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Energy Efficient Solar-Powered Street Lights using Sun-Tracking Solar Panel with Traffic Density Monitoring and Wireless Control System

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Abstract: Due to increasing demand of energy, utilization of renewable energy sources are getting larger attention from researchers all over the world. Solar Photovoltaic (PV) is a renewable source of great potential due to its abundancy, ease of accessibility, convertibility to the electricity and environmental friendliness. Solar PV system along with light emitting diode (LED) have become extremely popular nowadays for street lighting purposes. LED lamps are used due to their higher lumens yield with less wattage consumption. So, this paper presents an energy efficient sun-tracking solar PV powered auto LED-brightness controlled street light model based on traffic-density monitoring system with wireless control via nRF and GPRS technologies. The microcontroller based dual-axis sun-tracking system along with four light dependent resistor (LDR) sensors are used to keep the solar panels aligned with the sun in order to maximize the amount of harnessed solar power. The street lights are automatically switched on at the dusk and then switched off at the dawn using LDR sensors. Depending on traffic-density in the street, which is measured by ultrasonic and motion sensor based traffic-monitoring system and the yield of solar PV, the lumen-intensity of LED based street light is adjusted by pulse width modulation (PWM) to save more energy. We have also configured the system with nRF and GPRS technologies, which allow us to manually operate and monitor the street-lights wirelessly from remote places. Thus, the proposed system facilitates remote monitoring and generates 20% more energy than stationary solar panels while reduces LED power consumption by 15.7% per day.
Keywords: Solar PV, LED, LDR, Light intensity control, Traffic monitoring, Street lighting, GPRS, nRF.

I. INTRODUCTION

Nowadays, street lighting is an essential part of a city's infrastructure. It is used to illuminate the street during dark hours of the day. At the beginning of civilization, the street lighting was very simple as the number of streets and traffic density on the street were less. Hence, the power consumption and installation cost for street lighting purpose was low. But, with the increase of urbanization, the number of streets increased rapidly with high traffic density. This led to increase in number of street lights and investment associated with them. Furthermore, Power consumption is increased for street illumination purposes which engendered big energy cost for the municipal [1]-[3]. As we know that energy crisis has become the most perturbing matter for modern civilization throughout the world. Rapid urbanization is leading the world towards high consumption of energy. On the other hand, Due to the reduction of available fossil energy resources, conventional energy sources are diminishing at an alarming rate. So it is high time for us to seek new sources of energy for mitigating the power crisis all over the world [4]. In this circumstances, renewable energy sources are the best solution for electricity generation since they are naturally available, inexhaustible and non-polluting energy. One of the primary sources of renewable energy is solar energy. Solar energy is popular all over the world due to its attractive contribution on almost zero fuel cost and free from environmental pollution with ensuring forever energy supply. Solar PV based street lighting system is very common nowadays but it lacks of automation. Automation, cost effectiveness and less power consumption are now major considerations for technological advancement. Energy efficient technologies can reduce power consumption and improve utilization efficiency of energy [5]. Thus implementation of solar energy with modern technologies for lightening streets can save more energy and reduce expenses. In this paper our objective is to maximize the solar-energy storage and minimize the energy wastage of street light by combining modern technologies altogether.

Solar PV conversion is the technology that allows us to use solar energy in everyday life. It produces electricity in Direct current (DC) form [6]. It is desirable to maximize the power output form a Solar PV system to increase its efficiency. Such a Solar PV panel produces maximum electric power output when it is kept perpendicular to the solar radiation. In order to keep the Solar PV panels aligned with the sun's position, solar trackers are the most appropriate and popularized technology around the world [7]. The open loop solar trackers [8, 9] follow an algorithm or mathematical model that uses time, date and geographical information of a specific location to determine the azimuth and the elevation angles of the sun [10-13]. But this system has to be monitored continuously as the algorithm has to be changed with the change of season, weather or location.

To overcome this limitation, closed-loop solar trackers [5] have been introduced that use charge couple devices (CCDs) [14–16] or light dependent resistors (LDRs) [17–19] along with automation technologies [20, 21] to measure the position of the sun. Therefore, we have designed a closed-loop system with micro-controller and LDR sensors for our automated solar tracker. The difference in between two LDR sensor reading is used as feedback error signal, which is compared with previous error signal to determine the direction of rotation of solar panel. The panel rotates to minimize the error signal and thus keeps itself aligned to the sun perpendicularly and achieves maximum solar radiation. Solar trackers maintain both single-axis [22–24] and dual-axis [25–27] structures. A single-axis tracker follows the sun only from the east to the west while a dual-axis tracker follows both azimuth and the elevation angle of the sun. Most of the sun-tracking systems use steppers [25, 26] or DC motors [27, 28] as moving mechanism. But we have used servo motors for our closed-loop model of dual-axis sun-tracker, because unlike DC motors, servos can be programmed to rotate at a particular angle. Also unlike stepper motors, they can maintain high torque-level at high speed. Servos can be operated at 80-90% efficiency and do not suffer from vibration or resonance issues [29].

Moreover, our aim is to provide a better solution to minimize the electrical wastage or excess power consumption to increase the efficiency in operating street lights. The streets with irregular traffic do not require full intensity of light all over the night. Manually operated street lights requires continuous supervision of the operator which is often impossible to ensure. Moreover, such system cannot dim the streetlights according to necessity. Thus, we need an autonomous traffic density monitoring system to change the light-intensity of LED lamp according to the traffic-density in the street [3, 4]. So we have used motion and ultrasonic sensors with our street-light system to monitor traffic density. Based on the sensor-data, a PWM signal is generated by the micro-controller to control the current passing through the LED lamp and thus control its brightness. Initially, the lamp will glow at full brightness. Then light-intensity will decrease automatically based on the number of vehicles crossing the pole in a particular amount of time. We use high-efficiency lithium-iron-phosphate ($LiFePO_4$) battery rather than lead-acid battery to ensure optimum usage of the stored energy. Thus combining several energy-saving technologies, the proposed system becomes able to generate 20% more energy than stationary solar panels while reduces LED power consumption by 15% per day.

We have also equipped the system with wireless technologies so that the status of multiple street-light systems can be monitored and operated remotely from distant places using hand-held devices such as smart-phones or personal-computers. The wireless system uses nRF [30, 31] and GPRS [33] technologies for communication. The nRF transceivers allow multiple street light units of an area to communicate among themselves and GPRS modules can upload data from each system to an online server which is accessible from all over the world through internet. Thus the proposed street-light system not only ensures energy-efficiency but also facilitates remote monitoring and controlling at the same time that makes the system intelligent and user friendly.

II. SYSTEM CONFIGURATION

The proposed street lighting system consists of three individual systems. Those systems are: sun-tracking solar panel system, traffic density based light intensity control system and wireless control and monitoring system. All these systems are combined together to ensure higher energy efficiency and easy maintenance of street lighting system. The structural configuration of the proposed model is presented in fig. 1.

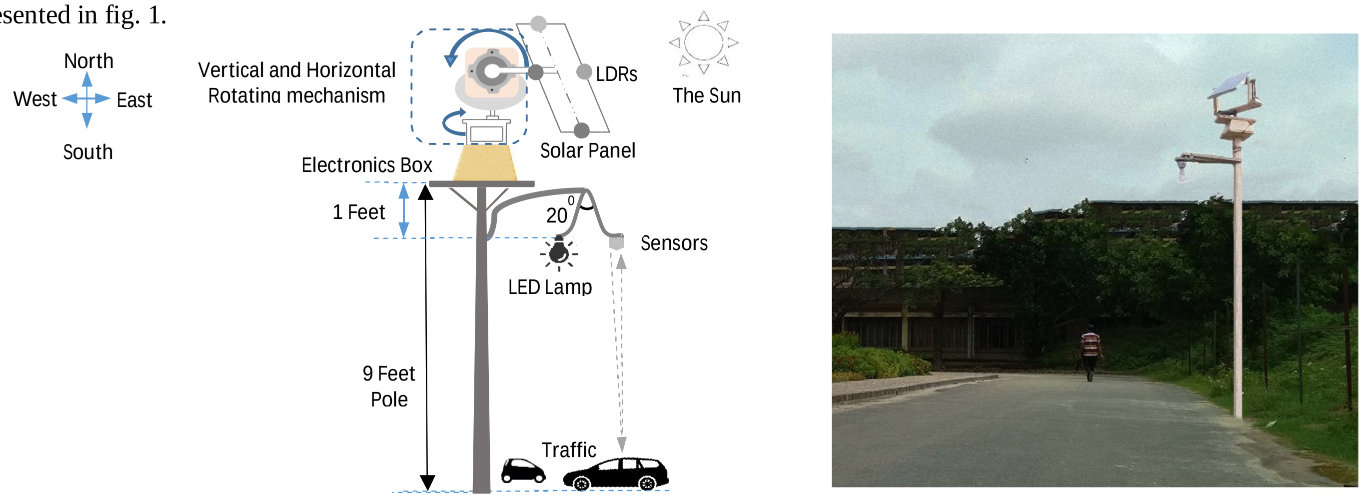

Fig. 1 Structural Configuration of the proposed solar-powered street-light model

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A nine feet tall pole holds the complete structure of the system. A horizontal surface is placed on the pole that holds a trapezium-shaped box on which the dual-axis servo motors are mounted. The box contains the complete circuitry to run the system that involves micro-controller, wireless communication modules and the $LiFePO_4$ battery. The solar panel is attached to the rotating wheel of the vertical servo motor. The LED light and sensors are attached to two different stands connected to the pole and the horizontal angle in between the stands is around 20 degrees. The flowchart of fig. 2 represents operational overview of the complete system.

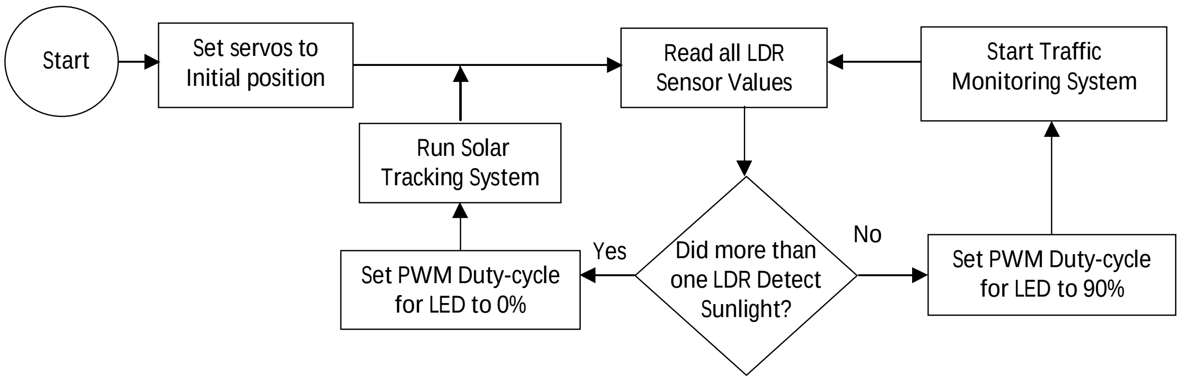

Fig. 2 Flowchart of operational overview of the system

The dual-axis servo motors control the moving mechanism of the solar-panel. The horizontal-servo rotates the panel to north-south and the vertical-servo rotates the panel to east-west direction. According to the flowchart of fig. 2, the servos are set to their initial positions at first. The initial angles of the vertical and horizontal servos are set to 0 degree and 90 degrees respectively so that the starting position of the rotating-panel becomes due-east. Micro-controller reads the LDR sensors and runs the sun-tracking system, keeping the LED-lamp switched-off (0% PWM duty-cycle) while more than one sensor detects sun-light. But the LED is switched-on (90% PWM duty-cycle) and traffic monitoring system starts running when it is dark and not more than one sensor can detect sun-light.

III.METHODOLOGY

The three sub-systems of the proposed street-light model involves dual-axis sun-tracking solar panel system for optimum solar-energy storage, traffic-density based light-intensity control system for reducing power-consumption, and wireless communication system for remote monitoring and controlling. In this section, we will discuss briefly about these three sub-systems.

A. Sun-tracking system

The purpose of the sun-tracking system is to keep the solar-panel aligned to the sun perpendicularly all over the day to ensure maximum solar-energy storage. The algorithm flowchart of the complete system is shown in fig. 3.

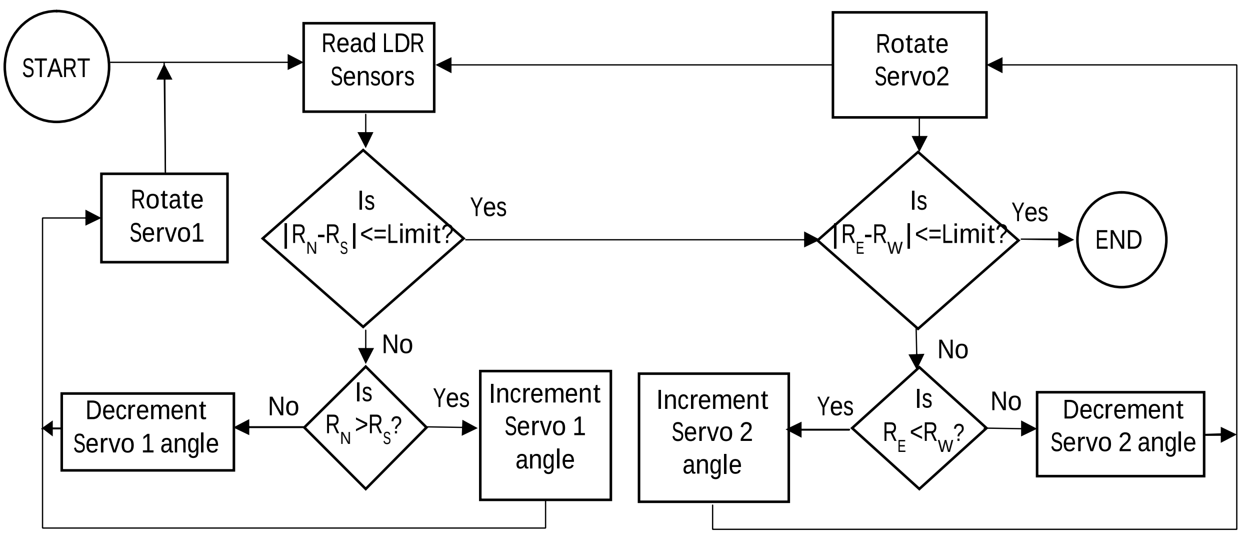

Fig. 3 Flowchart of sun-tracking system's operation

In the flowchart of fig. 3, the north, south, east and west LDR readings are represented by the symbols: R_N, R_S, R_E and R_W respectively. The term 'Limit' is considered as the negligible difference in LDR readings, which is set to 0.1 for simplicity. The system has four light-depending-resistors (LDRs), which are placed at each side of the panel. East and west LDRs are for daily tracking while north and south LDRs are for seasonal tracking of the sun. LDRs are connected to 10 bit ADCs to provide the sensor-data in digital values to the microcontroller. Those values are converted into analogue voltages using formula (*a*).

$$\text{Analog voltage of LDR} = \frac{\text{Digital value from ADC}}{\text{Resolution of ADC}} * \text{Source Voltage} \ldots \ldots \ldots (a)$$

Here in equation (*a*), the 5V output-voltage source of micro-controller is used as source voltage and resolution of 10 bit ADC is 1023. Thus microcontroller reads the analogue voltages of LDRs and rotates the servos when the difference in between same-axis LDRs is beyond limit. The vertical or horizontal servo moves to minimize the difference in between east-west or north-south LDR readings respectively. Two 8 bit PWM signals are generated from micro-controller to rotate two 12V servo motors.

B. Traffic Density Based Light Intensity Control System

The purpose of this system is to control the light-intensity of LED-lamp according to traffic-density. The algorithm flowchart of the system is shown in fig. 4.

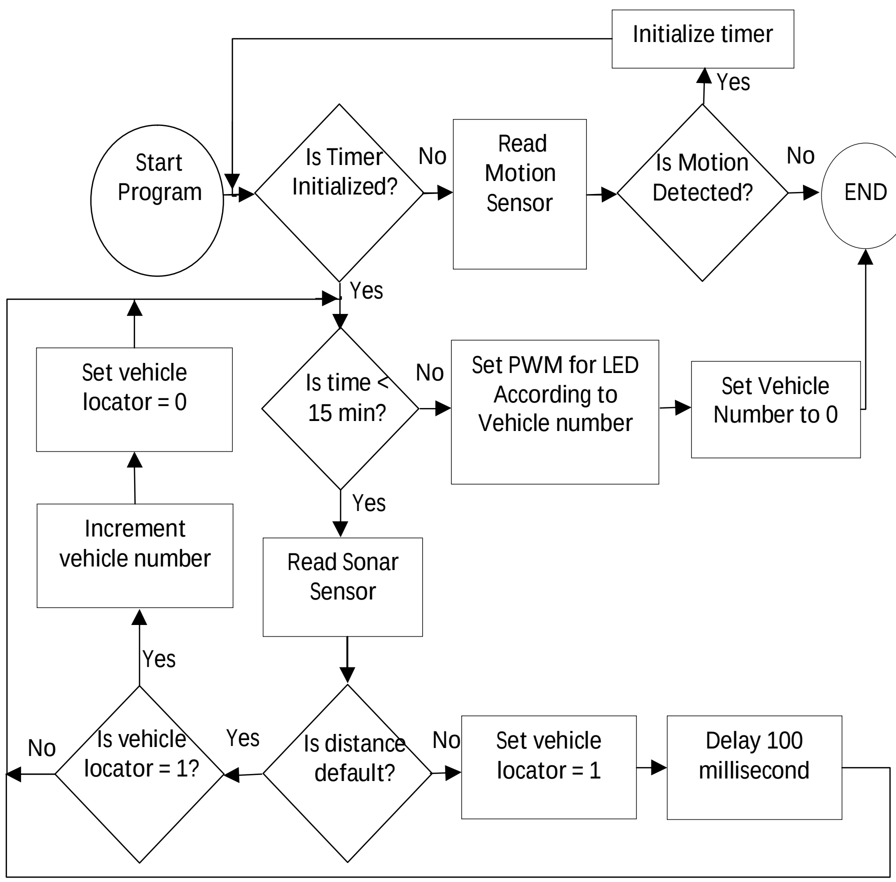

Fig. 4 Flowchart of Traffic density based light intensity control system's operation

From fig. 4, it is observed that, microcontroller keeps reading PIR motion sensor's output, until it detects motion in the street. A timer is initialized when the motion is detected. Then microcontroller keeps reading the distance value from sonar sensor until the timer completes counting 15 minutes. In the meantime, whenever the distance-value decreases from default due to a vehicle's crossing the sensor, micro-controller waits 100 millisecond for the value to increase again. Then one vehicle or people is considered to be counted, when the distance-value is increased to default again and the value of 'vehicle locator' variable is set to 1. Thus micro-controller counts the number of vehicles crossing the pole for 15 minutes and determines the duty-cycle percentage of the PWM signal for controlling LED-brightness according to TABLE I.

TABLE I
PWM DUTY CYCLE PERCENTAGE FOR DIFFERENT NUMBER OF VEHICLES

Number of vehicles crossed /15 minutes	PWM Duty Cycle (%)
>15	90
15-5	80
4-1	50
<1	30

In practice, the PWM signal controls the base-current of a MOSFET that controls current-flow through the LED-lamp. Power-consumption of LED lamp depends on the PWM duty-cycle according to formula (*b*).

Power consumed of LED lamp = Maximum power consumption * Duty cycle (%) … … …. (*b*)

It is observed from TABLE I that, the Duty-cycle percentage of PWM signal is set to 90% by default. And then it is decreased with the decrease of the number of counted vehicles.

C. Wireless Monitoring And Control System

The wireless monitoring system uses NRF and GSM technologies in order to manually control and monitor the solar-panel's movement or the lamp-intensity wirelessly from remote places. A diagram of data-flow in the system is shown in fig. 5.

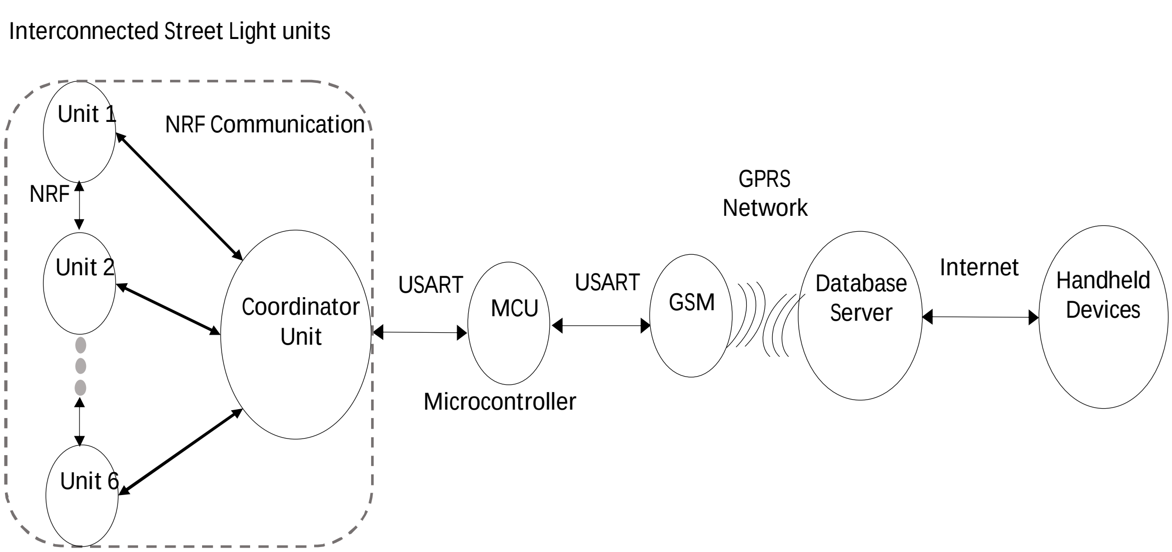

Fig. 5 Data-Flow in wireless monitoring and control system

The nRF transceivers allow one street-light unit to communicate with 6 other units at the same time within a coverage area of around 100 meters at high-speed radio-frequency of 2.4 GHz with up to 2 Mbps baud-rate [32]. Thus one coordinator unit can send or receive data from all other street-light units within the coverage area of the network and the micro-controller shares the information with an online server through GPRS data-communication system of GSM module [33] as shown in fig. 5. The online server is accessible through internet. Thus monitoring and controlling of all street-lights in an area becomes possible by using a computer or a smart phone from anywhere.

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D. Experimental Set-Up

The experimental set-up is a representation of the complete system-model including all mechanisms and sub-systems of the proposed street-light model, which is shown as a block-diagram in fig. 6.

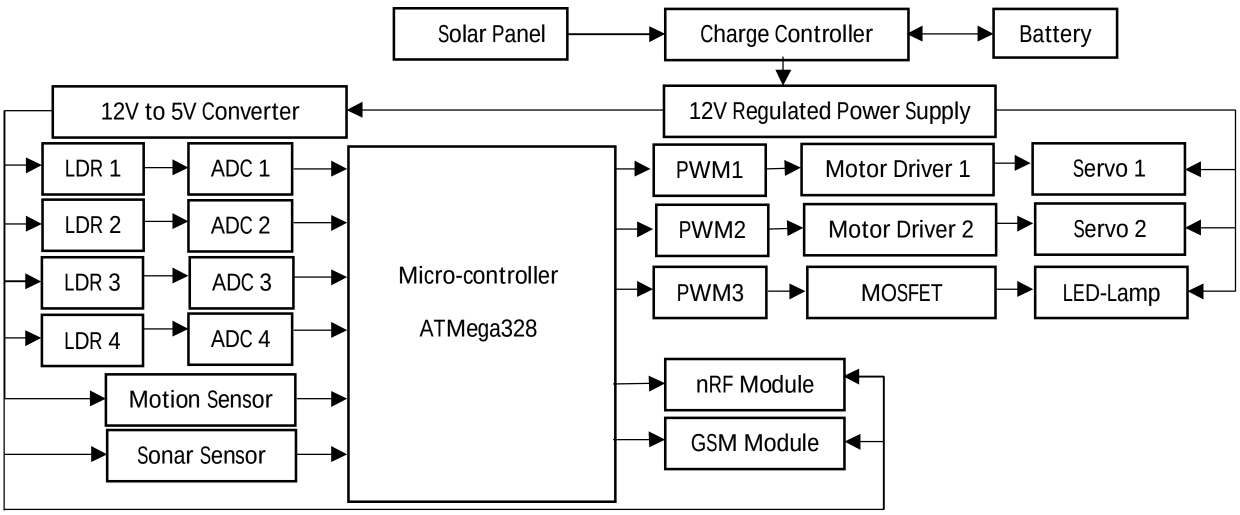

Fig. 6 Block diagram of the complete street-light system

The proposed street light model used a solar PV unit of 20 watts peak-capacity with output voltage of 17.95V and peak-current of 1.18Ah as the source of energy, which is connected to a 12V 6Ah $LiFePO_4$ battery through a 12V 10A Charge-controller. The 7W LED-lamp and servo motors are provided with regulated 12V supply from the battery through the charge-controller, as shown in the block-diagram of fig. 6. Current-flow through the LED-lamp is controlled by a MOSFET, which is operated using an 8 bit PWM signal form an ATMega328 micro-controller. The micro-controller also provides two additional 8 bit PWM signals to motor-drivers to operate the servos. Four LDRs are connected to four 10 bit ADCs of micro-controller for digital voltage reading and a 12V to 5V buck-converter is used to power all the electronics including sensors, motor-drivers and wireless modules. Sensitivity of PIR motion sensor is calibrated for vehicle and pedestrian detection. The sonar sensor with the widest and most sensitive beam-pattern is selected for reliable people detection or small object detection [34].

Now, instead of using a lead-acid battery, we have used LFP solar battery because, the output percentage of rated power or efficiency of lead-acid battery is around 65%, while efficiency of LFP battery is around 96% [35]. So we can use a conventional 12V 10Ah lead-acid battery to supply around 60 watts a day, or we can use a 12V 6Ah LFP battery instead for better performance. The required charging-time for the battery is calculated using formula (*c*)

$$\text{Battery charge time (approx.)} = \frac{\text{Battery Capacity (Watt hours)}}{\text{Panel Power (Watt)}} * \text{delay factor} \dots \dots \dots (c)$$

Here in formula (*c*), the 'delay factor' is considered due to voltage drop for internal resistance of multiple apparatus and connecting wires. Now our battery capacity is 12V 6Ah or 72Wh and panel capacity is 20W. So, if the delay-factor is considered to be 1.6, the approximate charging time becomes 5.76 hours. So we need around 5.76 hours of maximum sun-shine to completely charge our battery. Then the system becomes ready to perform its operations.

IV. RESULT AND DISCUSSION

In order to compare the efficiency of the proposed sun-tracking solar-panel with a stationary panel, we conducted the experiment of sun-tracking for two days. On 22 may 2018, our purpose was to monitor the azimuth and elevation angles of the sun-tracking solar panel at 11:59 am, so that we could use those values as ideal angles of the stationary panel on the next day. On 23 may 2018, at 6:00 am, we set the azimuth of the stationary panel to 99 degree east of due-south and the elevation to 79 degrees from vertical axis, as measured on the previous day. But the initial angles of the sun-tracking solar-panel was set to 0 degrees so that it can automatically align itself perpendicularly to the sun's position. Both panels were equipped with LDRs connected to two micro-controllers which were connected to a computer over USB serial communication ports. Then the voltage readings from east and west LDRs of both panels were observed once in every hour in computer's serial monitor. The readings were plotted graphically and represented in fig.

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7, where LDRs on the stationary panel are denoted as East LDR A and West LDR A. Similarly, LDRs on the sun-tracking panel are denoted as East LDR B and West LDR B.

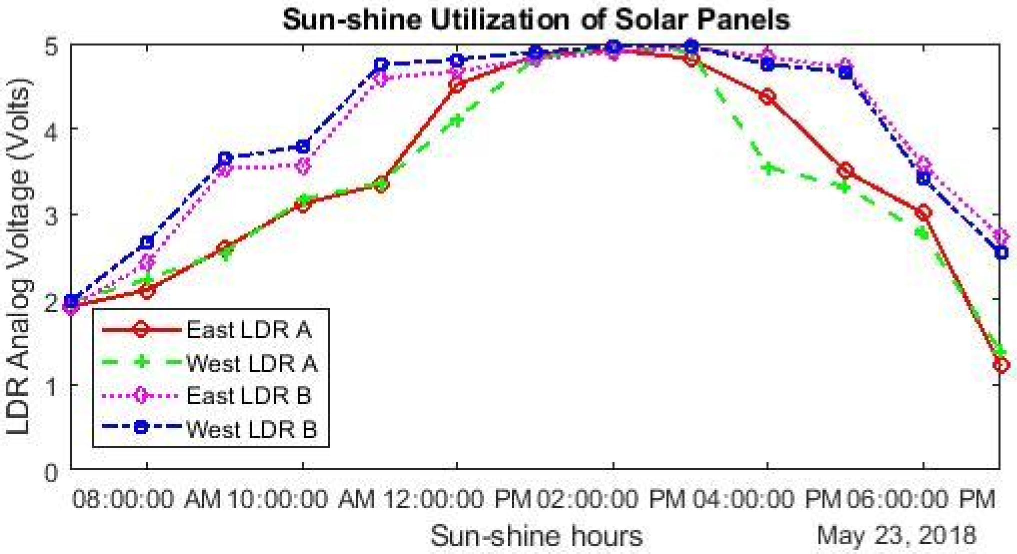

Fig. 7 Graphical Representation of LDR readings for Stationary and Sun-tracking solar panel

Fig. 7 is the graphical representation of sun-shine utilization efficiency for both stationary and sun-tracking solar panel. Here we can see that the maximum sun-shine hours for sun-tracking panel is almost 6 hours, while it is less than 4 hours for stationary panel. The average voltage of LDRs for stationary and sun-tracking panel is found to be 3.36V and 3.965V respectively, while peak output voltage of LDRs is 4.9V. So sunshine utilization efficiency of stationary and sun-tracking solar panel becomes 67.1% and 79.2% respectively. Therefore, sun-tracking panel utilizes more sun-shine than stationary panel by around 12%. We also observed the input voltage and current readings of the charge-controllers in every hour to monitor the average power output from both stationary and sun-tracking solar panels. The output-power readings form both panels are shown graphically in fig. 8.

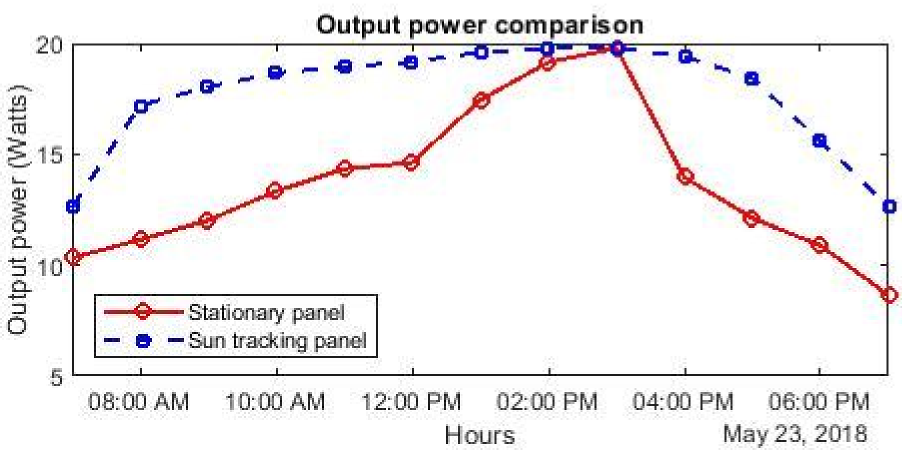

Fig. 8 Output power comparison in between stationary and sun-tracking solar panels

Fig. 8 represents power generation efficiency of both stationary and sun-tracking solar panels. The average power output from sun-tracking and stationary panel are 17.68W and 13.67W respectively, while peak output power of both panels are 20 watts. So, power generation efficiency of stationary and sun-tracking panels are 68.35% and 88.4% respectively. Thus the sun-tracking solar-panel produced 20.05% more power than the stationary panel. Now, using our traffic density monitoring system, we counted the number of vehicles crossing the pole per 15 minutes. We conducted the experiment on an average city-street of a residence area where traffic was found to be irregular. The experiment was conducted using TABLE I and formula (*b*) for 10 hours at night, to estimate the total power consumption of PWM-controlled LED lamp. The wattage consumption of LED-lamp was monitored for 10 hours with 15 minutes interval and then the readings were plotted graphically which is shown in fig. 9.

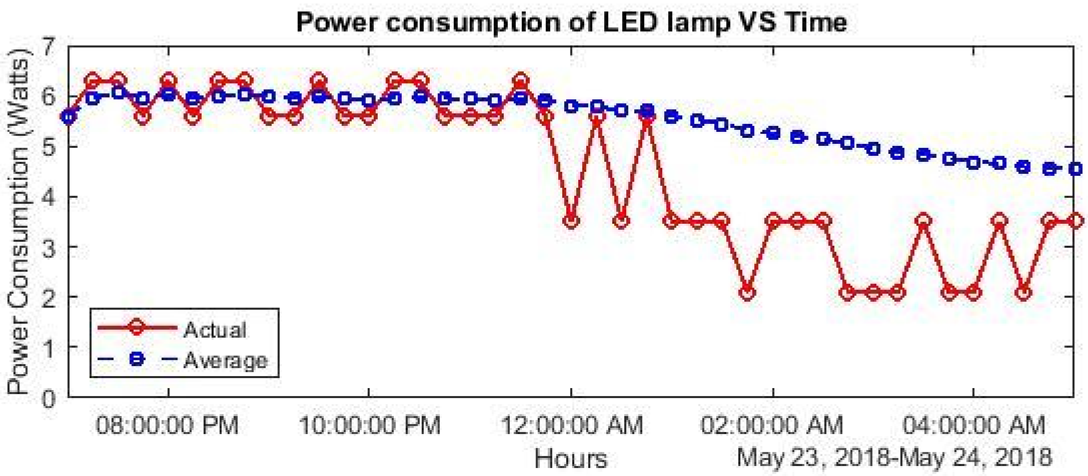

Fig. 9 Power comparison of LED lamp with respect to time

From fig. 9, it is observed that, the average power-consumption of LED lamp per hour started to decrease gradually after midnight and it was finally set to 4.54W after 10 hours. So the estimated total power consumption of the light for 10 hours is 45.4 watts. Now power-consumption at night may change from time to time and a small amount of power is also required for the electronic systems. Thus we multiply the estimated total power with the factor of 1.3 to predict the maximum power consumption of the system, which is 45.4W*1.3 or 59.02W. Now the peak power consumption of the lamp for 10 hours without PWM control is 7W* 10 or 70W. So, power-consumption is reduced by 15.7% for using traffic-density based light-intensity control system. Now we summarize the overall comparison of our energy efficient system with an ordinary solar-powered street light system in TABLE II.

TABLE II

COMPARISON OF THE PROPOSED SYSTEM WITH AN ORDINARY STREET LIGHT SYSTEM

Parameters	Proposed street-light system	Ordinary system	Comparison
Energy Generation efficiency	88.4%	68.35%	Dual-axis sun-tracking panel stores more solar energy than stationary panel by 20.05%
LED Power consumption	59.02 watts/day	70 watts/day	Traffic monitoring system saves energy by 15.7%
Battery efficiency	LFP battery with 96% efficiency	Lead-acid battery with 65% efficiency	LFP solar battery is more efficient than conventional Lead-acid battery by around 30%
Wireless control and monitoring Feature	Yes	No	Usage of nRF and GPRS technology is introduced in the proposed system

So it is observed from TABLE II that, the proposed street-light system generates around 20% more energy than stationary solar panel system while reduces LED power consumption by around 15.7% per day. It also provides wireless monitoring and control facilities.

V. CONCLUSIONS

Street-lights are one of the most important things in urbanized civilization, though they require lots of electric energy to lighten city-streets at night. Solar-powered street-lights have been introduced to replace grid-connected street-lights and save energy. Thus, in this paper, we investigated an approach to combine the modern technologies for increasing solar-powered street-light's efficiency. We used dual-axis sun-tracking technology with high-efficiency LFP battery to optimize solar-energy storage. Then we introduced traffic-density based light-intensity control for LED lamps to ensure complete automation of the system. Finally we configured the system with wireless technologies to facilitate remote monitoring and controlling of multiple units of the system. Thus combining modern technologies we were able to design such a system that is fully automated, wirelessly controllable and ensures around 20% more energy generation and 15.7% less power consumption per day than an ordinary solar-powered street-light system.

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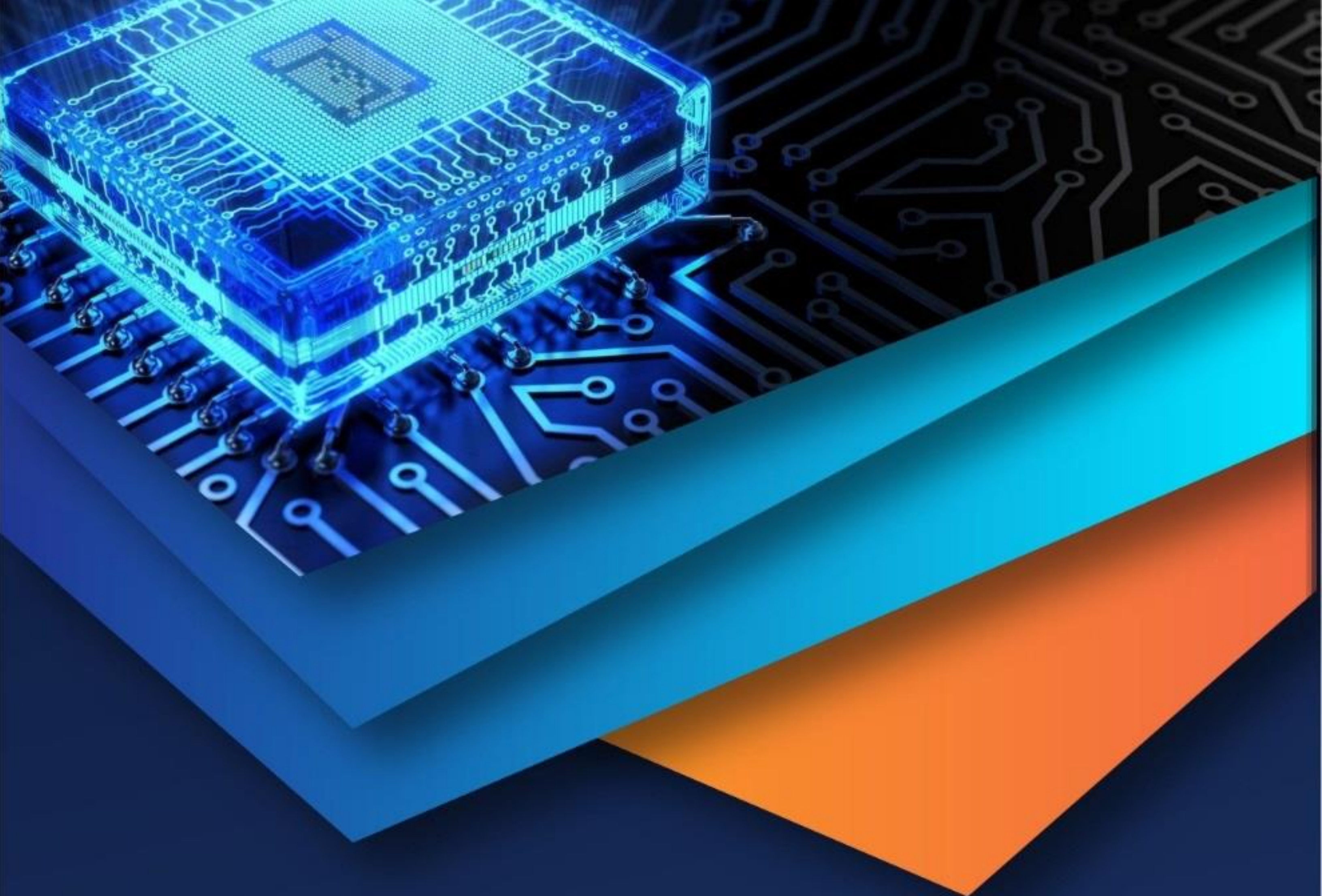

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