Robust System Thermal Management

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Today, process technology has advanced to 32nm, resulting in an increase in the number of transistors per unit area and a reduction in package size. At the same time, system designers are trying their best to reduce the system size by increasing the component density on boards, adding as many features in the design as possible to deliver the industries' best products in terms of space and size. Increased transistor density inside the chip, higher operating speeds, and increased component density on board in modern electronic systems has led to relatively more heat being generated in these systems. All this has made thermal management an integral and critical part of system management in all application domains, including automotive, industrial control, consumer electronics, battery powered systems, and so on. Many systems are equipped with cooling fans to deal with the heat generated. This has led designers to realize the need to come up with cost-effective, reliable, noise-free, and power efficient temperature-based closed loop fan control systems.

Before going to the implementation of the fan control system, let's have a quick look at the basics of heat generation and heat transfer. Electrical power dissipation (Voltage * Current) is indispensable in any electronics circuit. This electrical power dissipation results in the generation of heat and causes the junction temperature to increase above the ambient temperature. For the reliable operation of the device, the junction temperature of the device has to be kept within specified limits. Sometimes, the requirement is not only to keep the junction temperature within the specified operating range but, for some applications, to keep it at a specific value since these devices show different characteristics at different temperature ranges. For instance, oscillator frequency, ADC offset, and thermal noise are functions of temperature and variation in these parameters may be undesirable for some applications.

As long as power is dissipating in the device, junction temperature will be more than the ambient temperature. The ability of the device to transfer heat depends upon the thermal resistance. A thermal circuit can be considered similar to an electrical circuit. Figure 1 shows the equivalent circuit of thermal system:

Figure1: Thermal equivalent circuit

In this circuit, T1 and T2 are temperature and θ is thermal resistance. Temperature can be assumed to be analogous to voltage in electrical circuit. Thermal resistance is analogous to electrical resistance and heat flow is analogous to current flow. Considering this thermal-electrical analogy, it can be seen that a higher temperature difference increases the heat flow. Similarly, the lower the thermal resistance, the more heat flow there is.

Cooling Methods

In an IC, flow of heat from junction to ambient air depends upon the difference between the junction temperature and the ambient air temperature. Cooling fans operate by blowing away hot air and allowing more heat to flow from the junction to its external surroundings. There are several types of control systems used for fans:

No Control: The simplest way to use a fan for thermal management is the one which needs no feedback control. The fan runs at its maximum rated speed at all times, ensuring foolproof cooling with the least associated cost. However, while this reduces the installation/manufacturing cost, it increases the running cost of the system. The fan's lifetime is also decreased since the fan runs all the time (a fan's life is generally defined by the number of revolutions). Another major disadvantage of such a system is its high power consumption since the fan keeps running at its highest speed even though this behavior is not required at most times. In such systems, a fan is selected for the worst case cooling, and the system rarely runs in that condition. As there is no feedback and no control system, there is no way to check the fan's present condition. If the fan breaks down, smoke or system failure might be the only feedback the user gets.

Linear Control: Another way of controlling the fan is using a linear control system. In such a system, the speed of the fan is controlled by changing the voltage input to the fan. The lower the input voltage, the slower the fan speed. The advantage of linear control is its noise free operation due to lack of coil switching. If we look at the limitations of this control system, we see that the speed range is limited by the operating voltage range of the fan. For example, the minimum voltage needed to force the fan to run may be more than half the maximum operating voltage of the fan. Also important to consider is that the efficiency of linear regulators is less at lower output voltages, meaning these systems are not optimized for power consumption at lower fan speeds. Another major drawback is the cost of the linear voltage regulator circuit required for such a system.

PWM-based control: The most extensively used technique to control fan speed is using a PWM. Using this method, the fan either runs at its highest speed or it remains off. Major advantages of this control method over linear control include simplicity of the circuit, cost effectiveness, and efficiency. Another advantage is the average speed range possible since the lowest speed is not limited by the minimum operating voltage of the fan as it is in the case of a linear control system. The primary disadvantage of this method is the noise induced due to the switching of coils. However, this can be overcome by operating the fan outside the audible frequency range. Figure 2 shows the basic thermal management system block diagram using the PWM control method.

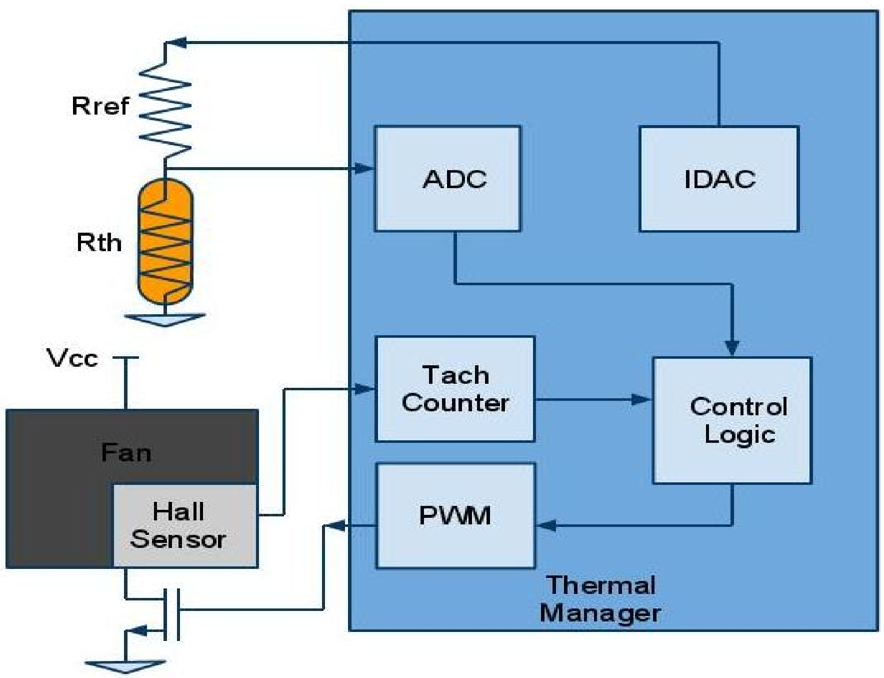

Figure 2: Thermal Management System

Fan Types

There are different variants of fans available, and each type can be the best fit for a particular application based upon cooling needs, system cost, reliability requirements, etc. These variants are generally classified based upon the number of wires used: 2-wire fans, 3-wire fans, and 4-wire fans.

A 2-wire fan has two terminals for power and ground. Its speed is controlled by changing either the supply voltage or the power duty cycle (which is equivalent to changing the average supply). This kind of fan is used mainly in open loop temperature control systems when there is no tachometer signal available to provide fan speed feedback to the control system. This type of fans is used in cheaper thermal management systems. The limitation of a tachometer isn't really a limitation, and it can be worked around. The winding commutation in the motor causes the fan's current consumption to fluctuate. If the frequency of the fluctuations and the number of permanent magnetic poles of the rotor is known, the mechanical rotation speed of the fan can be readily calculated. A key point to note here is that no one would like to pay for the additional current sensing circuit if there isn't any budget for a 3-wire or a 4-wire fan. As a consequence, a single chip which can do all the jobs of measuring the commutation frequency, temperature measurement, and controlling the fan speed by means of PWM will be an ideal choice for the application. Measuring the commutation frequency can be done by differentiating the current sense resistor's output, amplifying the signal, and then feeding it to a comparator which will control the capture input of a timer. Once the frequency is known, fan speed can be calculated. Sensing the current fluctuation also helps in recognizing if the fan is working or not. Figure 3 shows the block level implementation of a commutation frequency measurement using PSoC3/5 from Cypress.

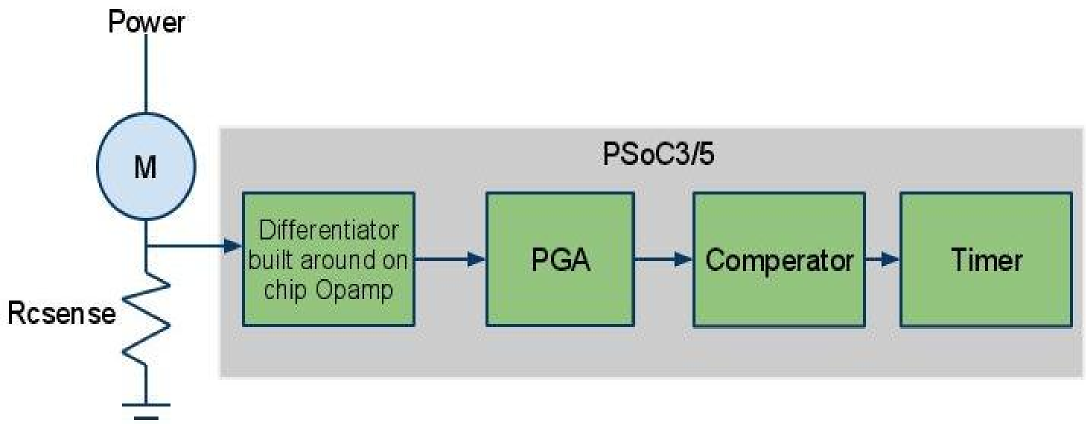

Figure 3: Measuring commutation frequency

A 3-wire fan which has an extra wire for a tachometer output. As far as controlling the fan speed is concerned, the method is the same as for a 2-wire fan. With a 3-wire fan, both the fan motor and hall sensor circuit share the same supply. Thus, the tachometer signal is valid only during the on period of the PWM that is controlling the fan. The tachometer signal reading must be synchronized with the PWM on time and must also be long enough to capture one complete tachometer cycle.

Generally, the tachometer output is a 50% duty cycle with two pulses per revolution. This signal is critical as it gives enough fan speed feedback to control the system. As the fan speed degrades with time and usage, this feedback can be used to determine whether the fan needs to be replaced. This behavior is an important asset for a reliable system. It can also be used to trigger an alarm in case a fan is not working. The tachometer output can also be used to run the fan at fixed speeds. The control system can change the PWM duty cycle based upon the tachometer output frequency.

4-wire fans are the easiest to interface to. These fans have one wire for power, one for ground and one for the tachometer output as in a 3-wire fan, with an additional wire for the PWM input. In these fans, the PWM input is used to control the speed of fan instead of switching the power to the entire fan. As power to the fan is available all the time, the tachometer output is also available at all times. These fans can be operated at a frequency outside the audible frequency range, eliminating any annoying switching noise from the system. This makes 4-wire fans the most sought after type of fan for thermal management for a vast variety of systems like laptops, projectors, set-top boxes, etc.

Reliability

Certain critical systems may need a standby fan in case the primary fan fails. For such applications, fan fault detection is the most critical function to be performed by the control system. Faults should be detected either by monitoring the voltage across a current sense resistor if there is no tachometer output or by monitoring the tachometer output. An alert can be generated if a fault is detected. In such a case, the standby fan must be switched on. Some systems are equipped with multiple fans due to higher cooling needs. To deal with a fan failure in such system, fans used in the system should be selected in such a way that when all fans are working, fans do not run at their maximum speed even for the worst-case temperature. Only in the case of a breakdown of a fan can the remaining fans be made to run at their maximum speed to compensate for the failed fan at worst-case temperatures.

In modern systems, at some stage it may be observed that the current cooling capacity does not meet changing system requirements. The control system should be flexible enough to accommodate a fan with a higher speed or different specifications without changing the control hardware. Available SoCs on the market, enabled with on-chip programmable peripherals, allow developers to modify a system's configuration with almost no change in hardware, thus saving cost, time, and development effort. PSoC3 and PSoC5 products from Cypress, for example, come with integrated ADCs with resolution up to 20 bit which is more than sufficient for thermal management applications, DACs to generate a reference for temperature sensor circuits, programmable gain amplifier(PGA) for input signal amplification, comparator, timer, and PWMs. DMA enables the reading of ADC Data and tachometer counter's value without CPU intervention to support high-frequency control algorithms. These devices are also equipped with on-chip PLDs which can be used to implement control logic in hardware to further avoid CPU overhead. Figure 4 shows one possible way to implement thermal management system using PSoC3 and PSoC5 devices.

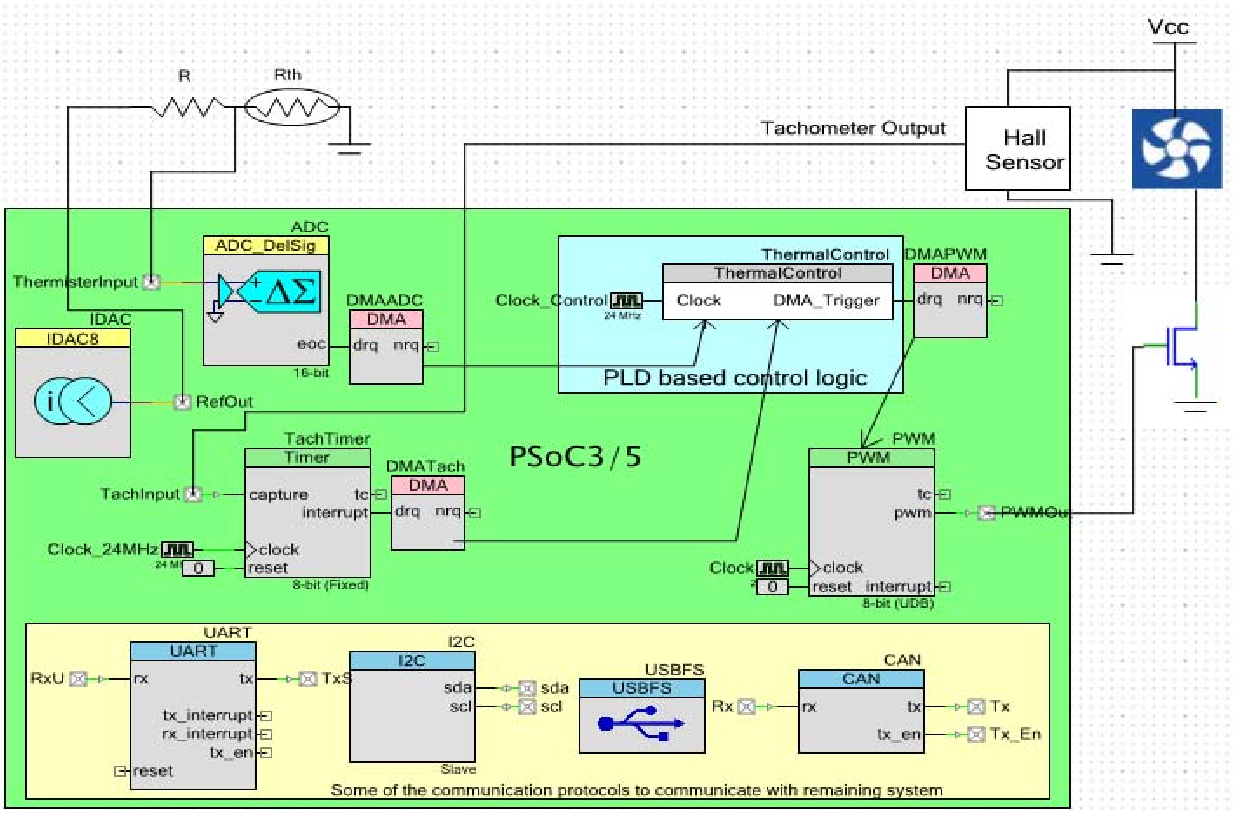

Figure 4: PSoC3/5 based implementation

In above implementation, the ADC data and tachometer timer value are read using DMA and written to registers used in the control logic. The entire control logic block is implemented using PLDs and other hardware digital programmable resources. The DMA then writes the required period value to the PWM. In this way, almost the complete thermal management control system can be implemented using hardware resources and leaving the CPU available for other tasks. Hence, SoC-based implementations allow the implementation of thermal management as a small function of a complex system on a single chip, thereby reducing system cost and board space requirements. Thermal management system should have some means to communicate with the host processor to update the status of fan. PSoC supports almost all the communication protocols (I2C, USB, UART, CAN, SPI, etc.) are used in modern embedded system design. This allows developers to implement a thermal management system effectively and efficiently with a single chip without much CPU usage, leaving plenty of headroom for other features.

An effective fan speed control system is needed to increase reliability, reduce power consumption, and decrease noise. There are different fan variants available with different control methods, and a PWM-based method provides the reliability, power consumption, cost, and noise required. Higher system integration also enables a complete thermal system to be integrated within a single chip at a lower cost that also optimizes power consumption. Finally, the flexibility of an SoC implementation enables developers to incorporate changes caused by the continuing change of requirements over time.

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