	13.84	3525	
E _v (steady)	14.82	2085	16.44 @ C _d = 0.11
B ₁ (steady)	18.52	1365	
F ₁ (steady)	26.50	1365	

As can be seen in Tables 5 and 6, it is possible to achieve between 1.5 and 3.5 SEER improvement by using the proposed variable-speed drive on the PSC compressor of a single-speed system. A base air conditioner rated at SEER 14 could improve up to SEER 16.5. Using this technology, the full-load efficiency remains unaffected by the drive performance, and the use of an electronic drive allows for low speed operation where the overall system runs much more efficiently.

5. Conclusion

The addition of a low power electronic drive to enable variable-speed operation of a fixed-speed compressor used in single-speed systems results in SEER improvements ranging from 10% to 25% depending on the compressor technology, without affecting the EER value at full load. Future work will include a detailed investigation of SEER improvements using this technology in conjunction with a variable airflow rate indoor system, yet preliminary results suggest that a 30% SEER improvement over the baseline is achievable.

It is expected that this technology could also positively impact the Heating Seasonal Performance Factor (HSPF), which is the pendant metric to SEER and is used to measure the efficiency of heat pumps.

References

- [1] ANSI/AHRI Standard 210/240 with Addenda 1 and 2 (Formerly ARI Standard 210/240) Performance Rating of Unitary Air-Conditioning & Air-Source Heat Pump Equipment.