Battery Capacity Estimation with Kalman Filter for Battery Management System of Public Street Lighting

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***Abstract* — Research this aims for evaluate effectiveness of Kalman Filter in increase State of Charge (SoC) estimation on the system management battery For Street Lighting based on ESP32 microcontroller. SoC is a crucial parameter in determine level filling battery on time certain . In study Here , we use random data from the INA219 voltage and current sensor to simulate various condition operational . We do analysis to use of Kalman Filter on this data use evaluate improvement accuracy estimate SoC. Studies literature show that the Kalman Filter has succeed applied in various application For repair estimate system based on measurement data that is not perfect . Through modeling and simulation , we compare SoC estimation obtained from Kalman Filter with estimate direct from sensor data. Experimental results show that the Kalman Filter is significant reduce variation and increase accuracy battery SoC estimation , with average error not enough from 1.5%. Findings This support that use of Kalman Filter in system management PJU batteries have potential big For increased reliability operational and efficiency use energy. Research This give donation important in development monitoring and management technology more battery sophisticated and accurate For applications in the field .**

Keywords —Battery Management System (BMS), ESP32 Kalman Filter Sensor INA219 State of Charge (SoC)

I. Introduction

Use energy renewable the more increasing throughout the world, one of which is the utilization of energy solar For Public Street Lighting (PJU). PJU system based on energy solar This battery dependent as storage energy generated by solar panels [1]. Therefore that , management effective battery become very important For ensure sustainability operational and efficiency use energy [2].

One of challenge main in management battery is predictive capacity battery in a way accurate . State of Charge (SoC) is indicator important to show percentage capacity available battery . [3]Know the SoC in real - time and accurately allow management more energy efficient , extend age battery , and prevent damage due to overcharging or over discharging [4].

In the research this , we use ESP32 microcontroller equipped with INA219 sensor for detect voltage and current battery [5]. Data obtained from this sensor will sent to the website database and displayed on the monitoring dashboard. For increase accuracy SoC measurements , we apply Kalman Filter algorithm . Kalman Filter is a method capable data processing repair SoC estimation with reduce noise and uncertainty in measurement [6].

Implementation of Kalman Filter in system This expected can give more SoC estimation accurate compared to method conventional , so that help in management system PJU battery in more efficient [7]. This paper will explain methodology used in study this , the results obtained , and the analysis to performance the system that has been implemented [8].

II. Methods

A. Lead-Acid Battery

Lead Acid Battery is one of the type the most common battery used For application power that is not disconnected (UPS), cars , and systems lighting road (such as PJU). Battery This consists of from cells containing electrolyte water based and electrodes made of from lead (Pb) and lead oxide (PbO_2) in atmosphere sour sulfate (H_2SO_4). Characteristics the main thing covering ability For give current big in time short and cost relatively low per capacity [9].

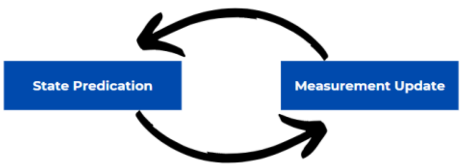


Fig. 1Filter Function

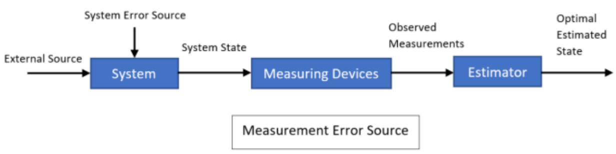


Fig. 2. Kalman Filter Block Diagram

B. State of Charge

State of Charge (SoC) is a measure that indicates amount stored energy in battery on a time certain , stated as percentage from capacity maximum battery . Accurate SoC estimation important For optimize use battery and prevent emptying excessive that can damage battery [10].

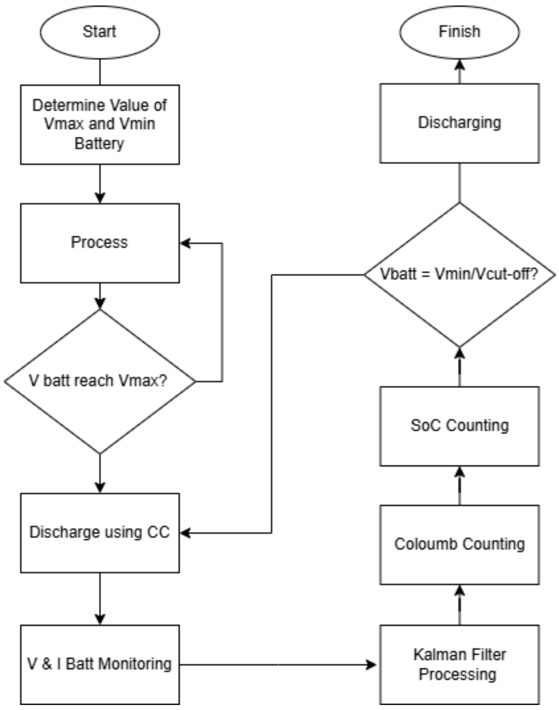


Fig. 3. Flowchart Study

State of Charge (SOC) is a crucial parameter in the Battery Management System (BMS) indicating capacity battery as percentage from capacity maximum . For calculate SOC, used the following integral equation :

$$SOC\ (\ t + \Delta t\ ) = SOC\ (\ t\ ) + 1\ cn\ .\ \int + \Delta tt\eta\ .\ IOt\ .\ dt \quad (1)$$

Here , SOC(t) is the state of charge at time tt t , Δt \Delta t Δt is addition time , CnC_n Cn is the nominal capacity of the battery in ampere-hours (Ah), and I(t)I(t) I (t) is the current moment function time tt t . Coulomb efficiency (η\ eta η) is taken into account For filling and emptying battery , and it is assumed worth 1. Method This depends on accuracy initial SOC calculation and measured current , which is difficult known in a way appropriate Because fluctuation current and voltage battery . Therefore that , the Coulomb Counting method does not can stand Alone without addition other methods for repair SOC estimation .

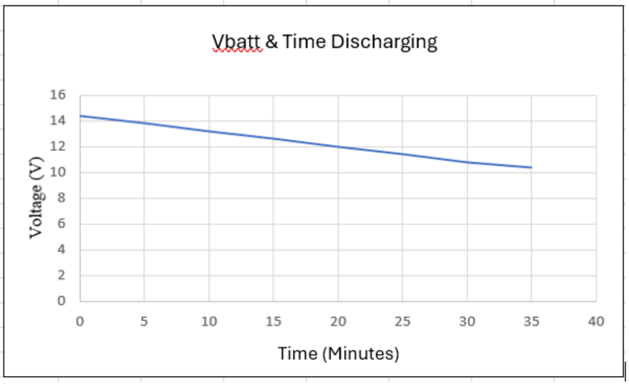


Fig. 4. Graphics Showing How Voltage Battery Changed Along with Time During the Emptying Process

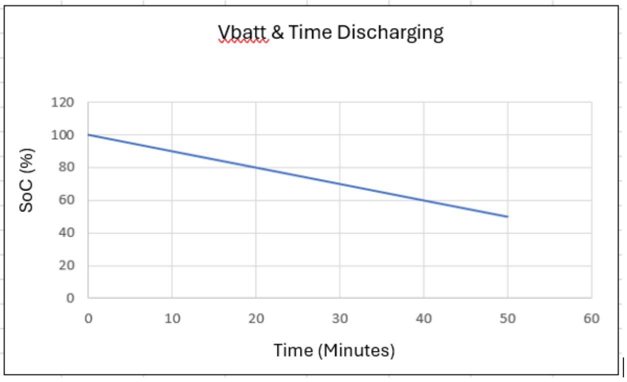


Fig. 5. Graphics Showing How SoCs Have Changed Along with Time During the Emptying Process

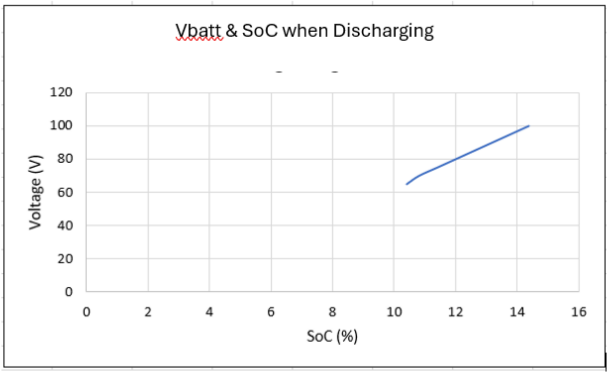


Fig. 6. Graphics Showing How The relationship between SoC and Voltage in Discharging Process

Table the displays voltage monitoring data battery and time emptying in trial context For determine connection between voltage battery and time moment battery experience emptying . Range voltage battery start from 14.4 V to 10.4 V, represented in column " Voltage Battery (V)", while time emptying in minute listed in " Emptying Time (Minutes)" column . This data used For observe decline voltage battery along the walk time , which can give understanding about performance and capacity battery in condition operational certain . Analysis graphic from this data expected can give clear visual image about behavior voltage battery during the emptying process , it is important in context management battery For application like Public Street Lighting (PJU) which utilizes ESP32 technology and INA219 sensor.

C. *Kalman Filter*

Kalman Filter is a method processing the signal used For estimate system status in real-time based on measurement data that is not perfect , like a sensor. This filter use approach statistics For count mark optimal prediction with take into account variation and accuracy measurement as well as the system model used [11].

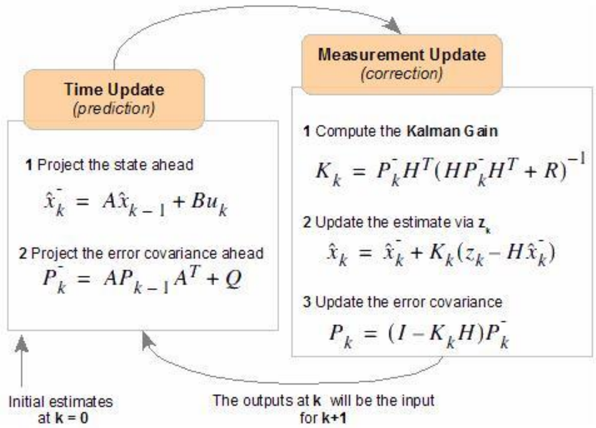


Fig. 7. Kalman Filter Calculation

D. *400 Watt Public Street Lighting*

PJU (Public Street Lighting) 400 Watt refers to the type light the road that uses Power of 400 Watts. This PJU generally used For lighting road raya or public area others and need system management efficient battery For ensure stable and economical operation energy [12].

E. *Battery Management System*

Battery Management System is a system electronics on duty For monitor and manage health , performance , and security battery . BMS usually equipped with sensor for monitor voltage , current , temperature , and system control For arrange filling and emptying battery in accordance with optimal [13]conditions .

Research process This consists of from organized stages with Good For reach findings supported by analysis scientific and conducted with fast as well as regular . Method research used in studies This refers to the Development Life Cycle (MDLC) Model which has six stages , namely Concept , Design, Collection Materials , Assembly , Testing , and Distribution . In explain activities and goals study this , research This based on the framework work (Figure 2) and Work Breakdown Structure (Figure 3), with stages as following :

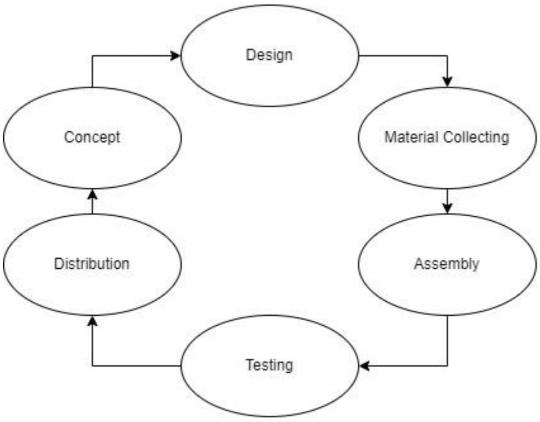


Fig. 8. Multimedia Development Life Cycle

1. Draft Stage This covers activity design base For the application that will built , especially related purpose and type the application that will made . At the stage Here , we identify need main For system management Kalman Filter based PJU battery , including objective main like Real-time SoC (State of Charge) monitoring and enhancement accuracy estimate capacity battery .

2. Design Stage design covers activity related detailed design program architecture , style , interface users (UI) , and material or component for the program. Specifications This must as detailed as possible Possible For avoid repetition at stage next , namely collection materials and assembly . At this stage design , various element such as storyboards, Unified Modeling Language (UML) diagrams, Use Case diagrams, Activity diagrams, Sequence diagrams , and schemas. channel system taken into account , as well as design appearance the screen is also part from this process .

3. Collection Material Stage This involving activity gather materials needed in the system in progress worked on , such as the INA219 sensor for detection voltage and current , ESP32 microcontroller , and device soft For programming and data processing .

4. Assembly Stage assembly covers activity making all object or material For application based on stage design , such as storyboards and structures navigation . At this stage this , device hardware (sensors and microcontrollers) and devices software (Kalman Filter algorithm) is integrated become One functional system . Data generated by the sensors are sent to the website database and displayed on the monitoring dashboard.

5. Trials Trial phase consists of from trial activity application to user end or owner PJU system . After that , the user or owner system will give evaluation or input For increase performance applications that have been made . Trial done For ensure accuracy SoC estimation and reliability system in various condition operational .

6. Distribution Stage distribution involving transfer and storage application on appropriate storage media . Stage this can also called as stage evaluation , which is carried out For increase quality product end . At the stage this , application system management PJU battery ready For implemented in a way wide and used in operational daily .

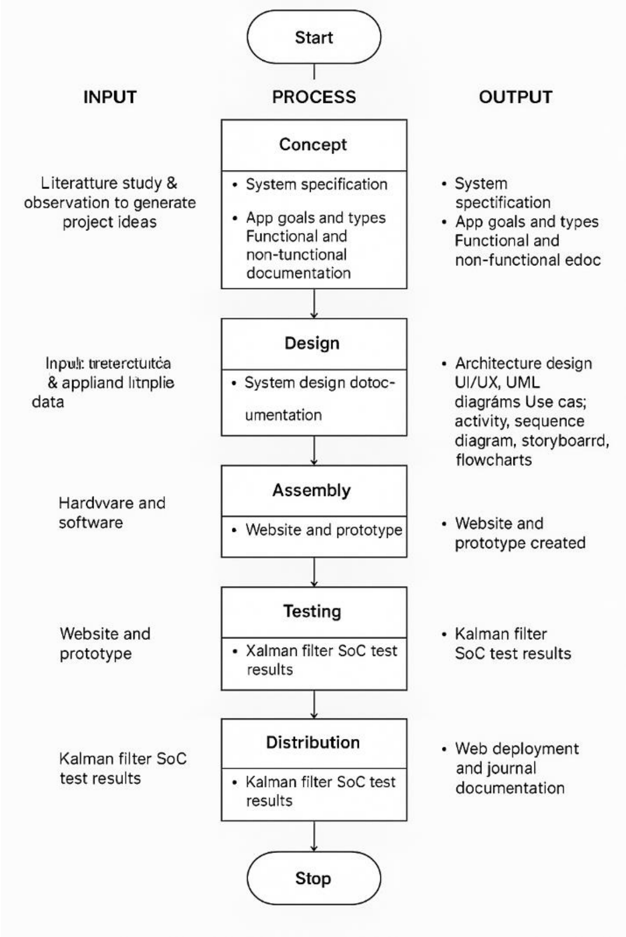


Fig. 9Project Framework

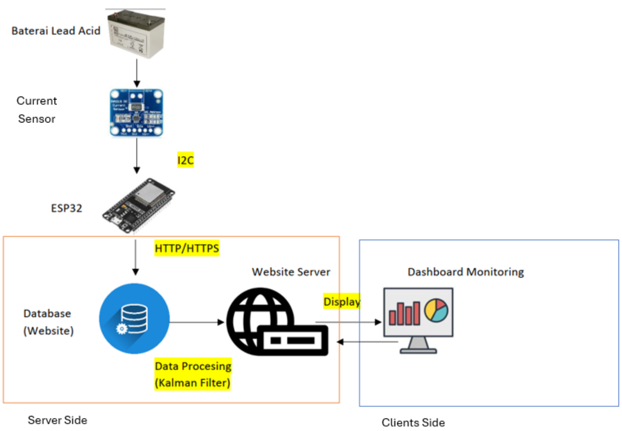


Fig. 10. Architecture Diagram

III. Results and Discussion

This paper designed a monitoring tool for now State of Charge (SoC) value with Kalman filter method. The battery used in this paper is lead- acid battery capacity 12 V 7 Ah/20 HR at a temperature of 25 degrees Celsius . Battery SoC value counted at the time emptying . In chapter This also carried out testing and calibration of current sensors and voltage sensors . This intended for to obtain mark accurate current and voltage at the time discharge, due to current and voltage parameters is important parameters for set battery SoC value. Stage furthermore the emptying process is carried out with supervise voltage and current obtained to define SoC using Kalman filter method. Measurement results and estimates This Then analyzed for evaluate accuracy and effectiveness method extended Kalman filtering for increase battery SoC estimation compared to with method direct sensor measurement.

A. *Current and Voltage Sensor Testing*

Current sensor is part a very necessary component in this SoC monitoring system , because accuracy measurement The current greatly influences the resulting SoC estimate . For to obtain mark accurate current , requires testing of the current sensor used in tool This . In this paper , the current sensor used is the INA219 sensor. The trial done with method compare results INA219 sensor measurement with tool measure what has been calibrated , namely a multimeter. The results of the INA219 current sensor test with various mark current shown in Table 1. From the trial results said , obtained that mark INA219 sensor measurement approaching the value measured by a multimeter, with an average error by 1.47%. Therefore that , can concluded that the current sensor used in this monitoring tool functioning with Good .

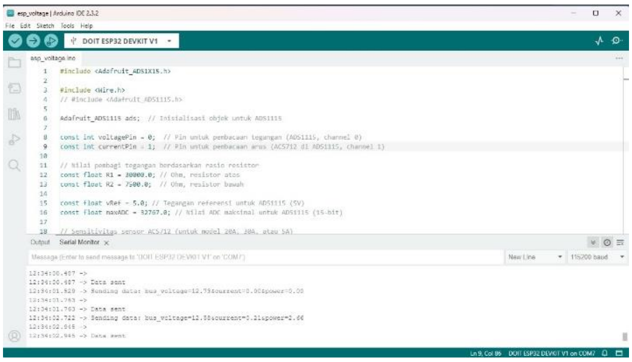
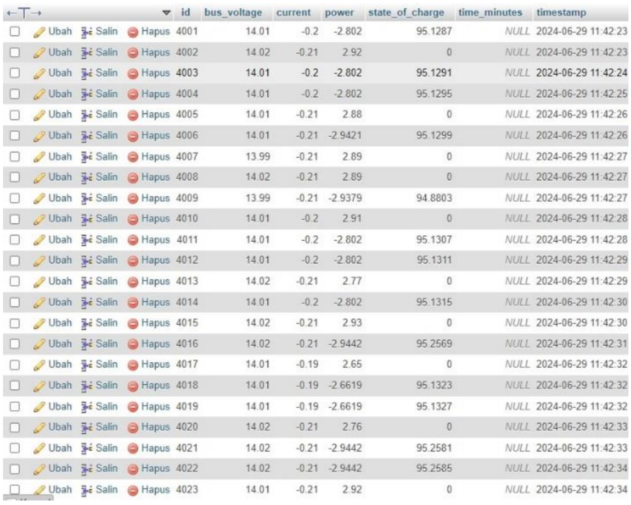


Fig. 11. Arduino IDE Serial Monitor Sending Sensor Data to Website



←T→	id	bus_voltage	current	power	state_of_charge	time_minutes	timestamp
Ubah Salin Hapus	4001	14.01	-0.2	-2.802	95.1287	NULL	2024-06-29 11:42:23
Ubah Salin Hapus	4002	14.02	-0.21	2.92	0	NULL	2024-06-29 11:42:23
Ubah Salin Hapus	4003	14.01	-0.2	-2.802	95.1291	NULL	2024-06-29 11:42:24
Ubah Salin Hapus	4004	14.01	-0.2	-2.802	95.1295	NULL	2024-06-29 11:42:25
Ubah Salin Hapus	4005	14.01	-0.21	2.88	0	NULL	2024-06-29 11:42:26
Ubah Salin Hapus	4006	14.01	-0.21	-2.9421	95.1299	NULL	2024-06-29 11:42:26
Ubah Salin Hapus	4007	13.99	-0.21	2.89	0	NULL	2024-06-29 11:42:27
Ubah Salin Hapus	4008	14.02	-0.21	2.89	0	NULL	2024-06-29 11:42:27
Ubah Salin Hapus	4009	13.99	-0.21	-2.9379	94.8803	NULL	2024-06-29 11:42:27
Ubah Salin Hapus	4010	14.01	-0.2	2.91	0	NULL	2024-06-29 11:42:28
Ubah Salin Hapus	4011	14.01	-0.2	-2.802	95.1307	NULL	2024-06-29 11:42:28
Ubah Salin Hapus	4012	14.01	-0.2	-2.802	95.1311	NULL	2024-06-29 11:42:29
Ubah Salin Hapus	4013	14.02	-0.21	2.77	0	NULL	2024-06-29 11:42:29
Ubah Salin Hapus	4014	14.01	-0.2	-2.802	95.1315	NULL	2024-06-29 11:42:30
Ubah Salin Hapus	4015	14.02	-0.21	2.93	0	NULL	2024-06-29 11:42:30
Ubah Salin Hapus	4016	14.02	-0.21	-2.9442	95.2569	NULL	2024-06-29 11:42:31
Ubah Salin Hapus	4017	14.01	-0.19	2.65	0	NULL	2024-06-29 11:42:32
Ubah Salin Hapus	4018	14.01	-0.19	-2.6619	95.1323	NULL	2024-06-29 11:42:32
Ubah Salin Hapus	4019	14.01	-0.19	-2.6619	95.1327	NULL	2024-06-29 11:42:32
Ubah Salin Hapus	4020	14.02	-0.21	2.76	0	NULL	2024-06-29 11:42:33
Ubah Salin Hapus	4021	14.02	-0.21	-2.9442	95.2581	NULL	2024-06-29 11:42:33
Ubah Salin Hapus	4022	14.02	-0.21	-2.9442	95.2585	NULL	2024-06-29 11:42:34
Ubah Salin Hapus	4023	14.01	-0.21	2.92	0	NULL	2024-06-29 11:42:34

Fig. 12. Website Database of Sensor Data Delivery Results

TABLE I. INA219 SENSOR TEST DATA DIFFERENT VALUES FOR EACH TRIAL DATA

I Tested (A) (INA219)	I Tested (A) (Multimeter)	Error (%)
0.50	0.51	2.00
1.00	0.98	2.04
1.50	1.52	1.32
2.00	1.97	1.52
2.50	2.48	0.81
3.00	3.05	1.64
Average value error		1.47

INA219 sensor for holding part tension measurement required to obtain the battery voltage value, because the battery cut-off voltage needs to be considered. SoC should not be less than 20%. INA219 reads the battery voltage when *charging* and *discharging* the battery. We need a measuring instrument such as an accurate multimeter to compare the test value of the measuring instrument with the INA219 sensor. For the test voltage source, we use a DC power supply. The test results on the multimeter are close to the test results on the INA219 sensor. The average error is only 1.22. Based on these results, it can be concluded that the INA219 sensor for voltage measurement used in this SoC monitoring system is accurate and works well.

TABLE II. INA219 SENSOR TEST DATA DIFFERENT VALUES FOR EACH TRIAL DATA

V Tested (V) (INA219)	V Tested (V) (Multimeter)	Error (%)
5.00	5.06	1.19
7.50	7.60	1.32
10.20	10.08	1.19
8.70	8.80	1.14
12.30	12.16	1.15
6.50	6.57	1.07
11.80	11.95	1.27
9.90	10.02	1.30
13.00	12.85	1.17
Average value error		1.22

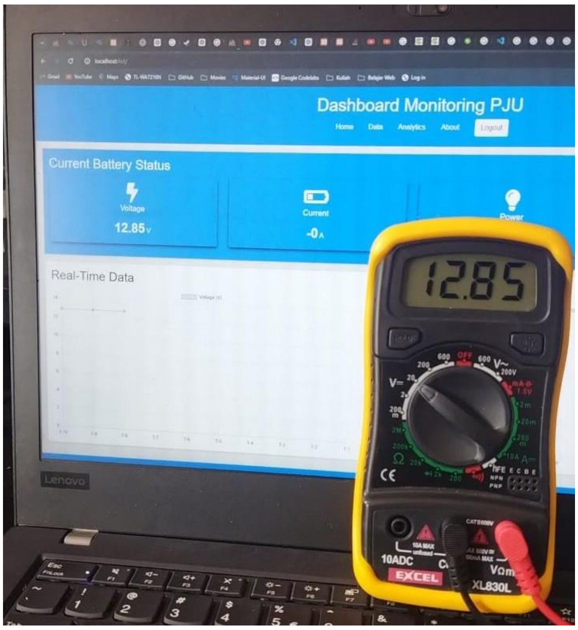


Fig. 13. Accuracy Test of INA219 Voltage Measurement Sensor

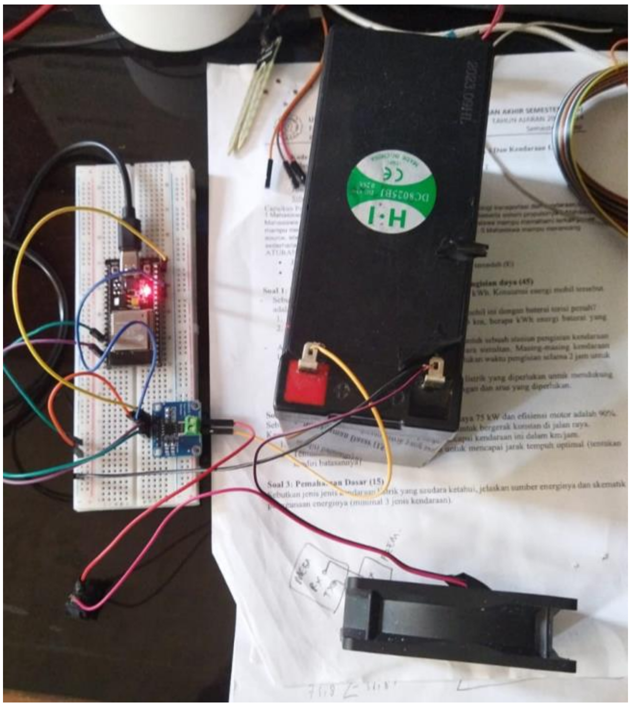


Fig. 14. Voltage and Current Monitoring Assembly Using INA219 Sensor

From the test results of the INA219 current and voltage sensor , it was obtained that both sensors show high accuracy with an average error of 1.47% and 1.22% respectively . This is show that the INA219 sensor can used in a way effective in SoC monitoring system for PJU, providing results accurate and reliable measurement in various condition operational . With Thus , the use of the INA219 sensor in this monitoring tool can reliable For to obtain accurate SoC estimation and improve reliability system management battery .

In the PJU battery SoC estimation system, the INA219 sensor measures voltage and current battery then this data collected by ESP32 via I2C protocol . ESP32 works manage the collected data and send it to the server using HTTP/HTTPS or MQTT protocol . Function This implemented in ESP32 code that collects data from the INA219 sensor. On the web server, the received data saved in the database and served For request from a web browser via PHP script or REST API. JavaScript on the web page then fetch data from server and display it in form chart using Chart.js. This data displayed on the interface user For give real-time information on battery status , including battery voltage , current , and State of Charge (SoC) .

B. Website Monitoring Development for Battery Management System

The compilation of this monitoring website involving a number of step important For ensure system functioning with OK . File and directory structure set up with neat , including the main file like ` index.php ` for page main site, `styles.css` for visual display , `script.js` for logic interactive , as well as some PHP files that handle storage , retrieval , and deletion of data in the database.

Fig. 15. Website Monitoring Dashboard Display

The dashboard will display data in realtime updated for 1 second . The data is got via the INA219 sensor which sends data to the ESP32 then sent to the website database for processed and displayed on the website dashboard. Data is processed in the form of Use of Kalman filter on battery SoC For prediction battery SoC percentage in a way more accurate

Interface design made simple and easy used , with login feature that ensures only user with correct credentials can access the dashboard. Data from connected sensors to ESP32 sent to the server and saved in the database, then displayed in real-time on the page main in form numbers and graphs . [14]Current value electricity used For calculate SoC (State of Charge) or level filling battery , providing information on voltage, current , power , and SoC status to users [15]. Data management allows deletion of certain data or all data from the database if necessary , so this website give real-time information and various feature For manage as well as analyze battery status light road general (PJU) [16].

C. Kalman Filter For Battery SoC Calculation

In application Kalman Filter method for count SoC (State of Charge) value of the battery , the initial parameters of the SoC play a role role important in to obtain accurate results . Before the filling process battery done , battery must be charged with proper charging current until reach voltage the maximum , namely about 13 V. When the battery reach voltage maximum , battery SoC considered worth 100%. [17].

In application Kalman Filter method for count SoC (State of Charge) value of the battery , the initial parameters of the SoC play a role role important in to obtain accurate results . Before the filling process battery done , battery must be charged with proper charging current until reach voltage the maximum , namely about 13 V. When the battery reach voltage maximum , battery SoC considered is worth 100%. In the discharge process , the initial SoC of battery is 100%. From the graph produced , the more A little the charge on the battery so battery SoC value will the more small . So that connection between the total charge on the battery with SoC the battery is proportional straight .

In operation battery , discharge graph shows that at first mark voltage battery tend own the decline that is not too significant , with mark voltage battery ranges from 11 V-12 V. However when battery used approach time 35 minutes , voltage battery tend experience quite a drop significant until reaches 10 V. Based on obtained graph , battery need operated at time intervals certain For to obtain mark optimal voltage so that equipment electricity supplied by battery can Work with Good .

In operation battery , battery SoC tend own connection compared to backwards with time on cycle discharge . The longer the battery used so the more Lots the load used , so that the battery SoC will the more decreased . Graph test results This show connection mark voltage battery with battery SoC value . From the graph the can see that mark voltage battery tend own decline value that is not too significant , with mark voltage battery around 12V-13V that occurs when SoC battery worth 60%-100%. However voltage battery will experience quite a drop significant when SoC battery is below 50% . Graph This can made into reference in operation battery as a storage medium energy . Considering battery when operated under 40% SoC will own mark low voltage , so will influence performance from existing equipment . In addition that , operation battery with DOD (Depth of Discharge) that is too high big will affect the lifetime of battery That alone . In its implementation , increasingly big DOD value used then the battery lifetime will the more decrease .

1. Kalman Filter Initialization
   - **Initial SoC (State of Charge)** :$\hat{x}_0 = 100\%$
   - **Initial Error Covariance** : $P_0 = 1$(assumption beginning)
   - **Process Noise Covariance** : $\mathrm{Q} = 0.01$(small assumption for small changes in the process)
   - **Measurement Noise Covariance** : $\mathrm{R} = 0.1$(assumption small For measurement uncertainty)
2. Prediction Model
   - **SoC Prediction** :

$$\hat{x}_{k|k-1=}\hat{x}_{k-1|k-1} - \frac{I.\Delta t}{C_n} \tag{2}$$

   - **Prediction Covariance Error** :

$$P_{k|k-1=}P_{k-1|k-1} + Q \tag{3}$$

3. Correction Model
   - **Kalman Gain** :

$$K_k = \frac{P_{k|k-1}}{P_{k|k-1}+R} \tag{4}$$

   - **SoC Correction** :

$$\hat{x}_{k|k=}\hat{x}_{k|k-1} + K_k(z_k - \hat{x}_{k|k-1}) \tag{5}$$

   - **Correct Covariance Error** :

$$P_{k|k} = (1 - K_k)P_{k|k-1} \tag{6}$$

4. Table Iterations per Second

TABLE III. ITERATIONS PER SECOND FOR 5 SECONDS

Time (s)	SoC Prediction	Error Covariance	SoC z k measurement	Kalman Gain K k	SoC $\hat{x}_{k\|k}$Correction	Correct Error $P_{k\|k}$
0	100%	1	100%	0.909	100%	0.0909
1	99.996 %	0.1009	99.9%	0.502	99.951%	0.0502
2	99.948 %	0.0602	99.8%	0.375	99.873%	0.0375
3	99.823 %	0.0475	99.7%	0.322	99.746%	0.0322
4	99.621 %	0.0422	99.6%	0.296	99.642%	0.0296
5	99.448 %	0.0296	99.5%	0.228	99.468%	0.0228

In Kalman Filter application for count SoC (State of Charge) value of the battery , the initial parameters of the SoC play a role role important in to obtain accurate results . Before the emptying process done , battery must be charged with proper charging current until reach voltage the maximum , namely about 13 V. When the battery reach voltage maximum , battery SoC considered worth 100%. In the discharge process , the battery used with average discharge current 0.3 A, time interval 1 second data capture , and the average load used customized with battery used .

In operation battery , discharge graph shows that at first mark voltage battery tend own the decline that is not too significant , with mark voltage battery ranges from 11 V-12 V. However when battery used approach time 35 minutes , voltage battery tend experience quite a drop significant until reaches 10 V. Based on obtained graph , battery need operated at time intervals certain For to obtain mark optimal voltage so that equipment electricity supplied by battery can Work with Good .

In operation battery , battery SoC tend own connection compared to backwards with time on cycle discharge . The longer the battery used so the more Lots the load used , so that the battery SoC will the more decreased . Graph test results This show connection mark voltage battery with battery SoC value . From the graph the can seen that mark voltage battery tend own decline value that is not too significant , with mark voltage battery around 12V-13V that occurs when SoC battery worth 60%-100%. However voltage battery will experience quite a drop significant when SoC battery is below 50% . Graph This can made into reference in operation battery as a storage medium energy . Considering battery when operated under 40% SoC will own mark low voltage , so will influence performance from existing equipment . In addition that , operation battery with DOD (Depth of Discharge) that is too high big will affect the lifetime of battery That alone . In its implementation , increasingly big DOD value used then the battery lifetime will the more down . In the process of emptying This is the initial SoC of battery is 100%. From the resulting graph , increasingly A little the charge on the battery so battery SoC value will the more small . So that connection between the total charge on the battery with battery SoC is compared to straight . The battery used in the process of emptying This own specification as following : Manufacturing 6-FM-7, capacity 7 Ah battery , and the nominal V of the battery is 12 V.

With using Kalman Filter, battery SoC prediction become more accurate and can reliable compared to with method calculation conventional . This allow management system more battery efficient and optimal operation , maintaining age battery and performance equipment supplied by batteries .

IV. Conclusion

Study This succeed implementing Kalman Filter in State of Charge (SoC) calculation of the battery on the system management battery For Public Street Lighting (PJU). With use ESP32 microcontroller and INA219 sensor for measure voltage and current , results sensor reading sent to the website database and monitored via dashboard. The Kalman Filter method has been proven effective in determine battery SoC in a way accurate , which allows management system more battery efficient .

According to the graph obtained , is visible that battery need operation at specified time intervals in order to obtain voltage optimal value so that equipment electricity supplied by battery can Work with good . Besides that , the use of old battery , causing The load used also increases many , so the battery SoC the more reduced . Relationship This show importance monitor and manage SoC for ensure optimal performance of equipment supplied by batteries .

Chart it also shows that battery operated under 40 % SoC will own mark low voltage , which can influence performance equipment . Operation battery with too much Depth of Discharge (DOD) big will affects battery lifetime , with the more large DOD used then the battery lifetime will the more decrease .

In general Overall , the implementation of the Kalman Filter in battery SoC management give more results accurate and can reliable compared to method calculation conventional . This is allow operation more optimal battery , maintaining age battery , and improve efficiency system management PJU battery . With Thus , the results study This can made into reference in development system management more battery good in the future .

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