Brushless Motor Drive based on Power Control Method for Direct Evaporative Air Cooler

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***Abstract*—Direct Evaporative air cooler (or evaporative cooler) with single-phase induction motor (SPIM) is one of the least efficient and commonly used appliances in Iran and over the world. For energy saving, new generation of evaporative coolers have been equipped with high efficient permanent magnet brushless (PMBL) motors. The control method of brushless motor is mostly based on the speed control, in which it works at two constant speeds. However, experimental tests show that, due to characteristics of the cooler's blower, the airflow rate is not related to the blower speed alone and increasing the length of duct reduces airflow rate. To solve this problem, in this paper, a novel control method is proposed to stabilize airflow rate, in which, instead of using speed control method, the motor is controlled in constant power control scheme. On this way, a 5000 m^3/h evaporative cooler equipped with brushless motor is tested in the reference laboratory under airflow test with speed and power control methods. The captured results verify the superiority of PMBL motor than SPIM, and also the performance enhancement of the cooler using power control rather than speed control method.**

Keywords*—brushless motor, electrical drive, energy saving, evaporative cooler, power control.

I. INTRODUCTION

Evaporative coolers are one of the most widely used household appliances due to the warm and dry climates of most regions in Iran. The official statistics show that there are 17 million evaporative coolers that work more than half of year. Considering the power consumption of 400 W per evaporative cooler and the efficiency of 70% for power transfer from electrical power plant to homes, consumption of evaporative cooler motors in the country is about 10 GW. It is about of 20% power electricity capacity of the country. Increasing efficiency and reducing energy consumption in these motors, due to the same pattern of consumption, leads to considerable help to reduce fossil fuel consumption and environmental pollution. A 30% energy saving for each motor of evaporative cooler results in savings of about 3 GW, which is equal to the power capacity of three great thermal power plants [1,2].

Permanent magnet brushless (PMBL) motor is one of the best choices as a substitution for single-phase induction motors (SPIMs) used in conventional evaporative coolers [3,4]. These motors generally have higher efficiency of 85% and considering the efficiency higher than 95% for PMBL drive, it could be expected overall efficiency is higher than 80%. Comparing with efficiency of SPIMs, it represents an increase at least 30% of efficiency. Along with higher efficiency, there are other attractive features, such as variable speed feature, remote control capability, and integration with building energy management systems. The requirements for the brushless motor used in this application have been determined by the Iranian National Standardization Organization joined with the power research institute. On this way a new national standard INSO 3772-30-1-3:2017 has been developed [5]. Most of evaporative coolers in the market are divided into three main categories with airflow rate of 3500, 5000 and 7000 (m^3/h). With respect to outlet power of corresponding centrifuge blowers of these coolers, the SPIMs used in coolers have the rated power of 1/3, 1/2 and 3/4 horse power (hp). So, the output power of brushless motors used in these three coolers are exactly considered as same as the three mentioned SPIMs.

There is few published research about using of brushless motor in evaporative coolers. Most researches have been carried out on other household air-conditioners, such as evaporative gas coolers and household compressors. In [6], an investigation has been carried out on the fault diagnosis of BLDC motor in the air handler unit (AHU). It has mainly focused on two severe problems in blower wheel, namely airflow blockage and unbalanced load of fan motor. Reference [7] has developed a sensorless operation of brushless dc motor drive designed for air conditioners. It has used the BLDC motor in a speed control mode. In [8,9], the power quality issues of using BLDC motor drive in the household air-conditioning system according to IEC61000-3-2. In all mentioned research and also even commercial evaporative coolers available on the market, control methodology of brushless motor drive is based on speed control method. To analogy with conventional coolers, the manufacturers of newly evaporative coolers equipped to brushless motor, design them at two speeds of low and high based on speed control method. But due to the characteristics of the cooler's blower, as the load on the brushless motor, the airflow rate is not only dependent on the speed of blower, but also depends to the length of duct. Increasing the length of duct can reduce air flow rate, and despite of the paid cost, the airflow rate will not be desirable for the owner.

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In order to solve this problem, this paper proposes a new method to maintain the airflow rate in longer ducts. For this purpose, instead of using speed control method, the motor is controlled in power control mode and the power output of the brushless motor is regulated at the desired value. In this case, depending on the length of the duct, the motor speed changes to ensure that the output power is kept constant.

In the rest of paper and in section II, results of the construction and testing of the brushless motor using dynamometer system are presented. In section III, the concept of new method for controlling the brushless motor for the evaporative cooler based on power control method is developed. In section IV, the results of airflow rate test with both speed and power control methods are compared. The last section discusses on the results.

II. MANUFACTURED BRUSHLESS MOTOR DRIVE AND DYNAMOMETER TEST RESULTS OF THE

A. Brushless Motor

The employed brushless motor in this research is an inner rotor with 8 poles. It is a 1/2 hp (375 W) with rated speed 1450 rpm that is designed for a 5000 m^3/h evaporative cooler. The stator is connected as star and consists of 12 slots. Also, ferrite PM is used in the rotor of manufactured brushless motor.

B. Conventional Control Strategy

The results of the finite element analysis and generator test indicate that induced back-EMF voltage of used PMBL motor is non-sinusoidal shape. Conventionally, when the induced back-EMF voltage is neither sinusoidal, nor trapezoidal, the control method used is dependent on the application. If very smooth torque is needed, special control methods such as selective torque harmonic elimination (SHE) or improved vector control techniques are used [10]. Otherwise, both vector control or six-step current control method can be used. In the application of the evaporative cooler, the recommended value for mechanical vibration and acoustic noise are 1.6 mm/s^2 and 55 dB respectively, which are not so rigorous. Therefore, for simplicity of drive structure, six-step current control method is employed. To improve the quality of developed torque, three current sensors are used and so,

Figure 2. Hysteresis type dynamometer for efficiency test of manufactured brushless motor-drive

instead of regulation the dc link current, the independent three-phase current regulation is used. Fig. 1 shows the block diagram of employed control system.

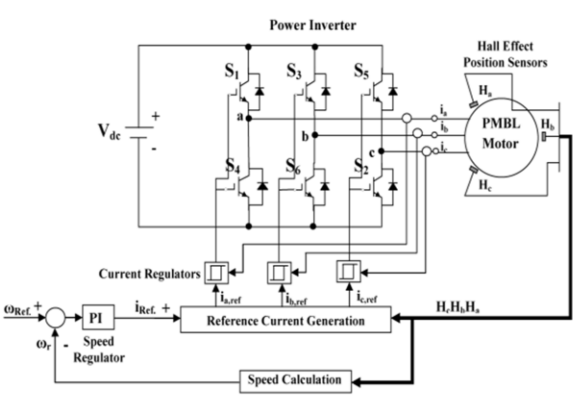


Figure 1. Conventional control system of brushless motor

C. Dynamometer Test Results

In order to confirm the performance of the built motor-drive assembly, the 1/2 hp brushless motor-drive is tested in the National Standard Laboratory in different conditions. A dynamometer shown in Fig. 2 is used to measure the motor-drive efficiency. This system measures the load torque, motor speed, and the absorbed power from the drive. Measurements are performed according to the national standard for brushless motors testing (INSO 3772-30-1-3). Dynamometer test is carried out at two blower's speeds of 450 rpm (high speed) and 300 rpm (low speed). It should be noted with considering the ratio of 256/70 for the blower's pulley diameter to motor's pulley diameter, the high/low speeds of the motor will be 1450/900 rpm respectively. To have a good sense of the captured results, they are compared with the dynamometer test results of a typical 1/2 hp single phase induction motor tested in the same working conditions.

The results of the performed tests are summarized in Table I. The overall efficiency of the brushless motor drive system in both high and low speeds are 83% and 84%, respectively. They exceed the standard requirement for brushless motors that are 66.3% and 81.1% for low and high speed respectively. It should be noted that achieved efficiency by brushless motor drive is 60~100% higher than the efficiency of SPIMs, and therefore using brushless motors results a significant improvement in energy savings.

III. PROPOSED POWER CONTROL METHOD

TABLE I. DYNAMOMETER TEST RESULTS OF BRUSHLESS (PMBL) AND SINGLE PHASE INDUCTION MOTOR (SPIM) FOR EVAPORATIVE COOLER

Quantity	Low speed (950 rpm)		High speed (1450 rpm)	
	PMBL	**SPIM**	**PMBL**	**SPIM**
Input power (W)	153	320	442	781
Output power (W)	124.4	120	368	372
Load torque (N.m)	1.25	1.21	2.5	2.5
Power factor of drive	.981	---	0.97	---
Input current of drive	0.7	1.45	2.57	2.5
THD current of drive	8.2	0	5	0
Efficiency (%)	83	37.6	84	48.3

A. Fluid Analysis of Fan Behavior

Nominal airflow rate of evaporative coolers is achieved with a specific length of duct. In the application based on constant speed control method, longer duct decreases the airflow rate from its nominal value and vice versa. But if the speed of cooler's fan is allowed to change, the airflow rate also changes. If the torque or power on the shaft is chosen for control, the fan speed will be changed automatically. In the following, it is shown that if the output power to be fixed, the airflow rate can be maintained.

Affinity laws represent the relationship between capacity (flow), rotational speed, and pressure of centrifuge fan such as blower of evaporative cooler [11]; the capacity of the fan varies with its rotational speed; the differential pressure developed by the fan varies as the square of the rotational speed; and the power required by the fan varies with cube of the rotational speed. The summary form of these laws is:

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \tag{1}$$

$$\frac{\Delta P_2}{\Delta P_1} = \left(\frac{N_2}{N_1}\right)^2 \tag{2}$$

$$\frac{P_2}{P_1} = \left(\frac{N_2}{N_1}\right)^3 \tag{3}$$

In above relationships, N is rotational speed of fan, Q is airflow rate, ΔP is differential pressure (or static pressure) between inlet and outlet of the airflow path (or duct), and P is the consumed power by fan. Fig. 3 shows the fan characteristic curve at two different rotational speeds N_1 and N_2. The fan curve is graph depicting the various points that the fan can operate. It indicates the amount of flow (Q) the fan will provide at a given total static pressure (ΔP), which is dependent on the connected ducted system. The two N_1 and N_2 speeds, which is $N_1 > N_2$, can be matched to the two speeds (high/low) of an evaporative cooler. The second curve that works in conjunction with the fan curve is the system resistance curve. This curve is summation of all the friction losses in the ducting system at varying flow (Q). The resistance or friction losses of the system depend on the length, bend and dimensions of the duct. If the resistance is lower, the system curve will shift to the right and higher resistance will cause the curve to shift to the left. For example, in Fig. 3, the curve SC_1 corresponds to a duct with less resistance, and the SC_2 curve is belonged to a longer duct that has higher resistance.

It has been shown that the amount of airflow rate blown by the fan can be changed by the system resistance and also by changing the fan speed. The operating point of the cooler is determined by the intersection of fan curve with system curve. As shown in Fig. 3, there are four operating points (A,B,C,D) corresponding to fan speeds of N_1 and N_2 and two different system curves SC_1 and SC_2. For the fan of evaporative cooler, according to Fig. 3, increasing the pressure (ΔP) causes a decrease in the airflow rate. In other words, by increasing the pressure from point A to point B (changing ΔP from ΔP_1 to ΔP_2), the airflow rate decreases from Q_1 to Q_2. To clarify this phenomenon, consider two identical evaporative coolers 5000 m^3/h equipped with two similar speed-controlled brushless motor drives. They are employed for air-conditioning of a 1-floor and bottom floor of 2-floors buildings at speed of 1450 rpm and are installed on the roof. Due to the longer length of the duct in the 2-floor building, higher pressure is created, and therefore the airflow rate will be less than airflow rate of cooler used in the 1-floor building. Therefore, the owner of 2-floor building will have to buy a higher capacity cooler (for example a 7,000 m^3/h instead of a 5000 m^3/h) and pay more money.

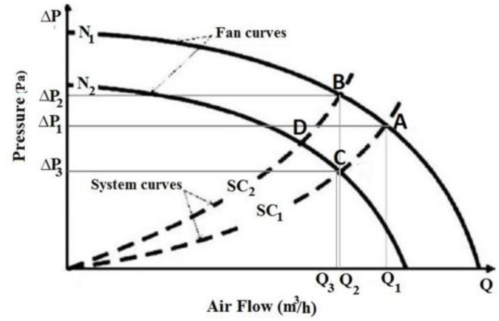


Figure 3. Fan characteristic curves and system resistance curves of a centrifuge fan at two different rotational speeds

To solve this problem, the claim of this paper is that if the brushless motor is controlled with power control method, the airflow rate can be constant in various length of duct. The reason for this behavior of the fan can be described with respect to fan curve (Q-ΔP) for a given constant power instead of fan curve in constant speed. The Q-ΔP curve of the same previous fan in constant power mode is shown in Fig. 4. The red curve shows the fan curve when the input power to the fan is kept constant in value of P_1. For a better comparison, the fan curve at constant speed N_1 is also plotted in Fig. 4. Also, to see the displacement of operating point on two curves (constant power and constant speed) due to change of system curve (SC_1 to SC_2), it is assumed that the operating associated with SC_2 curve of the constant power mode is exactly the same as the operating point of the constant speed mode.

As shown in Fig. 4, the fan curve in constant power mode has more slope than fan curve in constant speed mode. Therefore, for two curves of SC_1 and SC_2, the airflow rate will

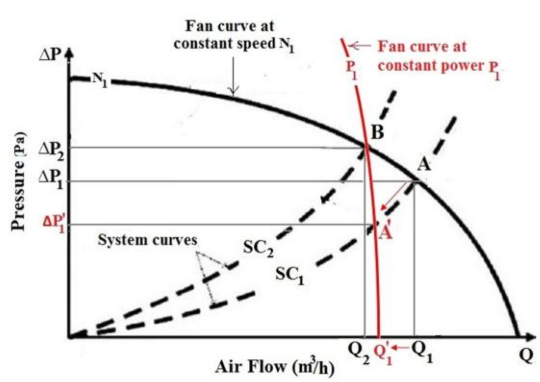


Figure 4. Fan characteristic curves and system resistance curves of a centrifuge fan at constant speed N_1 and constant power P_1

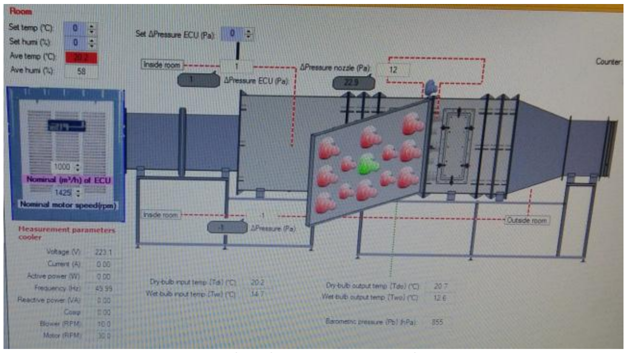


Figure 6. The schematic of airflow test system for evaporative cooler in the reference laboratory

be Q'_1 and Q_2 and operating point associated with the SC_1 curve in this case will be point A' instead of point A. It is clear that the displacement ($Q_1 - Q_2$) associated with constant speed curve is more than displacement ($Q'_1 - Q_2$) associated with constant power curve. It means that the reduction of airflow rate for two ducts with different lengths in constant power mode is less than one in constant speed mode. It should be noted that in constant power mode, the fan speed associated with SC_2 (point B) is higher than the fan speed associated with SC_1 (point A'). It means that for a duct with higher friction losses, the fan should rotate at higher speed. The reason for this phenomenon can be explained by Affinity fluid laws and Newton's motion law easily.

B. *Brushless Motor Drive Design in Power Control Method*

It has been proven that the control of the brushless motor in constant power method results in better stability of the outlet airflow rate for different system curves. Therefore, instead of designing an evaporative cooler with two speeds key (high/low), it can works in two cases high /low airflow. Such a design is not sensitive to changes in the length of duct, and the user may place the cooler without any extra duct, whether on the roof of a 1-floor building or on the roof of a higher building. The amount of high and low airflow rates can be adjusted by the designer in the factory. Even it can be designed three values for airflow rate as high/moderate/low.

The block diagram of the brushless motor drive control system is drawn based on the power control method is shown in Fig. 5. The main difference with the block diagram of the conventional brushless motor drive shown in Fig. 1 is only in

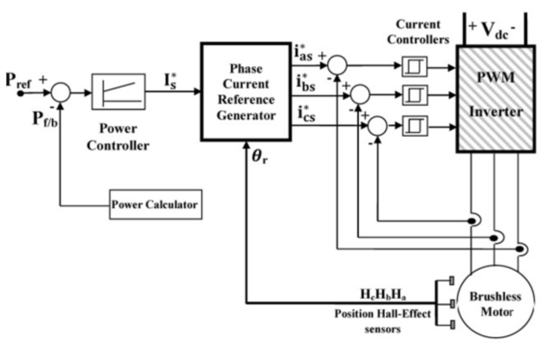


Figure 5. Block diagram of the suggested control system of brushless motor drive based on power control approach used for evaporative cooler

the outer control loop. The values of reference power (P_{ref}) corresponding to the desired outlet airflow rate is determined by the system designer and is selected by the customer. The feedback power $P_{f/b}$ is the actual delivered power to the fan that is equal to the output power of brushless motor. But the main question is that how the feedback power $P_{f/b}$ can be measured?

The actual power of the fan ($P_{f/b}$) is equal to the product of torque on the motor shaft and rotational speed. But using of torque sensor on the shaft is practically impossible due to economic reasons. Another solution is to estimate the developed torque using the estimators, which needs many parameters of the motor and fan that leads to a complicated system. Another method is to use the air-gap power of brushless motor, which is briefly described as follows. In accordance with the electrical equivalent circuit of the brushless motor [12], the air-gap power is obtained as follows:

$$P_{ag} = P_{f/b} = e_a i_a + e_b i_b + e_c i_c \tag{4}$$

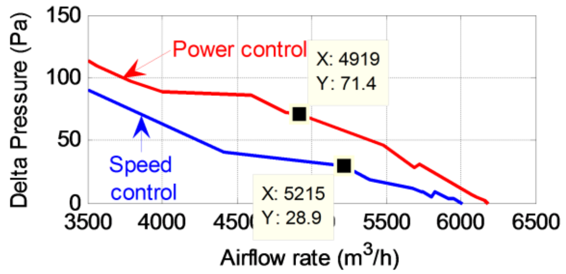
which e_a, e_b, e_c are the phase back-EMF voltages and their waveform depending on the type of motor, that can be sinusoidal, trapezoidal, or any other form. It is not possible to directly measure the back-EMF voltages. These voltages can be predicted via state estimators or calculated using terminal voltages. Because the efficiency of PMBL motor is high and varies a bit over the working speed range, the input power of the motor or drive can be considered as feedback power.

IV. AIRFLOW RATE TEST RESULTS

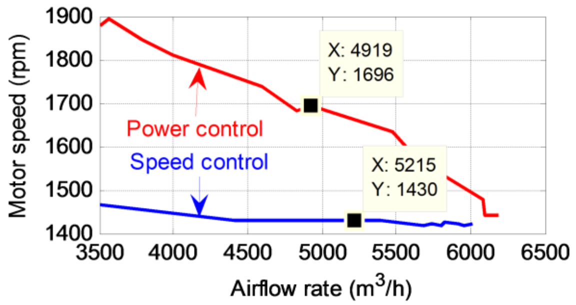
In order to evaluate the performance of the designed brushless motor under actual load, a 5,000 m^3/h evaporative cooler equipped to a 1/2 hp brushless motor is tested by the reference airflow measuring system. This test is carried out according to the ANSI/ASHRAE 133-2015 standard, which determines considerations for testing the standard evaporative coolers [13]. Fig. 6 shows the schematic test station in the laboratory of Lorch Company.

Two control methods of constant speed and constant power are applied to the brushless motor installed in a 5,000 m^3/h evaporative cooler. Fig. 7-a shows the fan characteristic curves of the evaporative cooler in both methods. As shown, a given airflow rate can be produced at a higher ΔP in the constant power method. For example, an airflow rate of about 5,000 m^3/h in constant speed method is produced at a differential pressure of ΔP = 30 Pa, whereas in the constant power method, it is obtained at ΔP = 70 Pa. This means that with a longer duct, it is still possible to create an arbitrary airflow rate. As described in detail in section III, the creation of an arbitrary airflow rate in the higher ΔP involves the fan to rotate at higher speed. This is clearly illustrated in Fig. 7-b.

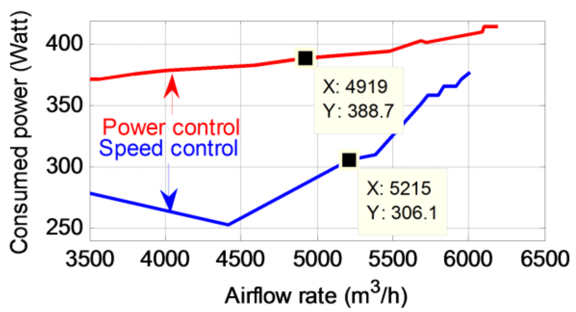
According to the Affinity laws, the creation of an arbitrary airflow at a higher pressure (ΔP) (or the creation of an arbitrary airflow rate through a longer duct) consumes more power and energy, which is well illustrated in Fig. 7-c. For example, for the airflow rate of about 5,000 m^3/h and the



a. Fan characteristic curve



b. Motor speed versus airflow rate



c. Consumed power by the motor versus airflow rate

Figure 7. Comparison of airflow rate test results of both constant speed and constant power methods

pressure ΔP = 30 Pa, in the constant speed method, the brushless motor consumes about 290 W, but to produce the same airflow at the pressure ΔP = 70 Pa, 385 W will be consumed. It is also observed that input power variation versus airflow rate is not much in the constant power method and its deviation is about 10%. But in the constant speed method, the power is reduced from 380 W to 250 W.

V. Conclusion

In this paper, for an evaporative cooler equipped to brushless motor, a newly constant power control method was developed instead of the conventional constant speed control method to solve the problem of reduction the airflow rate caused by using of longer duct in the buildings. The theory of this new method was explained and depending on the choice of feedback power, different solutions were expressed. For further work, because the efficiency of the drive is almost constant over wide range of speed and torque, it is possible to consider the input power of the drive as feedback power. Moreover due to unity power factor of the drive and constant voltage of the grid, the input current of the drive is proportional to the input power and may be employed instead of the power to stabilize the airflow rate.

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