Advanced Solar-Powered Fire Detection System: A Wireless Sensor Node Approach to Early Warning and Forest Fire Prevention

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Abstract. This article presents the design and implementation of a solar fire detection system using a Wireless Sensor Node (WSN). The system incorporates a temperature sensor, Bluetooth module, and intelligent battery charging management to provide real-time monitoring and early detection of forest fires, while also ensuring energy conservation and battery protection. By employing a DC-DC converter, the system maintains a stable 9V supply to the Arduino board under various power supply conditions. The integration of the temperature sensor and Bluetooth module enables accurate temperature data transmission to mobile or computer terminals for real-time monitoring. The energy-saving and battery protection features optimize charging cycles and prolong battery life, contributing to environmental sustainability and enhanced safety for communities at risk. The successful testing of the system demonstrates its reliability and potential as an effective early warning system to combat the devastating effects of forest fires.

Keywords: Solar fire detection system, Wireless Sensor Node, DC-DC converter, Temperature sensor, Intelligent battery charging management.

1. Introduction

Forest fires pose a significant threat to the environment, wildlife, and human safety. In recent years, the frequency and intensity of wildfires have increased globally, with devastating consequences for ecosystems, economies, and communities [1]. According to the National Interagency Fire Center, there were over 8350 wildfires in the United States alone in 2022, resulting in over 185,680 acres burned [2]. The impacts of wildfires extend beyond immediate damage, with long-term effects on weather hazards, and water resources [3, 4].

Effective early warning systems are critical for detecting forest fires as soon as they ignite, enabling rapid and efficient responses to prevent them from spreading. Current methods for forest fire detection include satellite-based monitoring systems, drones, and manual observation by forest rangers or local inhabitants [5, 6]. While these methods have proven useful in some instances, they are often limited by factors such as delayed detection, low spatial resolution, and the need for human intervention.

Wireless Sensor Networks (WSNs) have emerged as a promising alternative for early forest fire detection, offering real-time monitoring, high spatial resolution, and reduced human involvement [7]. Solar-powered WSNs are particularly appealing due to their self-sustainability and low environmental impact. This article is devoted to the design and implementation of a solar-powered fire detection system that utilizes a WSN for the early detection of forest fires.

The proposed system consists of a transmitter side, which includes a solar panel, temperature sensor, Bluetooth module, and a DC/DC converter for regulating power from the solar panel to an Arduino board. The receiver side comprises a computer or smartphone that displays the temperature information transmitted by the Bluetooth module. This system aims to provide a more efficient and reliable method for detecting forest fires compared to traditional techniques.

The article is structured as follows: Section 2 details the design of the DC/DC converter, including the calculation of component values and the building of the circuit. Section 3 discusses the integration of the temperature sensor and Bluetooth module, explaining their roles in detecting temperature fluctuations and transmitting data wirelessly. Section 4 presents energy-saving and battery protection strategies implemented in the system to ensure sustainable and efficient operation. Finally, Section 5 provides testing results to validate the effectiveness of the proposed solar fire detection system.

The entire system is shown in Fig. 1. On the transmitter side we have a solar panel, a 9Vbattary, an Arduino board, a temperature sensor, a Bluetooth module, and a DC/DC converter to regulate the power from the solar panel to the Arduino. In this experiment, due to limited space, a 5v power adapter is used instead of the solar panel on the receiving end, we have a computer or smartphone to display the temperature information [8-11].

By incorporating advanced technology and innovative design, the solar-powered fire detection system aims to offer a more reliable and effective early warning system for forest fires. This approach could significantly contribute to the prevention of wildfires, the protection of ecosystems, and the safety of communities living in fire-prone areas.

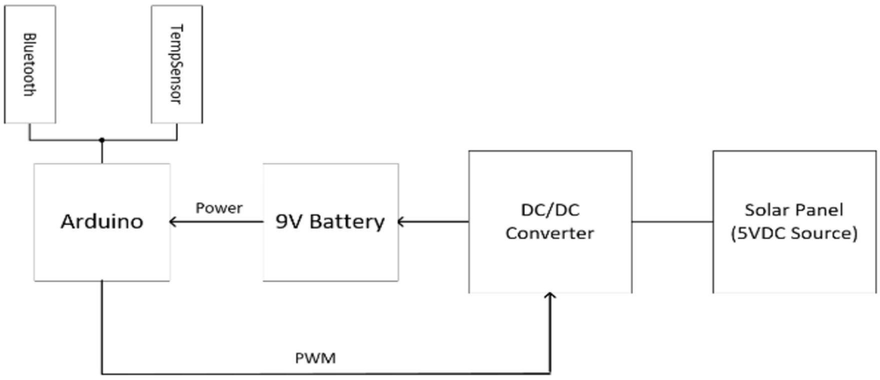

Figure 1. Block diagram of WSN

2. Converter Design

2.1. Boost Circuit

Boost, buck, and buck-boost circuits are types of DC-DC converters used in power electronics to regulate and control the voltage levels of a power supply. These converters help in transforming a given input voltage into a regulated output voltage, either higher or lower than the input, or a combination of both.

Because the solar panels and batteries used as power supply provide 5V voltage and the Arduino development board that realizes the sensor function needs to use 9V voltage as input. In this part design a boost circuit that converts 5V DC to 9V DC is included in this design. As seen in Fig. 2, a boost converter is a power electronic device that increases the input voltage to a higher output voltage. It is called a step-up converter because it "steps up" the voltage. The basic components of a boost circuit include an inductor, a diode, a capacitor, and a switch (usually a MOSFET or BJT). When the switch is closed, energy is stored in the inductor, and when the switch is opened, the stored energy is transferred to the load and output capacitor, creating a higher output voltage.

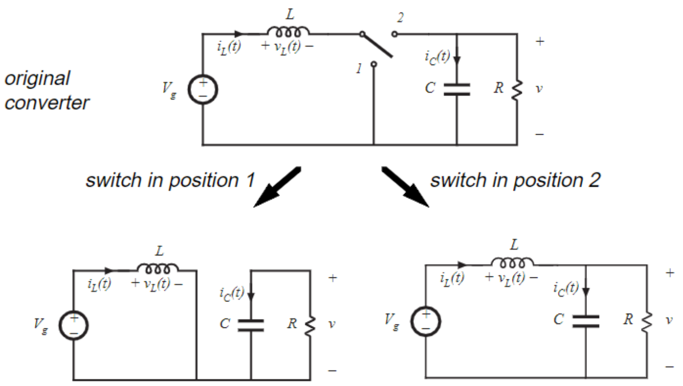

Figure 2. Boost converter analysis [12]

The circuit design is as Fig. 2. When the switch is in position1, inductor voltage, and capacitor current $v_L = V_g$, $i_C = \frac{-V}{R}$. When the switch is in position1, inductor voltage and capacitor current $v_L = V_g - V$, $i_C = \frac{i_L - V}{R}$. When giving a duty cycle D. Ideally the voltage conversion ratio is $M(D) = \frac{V}{V_g} = \frac{1}{D'} = \frac{1}{1-D}$. In this part ideally $M(D) = \frac{9}{5}$, $D = \frac{4}{9}$, $L = \frac{V_g D T_s}{2\Delta i_L}$ =4.93mH, $C = \frac{2\Delta v R}{D T_s}$=110uF.

Due to deviations in the actual circuit component values and some environmental elements, the final used circuit component values have been slightly adjusted so that the voltage can be boosted more accurately. The final circuit structure is shown in Fig. 3. The PWM pulses shown in the figure are provided in the next section using the Arduino board.

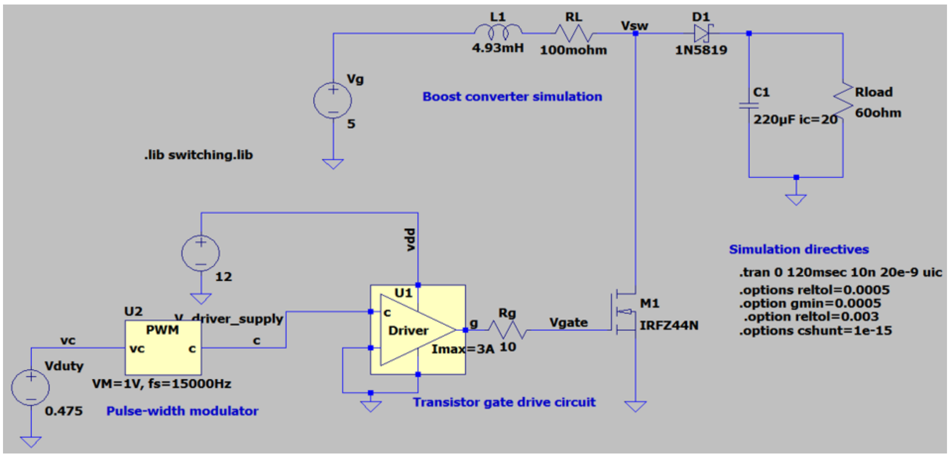

Figure 3. Boost converter circuit

It is designed to configure the Arduino's internal registers to generate a PWM signal at 15kHz. In the loop function, it calculates the temperature, stores it in the template variable, and performs a PID calculation every 50 microseconds. The PID controller Mbase adjusts the error between the measured value (redpoint) and the desired setpoint. The P, I, and D terms are calculated, and their sum is limited to a range of -1000 to 1000. The duty cycle is then adjusted based on the input value and the PID output. In this case, it can be automatically adjusted to the value of the Duty cycle by detecting the charging or discharging current of the battery, so that the battery remains at 9V/150ma regardless of charging or discharging.

3. Temperature Sensor and Bluetooth Module

After successfully boosting the input voltage of 5v to 9v, the temperature sensor and Bluetooth module need to be connected to the circuit through the Arduino board. Their function is to receive external temperature signals and transmit them to mobile phones or computer terminals

3.1. Temperature Sensor

NTC Thermistors are used for the temperature sensor. The way to use the temperature sensor is to connect a resistor in series with the sensor, measure the values at each end and use Arduino for analysis. The circuit diagram is shown in Fig. 4.

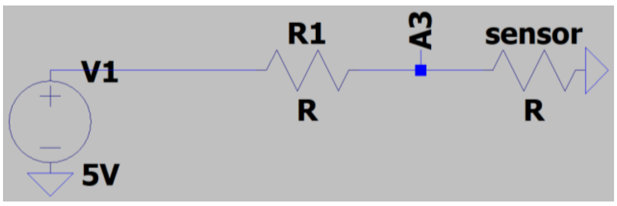

Figure 4. Temperature sensor circuit

The temperature is calculated within the loop function by reading multiple analog input pins (A0, A1, A2, A3). The difference between readings from A1 and A2 is stored in the redpoint variable, while the values from A0 and A3 are read and stored in the val and temp1 variables, respectively. Next, temp2 is computed by scaling temp1 to the 5V range, and finally, tempval is determined using a polynomial equation involving temp2. This polynomial serves as a calibration curve, translating the voltage reading (temp2) into a temperature value.

3.2. Bluetooth Module

The other part is a Bluetooth module to transmit the temperature data obtained in the previous temperature sensor to a mobile phone or computer terminal. It utilizes serial communication to send the temperature data (stored in the 'tempval' variable) followed by the unit "°C" and a newline character. In the context of this code, it's assumed that a Bluetooth module is connected to the Arduino board's serial pins, which will transmit the data wirelessly.

4. Energy-saving and Battery Protection Schemes

This part provided effectively combines temperature monitoring and intelligent battery charging management, contributing to energy conservation and battery protection. By transmitting temperature data every minute via a Bluetooth module, the system allows for real-time monitoring, enabling users to keep track of temperature fluctuations and respond accordingly. This continuous monitoring can help prevent overheating and improve overall safety. Additionally, the intelligent battery charging management employs a cyclical approach that adjusts charging modes between regular speed, slow motion, and stopping the charging process based on elapsed time. This method not only optimizes energy consumption but also safeguards the battery by avoiding overcharging and prolonging its lifespan, leading to more sustainable and efficient energy usage.

4.1. Energy Saving

Because the solar panel cannot supply power at night, only the battery can supply power. In order to save power, in this part the Bluetooth module transmits data every minute, as indicated by the delay (60000) line in the code snippet. The delay function takes an argument in milliseconds, and Since 60000 milliseconds equal 1 minute, the Bluetooth module sends temperature data every minute.

4.2. Battery Protection

The code in this part intelligently manages battery charging cycles by adjusting the charging mode based on elapsed time, measured in hours. It employs a timer that increments a counter every minute to keep track of the time elapsed, and based on the counter value, it adjusts the charging mode accordingly. The charging modes are Regular speed charging, active during the first 2.5 hours (150 minutes), where the battery charges at a normal rate; Slow-motion charging, active for the next 11.5 hours (690 minutes) after the initial 2.5 hours, where the battery charges at a reduced rate; Stop charging, active after a total of 14 hours (840 minutes) has elapsed, stopping the charging process for the next 10 hours (600 minutes); and Reset counter, which resets the counter once 24 hours (1440 minutes) have passed, starting the charging cycle again from the beginning.

5. Production Testing

5.1. DC-DC Converter Testing

After testing, the circuit can successfully supply a stable 9v voltage to the Arduino board no matter in the case of charging with a power supply or only using battery power.

5.2. Entire Temperature Detection Function Test

The system was tested once when simulating solar panel power supply and only using a battery power supply. After testing, the results show that in both cases, the temperature is successfully detected and displayed on the mobile terminal after one minute after a successful connection. In addition, the actual data in Fig. 5 shows that the system can successfully observe and display the temperature through the 24-hour indoor test (charging for 12 hours).

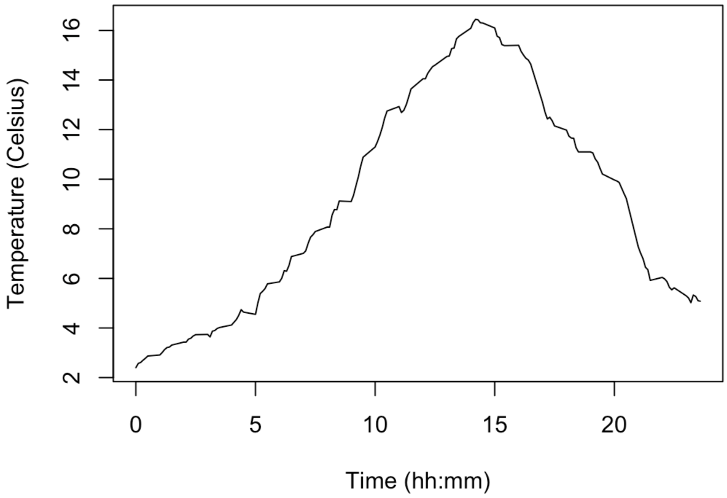

Figure 5. Temperature vs time throughout the day

6. Conclusion

In conclusion, this article presented the design and implementation of a Wireless Sensor Node (WSN) for solar fire detection. The system effectively combines temperature monitoring and intelligent battery charging management, contributing to both energy conservation and battery protection. By utilizing a DC-DC converter, the system ensures a stable 9V supply to the Arduino board, even when transitioning between the solar panel and battery power. The integration of a temperature sensor and Bluetooth module allows for efficient and accurate temperature data transmission to mobile or computer terminals, facilitating real-time monitoring and early detection of forest fires.

The energy-saving and battery protection features of the system ensure sustainable and efficient energy usage, optimizing the charging cycles based on elapsed time to avoid overcharging and prolonging battery life. The successful testing of the system under both solar panel and battery power supply conditions demonstrates its reliability and practicality in real-world applications. The development of this solar fire detection system not only contributes to the early detection and prevention of forest fires but also promotes environmental sustainability and safety for communities at risk.

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