A Constant Air Flow Rate Control of Blower for Residential Applications

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Abstract - This paper presents a technique to control blower for the residential applications at constant air flow rate using induction motor drive. The control scheme combines a variable Volt/Hertz ratio inverter drive and an average motor current regulation loop to achieve the control of the motor torque-speed characteristics, and consequently controlling the air flow rate of the blower which the motor is driving. The controller is simple for implementation and practical for commercialization, it is also reliable since no external pressure or air flow sensor is required. Both theoretical derivation and experimental verification for the control scheme are presented in the paper.

I. INTRODUCTION

Conventional HVAC system for residential applications such as furnace, heat pump and air-conditioner, typically use single phase motor for blower to move air. Single phase motors operate at fixed voltage, their speed varies with the air pressure on the blades of the blower, therefore the volume of air moved by the blower through the heat exchanging unit and into the ductwork also varies with the load pressure. It has been shown by the previous studies that the efficiency of a heating or cooling system will improve significantly when the air flow rate through the heat exchanging is maintained at constant level[1][2]. Recently the constant air flow rate control has become an important criteria for appliance manufacturers in selecting blower drive due to increase government regulations on system efficiency of air moving appliances. Besides advantage of higher system efficiency, constant air flow rate control can also provide better temperature and humidity control and raises the comfort level for the residents.

A number of researches have been directed toward development of constant air flow rate controller for blowers in residential HVAC systems[2][3]. In general, to control air flow rate to a set point regardless load variation the motor must vary its speed according to the air pressure in the ductwork. Thus a variable speed drive equipped with air pressure sensors in the ductwork is generally needed to realized the control. However, this approach is not practical from the cost and reliability point of view since pressure sensors increase cost and reduce reliability of the whole system. In this paper, a simple but effective method to control air flow rate of an inverter driven blower is proposed. In stead of measuring the air flow rate directly, the proposed scheme controls the motor to follow a prescribed torque-speed trajectory, and thus indirectly controls the air flow rate. A variable Volt/Hertz ratio inverter with an outer motor current control loop are utilized to achieve this control. The motor torque-speed relations for constant air flow rate output are derived based on the principle deduced from the fan laws.

The constant air flow rate control laws are derived and shown in Section II. The control scheme was implemented in a low cost 8-bit microprocessor and verified experimentally, implementation of the controller is shown Section III. Important experimental results and discussion of the control scheme are summarized in Section IV.

II. PRINCIPLE OF CONSTANT AIR FLOW RATE CONTROL

Assuming friction losses in the blower and the ductwork are negligible, then for a direct driven centrifugal blower the relationship between motor shaft torque and speed of the blower cage at two different operating conditions but with the same air flow rate can be derived from the basic laws for fan and blower to be[4]:

$$\frac{T_1}{\omega_1} = \frac{T_2}{\omega_2} \tag{1}$$

where T is the shaft torque, and ω is the speed of the blower cage and the motor. The above equation states that to maintain constant air flow rate at the blower outlet the motor output torque must be proportional to the motor speed regardless of the air pressure in the ductwork.

Although the control law shown in Eq. (1) can be realized easily with high performance drive systems such as vector controlled induction or BLDC drives, however, such systems are not practical for residential HVAC applications due to the cost of position/velocity sensor and its associate circuits. Moreover, motors with positional sensor require additional space for installation, and the physical space in blowers are often limited and can not be compromised. Therefore, a volt/hertz inverter drive with a novel control

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strategy is designed to realize the control law shown in Eq.(1).

Derivation of the control strategy is based on the conventional per-phase equivalent circuit of a three-phase induction motor shown in Fig. 1. Assuming no iron saturation and a nonlinear Volt/Hertz inverter is utilized such that the motor terminal voltage is an exponential function of the excitation frequency as follows:

$$E = K_v \omega_e \sqrt{\omega_e} \tag{2}$$

Notice E is the induced stator voltage, or the motor terminal voltage minus IR drop, and K_v is a scaling constant which can be selected to yield rated voltage for E at the rated frequency. Then solving the equivalent circuit with constraint of Eq. (2), the motor developed torque can be expressed in terms of motor parameters and E as:

$$T_e = 3\frac{P}{2}\frac{s\omega_e r_r\left(\frac{L_m}{L_s}\right)^2}{(s\omega_e)^2(\sigma L_r)^2 + r_r^2} K_v^2 \omega_e \tag{3}$$

also the stator current is:

$$I_s = \frac{s\omega_e\sqrt{\left(\frac{r_r L_m^2}{L_s}\right)^2 + \left(\frac{r_r^2}{s\omega_e} + s\omega_e \sigma L_r^2\right)^2}}{\left[(s\omega_e)^2(\sigma L_r)^2 + r_r^2\right] L_s} K_v \sqrt{\omega_e} \tag{4}$$

where the leakage factor $\sigma = 1 - \frac{L_m^2}{L_r L_s}$.

As can be seen from Eq. (3) that the motor generated torque is proportional to the excitation frequency if slip frequency is kept constant and the motor parameters do not change during the operation. Then the motor torque is proportional to the motor speed since the slip frequency is constant. On the other hand from Eq. (4), it is possible to keep the slip frequency constant if stator current is controlled to be a function of the excitation frequency as follows:

$$I_s = K_i \sqrt{\omega_e} \tag{5}$$

where K_i is a control constant.

The above derivation has shown an interesting result that motor torque/speed relationship for constant air flow rate control, i.e. Eq. (1), can be realized with two separate control laws: 1) motor voltage E proportional to $\omega_e\sqrt{\omega_e}$, and 2) stator current I_s proportional to $\sqrt{\omega_e}$. Note that K_i is the slope of the motor generated torque vs. frequency, and it determines the air flow rate output of the blower, higher K_i gives higher air flow rate. This controller is different from the conventional constant V/F drive, constant V/F drive controls motor voltage and frequency and let motor current follows the load, but the proposed control scheme impose functional relationships between the motor voltage, stator current and the excitation frequency, and the actual operating voltage, current and frequency are determined by the load.

Calculations to analyze the performance of the proposed control scheme is performed on a 200 V, 6 poles, 3 phase induction motor, the motor parameters can be found in the Appendix. Fig. 2 shows the motor voltage E vs. excitation frequency for the constant air flow rate control. Motor current vs. frequency curves at various motor voltage E, and typical stator current vs. frequency curves for the constant air flow rate control, i.e. Eq. (5) are also shown in Fig. 3. Three constant air flow rate controlled curves are shown in this figure, each curve corresponds to a particular air flow rate. Note the unit for air flow rate is cubic feet per minute, or simply "CFM". The relationship between Ki and the air flow rate varies with blower size and shape, and was found in the laboratory experimentally.

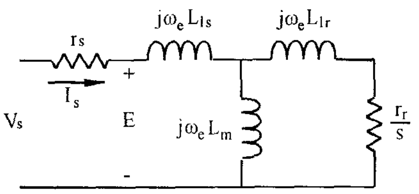

Fig. 1 Per-phase Equivalent Circuit of a Three Phase Induction Motor

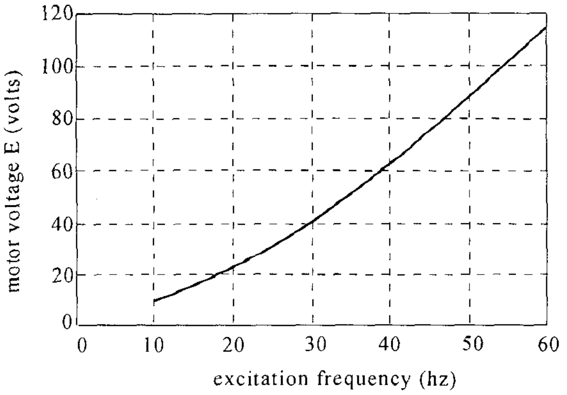

Fig. 2 Motor Voltage E vs. Frequency for Constant Air Flow Rate Control

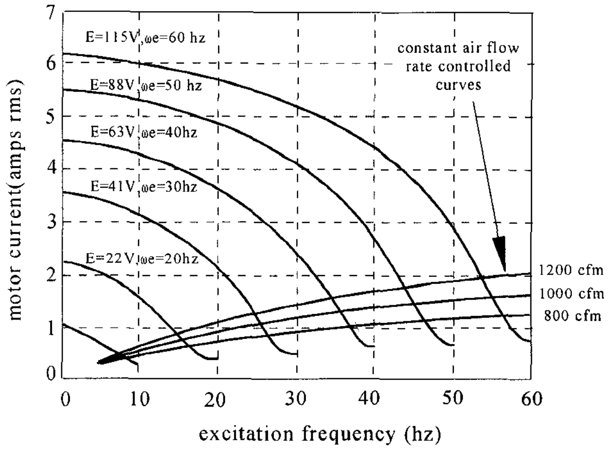

Fig. 3 Motor Current vs. Excitation Frequency Curves at Various Voltage E, and Current vs. Excitation Frequency for Air Flow Rate = 800, 1000, and 1200 CFM

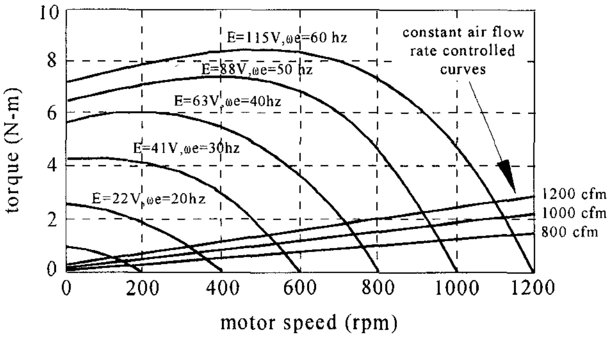

Fig. 4 Motor Torque vs. Speed Curves for Various Voltage E, and Motor Torque vs. Speed Curves for Air Flow Rate = 800, 1000, and 1200 CFM

Calculated motor torque vs. speed curves for various voltage E, and the motor torque vs. speed relations under constant air flow rate control for various set pints are shown in Fig. 4. It can be seen from Fig. 3 that there is a limitation on how low the air flow rate can be controlled. This limitation is due to the torque producing component of the motor current becomes very small as the rotor electrical speed gets near the supply frequency, and the controller becomes ineffective in controlling motor torque. The minimum air flow rate is around 400 CFM for the motor and blower analyzed in this paper.

Note that the controller is derived under the assumption of constant motor parameters. This assumption is in general not true since the controlled E/ω_e ratio is proportional to the square root of the supply frequency. Thus the level of iron saturation increases as the supplying frequency increase. In the calculation results shown above the saturation effect was approximated by treating the mutual inductance as a nonlinear function of stator flux [5]. However, it will be shown later from the experimental results that the error due to the saturation effect is small enough that there is no practical value to compensate for it.

III. IMPLEMENTATION OF THE CONSTANT AIR FLOW RATE CONTROL

The proposed control scheme was implemented with an NEC 8 bit microprocessor, block diagram of the controller is shown in Fig. 5. Air flow rate command from the external user interface is converted into an I_s vs. ω_e command curve first. All the possible I_s vs. ω_e command curve for air flow rate set points are stored as tabular form in the microprocessor. Although I_s is a nonlinear function of ω_e as indicated by Eq. (5), straight line approximation between I_s and ω_e is adopted to simplify calculations in the actual implementation. The error due to this approximation is very small since the working frequency is typically between 20-60 Hz, and I_s vs. ω_e curves is fairly linear in this region.

The motor current command is calculated by using the excitation frequency as the index to the I_s vs. ω_e command curve. In the experimental setup the excitation frequency was measured with a current transformer, a zero crossing circuit and a counter in the microprocessor. After the motor current command is calculated a PI regulator is performed to regulate the motor current error by manipulating the excitation frequency. Since the motor voltage is controlled to be a function of the excitation frequency as shown in Eq. (2), thus the operating E, I_s and ω_e are moving along the E vs. ω_e curve shown in Fig. 2 and the I_s vs. ω_e curve shown in Fig. 3. Note that since the blower load is highly damped and varies much slower than the motor electrical transient responses, the motor current regulation loop is essentially a steady state controller, or an average current controller. The sampling time for the PI regulation loop is designed to be around 0.5 sec.

A space vector PWM [5] for the motor voltage and frequency modulation is implemented in the microprocessor to reduce cost and size of the controller, the PWM switching frequency is about 3 KHz. The modulator also included an voltage compensator to compensate for the bus voltage drop due to the variation of the bus current when the motor load is varying, and also compensates for the motor IR drop since the actual controlled variable is the motor terminal voltage and not the voltage E.

IV. EXPERIMENTAL RESULTS

Experimental verification of the constant air flow rate control was performed on a three phase induction motor

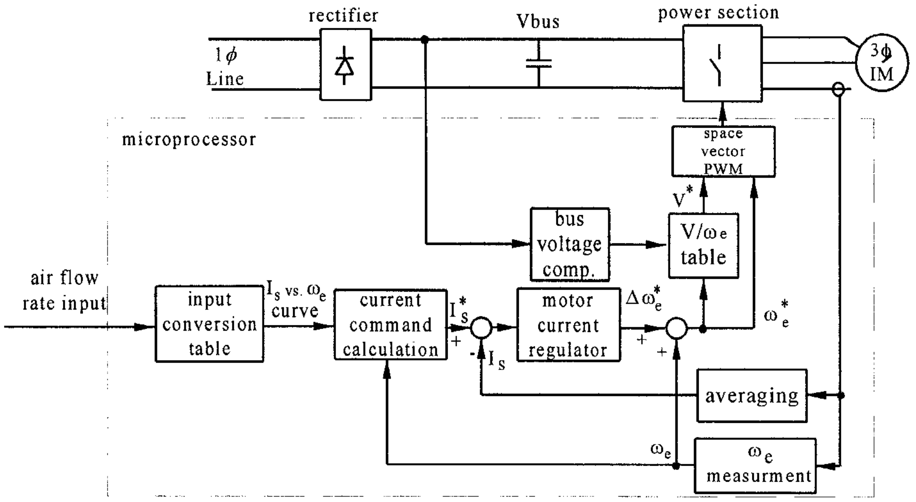

Fig. 5 Block Diagram of the Proposed Constant Air Flow Rate Controller

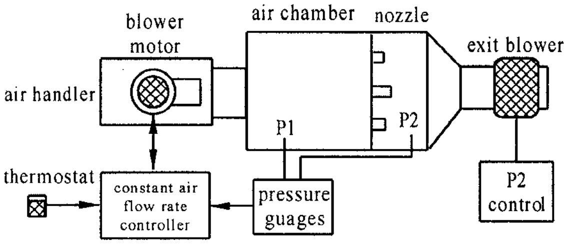

Fig. 6 Schematic of the Experimental Setup

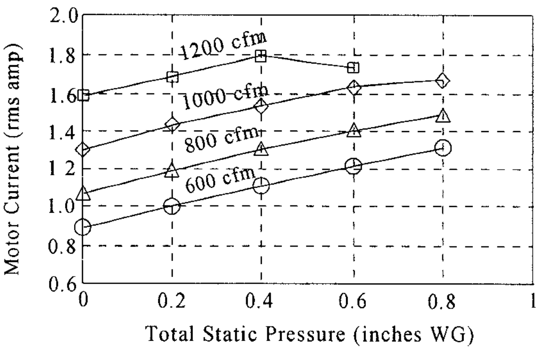

Fig. 8 Measured Motor Current vs. Total Static Pressure P1 under Constant Air Flow Rate Control

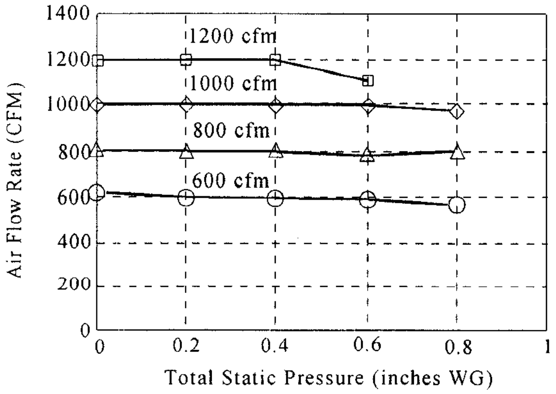

Fig. 7 Measured Air Flow Rate vs. Total Static Pressure P1 under Constant Air Flow Rate Control

mounted on a centrifugal blower, the motor parameters can be found in the Appendix. Schematic of the experimental setup is shown in Fig. 6. The blower was placed inside an air handler commercially commonly used for residential heating/and cooling applications. The outlet of the air handler was connected to an air chamber, the air chamber housed the pressure sensors used to measure air flow rate and also provided load to the air handler and blower motor. As can be seen from Fig. 6, P1 is the pressure at the input section of the air chamber and P2 is the pressure at the exit section of the chamber. Pressure difference between P1 and P2 can be used to calculate the air flow rate[7]. Motor load P1 can be adjusted by varying speed of the exit blower.

Four set points, 600, 800, 1000 and 1200 CFM, for the constant air flow rate control were tested with load pressure P1 varied from 0.0 inch WG (water column) to 0.8 inches WG. The measured air flow rate in CFM vs. load pressure P1 were shown in Fig. 7, and the measured motor current vs.

load pressure for the same tests were shown in Fig. 8. As can be seen from these data the air flow rates were approximately constant for all the set points, the error between each test data and their set points were all within +-30 CFM except for the 1200 CFM set point and when P1 = 0.6 inches WG. The reason for large error at this operating condition is because the controller has reached its maximum supply frequency, i.e. 60 Hz, when the load pressure was around 0.55 inches WG. Therefore the air flow rate can not be kept constant at 1200 CFM when the load pressure was increased beyond this point.

The torque-speed characteristics of the constant air flow rate control was also measured experimentally. A vector controlled induction motor drive was used to provide accurate load torque to the constant air flow rated controlled motor drive on a dynamometer. Load torque was measured via a shaft torque sensor. Three air flow rate set points, 800, 1000 and 1200 CFM, were tested, the measured torque vs. speed and slip frequency vs. speed curves are shown in Fig. 9 and Fig. 10 separately. It can be seen that the motor torque is linearly proportional to motor speed for all three set points, and the data is consistent with the calculated results shown in Fig. 4. Also the measured slip frequency for all the air flow rate set points are approximately constant. These results have demonstrated that the controller is working reasonably well in keeping constant air flow rate of the blower. Even though the motor parameter variations was not accounted for in the proposed control scheme, the experimental results have shown no significant error, and were closely resembled the calculated results.

CONCLUSIONS

A control scheme for constant air flow rate control of blower for residential HVAC applications was developed and presented in this paper. The proposed control scheme utilize an variable Volt/Hertz ratio PWM inverter drive, and does not required pressure sensor for air flow rate measurement. Both the air flow rate controller and the vector PWM were implemented with an 8-bit microprocessor. Experimental results have demonstrated that the controller was able to keep the air flow rate reasonably close to its set point regardless of the motor load.

APPENDIX

Test Motor: 1/2 hp, 3 phase, 6 poles, 1100 rpm, $R_s = 6$ ohms, $R_r = 7$ ohms, $L_{ls} = 21$ mH, $L_{lr} = 21$ mH, $L_m = 260$ mH

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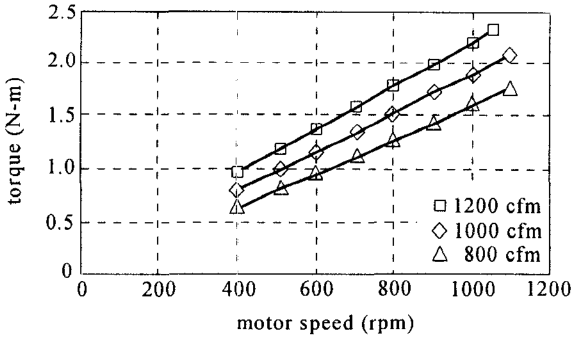

Fig. 9 Measured Shaft Torque vs. Speed under Constant Air Flow Rate Control

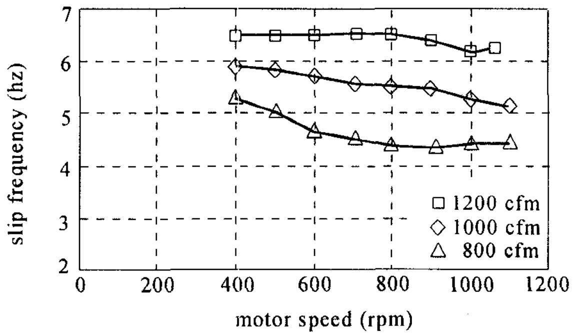

Fig. 10 Measured Motor Slip Frequency vs. Speed Constant Air Flow Rate Control

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