Intelligent Thermal Management Using Brushless DC Fans

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INTRODUCTION

The brushless DC fan (BDC Fan) has become the air mover of choice in computing equipment, office automation products, home entertainment systems, and the like. Unlike conventional DC fans, the BDC fan is mechanically robust because it contains no rotating commutator/brush assembly to shed dust particles, wear out, or act as an ignition source. In addition, its magnetic coils are stationary and are usually mounted within a rigid frame for superior structural integrity and thermal dissipation. BDC fans are electrically quiet: they lack the rotating magnetic fields of AC motors and the arcing of conventional DC motors that broadcast electronic noise.

Although BDC fans are superior to conventional fans, they are still a less than optimum thermal management solution. Because they are electromechanical devices, BDC fans do not achieve the same level of reliability as the system electronics they protect. BDC fan failure commonly results from wear-out mechanisms (primarily fan bearing failures), physical damage, blockage by foreign objects, or electrical failure. Like all air moving devices, BDC fans generate acoustic noise, a growing concern given the number of electronic systems introduced to the home and workplace. These issues can be minimized by adding BDC fan management circuitry to operate the fan only as necessary to maintain system temperature within limits.

SYSTEM CONSIDERATIONS

BDC fan management circuitry is tasked with making judicious use of the fan, while at the same time monitoring its operation. Speed control is employed to minimize fan wear, save power and reduce acoustic noise. This is accomplished by either running the fan only when measured temperature is above a prescribed limit (off/on control) or by modulating fan speed with measured temperature (temperature proportional control).

Since the BDC fan is likely to fail before the system electronics it protects, a fan monitor circuit must be included to provide the earliest possible warning of a fan malfunction. This monitoring circuitry should also include a separate over-temperature system shutdown to act as a “last line of defense” against system meltdown. A thorough design must take other factors into account:

1. The BDC fan consumes a significant amount of current, yet may not always be required. It is therefore advantageous to include a shutdown mode to support “Green” system operation.
2. Most systems generate heat from only one or two sources. Remote sensor capability is therefore mandated.
3. BDC fans may stall (or not start-up at all) under certain conditions. The BDC fan manager must have the ability to force a restart when such a condition is detected.
4. When sensed temperature is low, it may be desirable to continuously operate the fan at low speed, or to shut the fan off, depending on the system application. The appropriate behavior should be incorporated into the BDC Fan Manager.
5. As always, system component count, manufacturability, reliability, cost, size, and weight are underlying considerations.

SYSTEM ARCHITECTURES

Smart Fans

Some BDC fan manufacturers have attempted to address the issues of fan speed control and monitoring with “Smart Fans,” which are standard DC fans with added tachometer output and internal or external temperature sensor. Most Smart Fans have internal temperature sensors that measure the exhaust air temperature. Attempting to infer the system’s thermal condition in this manner is dangerous because of the considerable time lag between increased localized heat generation, and increased exhaust air temperature. Potentially hazardous thermal stress can occur before any indication of a problem is evident at the exhaust port. Changes in airflow and ambient temperature plus the addition of add-in cards serve only to complicate matters.

Smart Fans are significantly more expensive than standard two-wire fans (in some cases, as much as three times the price of an equivalent two-wire fan!). In addition, wiring harness and connector complexity increases, which not only decreases reliability, but also eliminates system retrofit capability. Smart Fans also create procurement problems: they are usually special order items, so the choices of fans and number of vendors is significantly reduced compared with standard two-wire fans. Dedicated BDC fan management circuitry is far more desirable.

BDC Fan Manager

Figure 1 illustrates the component parts of a BDC fan control and monitoring system. This system uses standard, two-wire fans; premium or semi-custom fans are not required. The configuration shown is typical of a modern personal computer power supply. As shown, temperature is sensed at the location of the primary heat source using a low cost temperature sensor and the signal routed to the input of the BDC Fan Manager. Sensing temperature directly at the source of heat results in the most accurate and most immediate measurements.

As previously stated, the BDC Fan Manager speed control scheme can be based on either off/on or temperature proportional speed control. Off/on control is the most basic fan control scheme. With this method, the fan is operated only when measured temperature is above a preset limit. When temperature is below this limit, the fan remains off. This scheme is viable only if the heat generated during normal system operation can be adequately passively dissipated (i.e. by convection and/or conduction). This being true, forced air cooling is required only in extraordinary circumstances, such as in the presence of high ambient temperature and/or heavy system loading.

This scheme is simple, extends fan life, and generates no acoustic noise during periods when the fan is off. However, the system thermal time constant, ambient temperature, and controller hysteresis may occasionally interact to produce frequent or otherwise undesirable patterns of fan operation, resulting in added stress to the fan and objectionable acoustic noise.

Temperature proportional fan speed control utilizes closed-loop feedback to maintain system temperature at a desired level. Fan speed is automatically increased and decreased with changes in sensed temperature. Fan service life is prolonged by virtue of low speed operation and gradual speed changes and acoustic noise are minimized since the fan is rarely (if ever) operated near full speed.

SYSTEM DESIGN

The primary design considerations are the choice of temperature sensor and the method of fan drive and speed control. The choice of sensor dictates the nature and complexity of the analog signal processing needed on the front end of the BDC Fan Manager. Output circuit size, cost, component count, and power dissipation determine the selection of speed control and drive methodology.

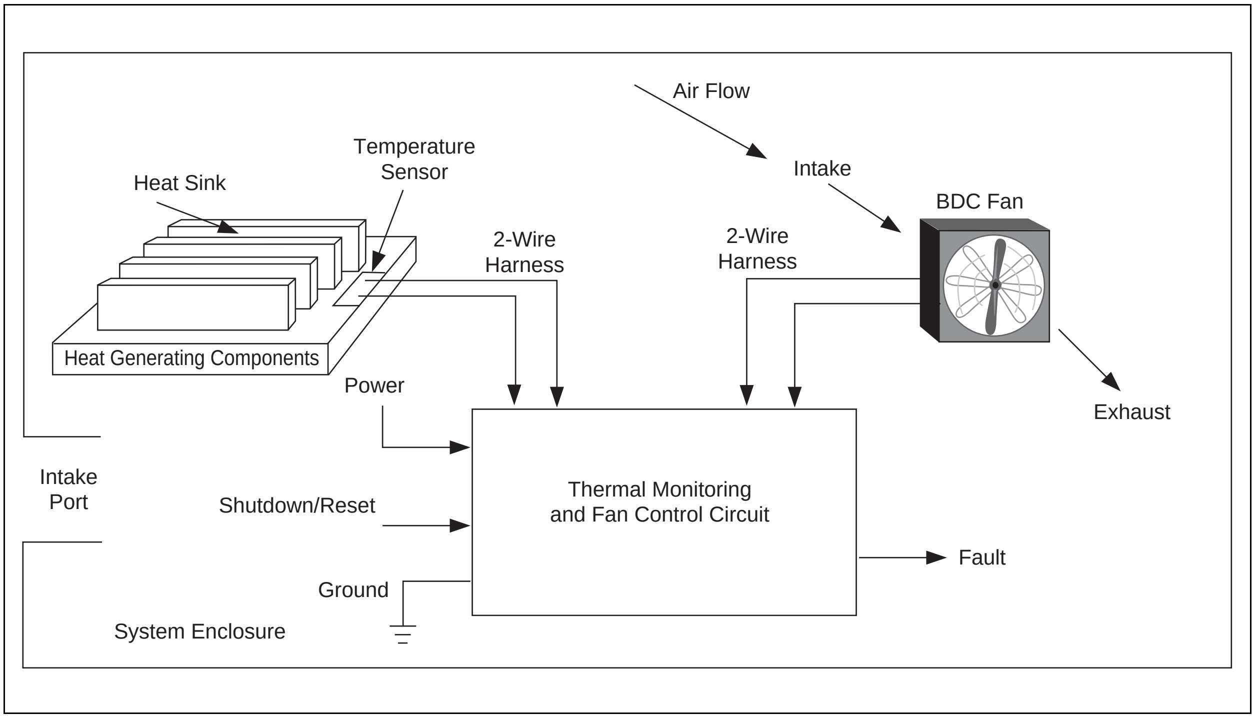

FIGURE 1: *BDC Fan Control and Monitoring System*

Temperature Sensing

The thermistor, or thermally sensitive resistor, has become the sensor of choice for general purpose temperature sensing. Thermistors are simple, two-terminal metal oxide devices that exhibit a known change in electrical resistance versus changes in body temperature. They are available from a number of manufacturers in a variety of physical configurations. The types commonly used in consumer electronics resemble small axial-leaded capacitors. Surface mount or screw mount types are also available. Due to certain aspects of their behavior, negative temperature coefficient thermistors (NTCs) are generally preferred over positive temperature coefficient thermistors (PTCs).

NTCs exhibit a non-linear resistance versus temperature response. By combining a thermistor with one or more standard resistors, a network is created which presents a reasonably linear voltage with respect to temperature. This is shown in Figure 2. It should be noted that linearity is not of great concern for monitoring discrete temperature thresholds nor in systems with feedback.

Various integrated circuits that provide a temperature-proportional voltage output are available from semiconductor vendors. These ICs are a convenient alternative to thermistors. Linearization and drive circuitry is included within the devices so that the output is directly usable. Figure 2 shows an example of these devices. These ICs are attractive because of their high integration, convenient IC packaging, linear behavior, and controlled impedance. In many situations, however, the thermistor is more appropriate because linearity is not of paramount importance, and the need for remote heat sink mounting renders the IC-type packages less convenient. In these situations, a thermistor will have a lower overall cost than an IC.

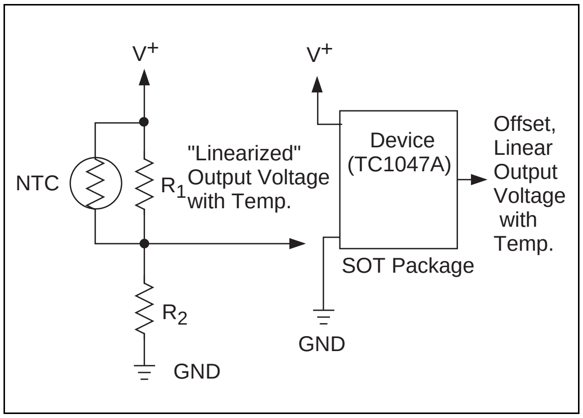

FIGURE 2: Temperature Sensors for BDC Fan Manager

Fan Control Methodology

As previously stated, temperature proportional speed control is superior to off/on control. Fan speed control can be accomplished using linear voltage speed control (voltage regulation), or pulse-width modulation (PWM). Linear voltage speed control is the classic method; its popularity stems from low cost and low component count. The limitations become apparent, however, when driving larger fans at higher power levels or when attempting to idle fans at low speeds in order to reduce acoustic noise and/or energy usage.

Linear Voltage Speed Control

Figure 3 shows a simplified linear voltage speed control system. A temperature-dependent voltage signal (V_{TEMP}) is amplified by a series of power transistors until the current handling capability is sufficient to drive the fan. Normally, several transistor stages in series are needed because the gain of low-cost power transistors is typically no more than 40 to 50. This complicates matters because a higher fan supply voltage is now required due to the additive V_{BE} drops between the supply rail and the fan itself. Multiple power supply voltages (e.g. +5V and -12V) may be used to overcome this problem instead of adding a dedicated power supply for the fan. In any case, the resulting design is inefficient, wasting a considerable amount of input power as heat.

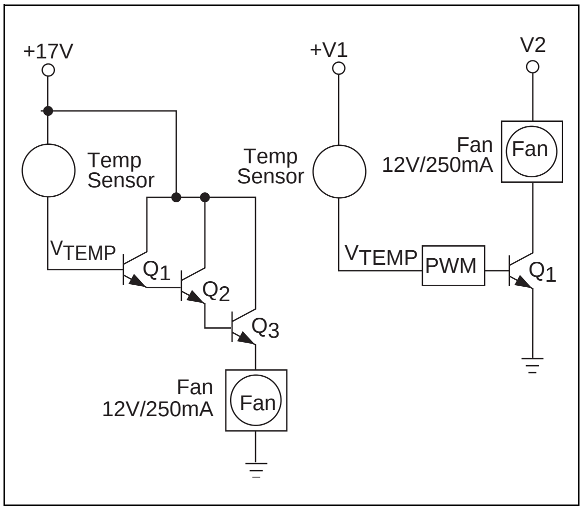

FIGURE 3: Linear Voltage Speed Control vs. PWM Speed Control

For example, consider the power dissipated by the circuit of Figure 3 when the fan is operated at 50% of full speed (6V applied to the fan). BDC fans consume current in roughly direct proportion with the applied voltage. This means that 11V at 125 mA is dropped across output transistor Q_3 in Figure 3 when the fan is operated at 50% of full speed.

With a fan current of 125 mA, the power dissipated in Q_3 is given by:

EQUATION:

$$P_{Q3}\,(W) \approx (17 - 6)V \times 0.125A = 1.4W$$

The power dissipated by the fan itself is only 6V x 0.125A = 750 mW; so the final drive stage consumes more power than the fan it drives! The need to dissipate these high power levels preclude the use of low-cost transistor packages, such as TO-92s or SOTs, and force the use of larger, more costly packages such as TO-220s. In the extreme, heat sinks may be required. Having a drive circuit that generates a large amount of heat defeats the goal of having a cooling system in the first place.

BDC fans may not consistently start if the power supply slew rate is not sharp enough to “kick” the fan into rotation. In addition, applying too low a control voltage will cause the fan to stall. Additional circuitry must therefore be added to any linear voltage speed control scheme to compensate for these contingencies. One can safely conclude that high driver power dissipation and start-up/stall concerns overwhelm the linear voltage drive circuit’s apparent elegance.

Pulse-Width Modulation (PWM)

PWM fan speed control methodology (Figure 3) has decided advantages over linear voltage speed control:

1. The output drive transistor (Q_1) is either on or off. The average power dissipation of Q_1 is therefore collector-to-emitter saturation voltage, (V_{CESAT}) times the fan current (I_{FAN}), times the duty cycle. Assuming a V_{CESAT} of 0.3V and a fan operating current of 250 mA, the maximum power dissipation of Q_1 is only 75 mW, eliminating the need for high power output transistors and their associated size, weight, and cost.
2. Unlike linear voltage speed control, there is negligible voltage loss in the PWM circuit, eliminating the need for special voltages or multiple power supply schemes.
3. The very nature of PWM dictates that the fan sees either, full-rated voltage, or 0V; the ratio of on-time-to-off time determines how fast the fan operates. This eliminates the BDC fan start-up and stall issues associated with linear voltage speed control, which operates fans at lower voltages.
4. Because BDC fans can be modulated only by a low-frequency signal (60 Hz or less), PWM functionality can be easily implemented in hardware or software at a very low installed cost. In contrast, linear voltage speed control is inefficient, sometimes requiring additional components such as heat sinks, which are not necessary with PWM methodology.

PWM fan speed control has historically been ignored, largely because of the perceived complexity and cost. Newly developed IC’s are changing this by offering low cost, highly integrated solutions dedicated to BDC fan management. The first ICs dedicated to this application are the TC642 and TC646 Fan Speed Controllers. These ICs, plus a few discrete devices, implement a speed control and monitoring circuit with all the features previously discussed. Both devices use PWM fan speed control. A block diagram for the TC642 appears in Figure 4.

The TC642 is the industry’s first BDC Fan Management IC. Designed to operate from 3V or 5V power supplies, the TC642 uses only a few low-cost discrete parts and implements a full feature BDC fan control and monitoring system.

The TC642 derives all of its timing from an on-board (typically 30 Hz) oscillator whose frequency is set by C_1. A temperature sensing network consisting of an NTC thermistor and linearizing resistors R_1 and R_2 supply a temperature-dependent control voltage over the required zero-to-full scale input range of 1.25V to 2.65V. A second resistor divider network on the V_{MIN} input (R_3, R_4) sets a minimum duty cycle (hence a minimum fan speed) at which the fan will operate when measured temperature is low. The control voltage range on V_{MIN} is identical to that of V_{IN}; this input also doubles as a shutdown input when pulled to ground by an external open collector device. The SENSE input is connected to a low value current sensing resistor in the return leg of the fan. When the BDC fan is running, commutation occurs as each pole of the fan is energized. This action causes brief interruptions in the fan current waveform seen as pulses across sense resistor R_6. The TC642 uses this information to detect if the fan is operating (see Figure 5).

When power is initially applied, the TC642 holds Q_1 on for a minimum of one second to ensure a reliable BDC fan start-up. In normal operation, this will cause the fan to start-up and accelerate to the minimum speed setting. As measured temperature rises, the voltage on V_{IN} is increased accordingly which, in turn, increases fan speed. This closed-loop action continues until either the system is turned off, or the TC642 is shutdown.

The TC642 fault monitor is sophisticated enough to detect a stuck, disconnected, or otherwise inoperative fan or system over-temperature condition, possibly due to a defective fan bearing or restricted airflow. An inoperative fan is detected as follows: if the TC642 is not in shutdown (i.e. V_{MIN} low), and no activity appears on SENSE, then a fault is indicated. When this occurs, the TC642 attempts to restart the fan by again initiating the fan start-up routine previously described. If still no pulses are detected at the SENSE pin, a fan fault is confirmed and the $\overline{\text{FAULT}}$ output is latched low and the fan drive signal is halted as a result.

The TC642 remains in this state until either power is cycled, or until a reset is issued by momentarily driving V_{MIN} low. A system over-temperature condition is detected as follows: if the signal on V_{MIN} becomes greater than that needed to drive 100% duty cycle on V_{OUT}, the $\overline{\text{FAULT}}$ output is driven active as long as this condition persists, but the fan is allowed to continue running.

The TC646 is identical to the TC642, with the exception being the minimum speed mode is changed to an auto-shutdown mode. When measured temperature is less than a user-programmed auto-shutdown setting, the TC646 halts fan operation. The fan is automatically restarted and enters temperature-proportional speed control mode when measured temperature exceeds the auto-shutdown threshold.

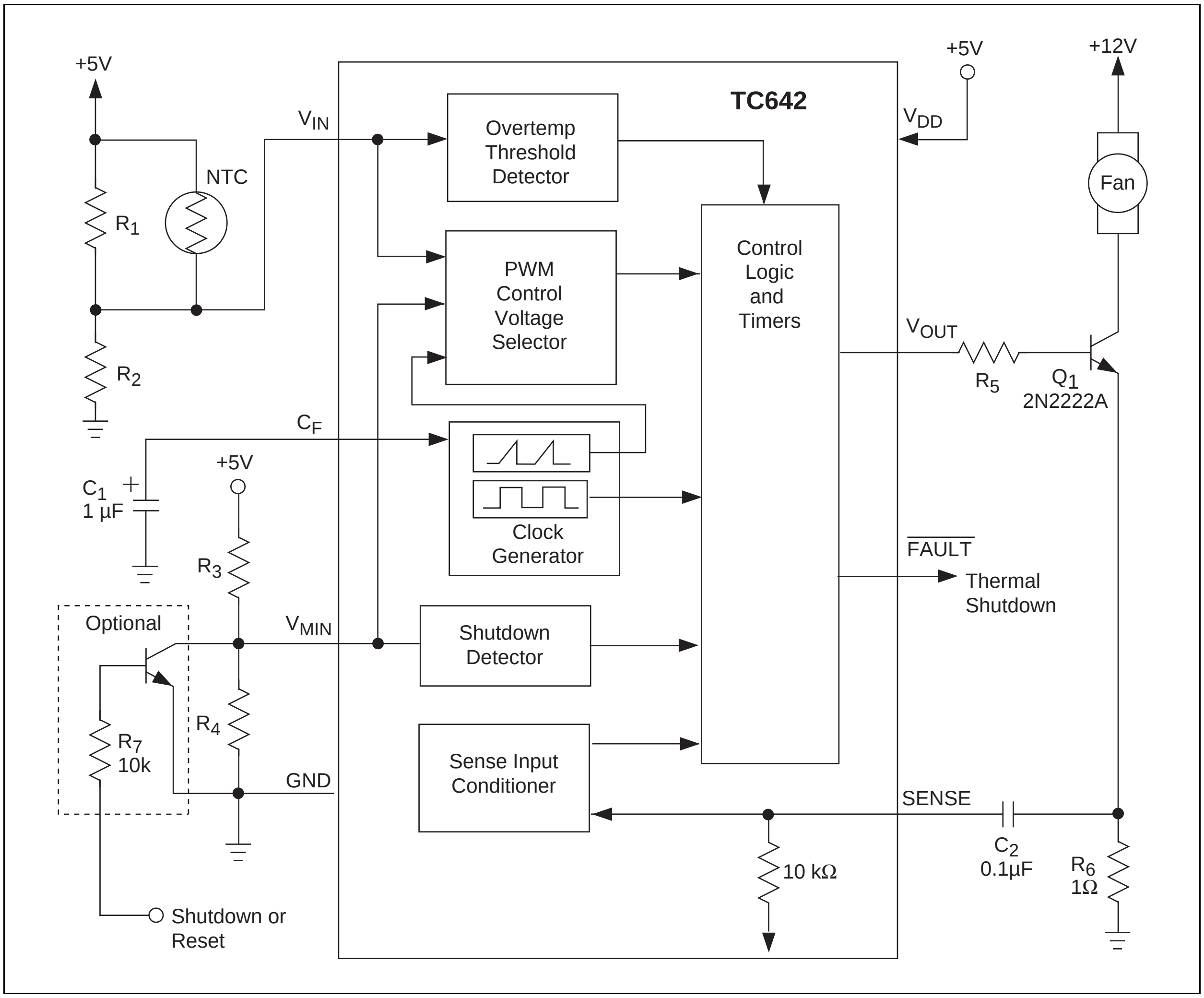

FIGURE 4: *TC642 Functional Block Diagram*

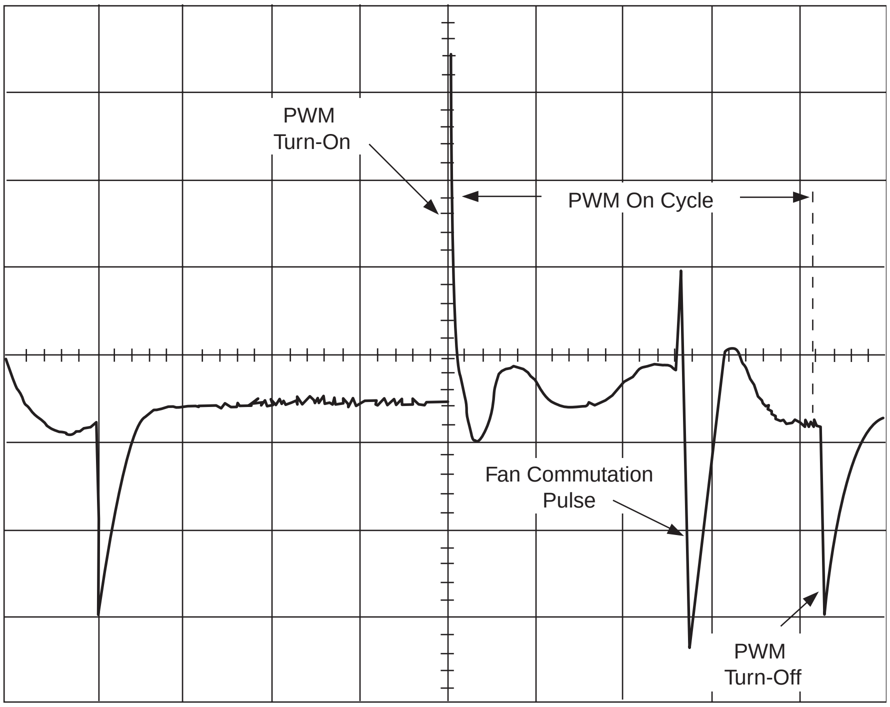

FIGURE 5: *Fan Waveform at SENSE Input*

DESIGN EXAMPLE

The TC646 combines the advantages of both off/on control and temperature proportional speed control. It features an auto-shutdown mode that automatically turns the fan completely off when measured temperature is below a user-defined minimum. The TC646 operates in a temperature-proportional speed control mode when measured temperature rises above the preset minimum value.

The TC646 is especially well-suited for NLX power supply applications. Application Note (AN764), "Implementing Temperature-Based Variable Fan Speed Control in NLX Power Supplies", discusses the NLX specification for fan speed control and gives design details about a reference design which uses the TC646 fan speed controller. The author's prototype circuit is built using through-hole components for easy prototyping. The demo board appears in Figure 6. Prototype boards are available from Microchip Technology Inc. The boards permit the user to configure a BDC fan manager to handle a wide variety of BDC fans.

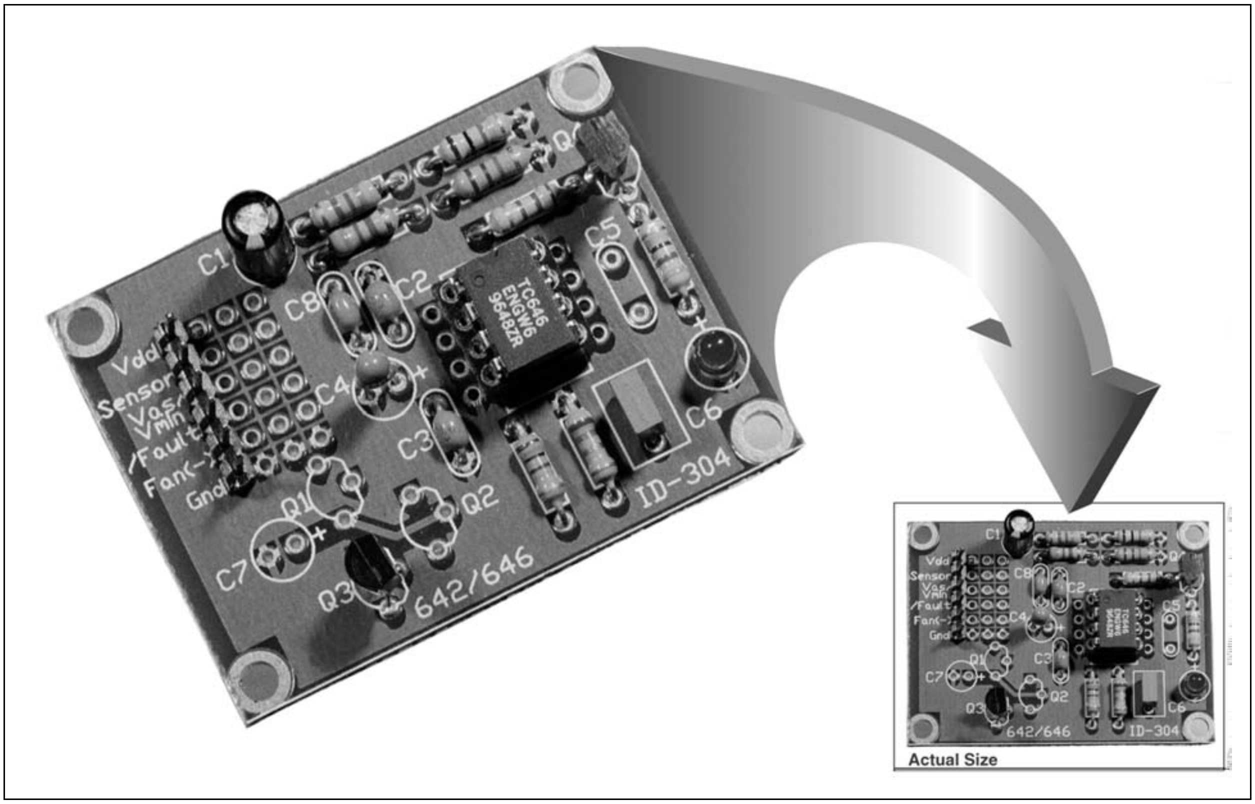

FIGURE 6: *Author's Demo Board for TC642/646*

NOTES:

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