White Paper
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ECM Motors in Series Flow Fan Powered Terminals and Unit Ventilators

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The first fan powered terminals were introduced to commercial buildings in 1974. They were immediately employed by a number of design engineers due to their significant advantages in energy use when compared to the reheat options available at that time. They also allowed designers to take advantage of building diversity through the recapture of plenum heat, which was often wasted when returned to the air handler. Initially, a parallel design, with the fan operating only when heat was required, was used. The series type, with constant fan operation, has increased in use due to its constant air supply and sound levels, at a slight increase in energy use. Unit ventilators have been in use for many years, primarily in classrooms, where they provide both comfort conditioning and ventilation in a single piece of equipment.

The issue of energy use has concerned the industry with the use of both of these devices, and has resulted in some negative press on their use. In addition, the series fan box design's somewhat non-constant airflow, as it responds to inlet pressure changes, has made the units difficult to balance. These issues are negligible compared to the several significant advantages offered by series-type fan powered terminals (Contracting Business, 1997), and the first cost advantages of unit ventilators. The use of extra heat and ventilation air resulting from building diversity more than overcomes the energy penalty and the balancing issue is a one-time concern. While difficult to verify directly, both series fan powered units and unit ventilators can offer significant energy savings over other alternate strategies for heating, cooling and ventilating spaces.

Both Fan powered terminals and unit ventilators employ direct-drive, fractional horsepower induction motors, typically of the permanent split / capacitor-start type. Many applications employ the use of an SCR speed controller on a single or 3-speed motor. This is not the most efficient technology, as they are fundamentally fixed-speed devices, but are very affordable from a first cost basis. Applications typically range from inefficient to very inefficient depending on the combination of motor, speed controller and selected operation point.

It is complex and expensive to control both speed and torque in an induction motor. Without active speed/torque control, fan outputs are highly pressure dependent, limited by a single fan curve. With fan powered boxes, the balancer therefore spends several trips to the unit as he balances both diffusers and the unit's SCR to achieve the desired airflow. This then changes as the inlet side is loaded and unloaded in response to the thermostat's changing load requirements, and resultant changes in varying primary air on the inlet side of the fan. This can be a noticeable nuisance for air balance personnel especially if the air intake port on the fan-powered box is too small. Upon an increase of primary air into the fanbox cavity, the cabinet is increasingly relieved of negative static pressure, therefore increasing fan performance. The resulting output error is referred to as fan shift and can be as much as 10-25% change in fan output depending on the difference between min and max air flow settings of the primary air valve. Balancing time has been reported to be as high as an hour per unit. Remote SCR setting, through the DDC system, often adds $100 or more to the first cost of a unit if fan airflow verification is included. If a three speed motor is used in either type of unit, the efficiency at less than full speed (or torque) is always reduces, often significantly, over full rpm / torque applications.

While there has been an increasing call from the industry over the last several years to solve these problems, there are few options that can solve both the set-up and energy use options. The use of a digitally controlled motor, developed for the residential industry, has demonstrated excellent reliability, energy reduction and control performance, and is responsible for a significant increase in energy ratings. Unfortunately, residential applications are either 115 or 220 VAC, where 80% of all commercial applications are 277 VAC (utilizing 1 leg of a 480 3-phase circuit also used for lighting applications). The jump from 220 to 277 VAC requires significant re-engineering to meet agency listings, and the market for this application is

1/100 that of the residential market. A new offering, the GE ECM™ is now available, however, in a 277 VAC rating. Several manufacturers have conducted the necessary research to be able to employ these motors on series flow fan terminals, and one in a Unit Ventilator.

Background

Motors and Airflow Control – Multiple-tapped, multiple or single speed induction motors controlled manual dampers or by wave choppers, also known as SCR's, are the most common technologies currently used to provide adjustable airflow in terminal units. All have disadvantages in controlling airflow and the resultant room air supply rates and acoustical environments. SCR's are relatively low cost electronic devices that switch – that is- duty-cycle a silicon-controlled rectifier to chop the effective voltage to an induction motor. As the voltage is reduced, the rotor slips to lower speeds, reducing the air delivery of the centrifugal fan. Several problems arise from this technology:

1. The SCR and motor combination creates electronic noise and voltage notching that lowers the power quality in a building.
2. The efficiency of the motor is reduced (the amperage is not reduced in proportion to the reduction in torque.).
3. They do not control torque directly, preventing precise airflow control.
4. They can increase the acoustical signature of the motor, especially at critical low frequencies that are difficult to attenuate.
5. When combined with multiple tap or multiple speed motors, an optimum match between motor and speed controller cannot be maintained at all settings or taps.

Tapped motors are usually used with SCR's. If they are not, additional means must be supplied to achieve desired flow rates, such as external dampers, which increase fan load, speed and noise therefore, reducing efficiency. Variable torque/hp taps may not be effective in changing the fan cfm if the motor/fan combination can operate at design rpm at the lowest torque/hp settings.

By far the main drawback of attempting to control airflow either with an SCR or tapped motors is the inefficient process by which they change the speed of the blower. Induction motors are designed to deliver maximum efficiency at a single voltage, load and speed, typically at their rated load and speed. Moving the motor's operation off of that point dramatically reduces the motor's efficiency from a peak, typically 55-65%, to as low as 15-20% efficiency.

The further away the motor operates from its design point, the greater are its losses and the hotter it gets. It is not uncommon for a motor to use as much current at minimum settings as it does at maximum, thus offsetting any savings that might be assumed with reduced flow. This reduced efficiency has a compounding effect on system energy use when the added system chiller load is included to offset the individual unit efficiencies. The digitally controlled motors, such as the GE ECM™ avoid all the disadvantages of both tapped motors and SCR-controlled motors while providing additional advantages.

The ECM has been applied in residential HVAC systems since 1985. The HVAC OEM's quickly realized their advantages:

1. Very high efficiency with power unloading very close to the centrifugal blower's power and speed cubic relationship, lowering operating costs significantly at reduced speeds.

2. Set-up versatility, allowing simple airflow and control settings.

3. Better functionality, increasing the product value by offering performance options not possible with conventional motors.

These motors are in use today by all major manufacturers of residential gas and electric furnaces and home air conditioners. The installed base exceeded 1 million units worldwide in 1998, with a rapidly increasing growth rate, increasing at more than 25% per year.

Electrically Commutated Motors

A requisite element of an ac induction motor is rotor slip. The rotor has to rotate at an rpm less than that of the synchronous speed set by the number of poles and current frequency. The speed difference, or slip, is what induces the current that produces torque. Unfortunately, these induced losses, created by the torque generating rotor current, can increase dramatically if the slip is more than a few percent. The ECM motor, on the other hand, is a brushless DC motor operating in a synchronous mode. There are no slip-induced losses. Speed and torque can be changed by simply adjusting the voltage and current applied to the motor, resulting in maximum efficiency over a wide operating range.

The rated efficiency of an ECM motor is 75-80% at its full rated output. At lower speeds its efficiency stays above 60%, even down to 400 rpm at 10% load! In comparison, a typical sleeve bearing induction motor operating at 600 rpm (its lowest recommended operating point) is as little as 18% efficient. The comparison cannot be shown graphically as the conventional motor's performance is off the bottom of the chart. When the motor and blower (in) efficiencies are added together, the centrifugal blower consumes nearly as much power at 600 rpm as at full load.

The advantages of the ECM motor becomes more apparent when installed in fan-powered units (and unit ventilators) and their performance and flexibility are compared. A typical fan powered box design utilizes several sizes of motor/blower combinations to cover the range from 200 to 3000 cfm. Due to the lower minimum and higher maximum rpm limits of the ECM only two ECM motor/blower combinations are required to cover this entire range. The reduced number of motor/blower combinations offers advantages both for the owner, who can use a single unit in a broad range of locations (the primary inlet size is easily changed), and stocking distributor as well. These units have been used on several projects where the flexibility and energy savings have been proven. There is even the potential to provide precise factory preset airflow, providing coordination is set up in advance. With a properly coordinated DDC system, the low voltage PWM signal used to control the ECM motor can be provided as a percent of capacity through the controller, with a very predictable output flow rate, eliminating the need for expensive flow verification pressure transducers. With Unit Ventilators, the motor speed can be easily changed in response to room load, reducing fan noise when loads are less than maximum. As the speeds are programmable, not fixed, they can be adjusted to meet individual zone load requirements.

The Variable Speed Motor and Electrical Energy

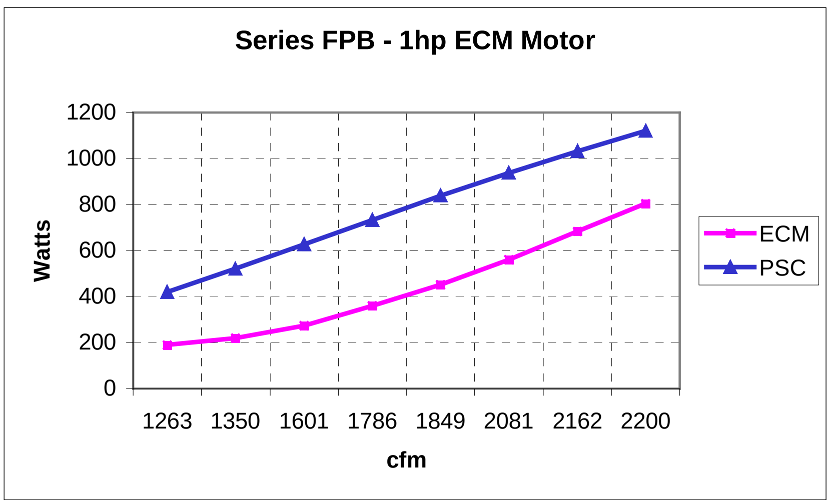
An ECM motor's electronics package, integral to the motor on the GE unit, provides two functions. First it switches the DC magnetic fields that make the motor operate. It acts as the commutator and brushes necessary in typical DC motors. Secondly, it controls torque and speed so that the proper airflow is maintained independent of the pressure seen by the fan. These tasks are handled by a microcomputer that has been programmed to match the output of the blower 's torque and speed requirements as well as surrounding cabinet geometry and its effects on motor/blower load.

The variable speed circuits in ECM motors employ electronics that utilize DC voltages. Most electronic devices, from TV's to computers employ 'off-line' ac-to-dc conversion from the available ac power. This process uses diodes and capacitors, and is sensitive to the 'cleanliness' of the available power signal, which in its purest form is a true sine wave. Loads on the line often disturb the sine wave form, and produce distortions that deviate from the ideal shape. Some devices are sensitive to these distortions. The SCR's used with conventional induction motors can create severe notching to the sine wave power line, and adversely effect operation of some equipment. The power conversion in the GE ECM uses a full wave rectifier that does not produce the type of line disturbance often seen with typical SCR speed controllers, but do contribute a small amount of easily controllable harmonic distortion.

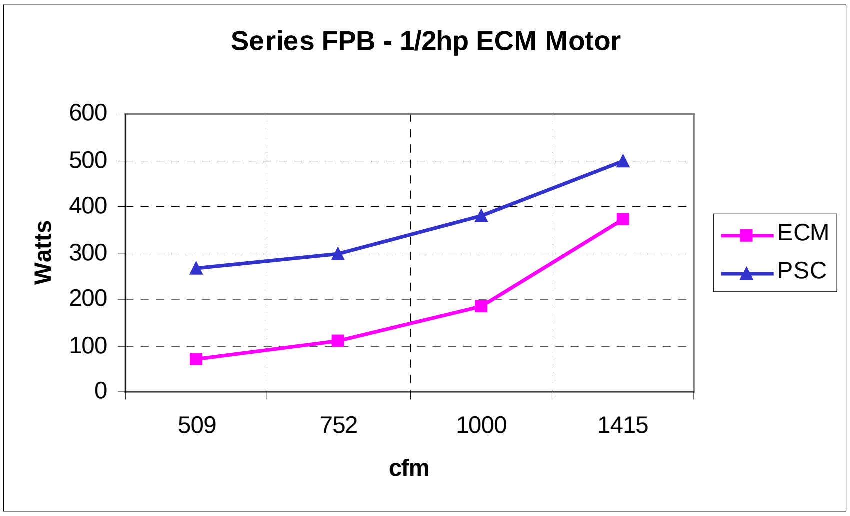
ECM vs Induction Comparison; For the purpose of comparison, both power and volt-amperes will be compared on the basis of delivered CFM from a series flow fan terminal. This data may be considered to be conservative, as some manufacturers have optimized the induction motor to blower combination more than others. This comparison therefore is based on a very efficient induction motor / blower combination and is also valid for a unit ventilator application.

The figures below illustrate the difference in energy use, as a function of watts, between a PSC and ECM motor on a typical fan powered terminal. Figure 1 shows the power consumption of the size 6, while figure 2 shows the data for the size 4.

Lab and field tests indicate that for a typical fanbox rated for 2300 cfm with a 1hp ECM motor, the watt decrease can be significant. Data is shown in comparison to a standard permanent split capacitor motor in the same unit. The average watt reduction over the above range is 335 watts.



Another unit with ½ hp ECM motor kW is shown in comparison to a standard permanent split capacitor motor. The average watt reduction over the above range is 178 watts.



The ECM motor when applied to a fan powered terminal offers significant energy savings over time to the owner when compared to conventional induction motors. However, the initial payback of the motor must be considered when applying ECM technology. Several variables will impact the payback of the ECM motor. Some of these are local electric rates, fan settings, whether occupancy schedules are in place for operating hours and the sizes of units installed in the application. An actual field trial, confirmed through bench testing, has produced an example of the potential energy savings when using the ECM motor.

When evaluating this reduction in watts for energy usage the following table shows, at various usage rates, the annual savings per motor. Annual savings assume a run time of 3000 hours per year (250 days at 12 hours/day).

Annual Dollar Savings

Usage	***KW/hr reductions***		
Rate	0.2872	0.35	0.405
$0.05	$43.08	$52.50	$60.75
$0.06	$51.70	$63.00	$72.90
$0.07	$60.31	$73.50	$85.05
$0.08	$68.93	$84.00	$97.20
$0.10	$86.16	$105.00	$121.50
$0.12	$103.39	$126.00	$145.80
$0.14	$120.62	$147.00	$170.10

Also, reduction in demand charges must also be considered. Typically, demand charges are calculated during a 15-minute peak window. Some utilities will qualify the peak demand to only the summer months and use this peak as the monthly charge throughout the remainder of the year while other utilities will calculate demand charges using that months peak kW requirement. The savings associated with reduced demand charges are substantial, as demand charges are usually several dollars per kW. As an example, a typical multi-story office application may require 200 fan terminals. Each fan terminal equipped with an ECM motor may have approximately 0.4 kW reduction in power. This translates to an 80 kW reduction in demand and with a demand rate of $10.00 per kW equates to a potential $800 per month reduction in the demand charges. While this model is simplistic, it is indicative of the payback potential of the motor. Utilities will vary not only in price but also in calculation methods with contract kW's versus actual kW usage so actual savings must be calculated according to local market conditions.

Coupling the usage and demand savings associated with the ECM motors can provide a payback of the motor in less than two years to the owner and provide substantial savings then throughout the life of the building. The use of power always results in a proportional amount of heat generation. With PSC motors, there is typically a 1-2 deg F rise through the unit from heat produced by the motor. In addition, there is some heat produced by the SCR (hence their sometimes significant heat sinks). The ECM motor, with its reduced energy consumption, adds no perceptible heat to the air stream, and the PWM generator has minimal electric consumption and heat generation. Additionally, lower heat generation increases the life of any motor. When combined with the ball bearing design, ECM motors are expected to last significantly longer than equivalent PSC motors.

In Unit Ventilators, the need for high speed operation is typically only a small percentage of the time, and therefore both sound levels and energy consumption are reduced.

Power Factor and Harmonics; The response of the building system to the application of ECM vs. PSC motors is different. There are issues of power factor and harmonics that warrant some discussion. Without presenting a discourse on the basics of alternating current, there are three issues that need some understanding:

1. **Displacement power factor**: PSC motors have a power factor that is primarily a function of the phase angle between line voltage and the line current flowing to the motor. The displacement power factor for ECM motors is 1. For PSC motors, it is about 90% at rated load, and can degrade to 60% at off load conditions.

2. **True power factor**: The true power factor is the ratio of power consumed (in watts) to the volt-amperes needed to supply the load. For PSC motors, the Displacement and True power factors are the same. For ECM motors, however, there are harmonic effects that can cause a difference between the two.

3. **Harmonic currents**: These are a collection of sine waves whose frequencies are integral multiples of the fundamental frequency of a non-linear waveform. These factors are significant in buildings with three phase wye-connected distribution systems, and are generally addressed in the power distribution design in order to contend with electronic ballasts, computer and other electronic loads.

The consequence of the differences between ECM and PSC motor applications is that the building electrical system must contend with the greater harmonic distortion created by the ECM motors, and that technicians should understand the potential of misreading amperages seen with ECM motors caused by these harmonics. These effects can be minimized through the installation of a low cost choke on the power line.

The building electrical layout should be designed to accommodate the resultant harmonics, and design features such as slightly increased neutral wire size at the electrical panel should be considered.

ECM Flow Capacity; Another striking advantage of the ECM motor is its greater operating range, allowing a single motor blower combination to be used over a very broad range of air flows. The extension of the unit's performance at low flows is due to two factors.

1. The typical PSC motor utilizes a sleeve bearing, both for low cost and for acoustical reasons. The minimum recommended rpm for a sleeve bearing is 600 rpm. This is due to the centrifugally lubricated mode of the bearing. Lower rpm results in increased weight on the sleeve bearing resulting in potential

bearing failure. The sleeve bearing, however, is somewhat quieter in the low frequencies than a ball bearing motor. The ECM motor, on the other hand, is designed with ball bearings in lieu of sleeve bearings allowing for increased loads and no minimum rpm limit. The slight increase in bearing noise is offset by the greatly reduced motor noise from the brushless dc motor.

2. The PSC motor becomes unstable at low rpm, the result of the chopped wave form produced by the SCR speed controller, and has very low start-up torque. Series flow fan terminals need a higher start-up torque to overcome the potential for backward rotation that is inherent in a series flow unit. In addition, PSC motors become very unstable at very high speeds, which is common when used with manual dampers.

3. Unit ventilators, which are typically set to run at multiple fan speeds, can be programmed to run at different points depending on the application. The ‘three-speed’ PSC motor cannot be changed after installation, and is never as efficient at the lower motor taps as it could be at a single speed winding. It is further limited to its lowest speed by the sleeve bearing limit of 600 rpm.

Application Features

The installation of an ECM motor in a fan terminal or unit ventilator requires significant laboratory time to develop the necessary constants for the motor/blower combination. Development of the ECM motor/blower combination is specific to the flow characteristics of each manufacture’s design. By carefully programming the motor's integral control computer, flow control independent of external static pressure can create an accuracy of +/- 5%. Developed fan curve graphs therefore show a 'constant volume' operating envelope. Within this area, the fan-powered terminal will deliver a constant airflow over the range of external pressures shown.

The control of fan speed is fundamentally different for an ECM motor than it is for a PSC motor. The PSC motor is controlled by modifying the power supplied to the motor through a wave 'chopper', typically an SCR, which reduces the available voltage to the motor, or through multiple ‘taps’, or both. The SCR device is installed on the high voltage line leading to the motor, and is usually adjusted with a screwdriver through a slot on the control enclosure of the unit. As described earlier, this control is very much an 'open loop' control, and the unit will change airflow in response to varying external pressures. There are a number of installed applications for DDC control of the SCR on fan terminals. These applications require a means of flow verification, typically a flow pick-up and pressure transducer, in order to assure delivery of the desired airflow.

The ECM, on the other hand, is controlled by sending a low voltage pulse width modified (PWM) control signal to the integrated circuit at the rear of the motor, commanding it to control to a fixed percentage of its programmed cfm flow range. The motor then computes the necessary motor parameters to achieve this commanded condition. Typically, a PWM generator is provided as a part of the ECM motor assembly/circuit. This device, which looks similar to the SCR, except that it does not require the often massive heat sinks associated with the later, and has a similar screwdriver adjustment potentiometer. It is not wired, however, on the high voltage side of the unit. Rather, it draws power from the low voltage (24 VAC) transformer in the unit, and sends the necessary control signal to the ECM through low voltage control circuitry. Alternately, the vav controller may send the desired PWM signal directly to the ECM motor.

This control module can also receive a variable control voltage signal from the DDC unit in the fan terminal, controlling the unit airflow directly from the DDC system. Because of the constant volume nature of the ECM motor, no flow verification is necessary to assure pressure independent air delivery. This eliminates the need for an additional pressure transducer and logic in the DDC controller. Unit ventilator controllers may change the desired flow rate as a function of demand.

While there may appear to be an opportunity to eliminate the air balancer in setting fan terminals, by providing a factory set flow range, this is probably not practical. Rather, the constant airflow will greatly reduce the effort required by the balancer in establishing proper flow at all the downstream diffusers, as the delivered flow will not change as the balancer adjusts the diffusers' dampers.

The real benefit of the ECM motor will be realized when the direct control of the fan is coordinated through the DDC system to optimize performance. While a typical installation of constant volume series flow terminals will benefit from the ECM motor's energy savings alone, significantly more savings can be realized by optimizing the airflow to the zone. Flows can be reduced in heating mode, where only the amount of 90^{o}F air necessary to handle the designed heat load, which is typically 1/2 of the cooling airflow requirement, is supplied to the zone. Flows can be reduced to ventilation minimums when a space is unoccupied, or when external loads equal interior loads. These and other innovative strategies can take advantage of the ECM's self-regulating airflow control through the interface, or even direct PWM control of the motor. These benefits are already being realized in some Unit Ventilator applications.

The benefits of using an ECM motor in fan-powered terminal units and unit ventilators are many. They provide cost paybacks increasing the investment value of an installation. They offer flexibility in design and control. They do require some care in designing the building's electrical system to accommodate the nature of the ECM's power requirements. The great range of air delivery performance allows fewer selections, simplifying the building owner's maintenance and increasing diversity, and at the same time allowing a stocking distributor more flexibility with less inventory.

There are IAQ benefits for the occupants as well. The pressure independent nature of the design allows consideration of high performance filters with insured delivery of the required amount of ventilation air. These issues lead to increased occupant confidence in their HVAC system, and increased productivity. With a 2000/1 ratio between productivity (salary and benefits) and energy costs, these may provide the greatest payback of all. It remains only for the control suppliers, design engineers, and building electrical designs to take advantage of this potential, for building owners to reap the benefits.

Summary

ECM motors offer the potential for both energy savings and indoor environmental improvements. The features of this technology have yet to be fully implemented, but promise to provide both building owners and occupants improved environments and economic advantages.