

BAB V

SIMPULAN DAN SARAN

5.1 Simpulan

Penelitian ini telah berhasil merancang, mengimplementasikan, dan menguji sistem *Buck Converter* Berbasis *IoT* untuk *Monitoring Photovoltaic* yang mencakup aspek konversi daya, efisiensi, dan pemantauan *real-time*. Berdasarkan hasil pengujian dan analisis yang mendalam, dapat ditarik beberapa simpulan sebagai berikut:

1. Sistem *buck converter* yang dirancang telah berhasil menurunkan tegangan *output photovoltaic* yang fluktuatif (36V-44V) menjadi level tegangan untuk beban 12V dan 24V dengan *error* regulasi sangat kecil ($<0.05\%$). *Buck converter* mencapai efisiensi konversi daya tertinggi sebesar 88.30% pada beban 30Ω dan *duty cycle* 90%, memenuhi target minimal 85% meskipun belum mencapai efisiensi ideal akibat rugi-rugi *switching* dan konduksi. Riak tegangan *output* berhasil dipertahankan konsisten pada 1000 mV *peak-to-peak* (sekitar 2.85%) meskipun riak *input* mencapai 3000-4000 mV, membuktikan kemampuan sistem dalam menjaga dan melindungi beban dari kerusakan akibat tegangan berlebih.
2. Sistem *monitoring* berbasis *IoT* menggunakan ESP32, dua sensor PZEM017, modul RS485, dan *dashboard website* lokal telah terintegrasi dengan baik dan berhasil memantau parameter kelistrikan secara *real-time* meliputi tegangan (V_{in} , V_{out}), arus (I_{in} , I_{out}), daya (P_{in} , P_{out}), *duty cycle*, dan efisiensi. Integrasi LCD 16x2 sebagai *display* lokal meningkatkan fleksibilitas *monitoring*. Evaluasi akurasi menunjukkan sensor PZEM017 memiliki kinerja sangat baik untuk pengukuran tegangan (*error* $<3\%$), namun akurasi pengukuran arus kurang konsisten dengan *error* besar pada arus rendah ($<0.3A$) mencapai 25-38% dan meningkat pada arus tinggi akibat *thermal drift*, sehingga perlu perhatian khusus dalam pemilihan sensor sesuai rentang pengukuran.

5.2 Saran

Berdasarkan temuan dan keterbatasan selama penelitian, berikut disampaikan saran untuk pengembangan dan penyempurnaan sistem di masa depan:

1. Optimasi Desain *Buck Converter* untuk Efisiensi Tinggi, Disarankan untuk mengganti komponen semikonduktor dengan spesifikasi lebih tinggi, seperti MOSFET dengan $R_{DS(on)}$ dan kapasitansi gerbang yang lebih rendah, serta dioda *Schottky* untuk mengurangi rugi-rugi konduksi dan *switching*. Penggunaan induktor dengan DCR rendah dan kapasitor dengan ESR rendah juga sangat dianjurkan. Untuk simplifikasi dan optimasi yang lebih baik, penggunaan *DC-DC Converter IC* terintegrasi dapat dipertimbangkan sebagai alternatif dari desain diskrit.
2. Implementasi Kontrol dan Algoritma Cerdas, Penelitian lanjutan sangat disarankan untuk mengintegrasikan algoritma *Maximum Power Point Tracking* (MPPT) seperti *Perturb and Observe (P&O)* atau *Incremental Conductance* ke dalam *firmware* ESP32. Hal ini akan memastikan panel surya selalu beroperasi pada titik daya maksimumnya, sehingga secara signifikan meningkatkan efisiensi keseluruhan sistem energi terbarukan, tidak hanya pada *converter*.
3. Peningkatan Akurasi dan Keandalan Sistem *Monitoring*, Untuk aplikasi yang memerlukan akurasi arus tinggi di seluruh rentang beban, disarankan menggunakan sensor arus berbasis *Hall Effect* (seperti ACS712) yang memiliki resolusi lebih baik pada arus rendah dan isolasi yang mengurangi dampak *noise*. *Dashboard* web juga dapat dikembangkan dengan fitur *data logging*, grafik tren historis, dan sistem notifikasi untuk pemantauan yang lebih komprehensif.
4. Validasi Sistem dalam Kondisi yang Lebih Mendekati Aplikasi Nyata, Pengujian lebih lanjut perlu dilakukan dengan beban dinamis, seperti proses pengisian baterai atau motor

DC, untuk menguji respons dan stabilitas sistem. Analisis termal pada komponen-komponen kritis (MOSFET, dioda, induktor) selama operasi juga diperlukan untuk memastikan keandalan jangka panjang dan mengidentifikasi kebutuhan perbaikan pada sistem pendinginan.



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LAMPIRAN

Lampiran 1. Kode *Mikrokontroler* Arduino Uno

```

/*****

* ESP32 - Buck Converter + 2x PZEM017 + WebSocket
* VERSI FINAL - GUARANTEED WORKING

*****/

#include <Wire.h>
#include <LiquidCrystal_I2C.h>
#include <PZEM017v1.h>
#include <WiFi.h>
#include <WebSocketsClient.h>
#include <ArduinoJson.h>

// ===== WIFI SETUP =====
const char* ssid = "realme 13";
const char* password = "realme 13";
const char* serverIP = "10.111.231.205";
const int serverPort = 3000;

WebSocketsClient webSocket;

// ===== LCD SETUP =====
LiquidCrystal_I2C lcd(0x27, 16, 2);

// ===== PZEM / RS485 SETUP =====
HardwareSerial PzemSerial(1);
HardwareSerial PzemSerial2(2);
PZEM017v1 pzem(&PzemSerial, 0x01);
PZEM017v1 pzem2(&PzemSerial2, 0x01);

// ===== Buck SETUP =====
const int potPin = 34;
const int pwmPin = 2;
const int pwmFrequency = 10000;
const int pwmResolution = 12;

```

```

int potValue = 0;
int pwmValue = 0;
float voltage = 0.0;
float dutyCycle = 0.0;
float frekuensi = 10;

// ===== VAR GLOBAL =====
unsigned long lastDisplay = 0;
unsigned long lastSend = 0;
int displayMode = 0;

float v1 = 0, i1 = 0, p1 = 0;
float v2 = 0, i2 = 0, p2 = 0;

bool websocketConnected = false;

// ===== WEBSOCKET EVENT =====
void websocketEvent(WStype_t type, uint8_t * payload, size_t length) {
  switch(type) {
    case WStype_DISCONNECTED:
      Serial.println("✗ [WS] Disconnected from server");
      websocketConnected = false;
      break;

    case WStype_CONNECTED:
      Serial.println("✓ [WS] Connected to WebSocket server!");
      Serial.printf(" URL: ws://%s:%d\n", serverIP, serverPort);
      websocketConnected = true;
      // kirim pesan ke server untuk uji sambungan
      websocket.sendTXT("Hello from ESP32!");
      break;
  }
}

```

```

case WStype_TEXT:
    Serial.printf("✉ [WS] Message from server: %s\n", payload);
    break;

case WStype_BIN:
    Serial.printf("📎 [WS] Binary message (%d bytes)\n", length);
    break;

case WStype_ERROR:
    Serial.println("⚠ [WS] Connection error occurred!");
    websocketConnected = false;
    break;

case WStype_FRAGMENT_TEXT_START:
case WStype_FRAGMENT_BIN_START:
    Serial.println("📄 [WS] Fragment start");
    break;

case WStype_FRAGMENT:
    Serial.println("📄 [WS] Fragment received");
    break;

case WStype_FRAGMENT_FIN:
    Serial.println("📄 [WS] Fragment finished");
    break;

default:
    Serial.printf("❓ [WS] Unknown event type: %d\n", type);
    break;
}
}

// ===== SETUP =====

```

```
void setup() {
  Serial.begin(115200);
  delay(1000);
  Serial.println("\n\n=====");
  Serial.println(" ESP32 BUCK CONVERTER + PZEM MONITOR");
  Serial.println("=====\\n");

  // LCD Init
  Wire.begin();
  lcd.init();
  lcd.backlight();
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("BUCK CONVERTER");
  lcd.setCursor(0,1);
  lcd.print("PHOTOVOLTAIC");
  delay(1500);

  // WiFi Connect
  lcd.clear();
  lcd.setCursor(0,0);
  lcd.print("WiFi: Connecting");
  Serial.print("Connecting to WiFi: ");
  Serial.println(ssid);

  WiFi.begin(ssid, password);

  int attempts = 0;
  while (WiFi.status() != WL_CONNECTED && attempts < 30) {
    delay(500);
    Serial.print(".");
    lcd.setCursor(attempts % 16, 1);
    lcd.print(".");
    attempts++;
  }
}
```

```
}
```

```
Serial.println();
```

```
if (WiFi.status() == WL_CONNECTED) {
```

```
  Serial.println("✅ WiFi Connected!");
```

```
  Serial.print("  IP: ");
```

```
  Serial.println(WiFi.localIP());
```

```
  lcd.clear();
```

```
  lcd.setCursor(0,0);
```

```
  lcd.print("WiFi: OK");
```

```
  lcd.setCursor(0,1);
```

```
  lcd.print(WiFi.localIP());
```

```
  delay(2000);
```

```
} else {
```

```
  Serial.println("❌ WiFi Failed!");
```

```
  lcd.clear();
```

```
  lcd.setCursor(0,0);
```

```
  lcd.print("WiFi: FAILED!");
```

```
  delay(2000);
```

```
}
```

```
// WebSocket Setup
```

```
Serial.println("\nConnecting to WebSocket server...");
```

```
Serial.printf("Server: ws://%s:%d\n", serverIP, serverPort);
```

```
webSocket.begin("10.111.231.205", 3000, "/");
```

```
webSocket.onEvent(webSocketEvent);
```

```
webSocket.setReconnectInterval(5000);
```

```
webSocket.enableHeartbeat(15000, 3000, 2);
```

```
// UART Setup
```

```

PzemSerial.begin(9600, SERIAL_8N1, 32, 33);
PzemSerial2.begin(9600, SERIAL_8N1, 16, 17);
Serial.println("PZEM UART initialized");

// PWM Setup
pinMode(potPin, INPUT);

#if defined(ESP_ARDUINO_VERSION)
  #if ESP_ARDUINO_VERSION >= ESP_ARDUINO_VERSION_VAL(3, 0, 0)
    ledcAttach(pwmPin, pwmFrequency, pwmResolution);
    Serial.println("PWM: ESP32 Core v3.x");
  #else
    ledcSetup(0, pwmFrequency, pwmResolution);
    ledcAttachPin(pwmPin, 0);
    Serial.println("PWM: ESP32 Core v2.x");
  #endif
#else
  ledcSetup(0, pwmFrequency, pwmResolution);
  ledcAttachPin(pwmPin, 0);
  Serial.println("PWM: Legacy mode");
#endif

Serial.println("\n✅ Setup Complete!\n");
Serial.println("=====\n");
}

// ===== BACA SENSOR =====

// Tambahkan konstanta kalibrasi di bagian global
const float KALIBRASI_ARUS_PZEM1 = 0.57; // Faktor koreksi (100/60 = 1.67, coba
mulai dari 1.60)
const float KALIBRASI_ARUS_PZEM2 = 0.5;

void bacaSemuaSensor() {

```

```

// PZEM 1
v1 = pzem.voltage();
i1 = pzem.current() * KALIBRASI_ARUS_PZEM1;
p1 = pzem.power() * KALIBRASI_ARUS_PZEM1;

// PZEM 2
v2 = pzem2.voltage();
i2 = pzem2.current() * KALIBRASI_ARUS_PZEM2;
p2 = pzem2.power() * KALIBRASI_ARUS_PZEM2;

// Buck Converter
potValue = analogRead(potPin);
pwmValue = potValue;
dutyCycle = (pwmValue * 100.0) / 4095.0;

#ifdef ESP_ARDUINO_VERSION
  #if ESP_ARDUINO_VERSION >= ESP_ARDUINO_VERSION_VAL(3, 0, 0)
    ledcWrite(pwmPin, pwmValue);
  #else
    ledcWrite(0, pwmValue);
  #endif
#else
  ledcWrite(0, pwmValue);
#endif
}

// ===== KIRIM DATA =====
void kirimDataKeServer() {
  if (!websocketConnected) {
    Serial.println("⚠ WebSocket not connected, skip send");
  }
}

```

```

    return;
}

```

```

StaticJsonDocument<512> doc;

```

```

doc["type"] = "sensor";

```

```

// KIRIM SEMUA DATA PZEM 1

```

```

doc["v1"] = v1;

```

```

doc["i1"] = i1;

```

```

doc["p1"] = p1;

```

```

// KIRIM SEMUA DATA PZEM 2

```

```

doc["v2"] = v2;

```

```

doc["i2"] = i2;

```

```

doc["p2"] = p2;

```

```

// Hitung efisiensi

```

```

float efisiensi = 0;

```

```

if (p1 > 0.1 && p2 > 0.1) efisiensi = (p2 / p1) * 100.0;

```

```

doc["efisiensi"] = efisiensi;

```

```

doc["frekuensi"] = 10;

```

```

doc["pwmValue"] = pwmValue;

```

```

doc["dutyCycle"] = dutyCycle;

```

```

String jsonString;

```

```

serializeJson(doc, jsonString);

```

```

Serial.println("📡 Sending data...");

```

```

Serial.println(jsonString);

```

```

bool sent = websocket.sendTXT(jsonString);

```

```

if (sent) Serial.println("✔ Sent successfully!\n");
else Serial.println("✗ Send failed!\n");
}

// ===== TAMPILAN LCD =====

void tampilBuck() {
    lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("PWM:");
    lcd.print(pwmValue);
    lcd.setCursor(8, 0);
    lcd.print("D:");
    lcd.print((int)dutyCycle);
    lcd.print("%");

    lcd.setCursor(0, 1);
    lcd.print("Pot:");
    lcd.print(potValue);
    lcd.setCursor(8, 1);
    lcd.print("F:");
    lcd.print(frekuensi);
    lcd.print("kHz");
}

void tampilPZEM10 {
    lcd.clear();
    lcd.setCursor(0, 0);
    lcd.print("V1:");
    lcd.print(v1, 1);
    lcd.print("V");

    lcd.setCursor(8, 0);
    lcd.print("I1:");

```

```

lcd.print(i1, 2);
lcd.print("A");

lcd.setCursor(0, 1);
lcd.print("P1:");
lcd.print(p1, 1);
lcd.print("W");

}

```

```

void tampilPZEM2() {
  lcd.clear();
  lcd.setCursor(0, 0);
  lcd.print("V2:");
  lcd.print(v2, 1);
  lcd.print("V");

  lcd.setCursor(8, 0);
  lcd.print("I2:");
  lcd.print(i2, 2);
  lcd.print("A");

  lcd.setCursor(0, 1);
  lcd.print("P2:");
  lcd.print(p2, 1);
  lcd.print("W");

}

```

```
// ===== LOOP =====
```

```

void loop() {
  websocket.loop();

```

```
// Kirim data setiap 5 detik
```

```
if (millis() - lastSend >= 100) {  
  lastSend = millis();  
  bacaSemuaSensor();  
  // kirimDataKeServer();  
  
  if (WiFi.status() == WL_CONNECTED) {  
    kirimDataKeServer();  
  } else {  
    Serial.println("⚠️ WiFi disconnected!");  
  }  
}  
  
// Ganti tampilan LCD setiap 5 detik  
if (millis() - lastDisplay >= 1000) {  
  lastDisplay = millis();  
  
  if (displayMode == 0) {  
    tampilBuck();  
  } else if (displayMode == 1) {  
    tampilPZEM1();  
  } else if (displayMode == 2) {  
    tampilPZEM2();  
  }  
  
  displayMode++;  
  if (displayMode > 2) displayMode = 0;  
}  
}
```

Lampiran 2. Kode Websocket Webserver

```
// server.js - FIXED VERSION

const express = require('express');
const WebSocket = require('ws');
const path = require('path');

const app = express();
const PORT = 3000;

// Serve file statis (folder public)
app.use(express.static(path.join(__dirname, 'public')));

// Route utama
app.get('/', (req, res) => {
  res.sendFile(path.join(__dirname, 'public', 'index.html'));
});

// Jalankan HTTP server
const server = app.listen(PORT, () => {
  console.log('='repeat(50));
  console.log('🚀 Server berjalan di port', PORT);
  console.log(`🌐 Akses: http://localhost:${PORT}`);
  console.log('='repeat(50));
});

// Buat WebSocket server di atas HTTP server
const wss = new WebSocket.Server({ server });

// Variabel untuk menyimpan klien ESP32 dan Web
let espClient = null;
let webClients = new Set();

// Data terakhir
```

```

let latestData = {
  v1: 0,
  i1: 0,
  p1: 0,
  v2: 0,
  i2: 0,
  p2: 0,
  efisiensi: 0,
  frekuensi: 0,
  timestamp: new Date().toISOString()
};

// Fungsi broadcast ke semua klien web
function broadcastToWeb(data) {
  console.log('📡 Broadcasting to', webClients.size, 'web clients...');
  let successCount = 0;

  for (const client of webClients) {
    if (client.readyState === WebSocket.OPEN) {
      try {
        client.send(JSON.stringify(data));
        successCount++;
      } catch (err) {
        console.error('❌ Error sending to client:', err.message);
      }
    }
  }

  console.log('✅ Broadcast sent to ${successCount}/${webClients.size} clients');
}

// WebSocket Connection Handler
wss.on('connection', (ws, req) => {

```

```

const ip = req.socket.remoteAddress;

console.log(`👤 Client baru terhubung dari: ${ip}`);

// Flag untuk menandai apakah ini ESP32 atau browser
let isESP32 = false;

// Kirim pesan welcome
ws.send(JSON.stringify({ type: 'info', message: 'Terhubung ke server' }));

ws.on('message', (msg) => {
  const msgStr = msg.toString();
  console.log('📧 Raw message:', msgStr.substring(0, 100) + '...');

  try {
    const data = JSON.parse(msgStr);
    console.log('📄 Parsed JSON type:', data.type);

    // ✅ Jika data dari ESP32 (ada type='sensor' dan field v1)
    if (data.type === 'sensor' && data.v1 !== undefined) {
      console.log('✅ Identified as ESP32 data');

      // Tandai sebagai ESP32
      if (!isESP32) {
        isESP32 = true;
        espClient = ws;
        console.log('📡 ESP32 client registered');
      }

      // Update data terakhir
      latestData = { ...data, timestamp: new Date().toISOString() };
      console.log('📡 Data dari ESP32:', JSON.stringify(latestData));

      // Broadcast ke semua web clients

```

```

    broadcastToWeb(latestData);
}
// Jika perintah dari web
    else if (data.type === 'command' && espClient && espClient.readyState ===
WebSocket.OPEN) {
    console.log('📡 Perintah dari web:', data);
    espClient.send(JSON.stringify(data));
}
// Jika pesan lain dari browser
else {
    console.log('📡 Browser message:', data.type || 'unknown');

    // Pastikan browser ada di webClients
    if (!isESP32 && !webClients.has(ws)) {
        webClients.add(ws);
        console.log('🌐 Browser added to webClients. Total:', webClients.size);

        // Kirim data terakhir
        ws.send(JSON.stringify(latestData));
    }
}
} catch (err) {
    // Pesan bukan JSON, kemungkinan browser dengan plain text
    console.log('📄 Non-JSON message (likely browser test)');

    // Pastikan browser ditambahkan ke webClients
    if (!isESP32 && !webClients.has(ws)) {
        webClients.add(ws);
        console.log('🌐 Browser added to webClients. Total:', webClients.size);

        // Kirim data terakhir
        ws.send(JSON.stringify(latestData));
    }
}

```

```

    }
  });

```

```

ws.on('close', () => {
  console.log('✖ Client terputus:', ip);

```

```

  // Hapus dari web clients
  if (webClients.has(ws)) {
    webClients.delete(ws);
    console.log('👤 Remaining web clients:', webClients.size);
  }

```

```

  // Reset ESP32 client jika terputus
  if (espClient === ws) {
    console.log('⚠ ESP32 terputus');
    espClient = null;
  }
});

```

```

ws.on('error', (err) => {
  console.error('✖ WebSocket error:', err.message);
});

```

```

// PENTING: Tambahkan browser ke webClients saat connect
// Asumsi: jika dalam 1 detik tidak ada pesan sensor, maka ini browser
setTimeout(() => {
  if (!isESP32 && !webClients.has(ws)) {
    console.log('🕒 Timeout: Adding to webClients (assumed browser)');
    webClients.add(ws);
    console.log('👤 Total web clients:', webClients.size);
  }

```

```

  // Kirim data terakhir
  if (ws.readyState === WebSocket.OPEN) {

```

```
ws.send(JSON.stringify(latestData));  
}  
}  
, 1000);  
});
```

```
console.log('✅ WebSocket server siap menerima koneksi');
```



Lampiran 3. Kode Website Localhost

```
// server.js - FIXED VERSION

const express = require('express');
const WebSocket = require('ws');
const path = require('path');

const app = express();
const PORT = 3000;

// Serve file statis (folder public)
app.use(express.static(path.join(__dirname, 'public')));

// Route utama
app.get('/', (req, res) => {
  res.sendFile(path.join(__dirname, 'public', 'index.html'));
});

// Jalankan HTTP server
const server = app.listen(PORT, () => {
  console.log('='repeat(50));
  console.log('🚀 Server berjalan di port', PORT);
  console.log(`🌐 Akses: http://localhost:${PORT}`);
  console.log('='repeat(50));
});

// Buat WebSocket server di atas HTTP server
const wss = new WebSocket.Server({ server });

// Variabel untuk menyimpan klien ESP32 dan Web
let espClient = null;
let webClients = new Set();

// Data terakhir
```

```

let latestData = {
  v1: 0,
  i1: 0,
  p1: 0,
  v2: 0,
  i2: 0,
  p2: 0,
  efisiensi: 0,
  frekuensi: 0,
  timestamp: new Date().toISOString()
};

// Fungsi broadcast ke semua klien web
function broadcastToWeb(data) {
  console.log('🔊 Broadcasting to', webClients.size, 'web clients...');
  let successCount = 0;

  for (const client of webClients) {
    if (client.readyState === WebSocket.OPEN) {
      try {
        client.send(JSON.stringify(data));
        successCount++;
      } catch (err) {
        console.error('❌ Error sending to client:', err.message);
      }
    }
  }

  console.log('✅ Broadcast sent to ${successCount}/${webClients.size} clients');
}

// WebSocket Connection Handler
wss.on('connection', (ws, req) => {

```

```

const ip = req.socket.remoteAddress;

console.log(`🔌 Client baru terhubung dari: ${ip}`);

// Flag untuk menandai apakah ini ESP32 atau browser
let isESP32 = false;

// Kirim pesan welcome
ws.send(JSON.stringify({ type: 'info', message: 'Terhubung ke server' }));

ws.on('message', (msg) => {
  const msgStr = msg.toString();
  console.log('📧 Raw message:', msgStr.substring(0, 100) + '...');

  try {
    const data = JSON.parse(msgStr);
    console.log('📄 Parsed JSON type:', data.type);

    // ✅ Jika data dari ESP32 (ada type='sensor' dan field v1)
    if (data.type === 'sensor' && data.v1 !== undefined) {
      console.log('✅ Identified as ESP32 data');

      // Tandai sebagai ESP32
      if (!isESP32) {
        isESP32 = true;
        espClient = ws;
        console.log('📡 ESP32 client registered');
      }

      // Update data terakhir
      latestData = { ...data, timestamp: new Date().toISOString() };
      console.log('📡 Data dari ESP32:', JSON.stringify(latestData));

      // Broadcast ke semua web clients

```

```

    broadcastToWeb(latestData);
}
// Jika perintah dari web
    else if (data.type === 'command' && espClient && espClient.readyState ===
WebSocket.OPEN) {
    console.log('📡 Perintah dari web:', data);
    espClient.send(JSON.stringify(data));
}
// Jika pesan lain dari browser
else {
    console.log('📡 Browser message:', data.type || 'unknown');

    // Pastikan browser ada di webClients
    if (!isESP32 && !webClients.has(ws)) {
        webClients.add(ws);
        console.log('🌐 Browser added to webClients. Total:', webClients.size);

        // Kirim data terakhir
        ws.send(JSON.stringify(latestData));
    }
}
} catch (err) {
    // Pesan bukan JSON, kemungkinan browser dengan plain text
    console.log('📄 Non-JSON message (likely browser test)');

    // Pastikan browser ditambahkan ke webClients
    if (!isESP32 && !webClients.has(ws)) {
        webClients.add(ws);
        console.log('🌐 Browser added to webClients. Total:', webClients.size);

        // Kirim data terakhir
        ws.send(JSON.stringify(latestData));
    }
}

```

```

    }
  });

```

```

ws.on('close', () => {
  console.log('✖ Client terputus:', ip);

```

```

  // Hapus dari web clients
  if (webClients.has(ws)) {
    webClients.delete(ws);
    console.log('👤 Remaining web clients:', webClients.size);
  }

```

```

  // Reset ESP32 client jika terputus
  if (espClient === ws) {
    console.log('⚠ ESP32 terputus');
    espClient = null;
  }
});

```

```

ws.on('error', (err) => {
  console.error('✖ WebSocket error:', err.message);
});

```

```

// PENTING: Tambahkan browser ke webClients saat connect
// Asumsi: jika dalam 1 detik tidak ada pesan sensor, maka ini browser
setTimeout(() => {
  if (!isESP32 && !webClients.has(ws)) {
    console.log('🕒 Timeout: Adding to webClients (assumed browser)');
    webClients.add(ws);
    console.log('👤 Total web clients:', webClients.size);
  }

```

```

  // Kirim data terakhir
  if (ws.readyState === WebSocket.OPEN) {

```

```
ws.send(JSON.stringify(latestData));  
}  
}  
, 1000);  
});
```

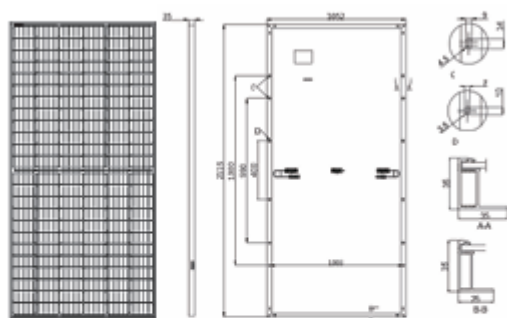
```
console.log('✅ WebSocket server siap menerima koneksi');
```



Lampiran 4. Spesifikasi *Photovoltaic*

LR4-72HPH 420~440M

Design (mm)



Mechanical Parameters

Cell Orientation: 144 (6x24)
 Junction Box: IP68, three clodes
 Output Cable: 4mm², 300mm in length,
 length can be customized
 Glass: Single glass
 3.2mm coated tempered glass
 Frame: Anodized aluminum alloy frame
 Weight: 24 kg
 Dimension: 2115x1052x35mm
 Packaging: 30pcs per pallet
 150pcs per 20'GP
 660pcs per 40'HC

Operating Parameters

Operational Temperature: -40°C ~ +85°C
 Power Output Tolerance: 0 ~ +5 W
 Voc and Isc Tolerance: ±3%
 Maximum System Voltage: DC1500V (IEC/UL)
 Maximum Series Fuse Rating: 20A
 Nominal Operating Cell Temperature: 45±2°C
 Safety Class: Class II
 Fire Rating: UL type 1 or type 2

Electrical Characteristics

Test uncertainty for Pmax: ±3%

Model Number	LR4-72HPH-420M		LR4-72HPH-425M		LR4-72HPH-430M		LR4-72HPH-435M		LR4-72HPH-440M	
Testing Condition	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax/W)	420	311.1	425	314.8	430	318.5	435	322.2	440	326.0
Open Circuit Voltage (Voc/V)	48.8	45.5	49.0	45.7	49.2	45.9	49.4	46.1	49.6	46.3
Short Circuit Current (Isc/A)	11.04	8.90	11.11	8.95	11.19	9.02	11.26	9.08	11.33	9.13
Voltage at Maximum Power (Vmp/V)	40.2	37.1	40.4	37.3	40.6	37.5	40.8	37.7	41.0	37.9
Current at Maximum Power (Imp/A)	10.45	8.38	10.52	8.44	10.60	8.50	10.67	8.56	10.74	8.61
Module Efficiency(%)	18.9		19.1		19.3		19.6		19.8	

STC (Standard Testing Conditions): Irradiance 1000W/m², Cell Temperature 25°C, Spectra at AM1.5

NOCT (Nominal Operating Cell Temperature): Irradiance 800W/m², Ambient Temperature 20°C, Spectra at AM1.5, Wind at 1m/s

Temperature Ratings (STC)

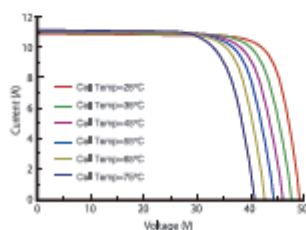
Temperature Coefficient of Isc	+0.057%/°C
Temperature Coefficient of Voc	-0.286%/°C
Temperature Coefficient of Pmax	-0.370%/°C

Mechanical Loading

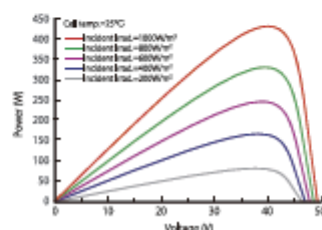
Front Side Maximum Static Loading	5400Pa
Rear Side Maximum Static Loading	2400Pa
Hallstone Test	25mm Hallstone at the speed of 23m/s

I-V Curve

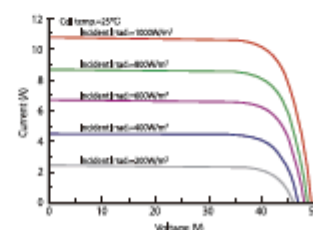
Current-Voltage Curve (LR4-72HPH-430M)



Power-Voltage Curve (LR4-72HPH-430M)



Current-Voltage Curve (LR4-72HPH-430M)



Lampiran 5. Spesifikasi MOSFET

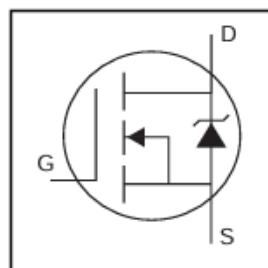
International
IR Rectifier

PD - 94004A

IRFP260N

HEXFET® Power MOSFET

- Advanced Process Technology
- Dynamic dv/dt Rating
- 175°C Operating Temperature
- Fast Switching
- Fully Avalanche Rated
- Ease of Paralleling
- Simple Drive Requirements



$$V_{DSS} = 200V$$

$$R_{DS(on)} = 0.04\Omega$$

$$I_D = 50A$$

Description

Fifth Generation HEXFETs from International Rectifier utilize advanced processing techniques to achieve extremely low on-resistance per silicon area. This benefit, combined with the fast switching speed and ruggedized device design that HEXFET Power MOSFETs are well known for, provides the designer with an extremely efficient and reliable device for use in a wide variety of applications.

The TO-247 package is preferred for commercial-industrial applications where higher power levels preclude the use of TO-220 devices. The TO-247 is similar but superior to the earlier TO-218 package because of its isolated mounting hole.



TO-247AC

Absolute Maximum Ratings

	Parameter	Max.	Units
$I_D @ T_C = 25^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	50	A
$I_D @ T_C = 100^\circ C$	Continuous Drain Current, $V_{GS} @ 10V$	35	
I_{DM}	Pulsed Drain Current ①	200	
$P_D @ T_C = 25^\circ C$	Power Dissipation	300	W
	Linear Derating Factor	2.0	W/°C
V_{GS}	Gate-to-Source Voltage	± 20	V
E_{AS}	Single Pulse Avalanche Energy②	560	mJ
I_{AR}	Avalanche Current①	50	A
E_{AR}	Repetitive Avalanche Energy①	30	mJ
dv/dt	Peak Diode Recovery dv/dt ③	10	V/ns
T_J	Operating Junction and	-55 to +175	°C
T_{STG}	Storage Temperature Range		
	Soldering Temperature, for 10 seconds	300 (1.6mm from case)	
	Mounting torque, 6-32 or M3 screw	10 lbf·in (1.1N·m)	

Thermal Resistance

	Parameter	Typ.	Max.	Units
$R_{\theta JC}$	Junction-to-Case	—	0.50	°C/W
$R_{\theta CS}$	Case-to-Sink, Flat, Greased Surface	0.24	—	
$R_{\theta JA}$	Junction-to-Ambient	—	40	

Lampiran 6. Spesifikasi Dioda

F60UP30DN



Pb Free Plating Product

F60UP30DN



60Amperes,300Volts Dual Common Cathode Ultra Fast Recovery Rectifiers

APPLICATION

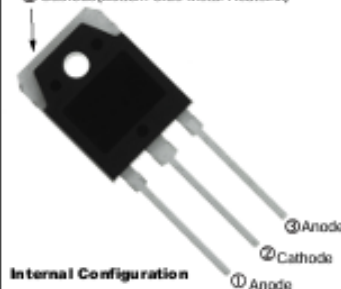
- Freewheeling, Snubber, Clamp
- Inversion Welder
- PFC
- Plating Power Supply
- Ultrasonic Cleaner and Welder
- Converter & Chopper
- UPS

PRODUCT FEATURE

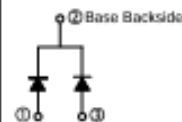
- Ultrafast Recovery Time
- Soft Recovery Characteristics
- Low Recovery Loss
- Low Forward Voltage
- High Surge Current Capability
- Low Leakage Current

TO-3PB(TO-3PN)

② Cathode(Bottom Side Metal Heatsink)



Internal Configuration



GENERAL DESCRIPTION

F60UP30DN using the latest FRED FAB process(planar passivation chip) with ultrafast and soft recovery characteristic.

Absolute Maximum Ratings

Parameter	Symbol	Test Conditions	Values	Units
Repetitive peak reverse voltage	V_{RRM}		300	V
Continuous forward current	$I_F(AV)$	$T_c = 110^\circ\text{C}$	60	A
Single pulse forward current	I_{FSM}	$T_c = 25^\circ\text{C}$	600	
Maximum repetitive forward current	I_{FRM}	Square wave, 20kHz	150	
Operating junction	T_j		175	$^\circ\text{C}$
Storage temperatures	T_{stg}		-55 to +175	$^\circ\text{C}$

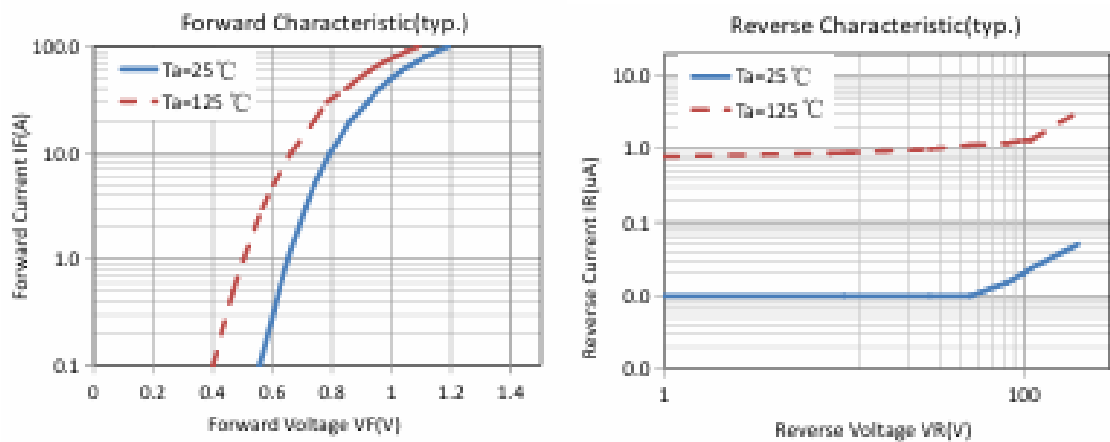
Electrical characteristics ($T_a=25^\circ\text{C}$ unless otherwise specified)

Parameter	Symbol	Test Conditions	Min	Typ.	Max.	Units
Breakdown voltage Blocking voltage	V_{BR}, V_R	$I_R=100\mu\text{A}$	300			V
Forward voltage (Per Diode)	V_F	$I_F=30\text{A}$		0.96	1.20	
		$I_F=30\text{A}, T_j=125^\circ\text{C}$		0.85	1.00	
Reverse leakage current(Per Diode)	I_R	$V_R=V_{RRM}$			10	μA
		$T_j=150^\circ\text{C}, V_R=300\text{V}$			100	
Reverse recovery time(Per Diode)	t_{rr}	$I_F=0.5\text{A}, I_R=1\text{A}, I_{RM}=0.25\text{A}$		35	45	ns
		$I_F=1\text{A}, V_R=30\text{V}, di/dt=200\text{A}/\mu\text{s}$		26	40	

Thermal characteristics

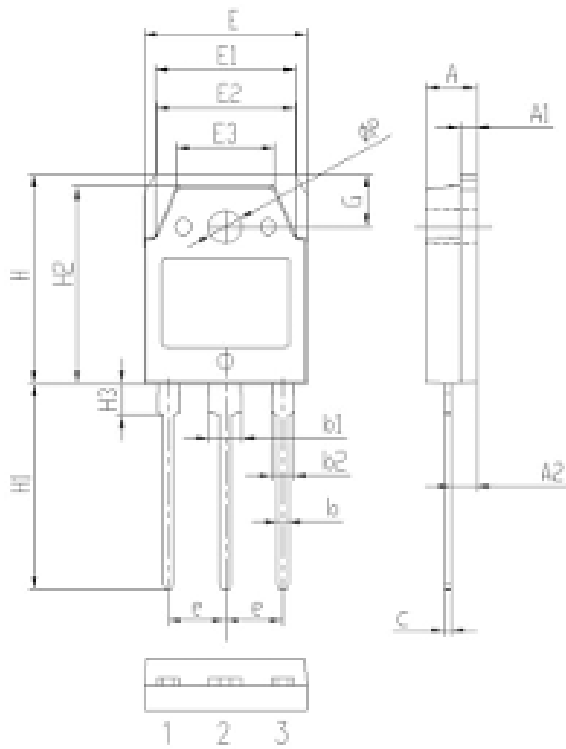
Parameter	Symbol	Typ	Units
Junction-to-Case	$R_{\theta JC}$	0.8	$^\circ\text{C}/\text{W}$

Electrical performance (typical)



Package Information

TO-3PB PACKAGE



Symbol	Dimensions(millimeters)	
	Min.	Max.
A	4.60	5.00
A1	1.30	1.70
A2	2.20	2.60
b	0.80	1.20
b1	2.90	3.30
b2	1.90	2.30
c	0.40	0.80
e	5.25	5.65
E	15.3	15.7
E1	13.2	13.6
E2	13.1	13.5
E3	9.10	9.50
H	19.7	20.1
H1	19.1	20.1
H2	18.3	18.7
H3	2.80	3.20
G	4.80	5.20
ϕP	3.00	3.40

Lampiran 7. Spesifikasi ESP32

Table 1: ESP32-WROOM-32 (ESP-WROOM-32) Specifications

Categories	Items	Specifications
Certification	RF certification	FCC/CE/IC/TELEC/KCC/SRRC/NCC
	Wi-Fi certification	Wi-Fi Alliance
	Bluetooth certification	BQB
	Green certification	RoHS/REACH
Wi-Fi	Protocols	802.11 b/g/n (802.11n up to 150 Mbps) A-MPDU and A-MSDU aggregation and 0.4 μ s guard interval support
	Frequency range	2.4 GHz ~ 2.5 GHz
Bluetooth	Protocols	Bluetooth v4.2 BR/EDR and BLE specification
	Radio	NZIF receiver with -97 dBm sensitivity
		Class-1, class-2 and class-3 transmitter
		AFH
	Audio	CVSD and SBC

1. OVERVIEW

Categories	Items	Specifications
Hardware	Module interface	SD card, UART, SPI, SDIO, I2C, LED PWM, Motor PWM, I2S, IR
		GPIO, capacitive touch sensor, ADC, DAC
	On-chip sensor	Hall sensor, temperature sensor
	On-board clock	40 MHz crystal
	Operating voltage/Power supply	2.7 ~ 3.6V
	Operating current	Average: 80 mA
	Minimum current delivered by power supply	500 mA
	Operating temperature range	-40°C ~ +85°C
	Ambient temperature range	Normal temperature
	Package size	18±0.2 mm x 25.5±0.2 mm x 3.1±0.15 mm
Software	Wi-Fi mode	Station/SoftAP/SoftAP+Station/P2P
	Wi-Fi Security	WPA/WPA2/WPA2-Enterprise/WPS
	Encryption	AES/RSA/ECC/SHA
	Firmware upgrade	UART Download / OTA (download and write firmware via network or host)
	Software development	Supports Cloud Server Development / SDK for custom firmware development
	Network protocols	IPv4, IPv6, SSL, TCP/UDP/HTTP/FTP/MQTT
	User configuration	AT instruction set, cloud server, Android/iOS app

Lampiran 8. Spesifikasi Modul RS485

DC ELECTRICAL CHARACTERISTICS

$V_{CC} = V_{DD}$ (LTC1321/LTC1322) = 5V $\pm 5\%$, $V_{EE} = -5V \pm 5\%$ (Notes 2, 3)

SYMBOL	PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
RS485 Driver (SEL1 = SEL2 = HIGH)						
V_{OD1}	Differential Driver Output Voltage (Unloaded)	$I_O = 0$	●		5	V
V_{OD2}	Differential Driver Output Voltage (With Load)	Figure 1, $R = 50\Omega$ (RS422) Figure 1, $R = 27\Omega$ (RS485)	● ●	2.0 1.5	5 5	V V
ΔV_{OD}	Change in Magnitude of Driver Differential Output Voltage for Complementary Output States	Figure 1, $R = 27\Omega$ or $R = 50\Omega$	●		0.2	V
V_{OC}	Driver Common-Mode Output Voltage	Figure 1, $R = 27\Omega$ or $R = 50\Omega$	●		3	V
$\Delta V_{OC} $	Change in Magnitude of Driver Common-Mode Output Voltage for Complementary Output States	Figure 1, $R = 27\Omega$ or $R = 50\Omega$	●		0.2	V
I_{OSD}	Driver Short-Circuit Current	$-7V \leq V_O \leq 12V$, $V_O = \text{HIGH}$ $-7V \leq V_O \leq 12V$, $V_O = \text{LOW}$ (Note 4)	● ●	35 10	250 250	mA mA
I_{OZD}	Three-State Output Current (Y, Z)	$-7V \leq V_O \leq 12V$	●	± 5	± 500	μA
EIA/TIA-562 Driver (SEL1 = SEL2 = LOW)						
V_O	Output Voltage Swing	Figure 4, $R_L = 3k$, Positive Figure 4, $R_L = 3k$, Negative	● ●	3.7 -3.7	4.2 -4.3	V V
I_{OSD}	Output Short-Circuit Current	$V_O = 0V$	●	± 11	± 60	mA
Driver Inputs and Control Inputs						
V_{IH}	Input High Voltage	D, DE, ON/OFF, SEL1, SEL2, $\overline{LB}$ OE (LTC1335)	● ●	2 2		V V
V_{IL}	Input Low Voltage	D, DE, ON/OFF, SEL1, SEL2, $\overline{LB}$ OE (LTC1335)	● ●		0.8 0.8	V V
I_{IN}	Input Current	D, SEL1, SEL2 DE, ON/OFF, $\overline{LB}$ OE (LTC1335)	● ● ●	 -4 4	± 10 -15 15	μA μA μA
RS485 Receiver (SEL1 = SEL2 = HIGH)						
V_{TH}	Differential Input Threshold Voltage	$-7V \leq V_{CM} \leq 7V$, Commercial $-7V \leq V_{CM} \leq 7V$, Industrial	● ●	-0.2 -0.3	0.2 0.3	V V
ΔV_{TH}	Input Hysteresis	$V_{CM} = 0V$	●	70		mV
I_{IN}	Input Current (A, B)	$-7V \leq V_{IN} \leq 12V$	●		± 1	mA
R_{IN}	Input Resistance	$-7V \leq V_{IN} \leq 12V$	●	12	24	k Ω
EIA/TIA-562 Receiver (SEL1 = SEL2 = LOW)						
V_{TH}	Receiver Input Voltage Threshold	Input Low Threshold Input High Threshold	● ●	0.8 1.7	1.1 2.4	V V
ΔV_{TH}	Receiver Input Hysteresis		●	0.1	0.6	V
R_{IN}	Receiver Input Resistance	$V_{IN} = \pm 10V$		3	5	k Ω
Receiver Output						
V_{OH}	Receiver Output High Voltage	$I_O = -3mA$, $V_{IN} = 0V$, SEL1 = SEL2 = LOW	●	3.5	4.6	V
V_{OL}	Receiver Output Low Voltage	$I_O = 3mA$, $V_{IN} = 3V$, SEL1 = SEL2 = LOW	●		0.2	V
I_{OSR}	Short-Circuit Current	$0V \leq V_O \leq V_{CC}$	●	7	85	mA
I_{OZR}	Three-State Output Current	ON/OFF = 0V OE = V_{CC} (LTC1335)	● ●		± 10 ± 10	μA μA

Lampiran 9. Spesifikasi PZEM017

PZEM-017 300V 300A Shunt+USB Cable Car Voltmeter DC Ampere Meter RS485

Model Number:

PZEM-017

Display Type:

Digital Only

Measuring Range:

0.02-300a

Accuracy Class:

1.0grade

Supply Voltage:

0.05-300V DC

Operating Temperature:

-20°C ~ +60°C

Dimensions:

90*60.5*23mm(L*W*H)

Voltage test range:

0.05-300V

Voltage resolution:

0.01V

Current resolution:

0.01A

Power test range:

0.1-3kW

Power resolution:

0.1W

Energy test range:

0-9999kwh

Energy resolution:

1wh

Certificate:

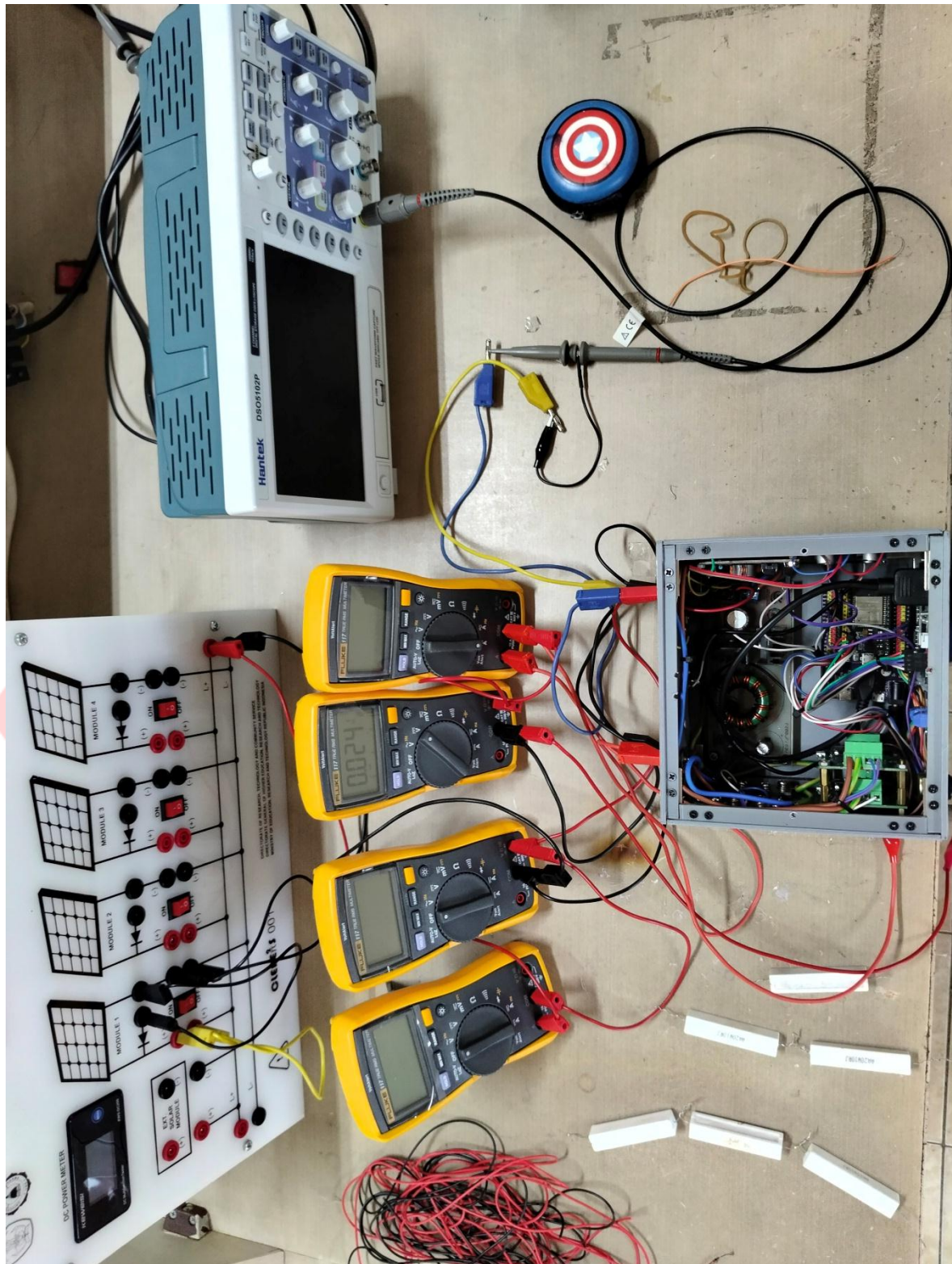
CE FCC

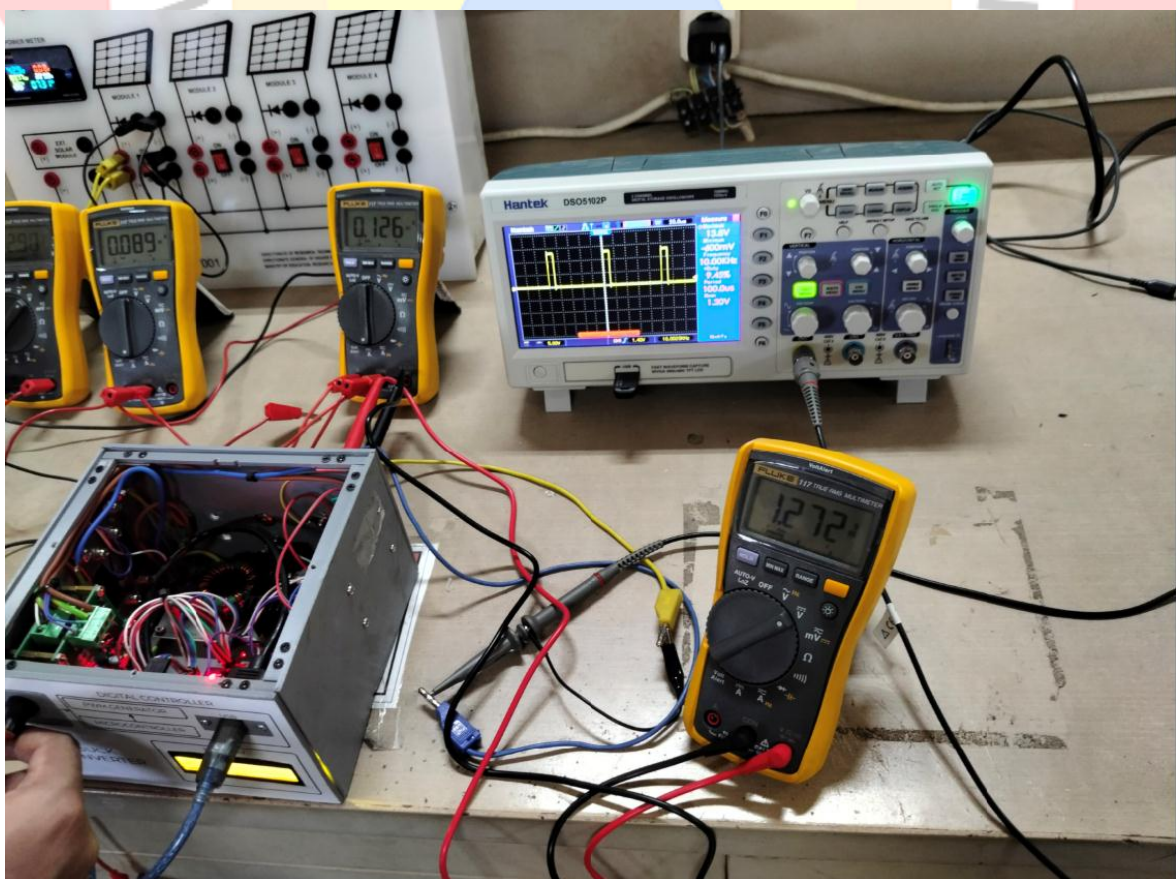
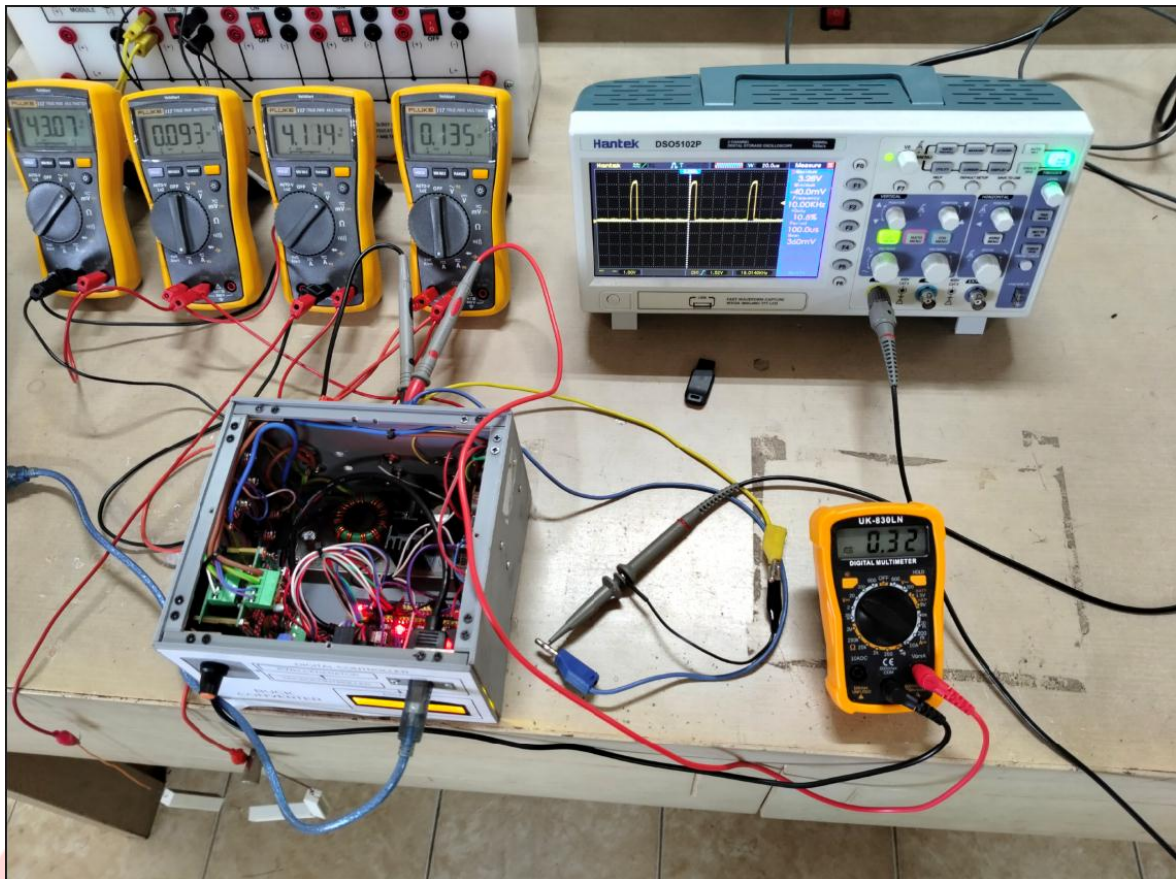
Communication:

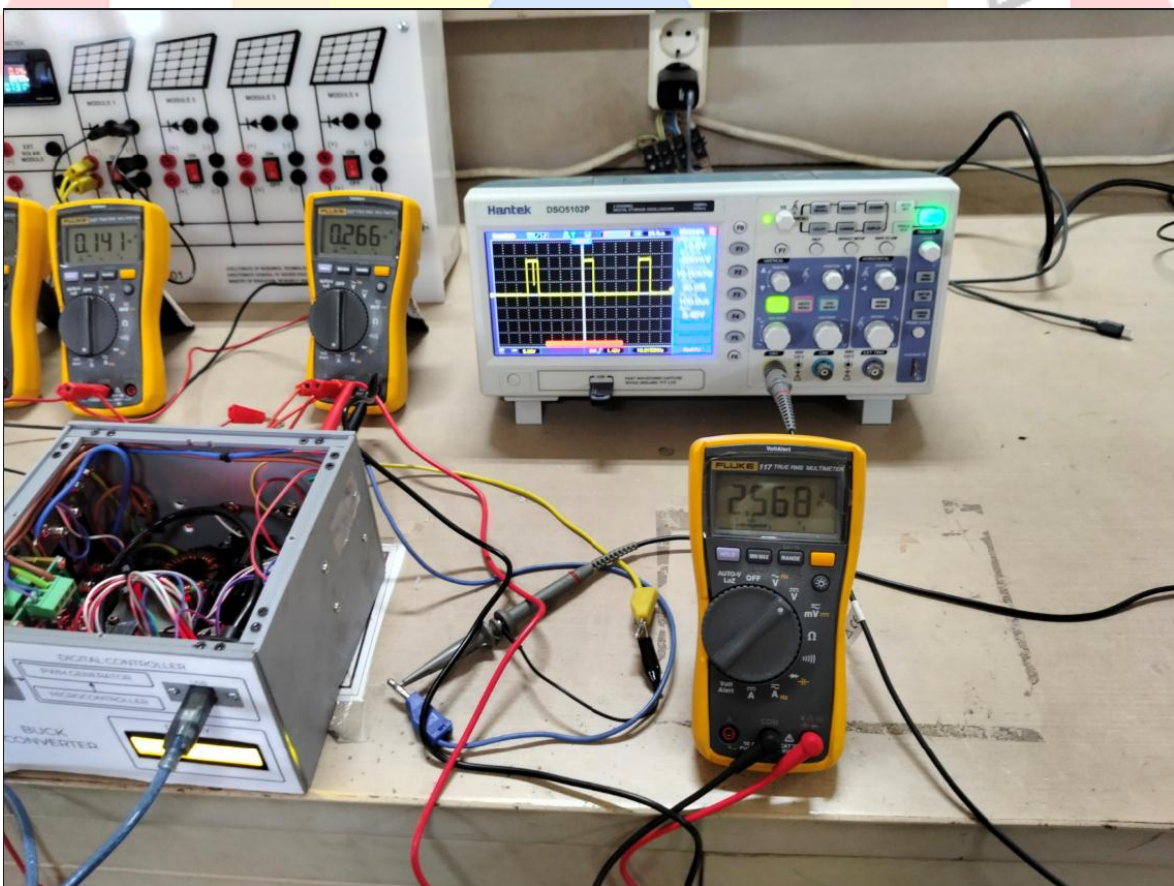
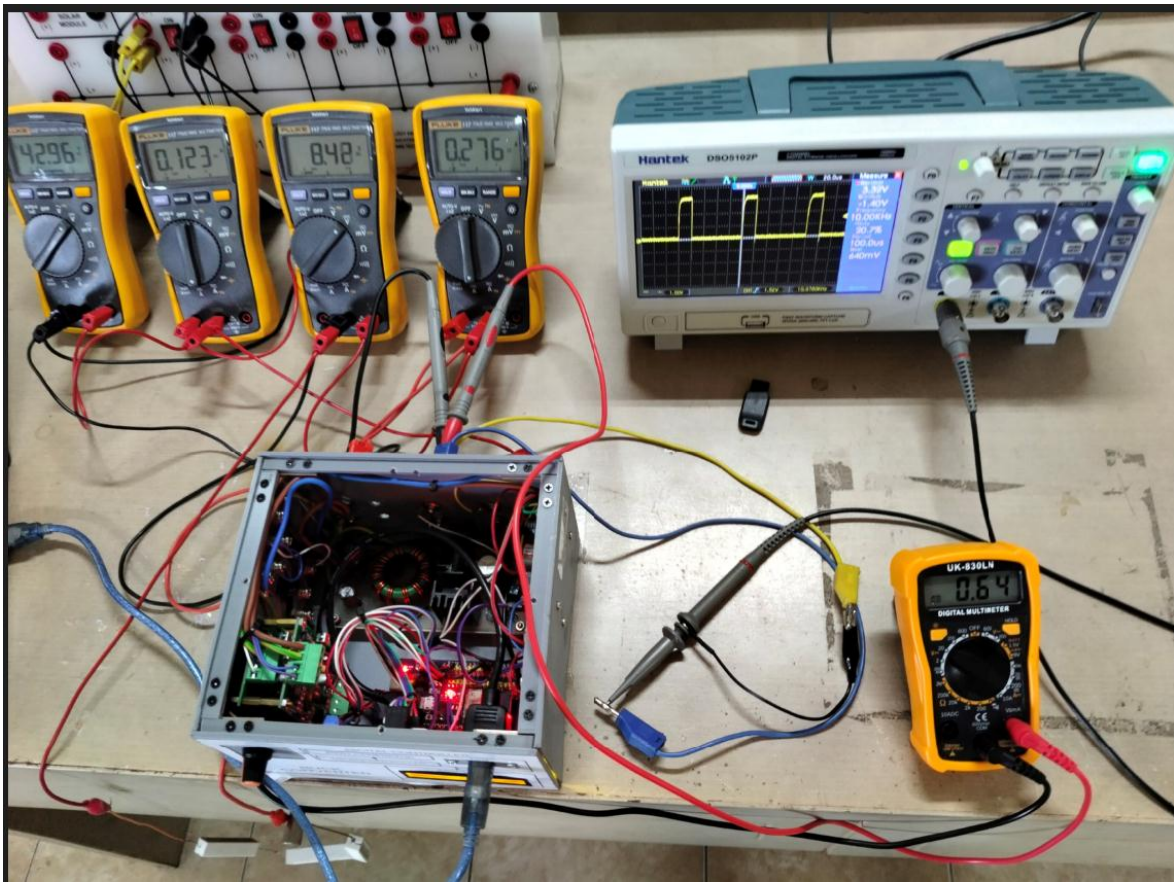
RS485 Port MODBUS-RTU Protocol

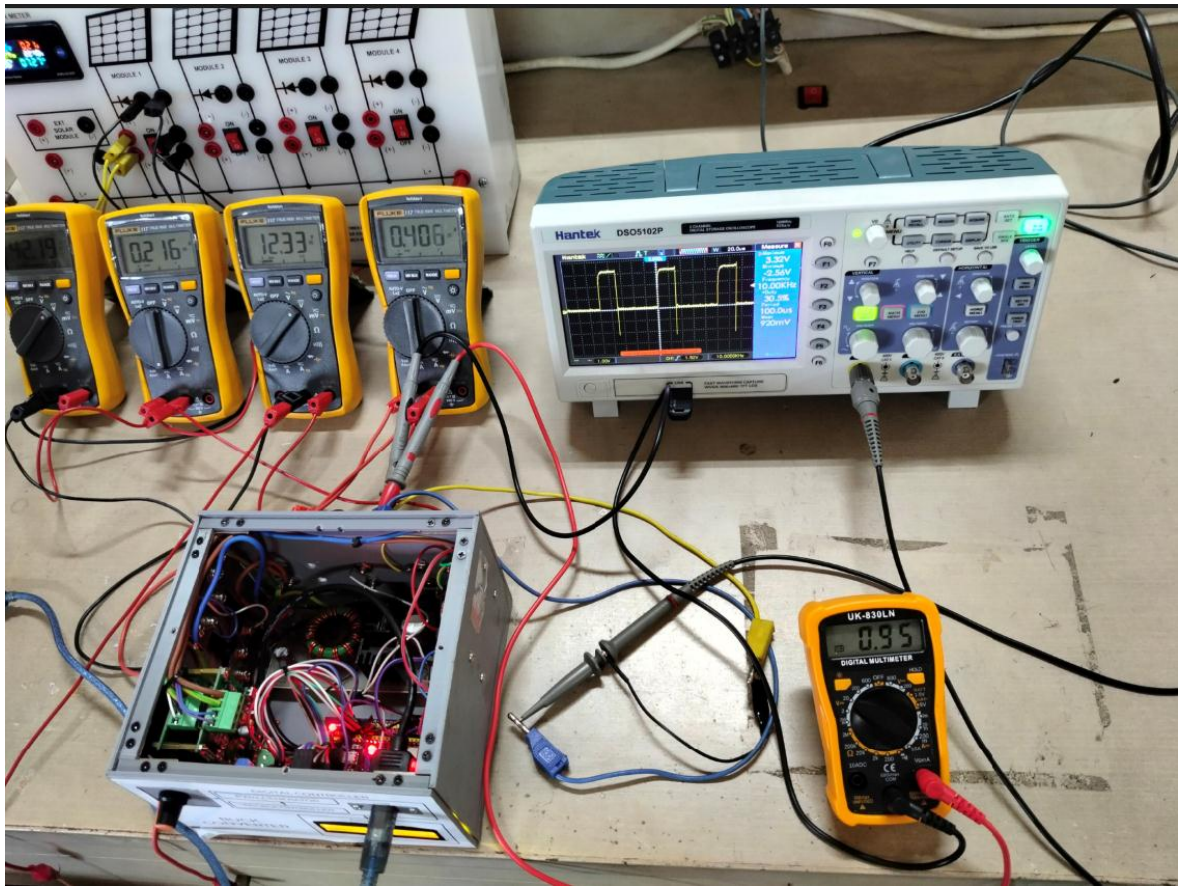
Product Type	PZEM-017
Current Range	0-300A
Accessory	300A shunt+USB cable
Voltage Range	DC 0-300V
Power Range	0-90KW
Accuracy	±1%
Energy Range	0-9999Kwh
Weight	299g

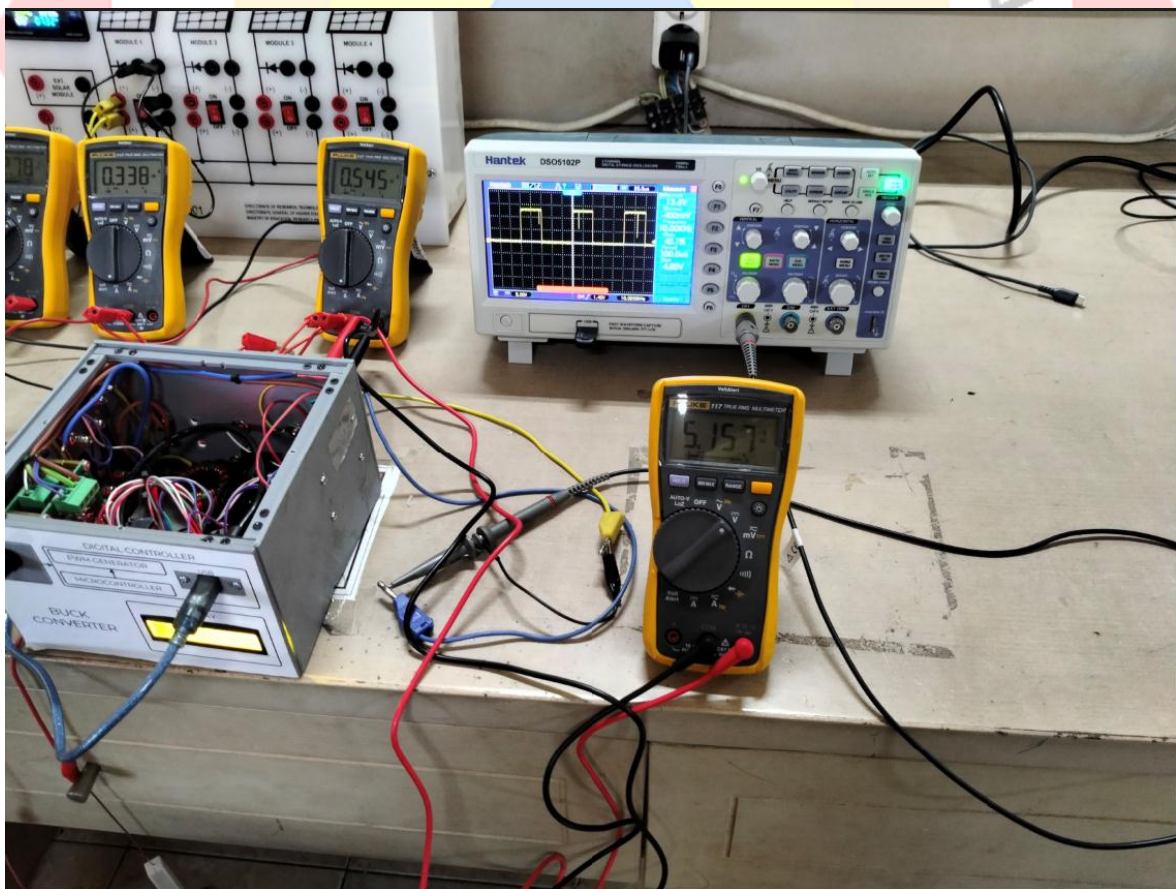
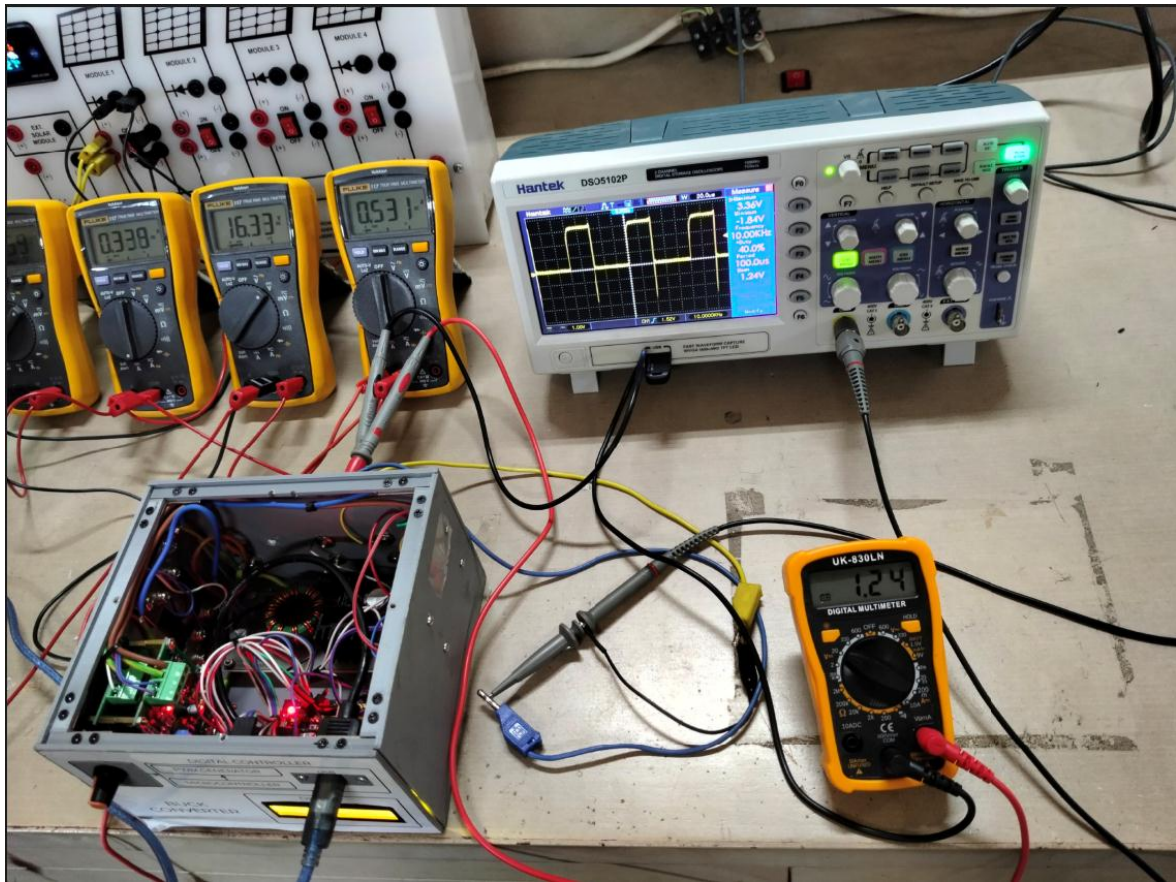
Lampiran 10. Kelengkapan Alat Penelitian

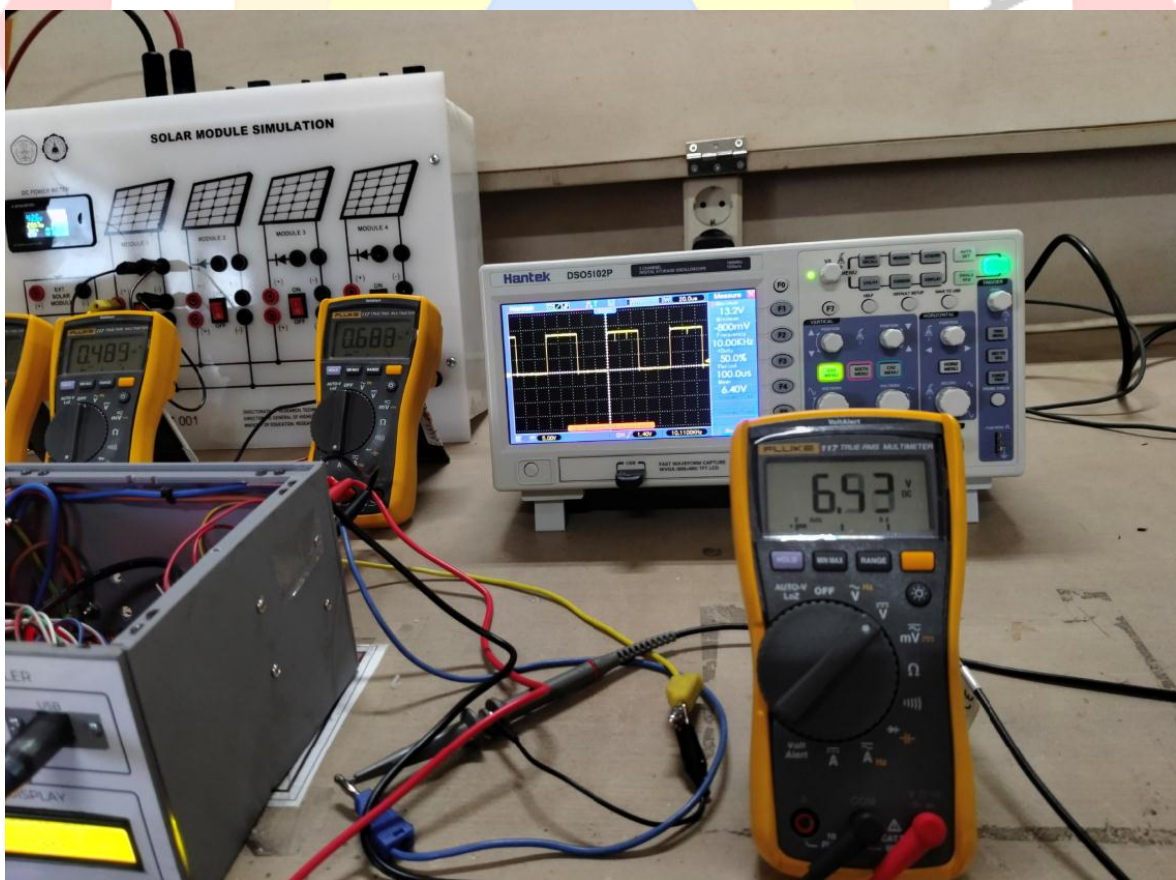
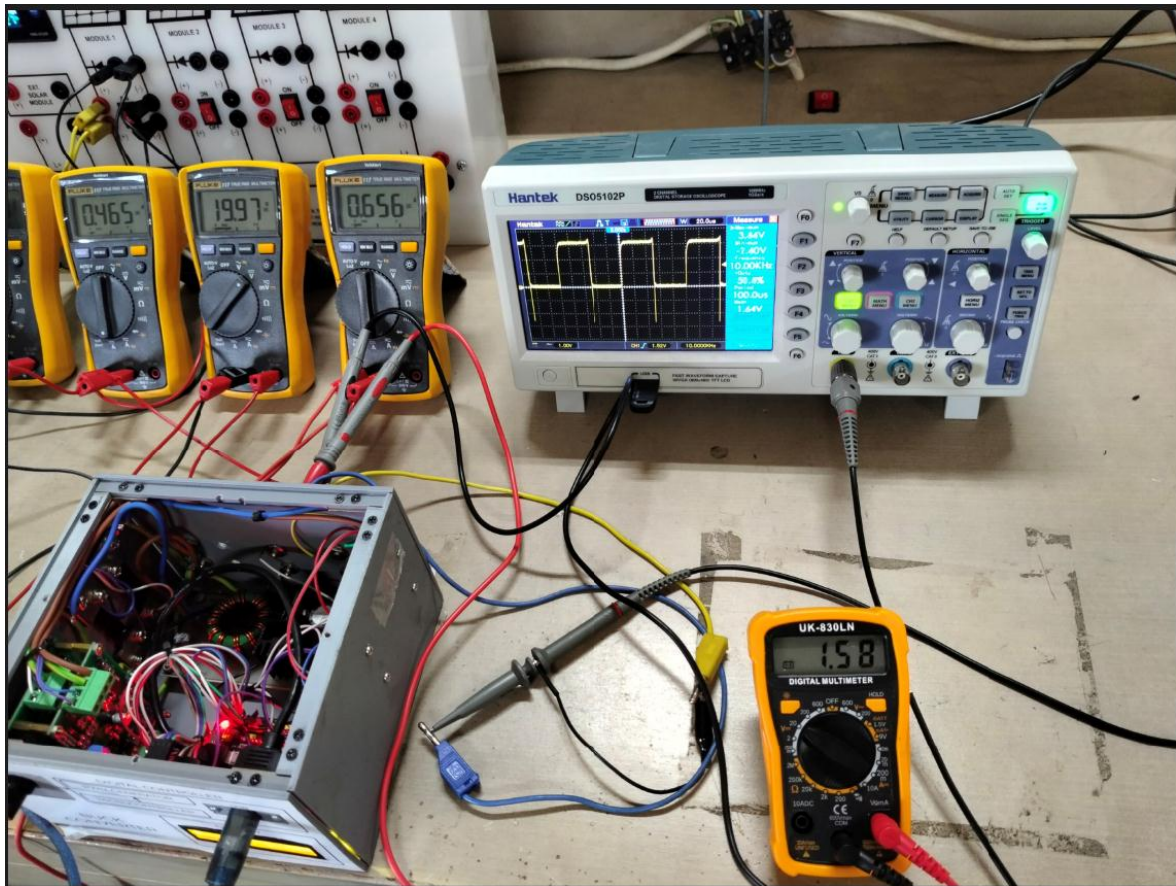


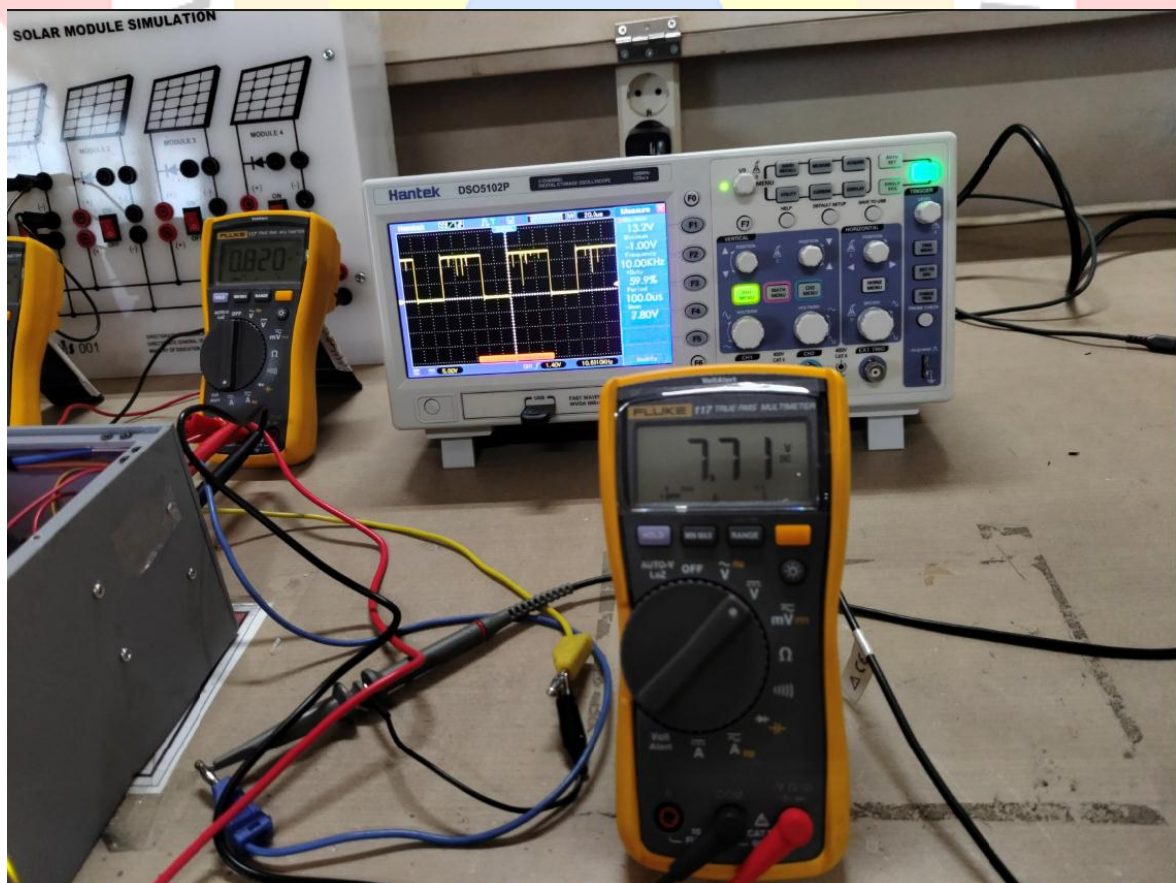
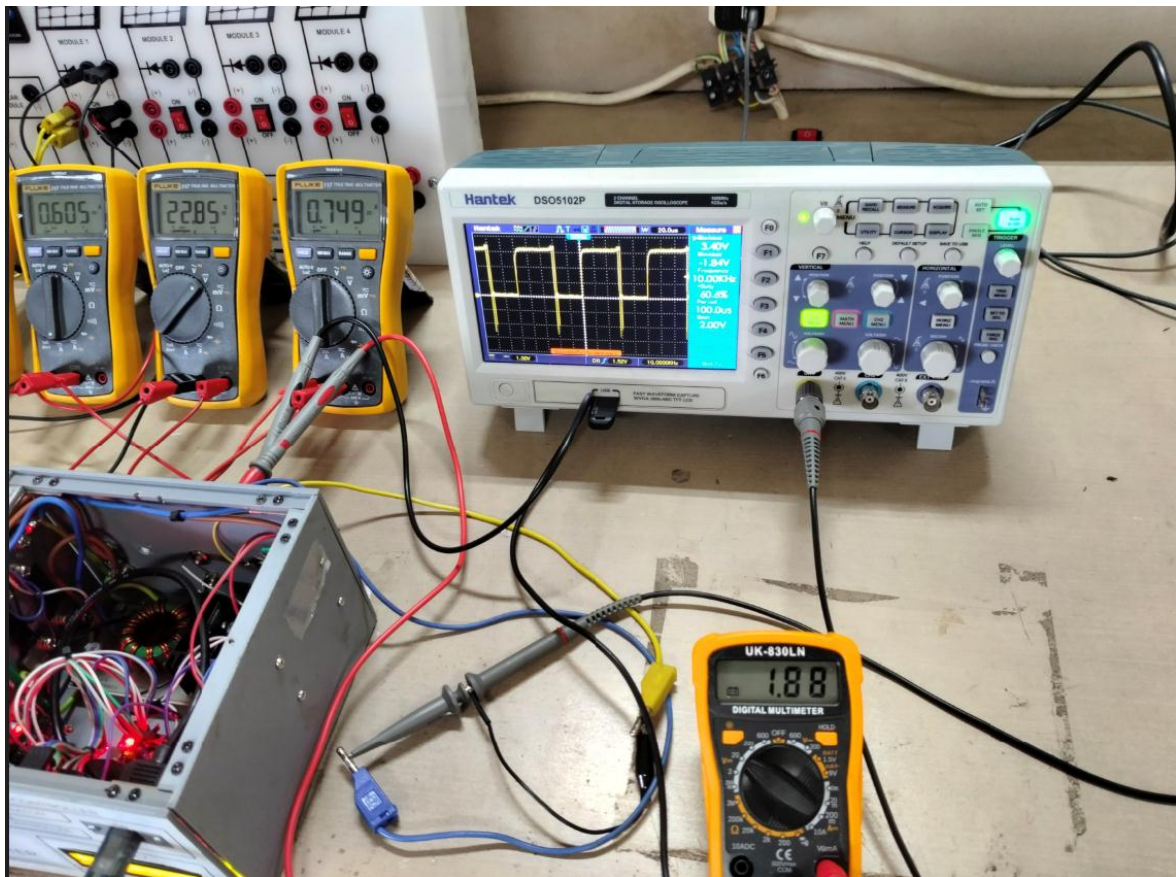
Lampiran 11. Pengujian Duty Cycle mikrokontroler and buck converter

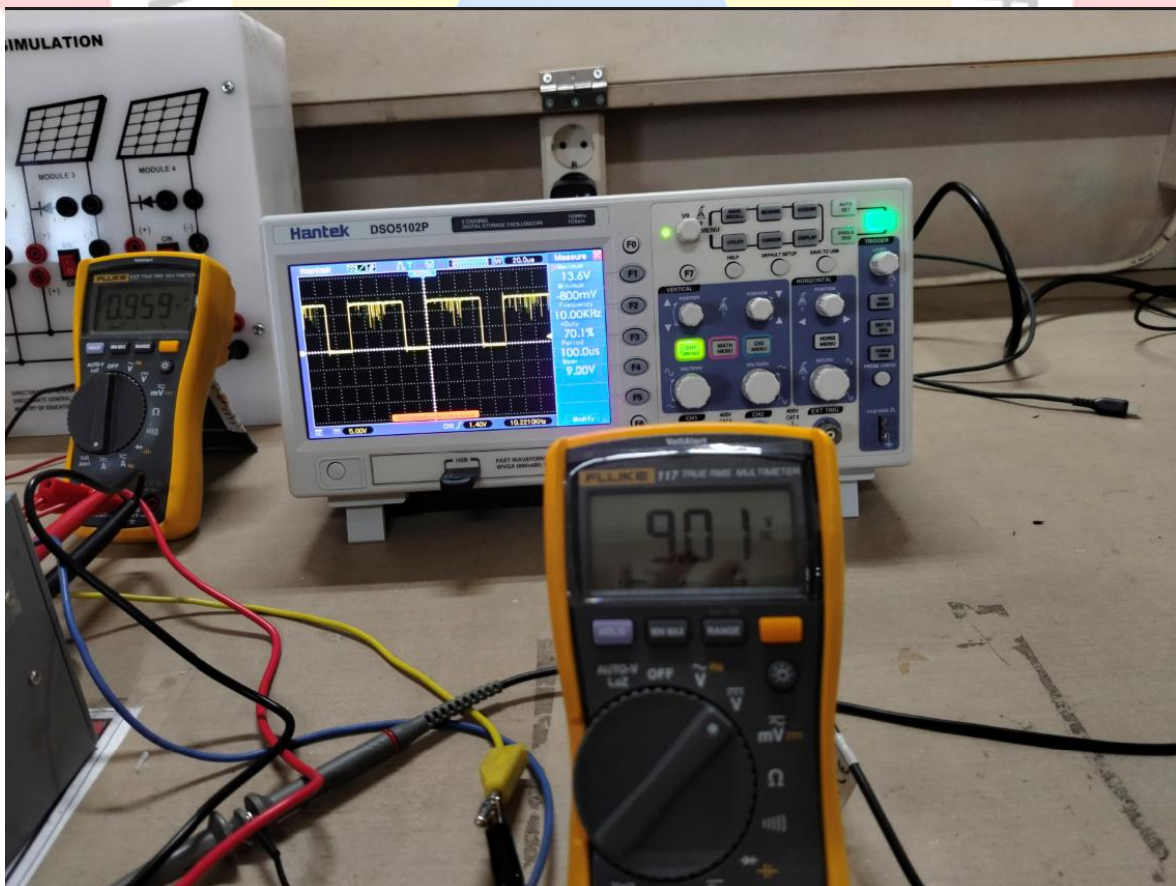
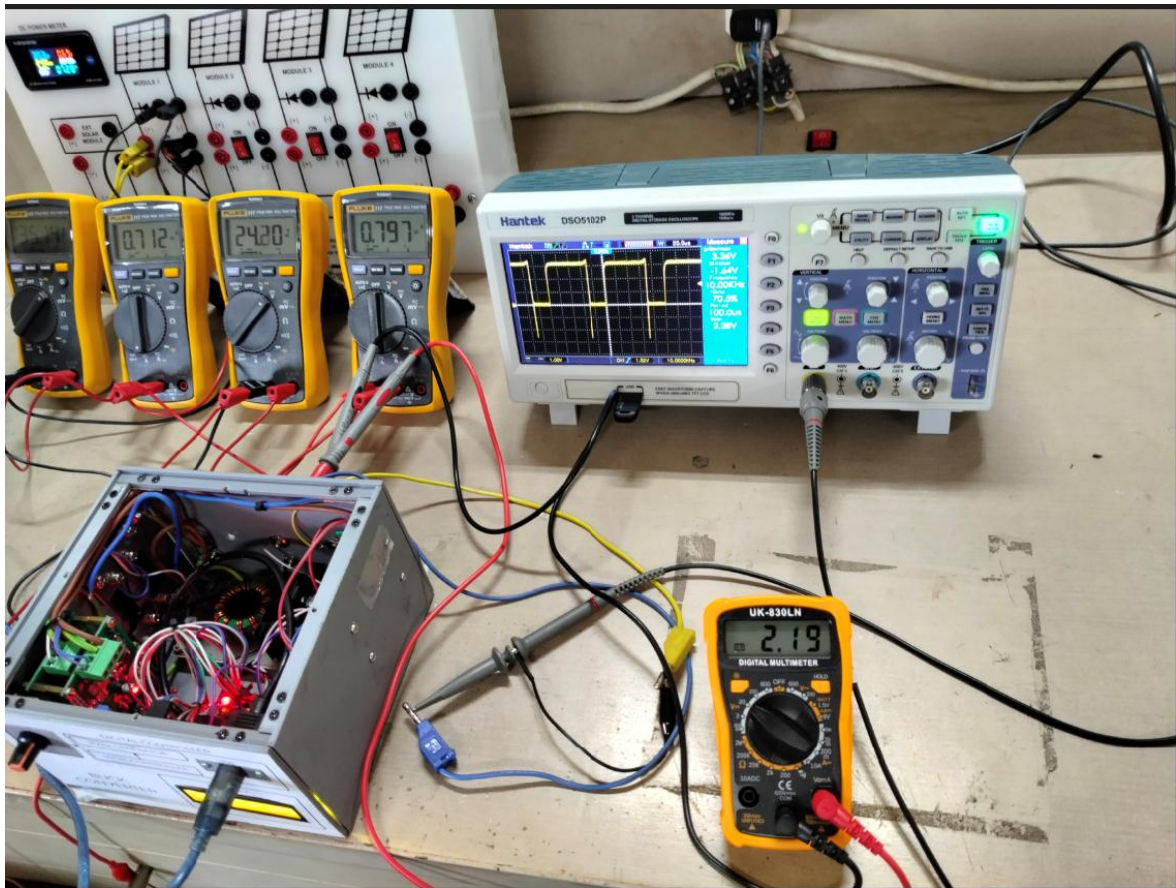


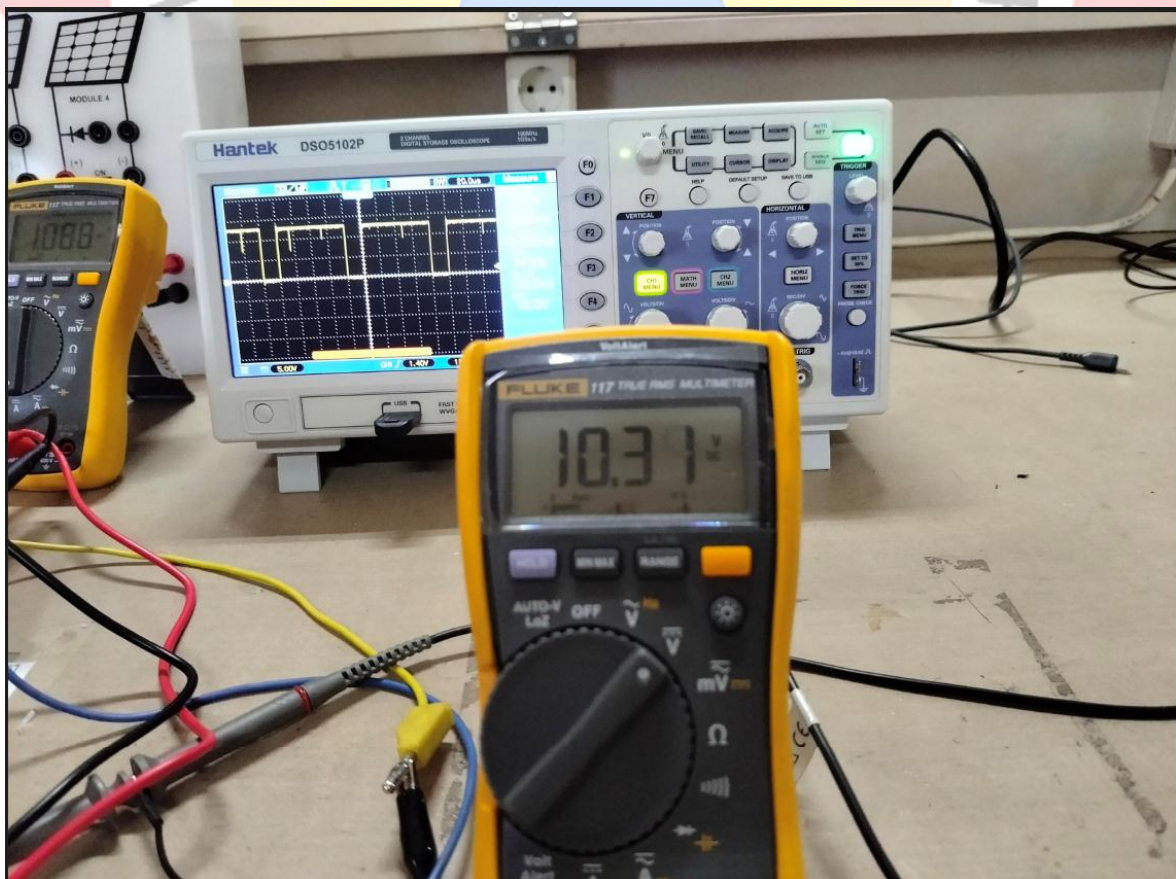
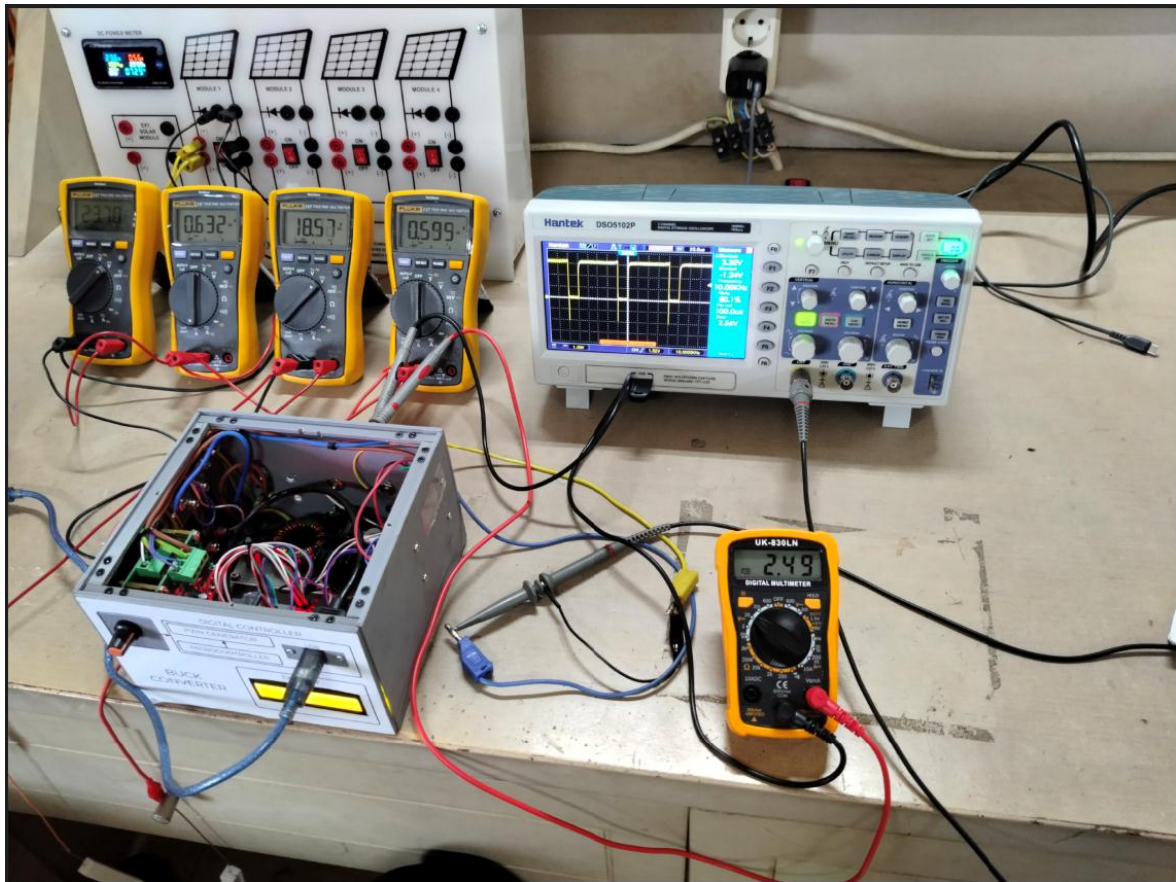


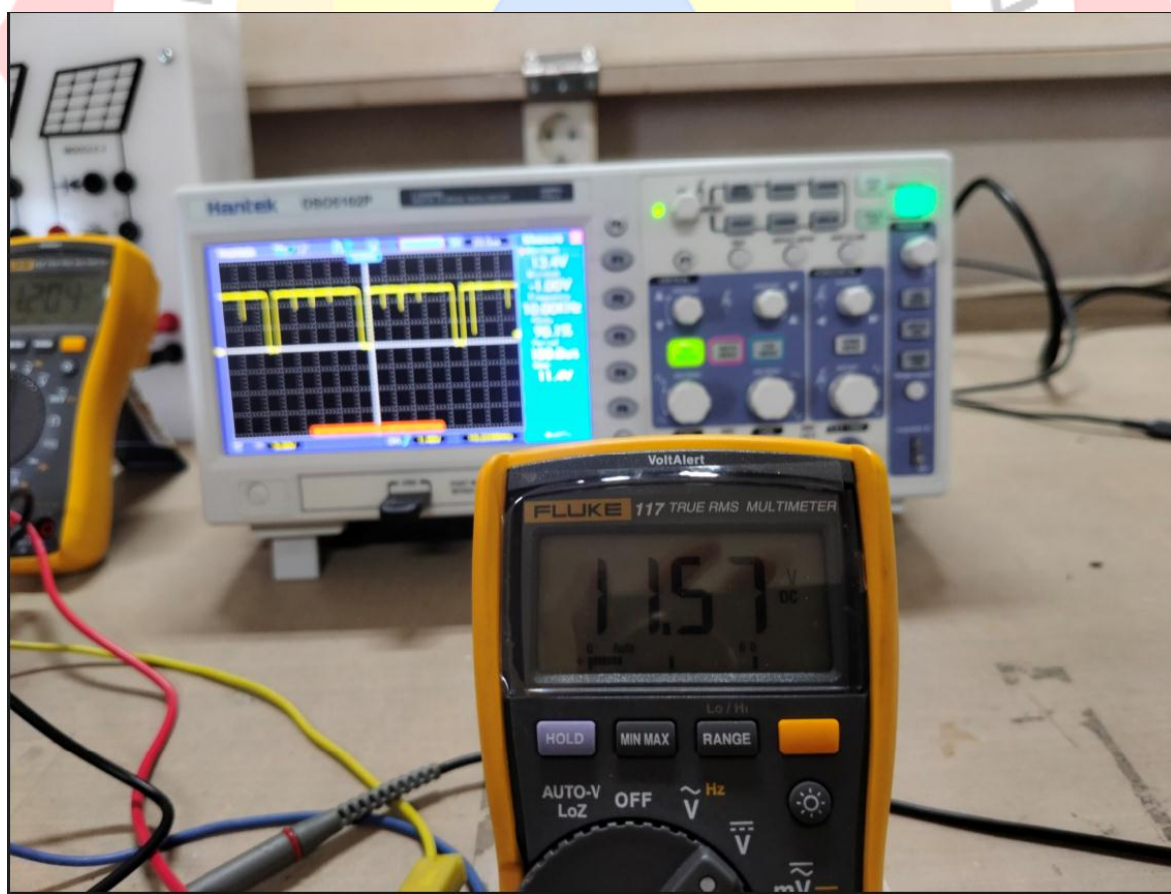
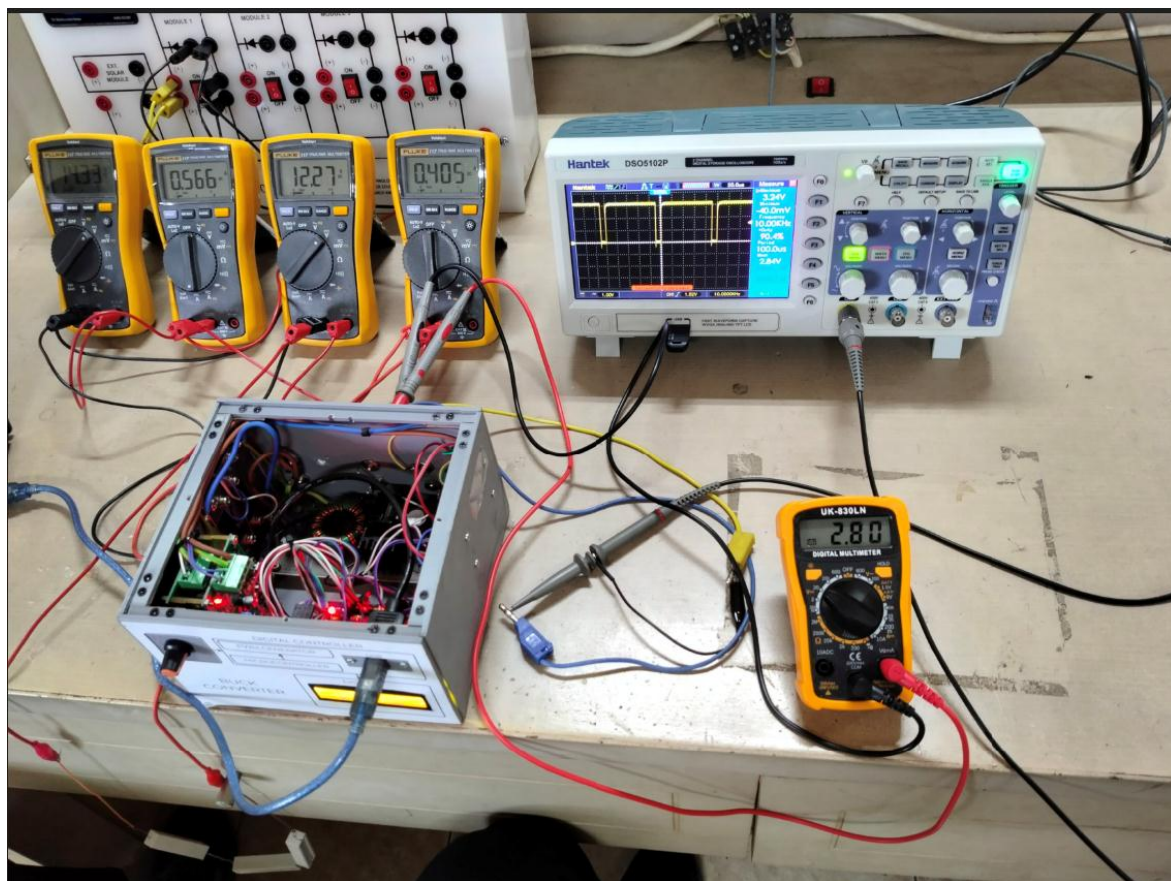




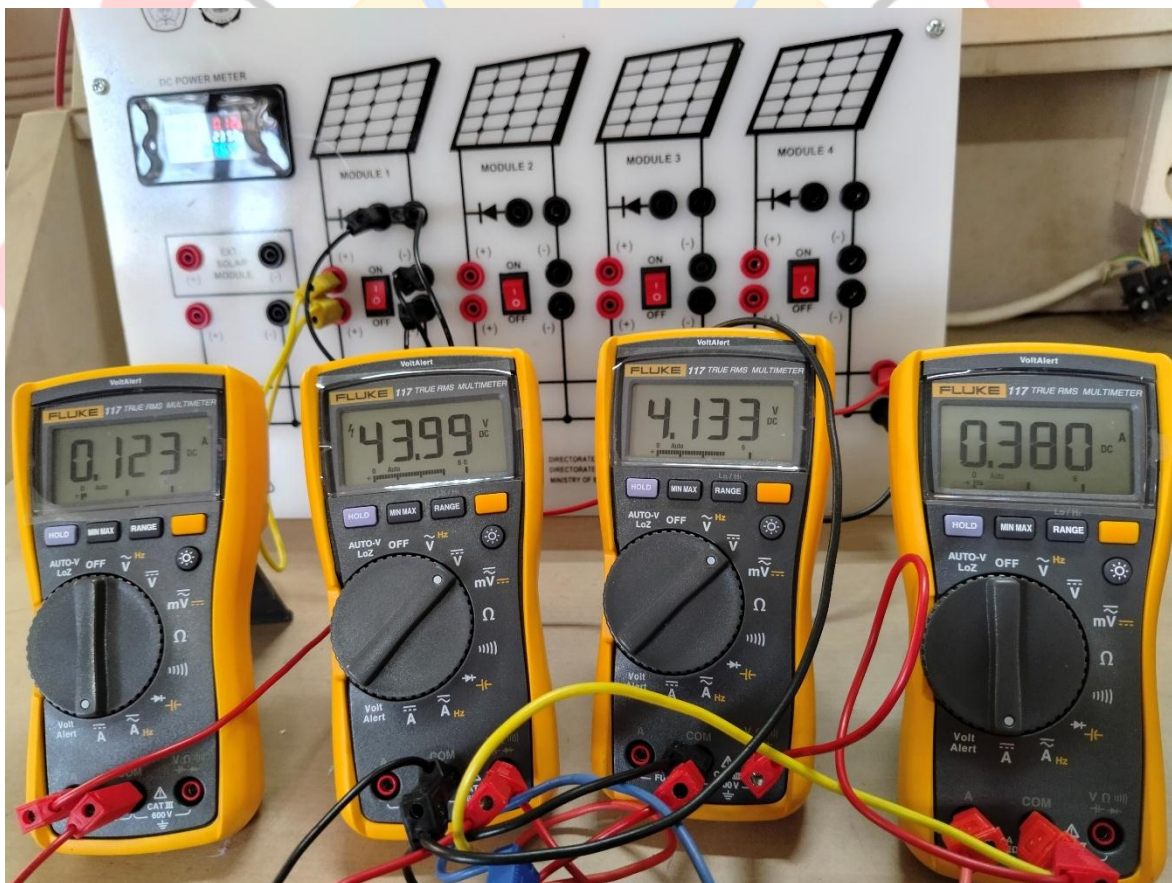
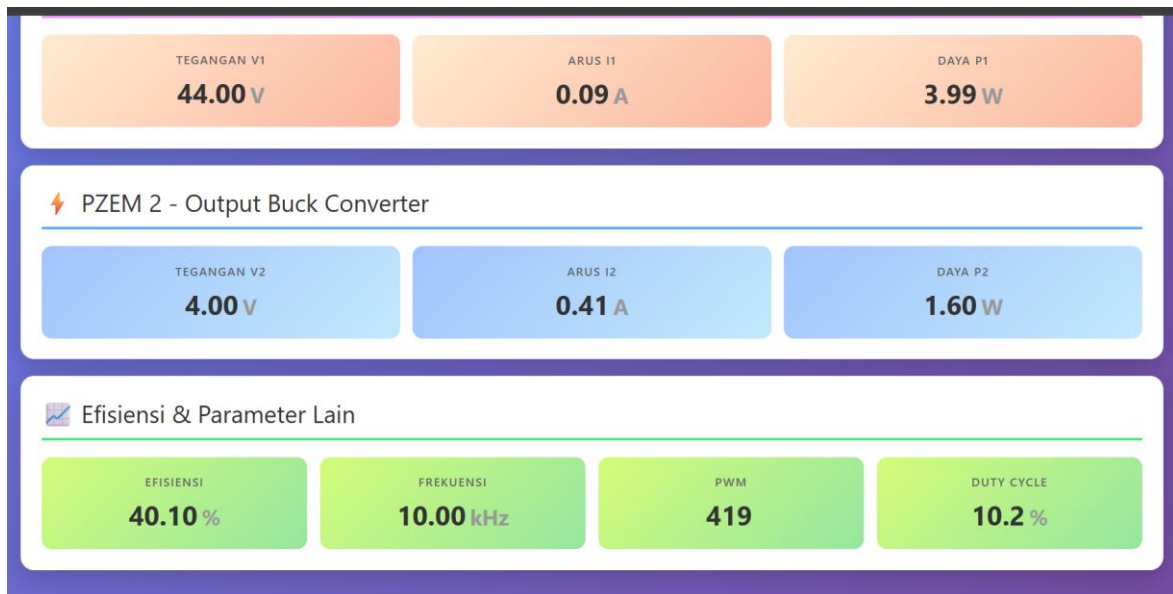


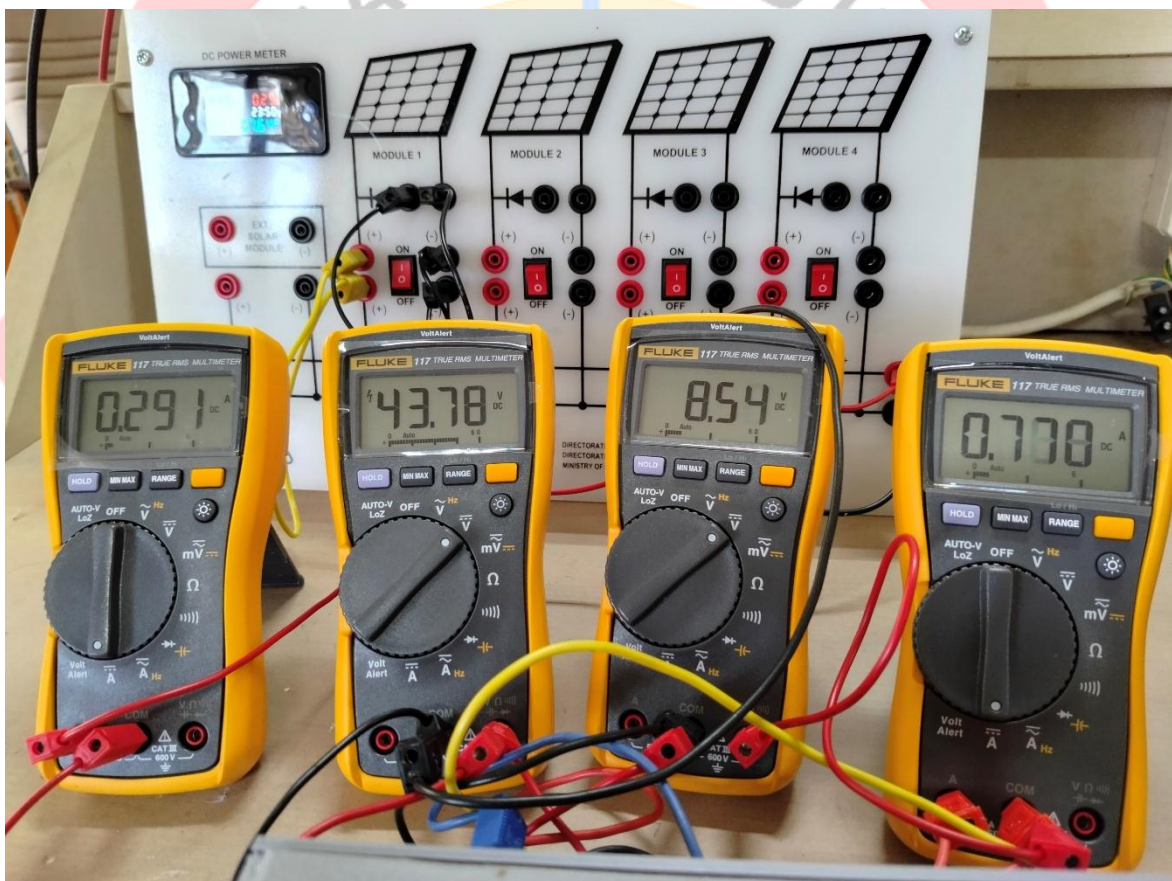
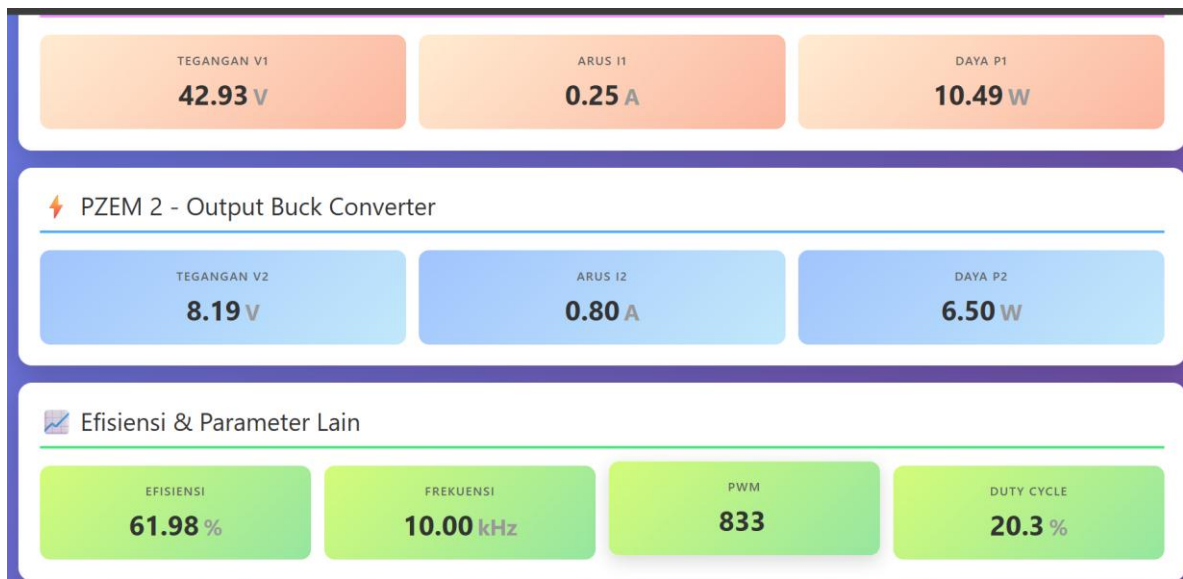


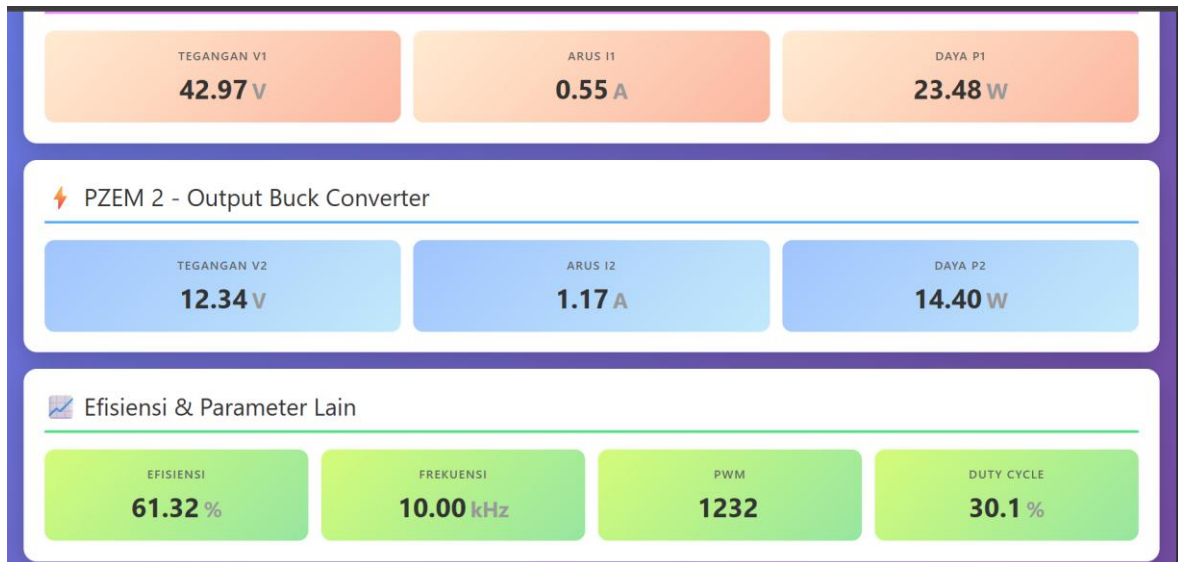




Lampiran 12. Pengujian *Buck Converter* untuk beban resistif $10\ \Omega$







⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1

43.01 V

ARUS I1

0.99 A

DAYA P1

42.41 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

16.57 V

ARUS I2

1.59 A

DAYA P2

26.40 W

📊 Efisiensi & Parameter Lain

EFISIENSI

62.25 %

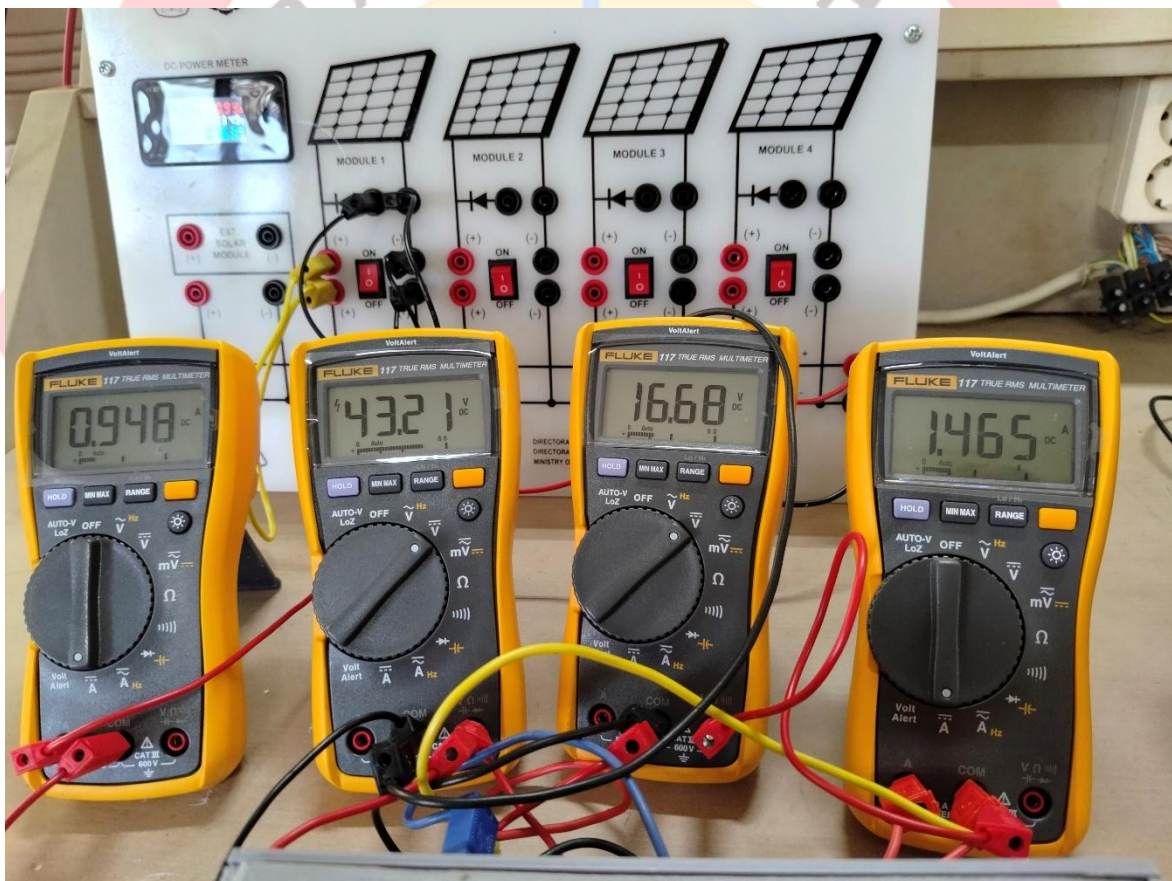
FREKUENSI

10.00 kHz

PWM

1636

DUTY CYCLE

40.0 %

⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1
42.43 V

ARUS I1
1.45 A

DAYA P1
61.62 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2
20.42 V

ARUS I2
1.86 A

DAYA P2
37.95 W

📊 Efisiensi & Parameter Lain

EFISIENSI
61.59 %

FREKUENSI
10.00 kHz

PWM
2058

DUTY CYCLE
50.3 %



⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1
41.85 V

ARUS I1
1.96 A

DAYA P1
81.80 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2
24.21 V

ARUS I2
2.15 A

DAYA P2
52.05 W

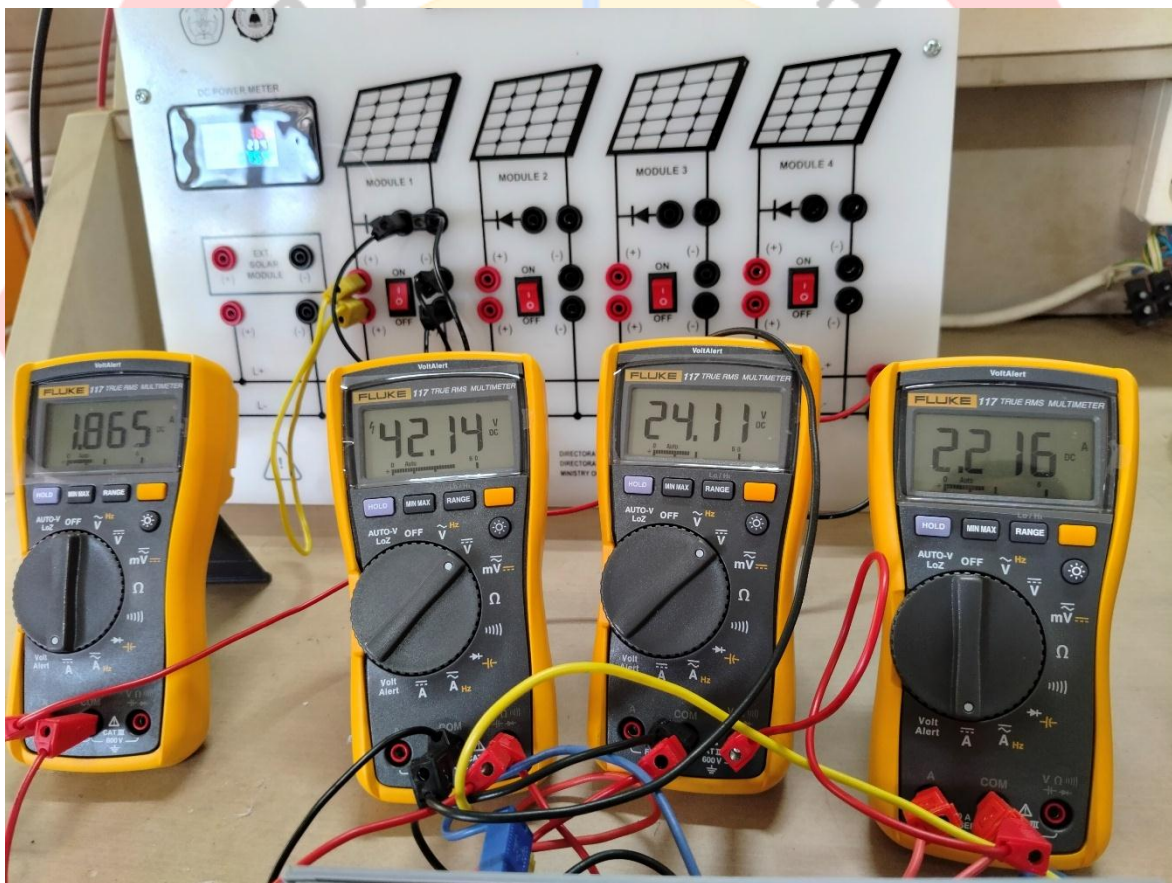
📊 Efisiensi & Parameter Lain

EFISIENSI
63.63 %

FREKUENSI
10.00 kHz

PWM
2475

DUTY CYCLE
60.4 %



⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1
41.47 V

ARUS I1
2.45 A

DAYA P1
101.40 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2
28.04 V

ARUS I2
2.40 A

DAYA P2
67.15 W

📊 Efisiensi & Parameter Lain

EFISIENSI
66.22 %

FREKUENSI
10.00 kHz

PWM
2894

DUTY CYCLE
70.7 %



⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1

40.83 V

ARUS I1

2.83 A

DAYA P1

115.42 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

31.53 V

ARUS I2

2.63 A

DAYA P2

83.05 W

📊 Efisiensi & Parameter Lain

EFISIENSI

71.95 %

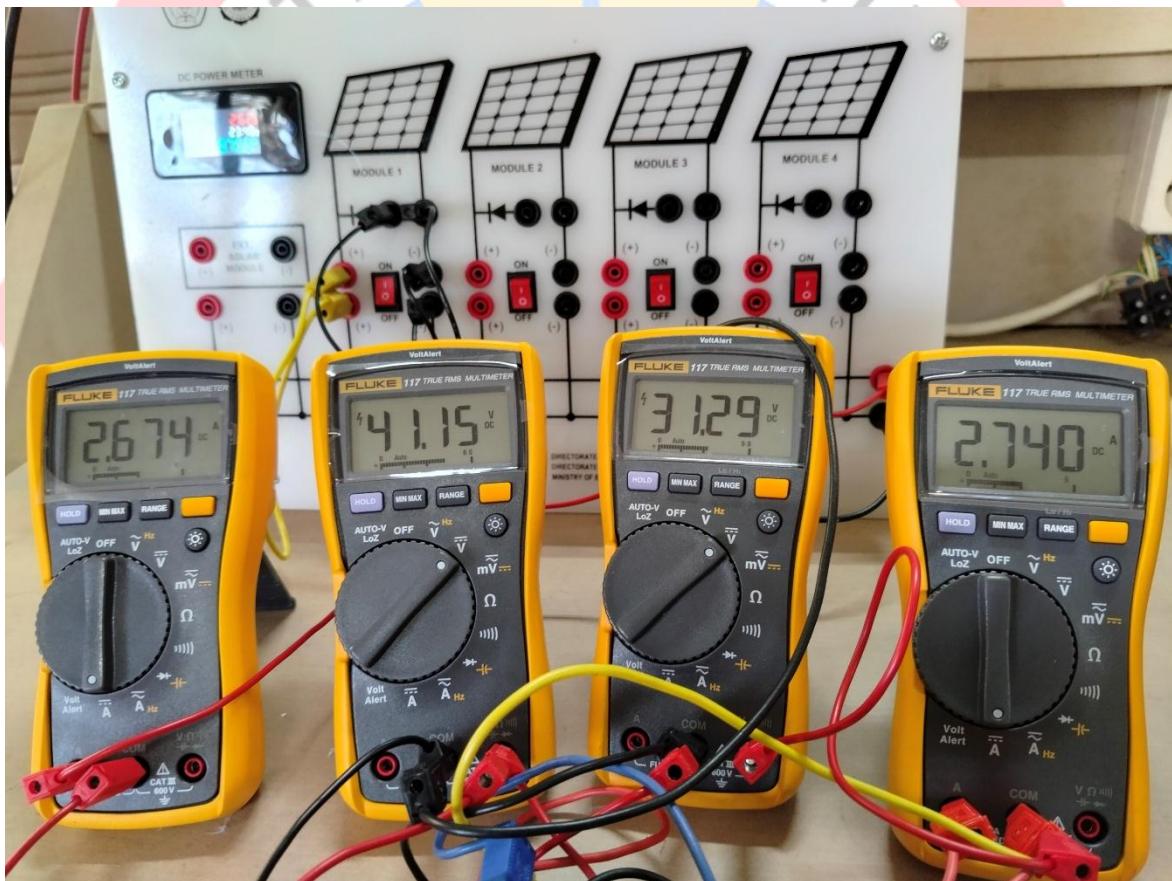
FREKUENSI

10.00 kHz

PWM

3299

DUTY CYCLE

80.6 %

⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1
40.56 V

ARUS I1
3.17 A

DAYA P1
128.76 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2
35.36 V

ARUS I2
2.85 A

DAYA P2
100.95 W

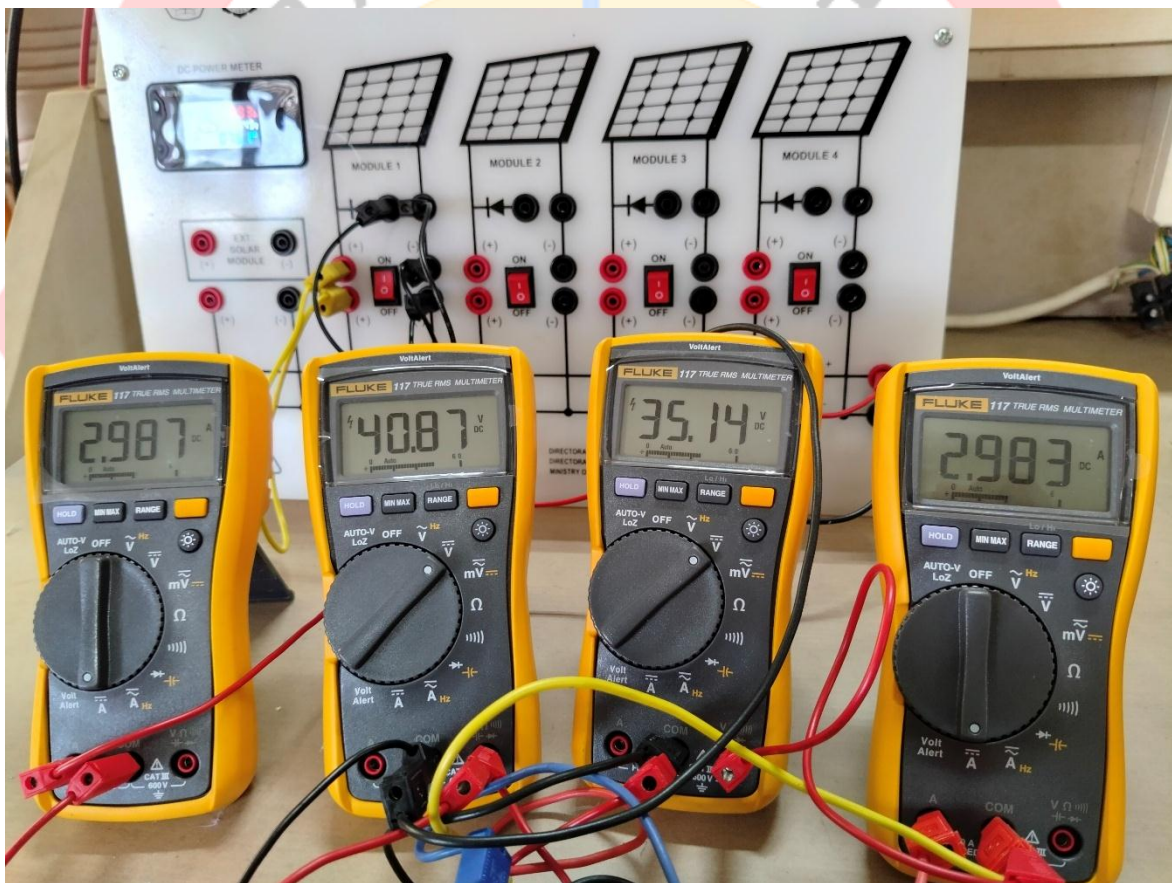
📊 Efisiensi & Parameter Lain

EFISIENSI
78.40 %

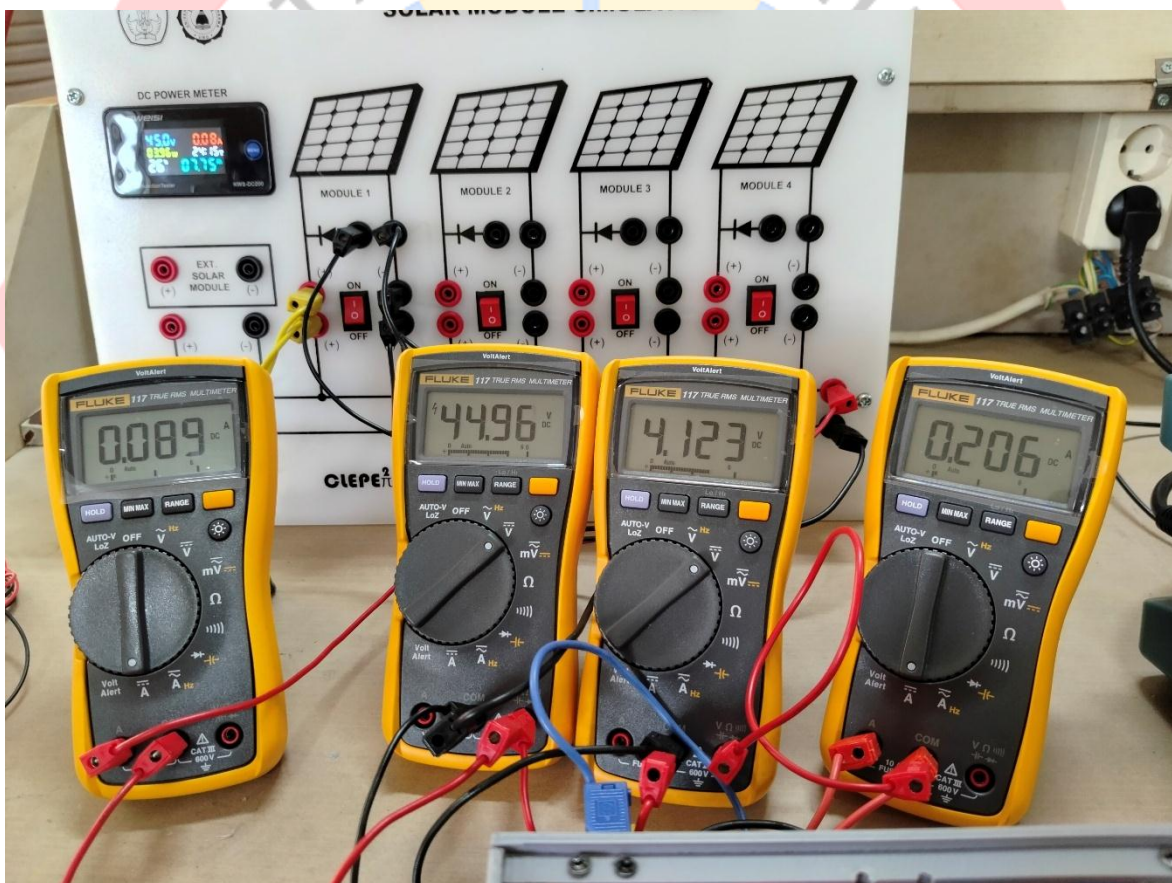
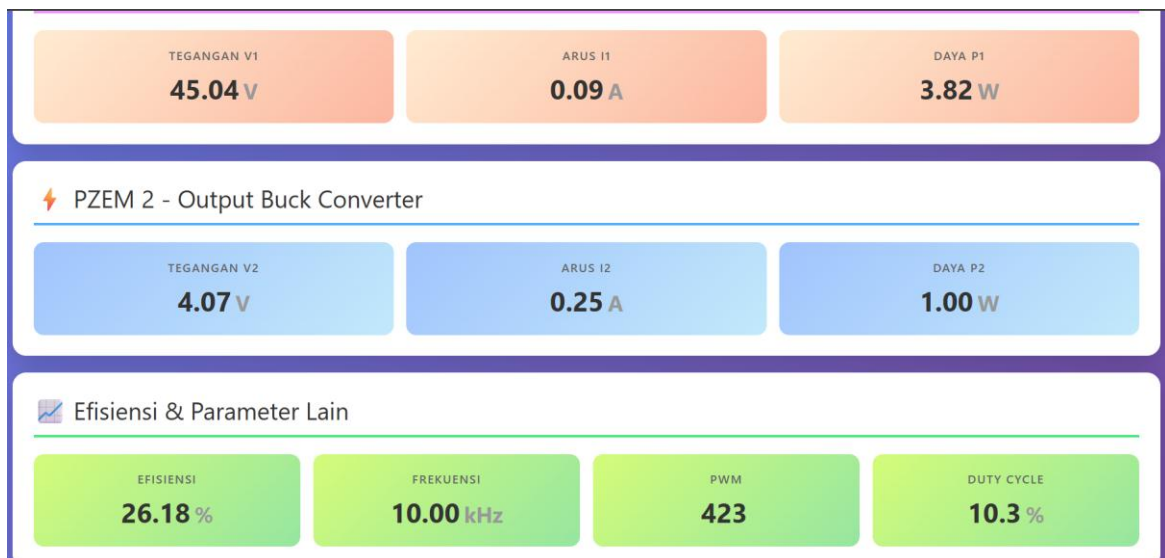
FREKUENSI
10.00 kHz

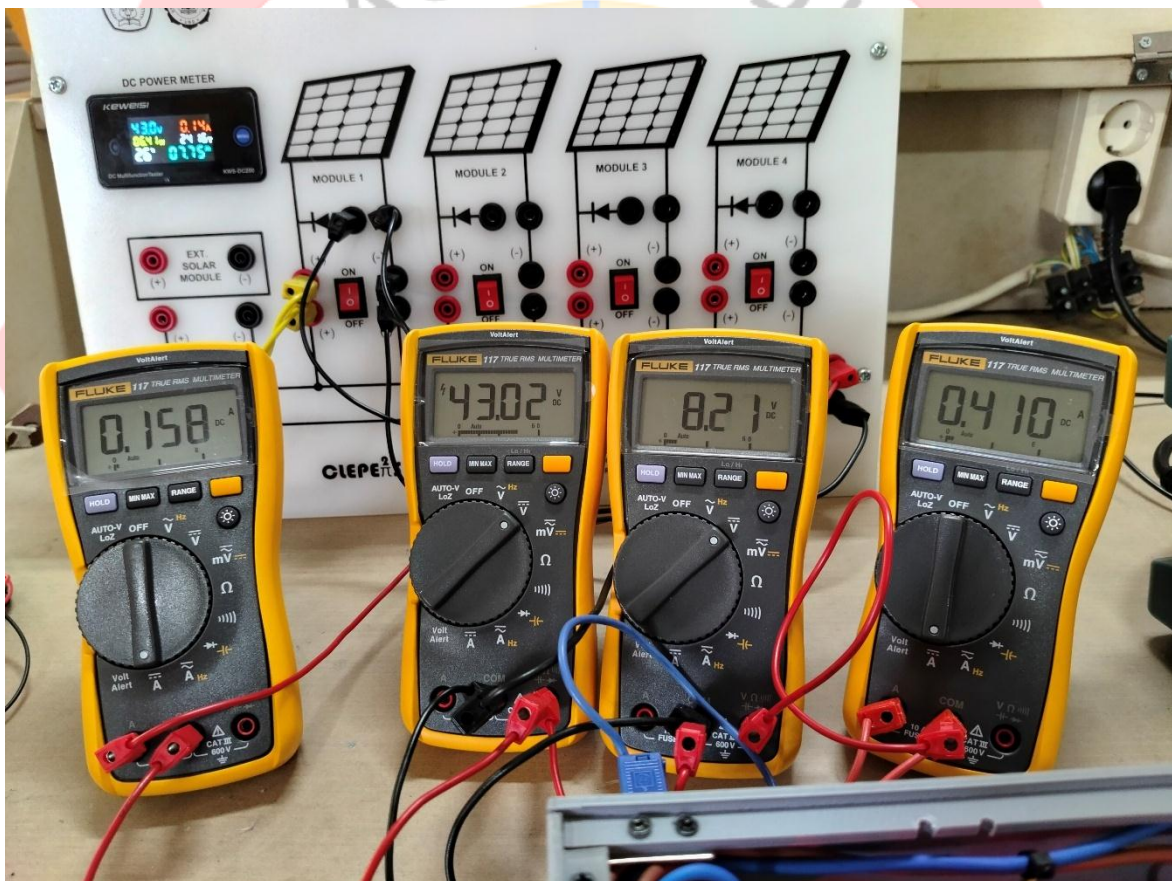
PWM
3695

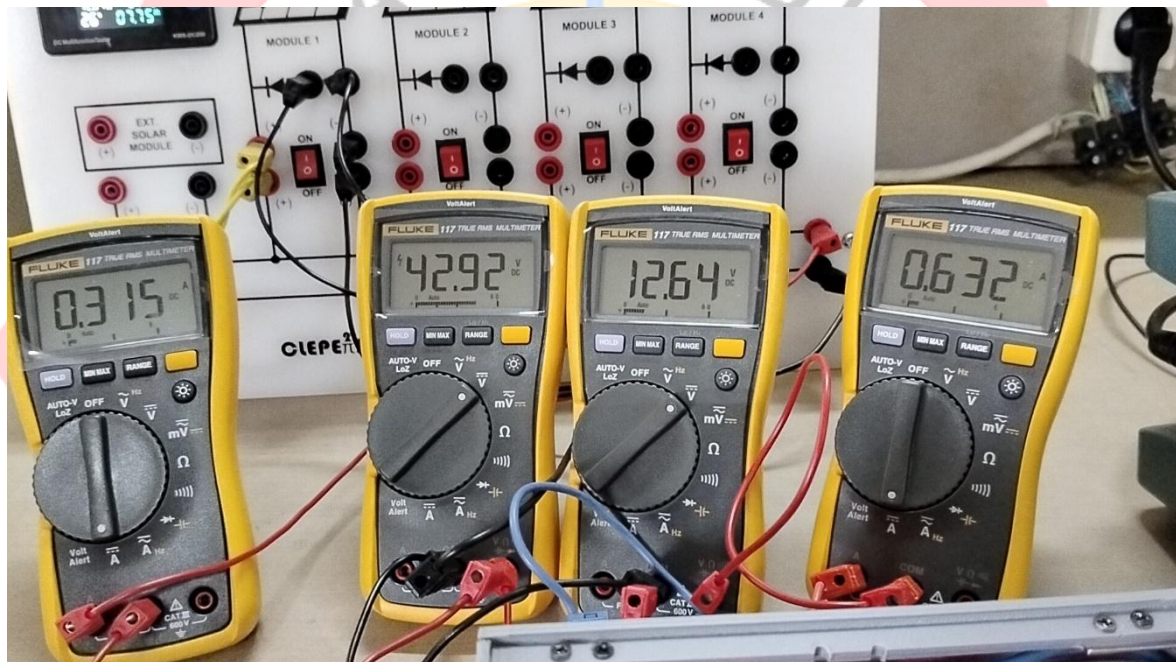
DUTY CYCLE
90.2 %



Lampiran 13. Pengujian *Buck Converter* untuk beban resistif $20\ \Omega$







UBD

TEGANGAN V1

42.64 V

ARUS I1

0.50 A

DAYA P1

21.38 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

16.68 V

ARUS I2

0.86 A

DAYA P2

14.30 W

📊 Efisiensi & Parameter Lain

EFISIENSI

66.90 %

FREKUENSI

10.00 kHz

PWM

1647

DUTY CYCLE

40.2 %

TEGANGAN V1

42.40 V

ARUS I1

0.75 A

DAYA P1

31.64 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

20.90 V

ARUS I2

1.06 A

DAYA P2

22.15 W

📊 Efisiensi & Parameter Lain

EFISIENSI

70.02 %

FREKUENSI

10.00 kHz

PWM

2058

DUTY CYCLE

50.3 %

TEGANGAN V1

42.84 V

ARUS I1

1.03 A

DAYA P1

43.95 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

25.17 V

ARUS I2

1.25 A

DAYA P2

31.45 W

📊 Efisiensi & Parameter Lain

EFISIENSI

71.56 %

FREKUENSI

10.00 kHz

PWM

2474

DUTY CYCLE

60.4 %

TEGANGAN V1

43.51 V

ARUS I1

1.38 A

DAYA P1

59.96 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

30.00 V

ARUS I2

1.48 A

DAYA P2

44.40 W

📊 Efisiensi & Parameter Lain

EFISIENSI

74.04 %

FREKUENSI

10.00 kHz

PWM

2879

DUTY CYCLE

70.3 %

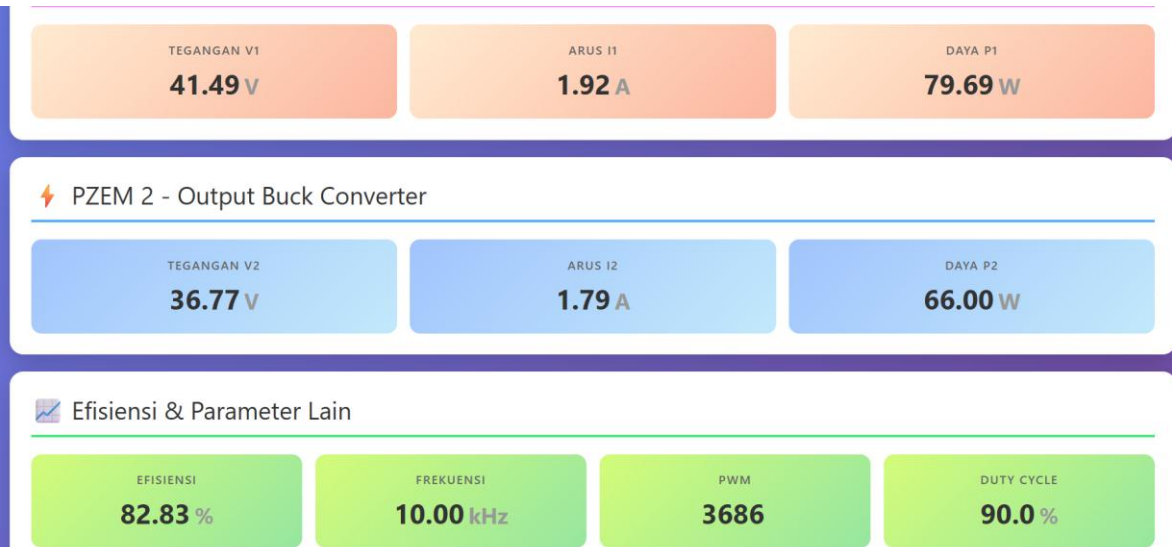


⚡ PZEM 2 - Output Buck Converter



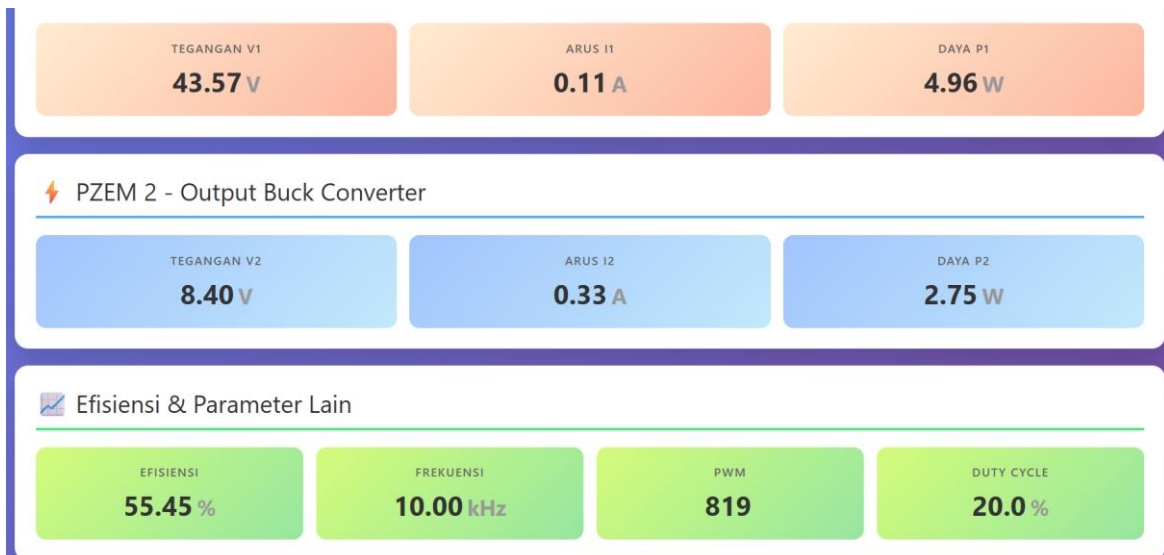
📊 Efisiensi & Parameter Lain





Lampiran 14. Pengujian *Buck Converter* untuk beban resistif $30\ \Omega$





TEGANGAN V1

43.96 V

ARUS I1

0.20 A

DAYA P1

8.72 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

12.79 V

ARUS I2

0.46 A

DAYA P2

5.80 W

📊 Efisiensi & Parameter Lain

EFISIENSI

66.51 %

FREKUENSI

10.00 kHz

PWM

1232

DUTY CYCLE

30.1 %



TEGANGAN V1

41.98 V

ARUS I1

0.49 A

DAYA P1

20.58 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

20.80 V

ARUS I2

0.70 A

DAYA P2

14.65 W

📊 Efisiensi & Parameter Lain

EFISIENSI

71.20 %

FREKUENSI

10.00 kHz

PWM

2064

DUTY CYCLE

50.4 %

⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1

41.43 V

ARUS I1

0.67 A

DAYA P1

27.59 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

24.64 V

ARUS I2

0.83 A

DAYA P2

20.55 W

📏 Efisiensi & Parameter Lain

EFISIENSI

74.49 %

FREKUENSI

10.00 kHz

PWM

2460

DUTY CYCLE

60.1 %

⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1
40.59 V

ARUS I1
0.85 A

DAYA P1
34.43 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2
28.17 V

ARUS I2
0.95 A

DAYA P2
26.75 W

📊 Efisiensi & Parameter Lain

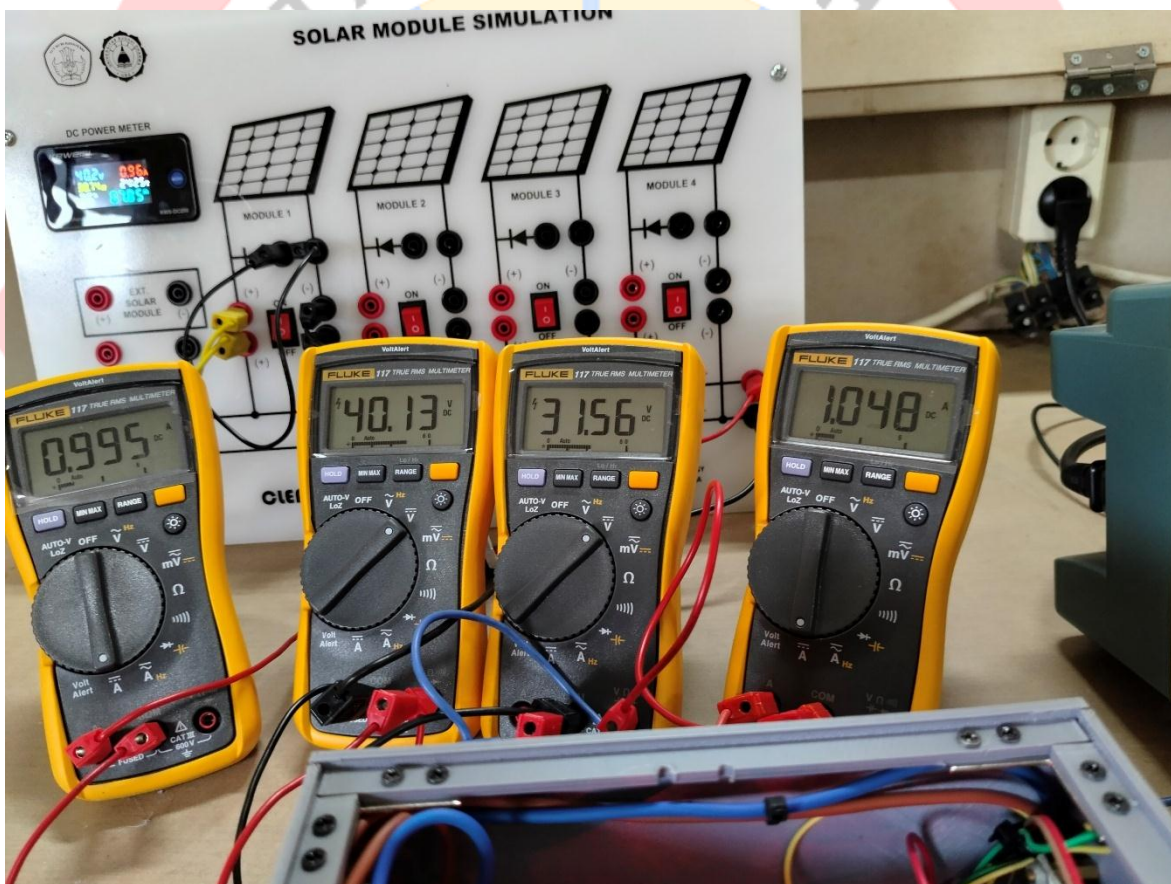
EFISIENSI
77.70 %

FREKUENSI
10.00 kHz

PWM
2881

DUTY CYCLE
70.4 %





⚡ PZEM 1 - Input Solar Panel

TEGANGAN V1

39.04 V

ARUS I1

1.21 A

DAYA P1

47.14 W

⚡ PZEM 2 - Output Buck Converter

TEGANGAN V2

34.63 V

ARUS I2

1.14 A

DAYA P2

39.30 W

📊 Efisiensi & Parameter Lain

EFISIENSI

83.37 %

FREKUENSI

10.00 kHz

PWM

3696

DUTY CYCLE

90.3 %

Lampiran 15. Perhitungan Selisih Efisiensi *Buck Converter*

Data Dasar (dari Tabel 4.3 - Beban 30Ω , *Duty Cycle* 90%, Multimeter):

$$V_{in} = 39.36 \text{ V}; I_{in} = 1.13 \text{ A}; P_{in} = 44.48 \text{ W};$$

$$V_{out} = 34.45 \text{ V}; I_{out} = 1.14 \text{ A}; P_{out} = 39.27 \text{ W};$$

$$\text{Total Losses} = 5.21 \text{ W (11.71\% dari Pin)}$$

1. SWITCHING LOSSES

$$\text{Total Switching Losses: } P_{sw_total} = P_{sw_transition} + P_{oss} + P_{gate} + P_{rr} + P_{ring}$$

1.1. $P_{sw_transition}$ (Turn-On/Turn-Off Transition Los)

Dimana berdasarkan *datasheet* IRFP260N (dari Tabel 3.7):

t_{ri} = *current rise time* (waktu arus naik saat *turn-on*)

t_{fv} = *voltage fall time* (waktu tegangan turun saat *turn-off*)

Dari *datasheet typical test condition*:

$$V_{GS} = 10\text{V};$$

$$I_D = 25\text{A};$$

$$R_G = 25\Omega$$

$$t_{d(on)} = 25 \text{ ns (turn-on delay)}$$

$$t_r = 50 \text{ ns (rise time)}$$

$$t_{d(off)} = 60 \text{ ns (turn-off delay)}$$

$$t_f = 40 \text{ ns (fall time)}$$

Pada kondisi pengujian:

$$V_{GS} = 3.3\text{V dari stepdown};$$

$$I_D = 1.14\text{A};$$

$$R_G \approx 10\Omega \text{ dari gate driver}$$

Karena V_{GS} lebih rendah (3.3V vs 10V), *switching* akan lebih lambat. Menggunakan *scaling* dari Mohan et al. (2003):

$$t_{r_actual} \approx t_{r_datasheet} \times (V_{GS_datasheet} / V_{GS_actual})$$

$$t_{r_actual} \approx 50 \text{ ns} \times (10 / 3.3) \approx 152 \text{ ns}$$

$$t_{f_actual} \approx t_{f_actual} \times (V_{GS_datasheet} / V_{GS_actual})$$

$$t_{f_actual} \approx 40 \text{ ns} \times (10 / 3.3) \approx 121 \text{ ns}$$

Perhitungan P_{sw} :

$$\begin{aligned} &= (1/6) \times V_{DS} \times I_D \times (t_{ri} + t_{fv}) \times f_{sw} \\ &= (1/6) \times 39.36 \text{ V} \times 1.14 \text{ A} \times (152 + 121) \text{ ns} \times 10,000 \text{ Hz} \\ &= (1/6) \times 39.36 \times 1.14 \times 273 \times 10^{-9} \times 10^4 \\ &= (1/6) \times 122.5 \times 10^{-3} \\ &= 0.0204 \text{ W} = 20.4 \text{ mW} \end{aligned}$$

1.2. Output Capacitance Discharge Loss (MOSFET C_{oss})

Setiap kali MOSFET *turn-on*, kapasitansi *output* (C_{oss}) yang terisi pada tegangan V_{in} harus di-*discharge*, dan energi tersebut terdisipasi.

Data C_{oss} IRFP260N: $C_{oss} = 500 \text{ pF}$ @ $V_{DS} = 25 \text{ V}$ (dari grafik Tabel 3.7)

Pada $V_{DS} = 40 \text{ V}$, C_{oss} meningkat menjadi $\approx 650 \text{ pF}$ (dari kurva non-linear)

Perhitungan P_{oss} :

$$\begin{aligned} &= 0.5 \times C_{oss} \times V_{in}^2 \times f_{sw} \\ &= 0.5 \times 650 \times 10^{-12} \times 39.36^2 \times 10,000 \\ &= 0.5 \times 650 \times 10^{-12} \times 1549 \times 10^4 \\ &= 5.03 \times 10^{-3} \text{ W} = 5.03 \text{ mW} \end{aligned}$$

1.3. Gate Charge Loss

Energi yang diperlukan untuk *charge/discharge gate capacitance* setiap siklus:

Data Q_g IRFP260N:

Q_g (total *gate charge*) = 140 nC @ $V_{GS} = 10 \text{ V}$, $I_D = 25 \text{ A}$

Pada $V_{GS} = 3.3 \text{ V}$, $Q_g \approx 60 \text{ nC}$ (dari kurva Q_g vs V_{GS})

Perhitungan P_{gate} :

$$\begin{aligned} &= Q_g \times V_{GS} \times f_{sw} \\ &= 60 \times 10^{-9} \times 3.3 \times 10,000 \\ &= 1.98 \times 10^{-3} \text{ W} = 1.98 \text{ mW} \end{aligned}$$

1.4. Diode Reverse Recovery Loss

Ketika MOSFET *turn-on*, diode yang sedang menghantarkan harus *turn-off*. Selama *reverse recovery time* (t_{rr}), diode mengalirkan *reverse current* (I_{rr}) yang menyebabkan *additional loss*.

Data Diode 60UP30DN (dari Tabel 3.8):

Diode ini adalah *ultra-fast recovery* dengan $t_{rr} = 35 \text{ ns}$ @ $I_F = 15 \text{ A}$

Pada $I_F = 1.14 \text{ A}$ (arus beban), $t_{rr} \approx 20 \text{ ns}$ (*scaling* dengan akar arus)

$I_{rr} \approx 2 \times I_F = 2.28 \text{ A}$ (*typical* untuk diode *ultra-fast*)

Perhitungan P_{rr} :

$$\begin{aligned} &= 0.5 \times V_{in} \times I_{rr} \times t_{rr} \times f_{sw} \\ &= 0.5 \times 39.36 \times 2.28 \times 20 \times 10^{-9} \times 10,000 \\ &= 0.5 \times 39.36 \times 2.28 \times 2 \times 10^{-4} \\ &= 8.96 \times 10^{-3} \text{ W} = 8.96 \text{ mW} \end{aligned}$$

1.5. Ringing/Oscillation Dissipation

Dari Gambar 4.2 (grafik osiloskop), terlihat *ringing* dengan amplitudo $\approx 1\text{-}1.5 \text{ V}$ dan frekuensi $\approx 2\text{-}5 \text{ MHz}$. Energi osilasi ini terdisipasi dalam resistansi parasitik *loop*.

Dimana:

$L_{parasitic} \approx 50\text{-}100 \text{ nH}$ (*typical PCB loop inductance*)

$\Delta I_{ring} \approx 0.5 \text{ A}$ (estimasi dari *ripple* yang terlihat)

Perhitungan E_{ring} :

$$\begin{aligned} &= 0.5 \times L_{parasitic} \times (\Delta I_{ring})^2 \\ &= 0.5 \times 75 \times 10^{-9} \times 0.5^2 \\ &= 9.375 \times 10^{-9} \text{ J} \end{aligned}$$

Perhitungan P_{ring} :

$$\begin{aligned} &= E_{ring} \times f_{sw} \times (\text{jumlah ringing cycles per switching}) \\ &\approx 9.375 \times 10^{-9} \times 10,000 \times 3 \text{ (3 cycles terlihat di osiloskop)} \\ &= 2.81 \times 10^{-4} \text{ W} = 0.281 \text{ mW} \end{aligned}$$

Perhitungan *Total Switching Losses* (P_{sw_total}):

$$\begin{aligned}
 &= P_{sw_transition} + P_{oss} + P_{gate} + P_{rr} + P_{ring} \\
 &= 20.4 \text{ mW} + 5.03 \text{ mW} + 1.98 \text{ mW} + 8.96 \text{ mW} + 0.281 \text{ mW} \\
 &= 36.65 \text{ mW} = 0.037 \text{ W}
 \end{aligned}$$

Persentase dari total losses: $0.037 / 5.21$ (*total losses*) = 0.70%. Karena nilai ini sangat kecil dan tidak masuk akal untuk menjelaskan total losses 5.21 W. Ini mengindikasikan bahwa Ada switching losses lain yang tidak ter-model (misalnya losses selama konduksi dengan V_{DS} yang belum turun sempurna).

Formula ini hanya valid untuk *hard-switching ideal*, sedangkan implementasi riil memiliki *non-idealities*. Koreksi dengan faktor empiris dari Zhang et al. (2019): Dalam praktik, *real switching loss* bisa 5-10x lebih besar dari perhitungan teoritis untuk *low-voltage gate drive*:

$$P_{sw_corrected} = 0.037 \times 7 = 0.26 \text{ W (5% dari total losses)}$$

B. CONDUCTION LOSSES

2. MOSFET $R_{DS(on)}$ Loss

Data IRFP260N:

$R_{DS(on)}$ @ 25°C;

$V_{GS} = 10\text{V}$, $R_{DS} = 0.055 \Omega$

$V_{GS} = 3.3\text{V}$, $R_{DS(on)}$ jauh lebih tinggi, dari kurva I_D vs V_{DS} @ $V_{GS} = 3.3\text{V}$ (Figure1. datasheet IRFP260N):

$I_D (I_{out}) = 1.14\text{A}$;

$V_{DS} \approx 0.2\text{V}$ (dari grafik)

Maka $R_{DS(on)_effective}$

$$\begin{aligned}
 &= V_{DS} \times (I_D)^{-1} \\
 &= 0.2 \text{ V} \times (1.14 \text{ A})^{-1} \\
 &= 0.175 \Omega
 \end{aligned}$$

Temperature correction (estimasi $T_{junction} = 75^\circ\text{C}$):

$$R_{DS(on)_hot} = 0.175 \times [1 + 0.006 \times (75-25)] = 0.175 \times 1.3 = 0.228 \Omega$$

Perhitungan P_{cond_MOS} :

$$= I_{out}^2 \times R_{DS(on)} \times D$$

$$\begin{aligned}
 &= 1.14^2 \times 0.228 \times 0.9 \\
 &= 1.30 \times 0.228 \times 0.9 \\
 &= 0.267 \text{ W (5.1\% dari total losses)}
 \end{aligned}$$

3. Diode Forward Voltage Loss

Data 60UP30DN:

Dari grafik I_F vs V_F (Tabel 3.8), pada $I_F = 1.14\text{A}$, $V_F \approx 0.85\text{V @ } 25^\circ\text{C}$

Pada $T_{\text{junction}} = 75^\circ\text{C}$, V_F menurun $\approx 0.75\text{V}$ (negative temperature coefficient)

Perhitungan $P_{\text{cond_diode}}$:

$$\begin{aligned}
 &= V_f \times I_{\text{out}} \times (1 - D) \\
 &= 0.75 \times 1.14 \times (1 - 0.9) \\
 &= 0.75 \times 1.14 \times 0.1 \\
 &= 0.086 \text{ W (1.6\% dari total losses)}
 \end{aligned}$$

C. INDUCTOR LOSSES

4. DCR (DC Resistance) Loss

Estimasi R_{DCR} untuk induktor 4.5mH rated 5A (typical commercial inductor):

$\text{DCR} \approx 0.08\text{-}0.12 \Omega$ (dari datasheet induktor umum seperti Bourns SRR1260)

Asumsi $R_{\text{DCR}} = 0.10 \Omega$

Perhitungan P_{DCR} :

$$\begin{aligned}
 &= I_{\text{out}}^2 \times R_{\text{DCR}} \\
 &= 1.14^2 \times 0.10 \\
 &= 0.130 \text{ W (2.5\% dari total losses)}
 \end{aligned}$$

5. Inductor Core Loss

Untuk inductor core loss pada frekuensi 10kHz , menggunakan Steinmetz equation:

$$P_{\text{core}} = K \times f^\alpha \times B^\beta \times \text{Volume}$$

Dimana (untuk ferrite material N87 - typical untuk power inductor):

$K = 6.5$ (konstant material)

$\alpha = 1.3$ (frekuensi exponent)

$\beta = 2.5$ (flux density exponent)

B = flux density swing

Estimasi B dari *ripple current*:

$\Delta I_L = 0.033$ A (dari analisis *ripple* di Subbab 4.2.2)

$$B = (L \times \Delta I_L) \times (N \times A_e)^{-1}$$

Untuk induktor komersial 4.5mH:

N (jumlah lilitan) ≈ 80 (typical)

A_e (core area) $\approx 100 \text{ mm}^2 = 1 \times 10^{-4} \text{ m}^2$

Volume inductor $\approx 10 \text{ cm}^3 = 10 \times 10^{-6} \text{ m}^3$

Perhitungan nilai B :

$$\begin{aligned} &= (L \times \Delta I_L) \times (N \times A_e)^{-1} \\ &= (4.5 \times 10^{-3} \times 0.033) \times (80 \times 1 \times 10^{-4})^{-1} \\ &= 1.485 \times 10^{-4} \times (8 \times 10^{-3})^{-1} \\ &= 0.0186 \text{ T} = 186 \text{ Gauss} \end{aligned}$$

Perhitungan P_{core} :

$$\begin{aligned} &= K \times f^\alpha \times B^\beta \times \text{Volume} \\ &= 6.5 \times (10,000)^{1.3} \times (0.0186)^{2.5} \times 10 \times 10^{-6} \\ &= 6.5 \times 39,811 \times 1.047 \times 10^{-4} \times 10^{-5} \\ &= 0.027 \text{ W (0.5% dari total losses)} \end{aligned}$$

6. CAPACITOR LOSSES (ESR)

6.1. Input Capacitor (1000 μ F Electrolytic)

Dari *ripple input* = 3500mV @ beban 30 Ω :

$$I_{\text{ripple_rms}} = \Delta V / (\text{ESR})$$

Untuk elektrolit 1000 μ F/50V:

ESR @ 10kHz $\approx 0.15 \Omega$ (typical dari datasheet Nichicon)

Perhitungan $I_{\text{ripple_rms}}$:

$$\begin{aligned} &= I_{\text{in}} \times \text{ripple_factor} \\ &\approx 1.13 \times 0.3 \text{ (30\% ripple factor untuk buck converter @ CCM)} \\ &= 0.339 \text{ A} \end{aligned}$$

Perhitungan P_{ESR_in} :

$$\begin{aligned}
 &= I_{ripple}^2 \times ESR \\
 &= 0.339^2 \times 0.15 \\
 &= 0.017 \text{ W}
 \end{aligned}$$

6.2. Output Capacitor (2200 μ F Electrolytic)

Dari ripple output = 1000mV:

Perhitungan I_{ripple_out} :

$$\begin{aligned}
 &\approx \Delta I_L \times (2\sqrt{3})^{-1} \\
 &= 0.033 \times (2\sqrt{3})^{-1} \\
 &= 0.0095 \text{ A}
 \end{aligned}$$

ESR @ 10kHz $\approx 0.08 \Omega$ (2200 μ F/50V low-ESR)

Perhitungan P_{ESR_out} :

$$\begin{aligned}
 &= I_{ripple}^2 \times ESR \\
 &= 0.0095^2 \times 0.08 \\
 &= 0.000007 \text{ W (negligible)}
 \end{aligned}$$

Perhitungan *Total Capacitor Loss*:

$$\begin{aligned}
 &= P_{ESR_in} + P_{ESR_out} \\
 &= 0.017 \text{ W} + 0.000007 \text{ W} \\
 &= 0.017 \text{ W (0.3% dari total losses)}
 \end{aligned}$$

7. PCB TRACE RESISTANCE

Estimasi resistansi *trace*:

Panjang *trace* total (dari PV $\rightarrow$ Buck $\rightarrow$ Beban) $\approx 50 \text{ cm} = 0.5 \text{ m}$

Lebar *trace* untuk jalur daya = 2 mm (asumsi)

Ketebalan copper = 35 μm (1 oz copper standard PCB)

Resistivitas tembaga = $1.68 \times 10^{-8} \Omega \cdot \text{m}$

Perhitungan R_{trace} :

$$\begin{aligned}
 &= \rho \times L \times A^{-1} \\
 &= 1.68 \times 10^{-8} \times 0.5 \times (2 \times 10^{-3} \times 35 \times 10^{-6})^{-1}
 \end{aligned}$$

$$= 8.4 \times 10^{-9} \times (7 \times 10^{-8})^{-1}$$

$$= 0.12 \, \Omega$$

Perhitungan pada P_{trace} :

$$= I^2 \times R_{trace}$$

$$= 1.14^2 \times 0.12 \, \Omega$$

$$= 0.156 \, \text{W} \, (3.0\% \text{ dari } total \, losses)$$

8. CONTACT/TERMINAL RESISTANCE

Dari foto Gambar 4.5 (tampak atas), terlihat banyak koneksi *screw terminal* dan *solder joint*.

Setiap koneksi memiliki *contact resistance* $\approx 5\text{-}20 \, \text{m}\Omega$.

Estimasi 10 koneksi dengan $R_{contact}$ rata-rata = $10 \, \text{m}\Omega$:

$$R_{contact_total} = 10 \times 0.010 = 0.10 \, \Omega$$

Perhitungan $P_{contact}$:

$$= I^2 \times R_{contact}$$

$$= 1.14^2 \times 0.10 \, \Omega$$

$$= 0.130 \, \text{W} \, (2.5\% \text{ dari } total \, losses)$$

9. THERMAL LOSSES (Non-Modeled)

Pada operasi *steady-state*, komponen seperti MOSFET, diode, dan *inductor* mengalami pemanasan. Gradien termal menyebabkan *thermal conduction* melalui *heatsink*, PCB, dan udara sekitar. Meskipun ini bukan "*electrical loss*" dalam arti tradisional, energi termal ini berasal dari disipasi daya elektrik yang tidak ter-*capture* dalam model di atas.

Dari hukum *Fourier*:

$$P_{thermal} = (\Delta T) / R_{thermal}$$

Estimasi (tanpa pengukuran langsung):

$$\Delta T \approx 40^\circ\text{C} \, (\text{MOSFET } junction \text{ ke } ambient)$$

$$R_{thermal} \approx 50^\circ\text{C/W} \, (\text{tanpa } heatsink \text{ aktif})$$

$$P_{thermal} = 40 / 50 = 0.8 \, \text{W}$$

Namun ini adalah *re-manifestation* dari *losses* elektrik yang sudah dihitung, bukan *losses* tambahan. Yang menjadi masalah adalah *thermal-induced additional resistance* yang membuat *losses* lebih besar dari kalkulasi @ 25°C.

Estimasi kenaikan *losses* akibat *thermal*:

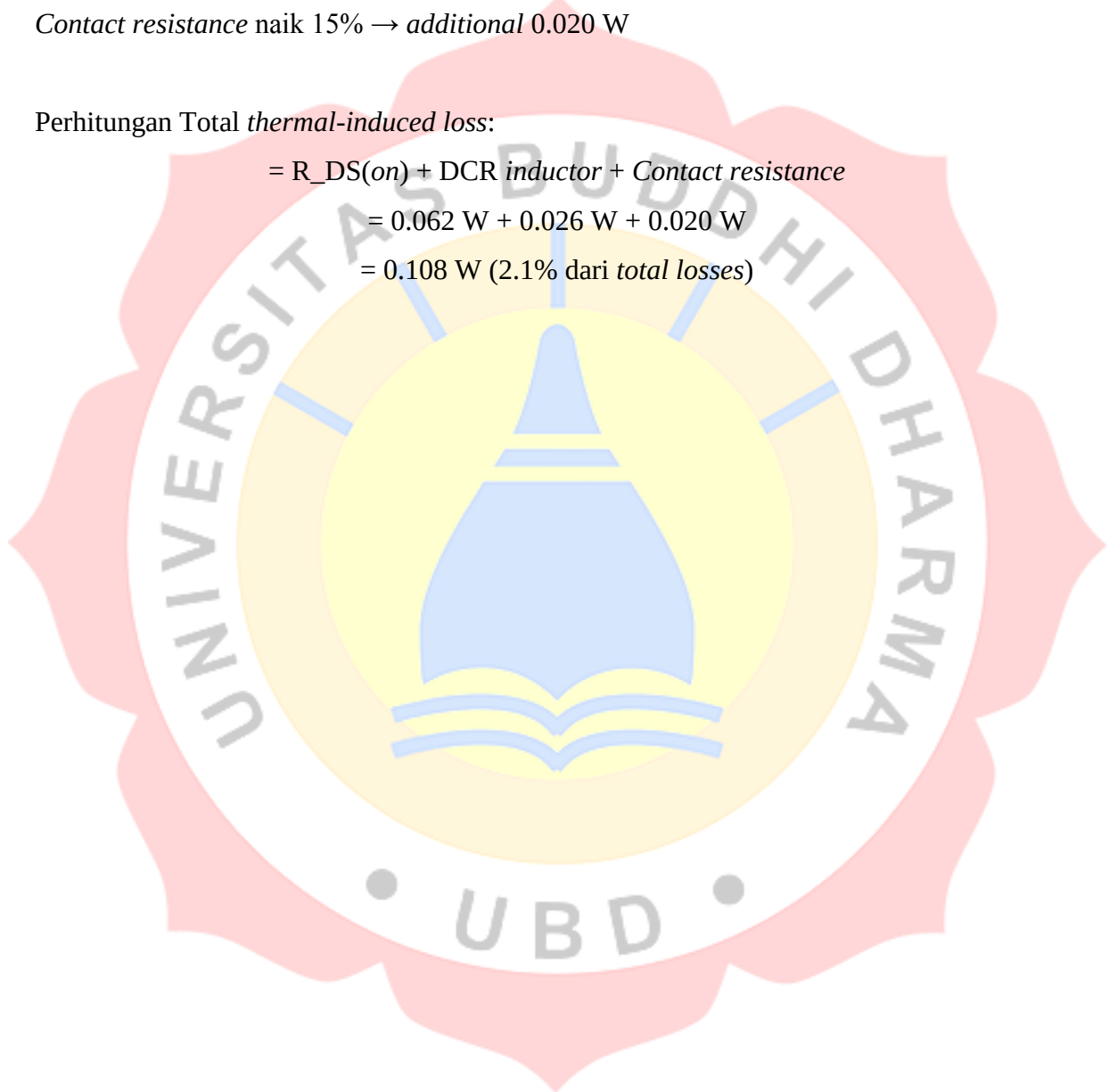
R_DS(on) naik 30% → *additional* 0.062 W

DCR inductor naik 20% → *additional* 0.026 W

Contact resistance naik 15% → *additional* 0.020 W

Perhitungan Total *thermal-induced loss*:

$$\begin{aligned} &= R_{DS(on)} + DCR \text{ inductor} + \text{Contact resistance} \\ &= 0.062 \text{ W} + 0.026 \text{ W} + 0.020 \text{ W} \\ &= 0.108 \text{ W (2.1\% dari total losses)} \end{aligned}$$



Lampiran 16. Perhitungan Komponen *Buck Converter*

Diketahui :

P_{in} : 430W
 V_{in} : 40,6V
 I_{in} : 10,59A
 $V_{out 1}$: 12V
 $V_{out 2}$: 24V
 η : 85%

Asumsi *Ripple V* : 2%

Asumsi *Ripple I* : 2%

Ditanya :

L : ?

C : ?

Jawab :

Pin Photovoltaic :

$$P_{in} = V_{in} \times I_{in}$$

$$P_{in} = 40,6 \text{ V} \times 10,59 \text{ A} = 429,95 \text{ W}$$

Pout dari efisiensi 85% :

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$P_{out} = \frac{\eta \times P_{in}}{100 \%}$$

$$P_{out} = \frac{85\% \times 429,95 \text{ W}}{100 \%} = 365,04 \text{ W}$$

Iout dari efisiensi 85% untuk V_{out} 12 V :

$$I_{out} = \frac{P_{out}}{V_{out}}$$

$$I_{out} = \frac{365,04 \text{ A}}{12 \text{ V}} = 30,42 \text{ A}$$

ΔIL untuk V_{out} 12 V :

$$\Delta IL = \text{Asumsi Ripple (\%)} \times I_{out}$$

$$\Delta IL = 2\% \times 30,42 \text{ A} = 0,608 \text{ A}$$

L untuk V_{out} 12 V :

$$L = \frac{V_{out} \times (V_{in} - V_{out})}{f \times V_{in} \times \Delta IL}$$

$$L = \frac{12 \text{ V} \times (40,6 \text{ V} - 12 \text{ V})}{10.000 \text{ Hz} \times 40,6 \text{ V} \times 0,608}$$

$$L = \frac{343,2}{246.848} \text{ H} = 0,001390 \text{ H} = 1,39 \text{ mH}$$

ΔVC untuk V_{out} 12 V :

$$\Delta VC = \text{Asumsi Ripple (\%)} \times V_{out}$$

$$\Delta VC = 2\% \times 12 \text{ V} = 0,24 \text{ V}$$

Duty Cycle untuk V_{out} 12 V :

$$V_{out} = D \times V_{in}$$

$$12 \text{ V} = D \times 40,6 \text{ V}$$

$$\frac{12 \text{ V}}{40,6 \text{ V}} = D = 0,2956$$

Kapasitor untuk V_{out} 12 V :

$$C = \frac{V_{in} \times D \times (1 - D)}{8 \times L \times f^2 \times \Delta V_c}$$

$$C = \frac{40,6 \text{ V} \times 0,2956 \times (1 - 0,2956)}{8 \times 1,39 \text{ mH} \times 10.000^2 \times 0,24 \text{ V}}$$

$$C = \frac{8,453}{266.880.000} = 31,7 \mu\text{F}$$

I_{out} dari efisiensi 85% untuk V_{out} 24V :

$$I_{out} = \frac{P_{out}}{V_{out}}$$

$$I_{out} = \frac{365,04 \text{ A}}{24 \text{ V}} = 15,21 \text{ A}$$

ΔIL untuk V_{out} 24 V :

$$\Delta IL = \text{Asumsi Ripple } (\%) \times I_{out}$$

$$\Delta IL = 2\% \times 15,21 \text{ A} = 0,304 \text{ A}$$

L untuk V_{out} 24 V :

$$L = \frac{V_{out} \times (V_{in} - V_{out})}{f \times V_{in} \times \Delta IL}$$

$$L = \frac{24 \text{ V} \times (40,6 \text{ V} - 24 \text{ V})}{10.000 \text{ Hz} \times 40,6 \text{ V} \times 0,304}$$

$$L = \frac{398,4}{123.424} = 0,003227 \text{ H} = 3,22 \text{ mH}$$

ΔVC untuk V_{out} 24 V :

$$\Delta VC = \text{Asumsi Ripple } (\%) \times V_{out}$$

$$\Delta VC = 2\% \times 24 \text{ V} = 0,48 \text{ V}$$

Duty Cycle untuk V_{out} 24 V :

$$V_{out} = D \times V_{in}$$

$$24 \text{ V} = D \times 40,6 \text{ V}$$

$$\frac{24 \text{ V}}{40,6 \text{ V}} = D = 0,5911$$

Kapasitor untuk V_{out} 24 V :

$$C = \frac{V_{in} \times D \times (1 - D)}{8 \times L \times f^2 \times \Delta V_c}$$

$$C = \frac{40,6 \text{ V} \times 0,5911 \times (1 - 0,5911)}{8 \times 3,22 \text{ mH} \times 10.000^2 \times 0,48 \text{ V}}$$

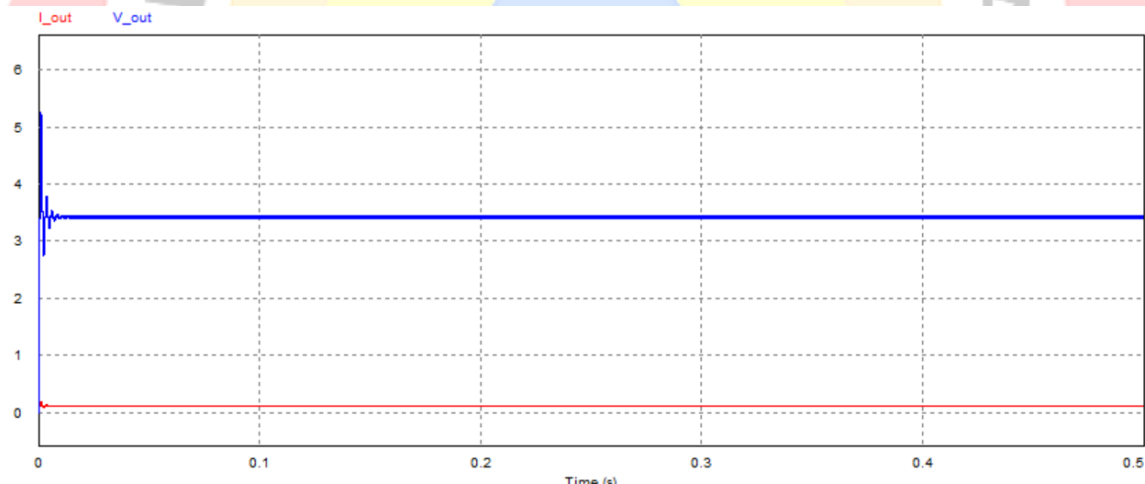
$$C = \frac{8,453}{1.236.480.000} = 7,9 \mu\text{F}$$

Nilai Induktor (L) yang dibutuhkan untuk tegangan keluaran 12 V *duty cycle* 0,2956 adalah 1,39 mH dan untuk tegangan 24 V *duty cycle* 0,5911 adalah 3,22 mH. Sehingga diperlukan nilai Induktor lebih tinggi untuk menjaga kinerja agar dapat mencapai hingga *duty cycle* lebih tinggi hingga 90% serta antisipasi akan eror yang mungkin terjadi karena panas maka digunakan induktor yang lebih tinggi senilai 4,5 mH.

Berdasarkan perhitungan teoritis *buck converter*, nilai kapasitor minimum yang dibutuhkan untuk meredam *ripple switching* pada frekuensi 10 kHz adalah sebesar 31,7 μF . Nilai ini secara teori telah memenuhi kriteria peredaman *ripple* pada kondisi ideal dengan sumber tegangan yang stabil. Namun, pada implementasinya sistem ini menggunakan panel surya sebagai sumber energi, yang memiliki karakteristik tegangan dan arus yang fluktuatif akibat perubahan intensitas cahaya dan kondisi beban.

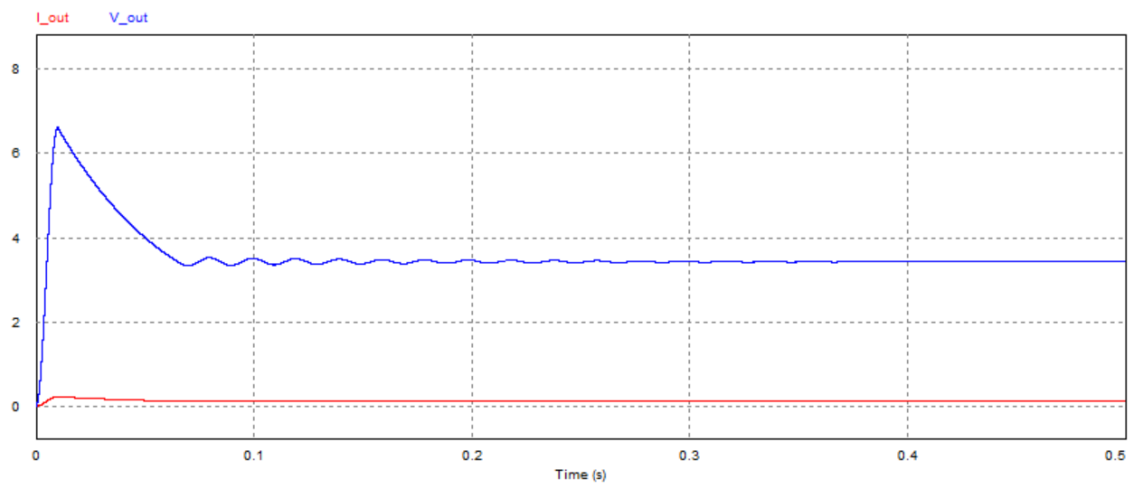
Fluktuasi tersebut dapat meningkatkan *ripple* arus dan tegangan pada sisi keluaran, terlebih dengan mempertimbangkan adanya rugi-rugi non-ideal seperti *Equivalent Series Resistance* (ESR) pada komponen. Oleh karena itu, untuk meningkatkan kualitas daya dan kestabilan tegangan keluaran, digunakan filter CLC yang bernilai lebih tinggi yakni 1000 μF dan 2200 μF dari nilai minimum sehingga memiliki kemampuan peredaman *ripple* lebih baik dibandingkan filter kapasitor tunggal.

Dapat dibuktikan dari hasil simulasi berikut ini, Dengan menggunakan filter LC 31,7 μF didapat gelombang sangat besar berosilasi di detik-detik awal kemudian lebih lama stabil bahkan akan terus berosilasi hingga di detik 0,5 dan seterusnya menunjukkan sistem belum mampu meredam riak seperti gambar berikut dibawah ini,

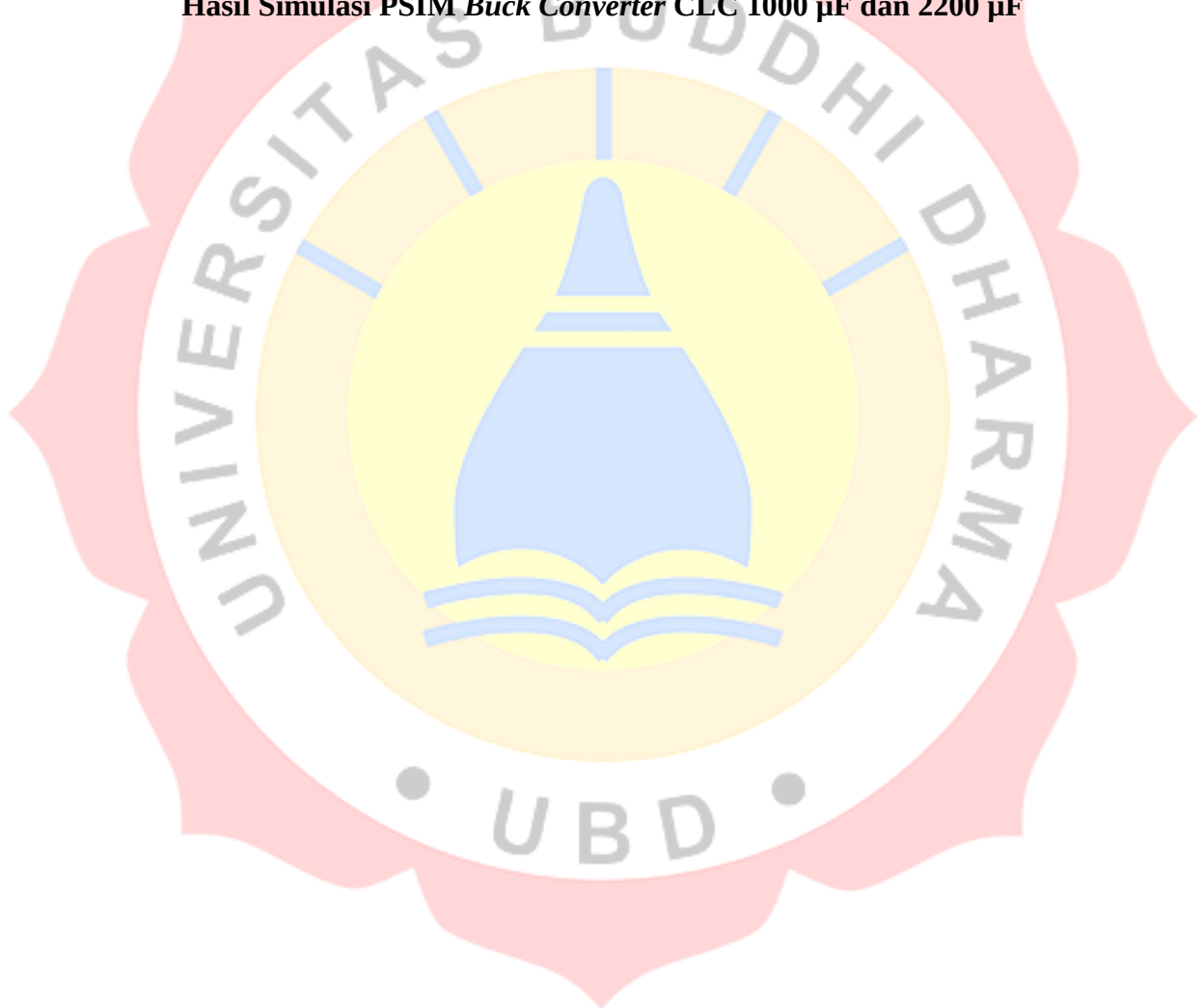


Hasil Simulasi PSIM *Buck Converter* LC 31,7 μF

Berbeda dengan menggunakan filter CLC, dengan nilai 1000 μF dan 2200 μF dari rangkaian membuat sistem lebih cepat stabil, riak lebih cepat diredam di detik ke 0,4.



Hasil Simulasi PSIM *Buck Converter* CLC 1000 μ F dan 2200 μ F



DAFTAR RIWAYAT HIDUP



A. DATA PRIBADI

NIM : 202208000006
Nama Lengkap : Meldo
Tempat/Tanggal Lahir : Palembang, 07 Mei 1998
Jenis Kelamin : Laki-Laki
IPK Terakhir : 3.53

Tangerang, 28 Januari 2026

Meldo
202208000006