Laboratory Manual

EEE319: SMART GRID & ELECTRIC VEHICLE LABORATORY

VII Semester

B. Tech. Electrical & Electronics Engineering (SG & EV)

July 2025

School of Electrical & Electronics Engineering
SASTRA Deemed University
Thanjavur, Tamil Nadu, India

SASTRA

ENGINEERING · MANAGEMENT · LAW · SCIENCES · HUMANITIES · EDUCATION

DEEMED TO BE UNIVERSITY

(U/S 3 of the UGC Act,1956)

THINK MERIT | THINK TRANSPARENCY | THINK SASTRA

LABORATORY RECORD NOTEBOOK

<u>BONAFIDE CERTIFICATE</u>

Certified that this is the bona-fide record of work done by Mr./Ms.____

with **Register No.** _________________________ during his / her **VII** semester in the **EEE319: SMART GRID & ELECTRIC VEHICLE LABORATORY** during the academic year 2025-2026.

Staff In-charge

Submitted for the University examination held on _________

Examiner – I **Examiner – II**

TABLE OF CONTENTS

Expt. No.	Date	Name of the Experiment	Page No.	Marks	Signature
11.					
12.					
			Average marks		

L	T	P	C
0	0	2	1

Course Code: EEE319
Semester : VII

SMART GRID & ELECTRIC VEHICLE LABORATORY

COURSE OBJECTIVE

This course enables the learners to

1. Analyze the grid integration issues of renewable energy sources.
2. Design the control strategies for the integrated operation of renewable energy sources
3. Analyze the power quality issues for various mode of operations
4. Conduct laboratory test to develop battery models and use it for parameter estimation
5. Analyze electric vehicle models for Indian driving conditions

LIST OF EXPERIMENTS

1) I-V and P-V characteristics of solar panel under normal and partial shading conditions
2) Performance analysis of solar and battery energy storage-based DC microgrid operation in standalone mode
3) Operation of solar and battery energy storage-based DC microgrid in grid connected mode
4) Performance analysis of DFIG based wind source and battery energy storage-based DC microgrid operation in standalone mode
5) Operation of DFIG based wind energy source in standalone mode and grid connected mode
6) Hybrid operation of solar, DFIG based wind and battery energy storage-based DC microgrid in standalone mode
7) Integration of solar, DFIG based wind and battery energy storage-based DC microgrid in grid connected mode of operation
8) Power quality improvement in DC microgrid using STATCOM controller
9) Battery Balancing and parameter estimation for Li-ion batteries
10) Thermal modelling of Li-ion batteries
11) Development of an enhanced self-correcting model of Li-ion battery and determination of its coulombic efficiency
12) Modelling and analysis of a hybrid electric vehicle drivetrain with modified Indian driving cycle
13) Development of supervisory control algorithms for battery management systems
14) Analysis of state of charge estimation algorithm using the extended Kalman Filter and Unscented Kalman Filter

OPEN ENDED EXPERIMENTS

1. Development and Implementation of various MPPT algorithms for solar charger
2. Development of control algorithms for STATCOM
3. Development of various control strategies for power converters through FPGA Processor
4. Generation of firing pulses through dSPACE for various power converters
5. Development of energy management strategies for chargers and electric vehicle powertrain

LABORATORY LEARNING OUTCOMES

Upon successful completion of each experiment, the learner will be able to:

- Analyze the operational characteristics of wind, solar based renewable energy sources, battery energy storage and its operation in standalone and grid integration mode
- Develop equivalent circuits for Li-ion battery and use them for parameter estimation
- Perform power quality studies on EV chargers

Expt. No: 1

Date :

I-V and P-V Characteristics of Solar Panel Under Normal and Partial Shading Conditions

Aim:

To study the I-V and P-V characteristics of the solar panel under varying illuminated condition.

Theory:

Solar cell is the basic unit of solar energy generation system where electrical energy is extracted directly from light energy without any intermediate process. The working of a solar cell solely depends upon its photovoltaic effect, hence a solar cell also known as photovoltaic cell. A solar cell is basically a semiconductor p-n junction device. It is formed by joining p- type (high concentration of hole or deficiency of electron) and n-type (high concentration of electron) semiconductor material. at the junction excess electrons from n-type try to diffuse to p-side and vice-versa. Movement of electrons to the p-side exposes positive ion cores in n side, while movement of holes to the n-side exposes negative ion cores in the p-side. This results in an electric field at the junction and forming the depletion region.

When sunlight falls on the solar cell, photons with energy greater than band gap of the semiconductor are absorbed by the cell and generate electron-hole (e-h) pair. These e-h pairs migrate respectively to n- and p- side of the PN junction due to electrostatic force of the field across the junction. In this way a potential difference is established between two sides of the cell. Typically, a solar or photovoltaic cell has negative front contact and positive back contact. A semiconductor p-n junction is in the middle of these two contacts like a battery. If these two sides are connected by an external circuit, current will start flowing from positive to negative terminal of the solar cell. This is basic working principle of a solar cell. For silicon, the band gap at room temperature is E_g = 1.1 eV and the diffusion potential is UD = 0.5 to 0.7 V.

The solar cell VI characteristics is Curve is the Superposition of the VI curves of the solar cell diode is absence (dark) and in presence of light. Illuminating a cell add to the normal dark current in the diode so that the diode law becomes:

$$I=I_0\left[\exp\left(\frac{qV}{nKT}\right)-1\right]-I_L$$

where,

I_0 = "dark saturation current" or diode leakage current in absence of light

q = electronic charge

V = applied voltage across the terminals of the diode

n = ideality factor

k = Boltzmann's constant

T = temperature

I_L= light generated current.

A typical circuit for measuring V-I characteristics is shown in figure 1. From these characteristic various parameters of the solar cell can be determined, such as: solar open-circuit voltage (VOC), the fill factor (FF) and the efficiency. The rating of a solar panel depends on these parameters.

The short-circuit current is the current through the solar cell when the voltage across the solar cell is zero (i.e., when the solar cell is of light-generated carriers. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light circuit current is the largest current which may be drawn from the solar cell.

The open-circuit voltage, VOC occurs is the maximum voltage available from a solar cell, and this occurs at zero current. The open circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light

The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. Graphically, the FF is a measure of the "square-ness" of the solar cell and is also the area of the largest rectangle which will fit in the I-V curve as shown in Figure 3.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun. In addition to reflecting the performance of the solar cell itself, the efficiency depends on the spectrum and intensity of the incident sunlight and the temperature of the solar cell.

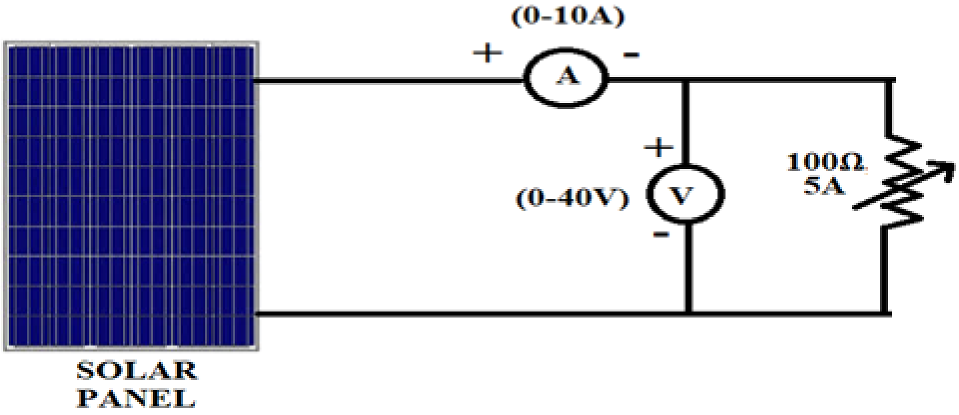


Fig.1 Circuit for I-V Characteristics of Solar Cell

Apparatus Required

1. Solar Module
2. Load Modules (Rheostat)
3. Demonstration Ammeter / Voltmeter
4. Connecting wires
5. Cardboard

Precautions

1. Connections should be made as per the connection diagram.
2. Set the Load Rheostat at the minimum.
3. All connections should be tight.
4. Do not touch live conductors.
5. Reading should be taken carefully.

Procedure

I. <u>Normal Condition</u>

1. Connect the solar cell to voltmeter and ammeter as shown in Fig.1.
2. Connect the load rheostat with solar modules.
3. Switch on the lamp and adjust further so that maximum area of the solar cell can be illuminated.
4. Vary the load rheostat and record the values of current and voltage across the solar cell.
5. Plot the I-V curve and estimate Short Circuit Current (Isc), Open Circuit Voltage (Voc).
6. Plot the Power Vs Voltage curve (P-V) and mark the maximum power on the PV curve.

Partially Shaded Condition

1. Place the solar module on a solid base and cover it completely with a piece of black cardboard.
2. Connect the solar cell to voltmeter and ammeter as shown in Fig.1.
3. Connect the load rheostat with its solar modules.
4. Switch on the lamp so that maximum area of the solar cell can be illuminated.
5. Vary the load rheostat and record the values of current and voltage across the solar cell
6. Plot I-V curve and estimate short circuit current, no load voltage.
7. Determine the maximum power output at the turning points on the curves (marked by a circle in Fig.3).
8. Plot the power Vs voltage curve (P-V) and mark the maximum power on the PV curve

Model Graph:

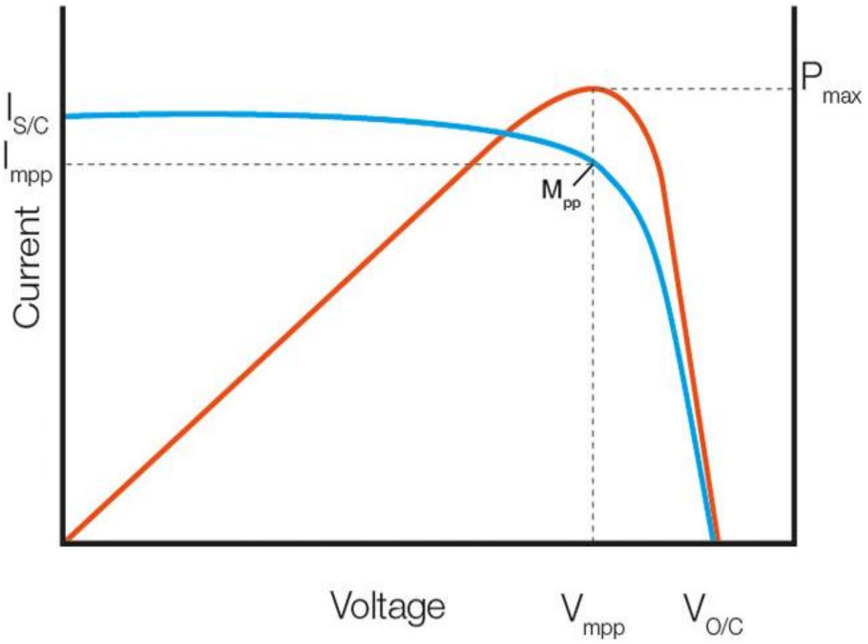


Fig. 2 A typical I-V curve and P-V curve of a solar cell

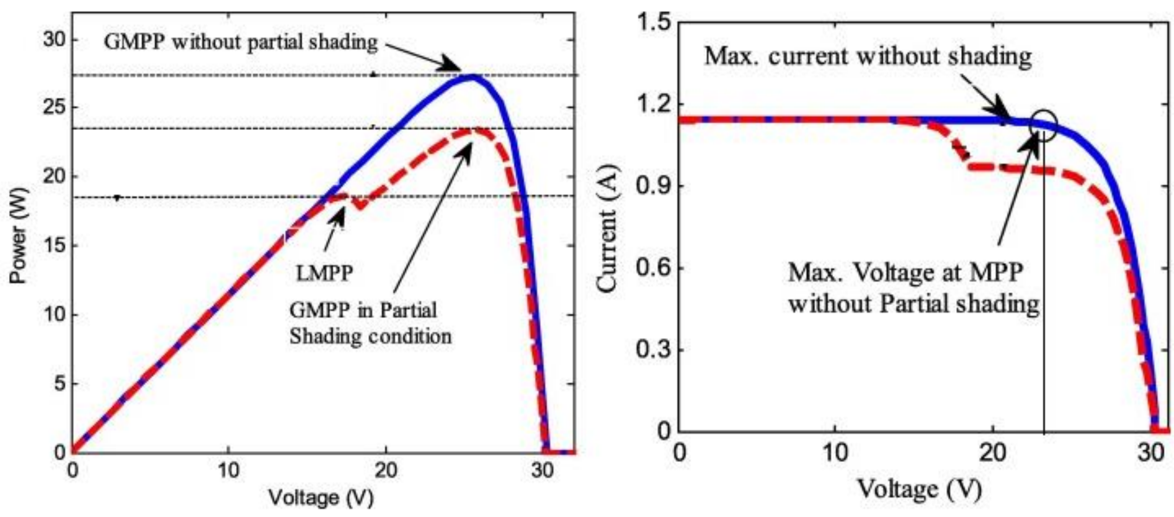


Fig. 3: A typical P -V curve and I-V curve with / without shading condition

Tabulation:

	Normal Condition		**Partially Shaded Condition**	
S. No	**Voltage (V)**	**Current (A)**	**Voltage (V)**	**Current (A)**

Result

Thus, the V-I and P-V characteristics of the chosen solar panel have been obtained under normal and partially shaded condition.

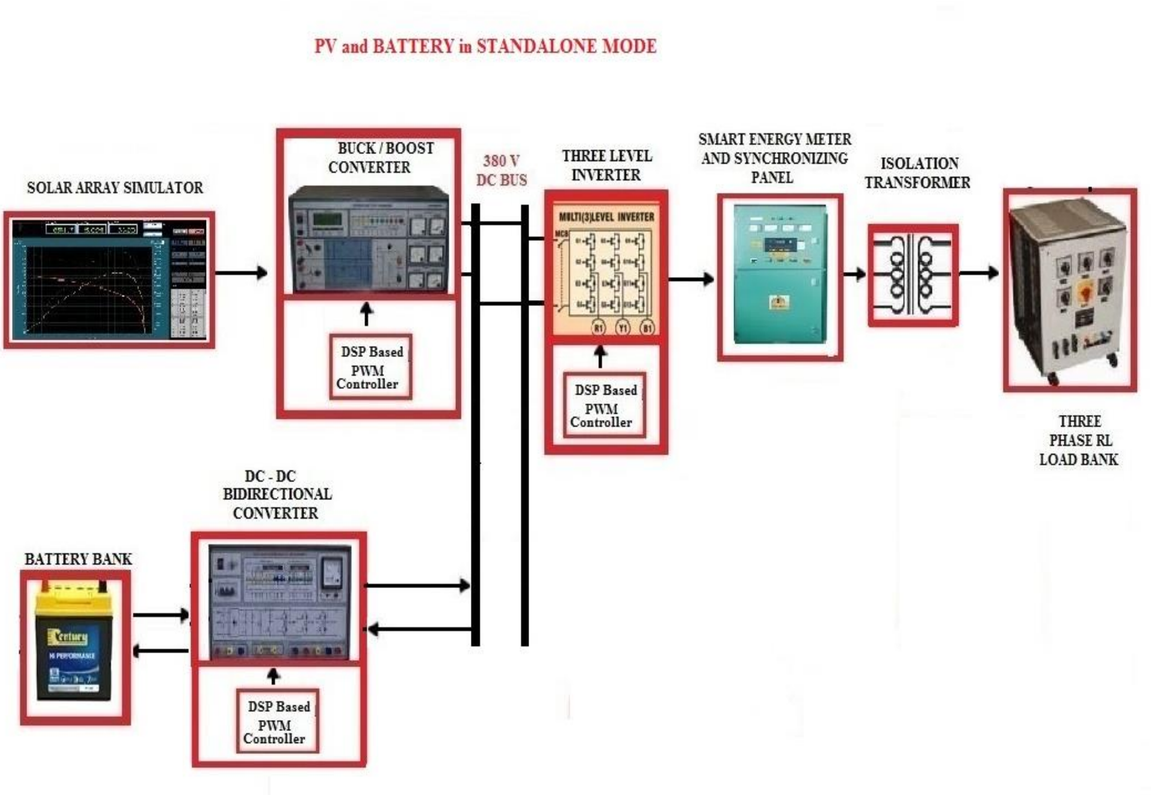
Expt. No : 2
Date   :

Performance analysis of solar and battery energy storage-based DC microgrid operation in standalone mode

Aim:

To study the coordinated operation of PV and battery energy storage to supply the AC load in isolated mode of operation

Schematic diagram:



Operating Procedure Steps:

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a PV and battery connected micro-grid, first we need to start the bidirectional converter (battery). To start the bidirectional converter (battery) panel, read the following steps carefully,

- Before turning on the power supply, check the connections carefully, if everything is in normal condition **TURN ON the control supply** (push button) for the bidirectional converter (battery) panel.

- After turning on the control supply, keypad display will glow; this means control supply for the converter is ON condition. If not, check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON the DC bus** (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage, check the fuses
- Before starting the converter, we need to set the DC bus voltage reference. For that, go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. Now set the DC bus volt ref value as per operation.
- Now to start the converter, press **FWD/REV** button. We can see the output voltage (Vdc) as per the set value (DC bus volt Ref). Use the same button to stop the converter.

Now the battery bank is connected to the **DC bus**, we can Charge / Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR

To operate the solar array simulator, follow the steps mentioned below:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel. If not, check the power supply.
- Solar array simulator consists of FEC and DC-DC Converter. TURN ON the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.
- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.

- In both cases, keypad / HMI the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter, press **FWD/REV** button. Use the same button to stop the converter
- Now the solar array simulator is connected to buck / boost converter

3. BUCK / BOOST CONVERTER (SOLAR)

buck / boost converter input is connected to the solar array emulator and output terminals connected to the DC bus.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to TURN ON the DC bus. Observe the DC bus voltage in keypad display.
- Choose the max MPPT ref by pressing **→ PV MPPT para → MAX MPPT Ref**
- To **START** the converter press **FWD/REV** button. Use the same button to stop it.
- Now the buck / boost converter is connected to the DC bus.

Now the battery is already connected to the DC bus and buck / boost converter also connected to the DC bus. Based on the PV parameters values, current will inject to the battery bank via buck / boost converter and bidirectional converter (Battery). We can see the battery charging in battery panel **CC** in keypad and respective current value.

4.THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- We can operate three level inverter in two modes **GRID/STANDALONE** mode

<u>Stand-alone mode:</u>

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220/415V).
- **<u>Make sure close the all MCB's in Synchronizing panel.</u>**
- To select in Stand-alone mode, go to **→Mode selection→enter→operation mode→enter→change it to Stand-alone→esc→save** it.
- Choose the operation and parameters accordingly.
- Press the DC bus on button we can observe the DC bus voltage in keypad display. And to **start** the inverter press **Start**/**Stop** button.

- To see the inverter **output voltage** in display, **press enter** in main page.
- To load the Three level inverter, TURN ON the MCB2 in STATCOM panel. Now it is connected to the load, vary the load accordingly.

Mode 1: PV Source : Used to charge the battery:

Sl. No	PV Module Profile	Buck / Boost Converter	Battery
		Buck Current Ref.(A)	**Charging Current (A)**
	Voc:		
	Isc:		
	Operating irradiance (W/m^2):		
	Operating Temperature:		

Mode 2 : PV and battery sources are used to supplying AC load:

Sl.No	PV Module Profile	Buck / Boost Converter	Battery	Load (A)	AC Load Current (A)		
		Buck Current Ref.(A)	**Discharging Current (A)**		**R**	**Y**	**B**
	Voc:						
	Isc:						
	Operating irradiance (W/m^2):						
	Operating Temp:						

Mode 3: PV source: Used to charge the battery and supplying AC load:

Sl. No	PV Module Profile	Buck / Boost Converter	Battery	Load (A)	AC Load Current (A)		
		Buck Current Ref.(A)	Charging Current (A)		R	Y	B
	Voc:						
	Isc:						
	Operating irradiance (W/m^2):						
	Operating Temp:						

Mode 4: Battery alone is used to supply AC load:

Sl. No	AC Load (A)	Battery Discharging Current (A)

Mode 5: Battery alone is used to supply DC load:

Sl. No	DC Load (Watts)	Battery Discharging Current (A)

Result:

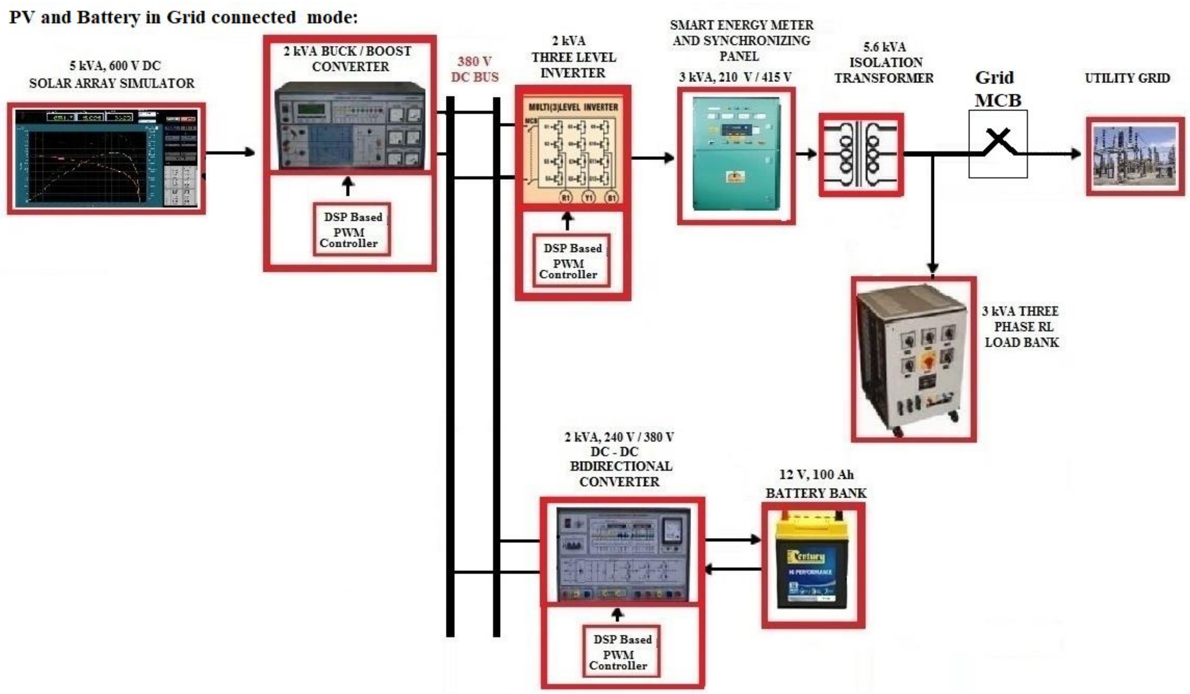
Expt. No : 3
Date :

Operation of solar and battery energy storage-based DC microgrid in grid connected mode

Aim:

To study the coordinated operation of PV and battery energy storage to inject power to the AC grid

Schematic diagram:



Operating Procedure Steps:

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a PV and battery connected micro-grid, first we need to start the bidirectional converter (battery). To start the bidirectional converter (battery) panel, read the following steps carefully,

- Before turning on the power supply, check the connections carefully, if everything is in normal condition **TURN ON the control supply** (push button) for the bidirectional converter (battery) panel.
- After turning on the control supply, keypad display will glow; this means control supply for the converter is ON condition. If not, check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON the DC bus** (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage, check the fuses
- Before starting the converter, we need to set the DC bus voltage reference. For that, go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. Now set the DC bus volt ref value as per operation.
- Now to start the converter, press **FWD/REV** button. We can see the output voltage (Vdc) as per the set value (DC bus volt Ref). Use the same button to stop the converter.

Now the battery bank is connected to the **DC bus**, we can Charge / Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR

To operate the solar array simulator, follow the steps mentioned below:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel. If not, check the power supply.
- Solar array simulator consists of FEC and DC-DC Converter. TURN ON the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.
- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.

- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.
- In both cases, keypad / HMI the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter, press **FWD/REV** button. Use the same button to stop the converter
- Now the solar array simulator is connected to buck / boost converter

3. BUCK / BOOST CONVERTER (SOLAR)

buck / boost converter input is connected to the solar array emulator and output terminals connected to the DC bus.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to TURN ON the DC bus. Observe the DC bus voltage in keypad display.
- Choose the max MPPT ref by pressing **→ PV MPPT para → MAX MPPT Ref**
- To **START** the converter press **FWD/REV** button. Use the same button to stop it.
- Now the buck / boost converter is connected to the DC bus.

Now the battery is already connected to the DC bus and buck / boost converter also connected to the DC bus. Based on the PV parameters values, current will inject to the battery bank via buck / boost converter and bidirectional converter (Battery). We can see the battery charging in battery panel **CC** in keypad and respective current value.

4.THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- We can operate three level inverter in **GRID** mode

GRID MODE:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220 / 415V).
- **Make sure close the all MCB's in Synchronizing panel**

- To select in Grid mode: go to →**Mode selection**→**enter**→**operation mode**→**enter**→**change it to grid mode**→**esc**→**save** it.

- In Grid mode, we have two options 1) take the power from the grid 2) Injecting power to the grid. If we select the **Master** mode, it'll **draw the power** from the grid based on reference value. If we select the **slave** mode, it'll **inject power** to the grid based on the reference value.

- The selection as follows
  Goto→**Mode selection**→**enter**→**parallel-mode**→**choose Master/Slave**.

- The grid current reference value can be increases/decreases as follows
  Go to →**Frequent modes**→**enter**→**Grid CUR Ref** INC/DEC

- Choose the operation and parameters accordingly.

- Press the DC bus on button we can observe the DC bus voltage in keypad display. And to **start** the inverter press **Start**/**Stop** button.

- To see the inverter **output voltage** in display, **press enter** in main page.

- In master mode i.e., The power can be drawn from the grid. The three-level inverter inject the power to the DC bus (330/380V) based upon the reference value (**Grid CUR Ref**). If only battery charger is connected to the DC bus(330/380V), we can observe the charging of battery (CC) in battery panel from the grid.

- In slave mode i.e., The power can be injected into the grid from microgrid sources. the three-level inverter draw the power from the DC bus(330/380V) based upon the reference value (**Grid CUR Ref**). If only battery charger is connected to the DC bus(330/380V) we can observe discharging of battery (DC) in battery panel to grid.

- **To load** the three-level inverter, **TURN ON** the **MCB2** in **STATCOM** panel. Now it is connected to the load, vary the load accordingly.

Mode 1: PV Source: Used to charging the battery and Injecting Power to GRID:

Sl. No	PV Module Profile	PV-Buck/ Boost Converter	Battery	Injected Grid Current (A)		
		Buck Current Ref. (A)	Charging Current (A)	R	Y	B
	Voc:					
	Isc:					
	Operating Irradiance (W/m^2):					
	Operating Temp:					

Mode 2 : PV + Battery: Used to supplying AC load+ Injecting power to GRID

Sl.No	PV Module Profile	PV-Buck / Boost Converter	Battery	Load	AC Load Current (A)			Injected Grid Current (A)		
		Buck Current Ref.(A)	Discharging Current (A)		R	Y	B	R	Y	B
	Voc:									
	Isc:									
	Operating Irradiance (W/m^2):									
	Operating Temp:									

Mode 3 : PV + Grid: Supplying AC load and Charging Battery

Sl.No	PV Module Profile	PV-Buck / Boost Converter	Battery	Load	Load Current			Current drawn from the Grid (A)		
		Buck Current Ref.(A)	Charging Current (A)		R	Y	B	R	Y	B
	Voc:									
	Isc:									
	Operating Irradiance (W/m^2):									
	Operating Temp:									

Mode 4: Battery as source to supplying AC load and injecting power to Grid

Sl.No	Battery Discharging Current (A)	Load	Load Current			Current Injected to Grid (A)		
			R	Y	B	R	Y	B

Sl.No	Battery Charging Current (A)	Load	Load Current			Current drawn from the Grid (A)		
			R	Y	B	R	Y	B

Mode 5: Grid as source to supplying AC load and charging the battery

Result:

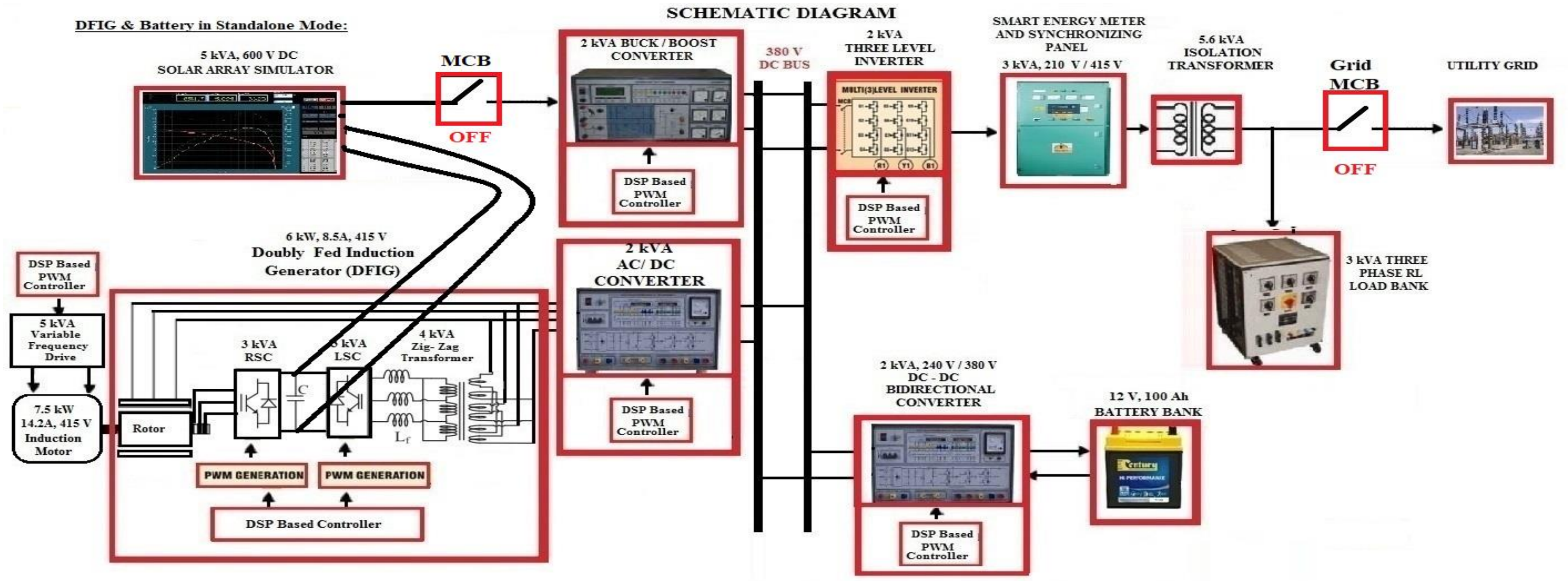
Expt. No : 4
Date :

Performance analysis of DFIG based wind source and battery energy storage-based DC microgrid operation in standalone mode

Aim:

To study the coordinated operation of DFIG based wind source and battery energy storage systems operated in standalone mode

Schematic diagram:



<u>Operating Procedure Steps:</u>

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a wind source based micro-grid, first we need to start the bidirectional converter (Battery). To start the bidirectional converter (battery) panel read the following steps carefully,

- Before turning on the power supply, check the connections carefully, if everything is in normal condition **TURN ON the control supply** (push button) for the bidirectional converter (Battery) panel.
- After turning on the control supply keypad display will glow, this means control supply for the converter is ON condition. If not check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON the DC bus** (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage check the fuses.
- Before starting the converter, we need to set the DC bus voltage reference, for that go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. Now set the DC bus volt ref value as per operation.
- Now to start the converter press **FWD/REV** button, we can see the output voltage (Vdc) as per the set value (DC bus volt Ref). use the same button to stop the converter.
- Now the battery bank is connected to the **DC bus**

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR O/P USED TO START DFIG

Steps to operate the solar array simulator.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Solar array simulator consists of FEC and DC-DC Converter. **TURN ON** the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.

- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.
- In both cases keypad / HMI, the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter press **FWD/REV** button. Use the same button to stop the converter.
- Now the solar array simulator output voltage (600 V) is connected across the DC link capacitor between RSC and LSC to boost its voltage up to 600V once the MCB inside the simulator is switched ON.

3. DFIG STARTING PROCEDURE

DFIG and VFD are coupled together as shown in diagram. DFIG can be operated standalone / GRID mode based on selection.

a) Variable Frequency Drive (VFD):

- **TURN ON** the blower fan MCB supply.
- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel. If not, check the power supply.
- Press the DC bus button to TURN ON the DC bus. Observe the DC bus voltage in keypad display
- Go to **Frequent modes→ enter→Frequency Ref→enter→set the value→save it**.
- Now to **START** the VFD press **Start /Stop** button, we can observe the machine will rotate as per the set frequency.
- We can observe the speed, voltage, current in keypad display.

STANDALONE MODE:

b) Rotor Side Inverter (RSC):

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel. If not, check the power supply.
- Before starting the RSC, we need to **pre-charge the DC bus of RSC and LSC**, For that we will precharge with the solar array emulator. Start the solar array emulator as usual and **TURN ONTHE MCB** provided in the **SOLAR ARRAY SIMULATOR** for Precharging of RSC and LSC.
- To operate the DFIG in standalone mode, set the operation mode in standalone mode **→OPERATION_MODE→ENTER→REGULATION_MODE→ENTER→ CHOOSE WRIM STAND CTRL→SAVE it**
- Now press the **DC bus ON button** we can observe the DC link voltage in keypad display. Then press **enter** in main page→**Go to** until **DC link voltage** appears→ here we can see the DC link voltage. If not check the fuses/fault conditions
- To **start** RSC, press **START/STOP button**. Here we can see the stator frequency, voltage, current of DFIG in keypad display. For e.g., if VFD is running at rated speed here we can see 50Hz, 402V. If not displayed, please check for the fuses/fault conditions.
- To check the **rotor voltage,** press enter in **main page**→ go to until **Rotor Voltage** appears→ we can see the rotor voltage.

c) Line Side Converter (LSC):

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- The pre-charging of LSC is already done because **RSC** and **LSC** DC side terminals are connected together.
- Press the DC bus on button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- DFIG stator voltage is already build-up and we can observe the DC bus voltage raised above the pre-charge level in LSC panel.
- Now **TURN OFF** the **MCB** provided in the **Solar array simulator** before starting the LSC.
- To **start** the LSC, press **Start/stop** button. Now we can see the VDC value in keypad display raised to set value which is **→Frequent modes→ enter→DC link volt ref**

- Now the DFIG is connected to AC/ DC converter via 415/210V transformer. AC/ DC converter further connected to MAIN DC BUS.

4) AC/ DC CONVERTER (DFIG):

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus ON button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- To start the AC/ DC converter, press Star/Stop button. Now AC/ DC converter is connected to DC bus
- We can inject the current to DC bus by varying **Active cur ref**
  →Frequent modes→enter→Active cur ref→enter to change value→esc/save
- We can observe **Power** is drawn from the **DFIG** by **increasing** the **active cur ref** value which we can **observe** in **RSC** panel main page.
- Extracted power from DFIG will be pumped to DC bus, where bidirectional converter (Battery) is connected already so **battery** starts to **charging** that we can **observe** in **bidirectional converter (Battery) panel**.

5) THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- We can operate three level inverter in **STANDALONE** mode

Stand-alone mode:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220/415V).
- <u>Make sure close the all MCB's in synchronizing panel.</u>
- To select in Stand-alone mode, go to **→Mode selection→enter→operation mode→enter→change it to Stand-alone→esc→save** it.
- Choose the operation and parameters accordingly.
- Press the DC bus ON button. We can observe the DC bus voltage in keypad display and to **start** the inverter, press **Start**/**Stop** button.
- To see the inverter **output voltage** in display, **press enter** in main page.

- To load the three-level inverter, **TURN ON** the **MCB2** in STATCOM panel. Now it is connected to the load, vary the AC load accordingly.

Mode 1: DFIG based Wind source used to charge the battery:

Sl.No	PV Module Profile	Wind-AC/DC Converter	Battery
		Active Current Ref.(A)	**Charging Current (A)**
	Voc:		
	Isc:		
	Operating Irradiance (W/m^2):		
	Operating Temp:		

Mode 2 : DFIG based Wind source used to charging the battery and supplying AC load:

Sl.No	Wind- AC/DC Converter	Battery	Load	Load Current		
	Active Current Ref.(A)	**Charging Current (A)**		**R**	**Y**	**B**

Mode 3: DFIG based Wind and Battery as source supplying AC load:

Sl.No	Wind- AC/DC Converter	Battery	Load	Load Current		
	Active Current Ref.(A)	Discharging Current (A)		R	Y	B

Result:

Expt. No : 5

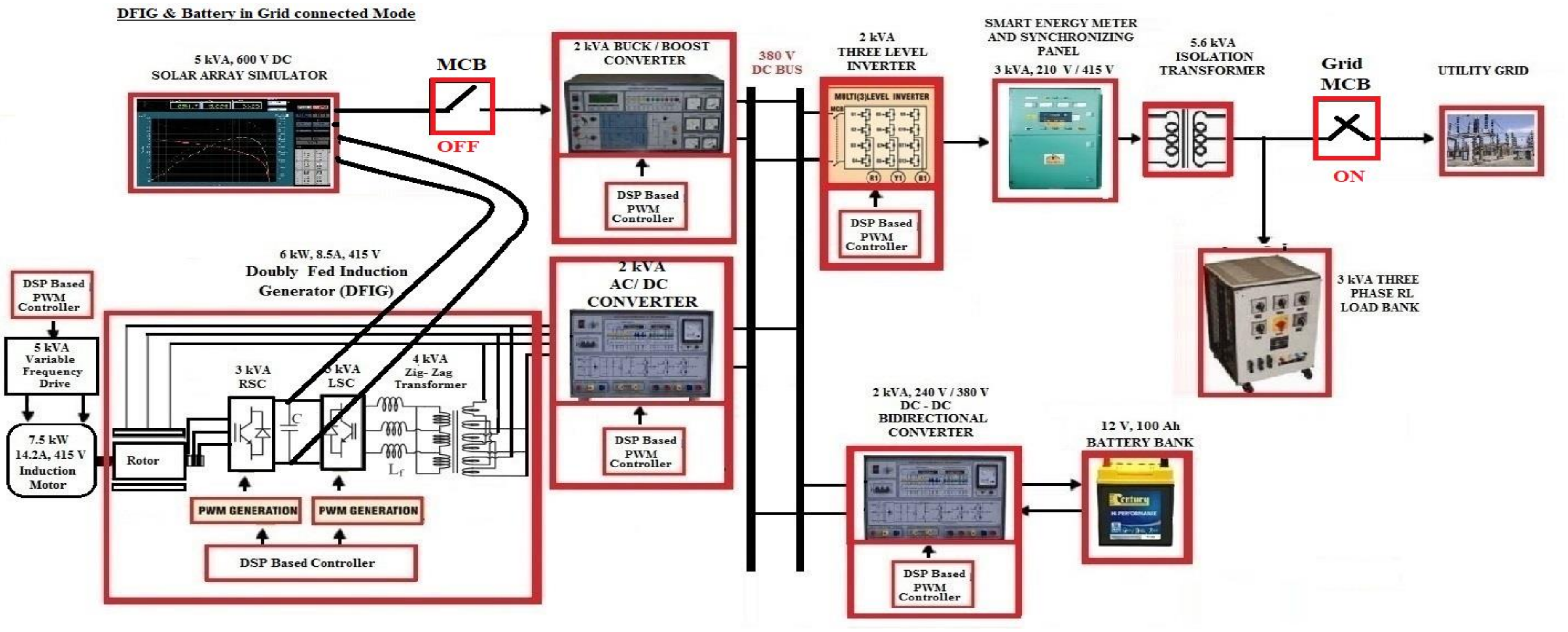
Date :

Operation of DFIG based wind energy source in standalone mode and grid connected mode

Aim:

To study the coordinated operation of DFIG based wind source and battery energy storage to inject power to the AC grid

Schematic diagram:



<u>Operating Procedure Steps</u>

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a micro-grid first, we need to start the bidirectional converter (Battery). To start the bidirectional Converter (Battery) panel, read the following steps carefully,

- Before turning on the power supply check the connections carefully, if everything is in normal condition **TURN ON** the control supply (push button) for the bidirectional converter (Battery) panel.
- After turning on the control supply keypad display will glow, this means control supply for the converter is on condition. If not check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON** the DC bus (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage check the fuses
- Before starting the converter, we need to set the DC bus voltage reference, for that go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. now set the DC bus volt ref value as per operation.
- Now to start the converter press **FWD/REV** button, we can see the output voltage (Vdc) as per the set value (DC bus volt Ref). use the same button to stop the converter.
- Now the battery bank is connected to the **DC bus**, we can Charge / Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR O/P USED TO START DFIG

Steps to operate the solar array simulator.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Solar array simulator consists of FEC and DC-DC Converter. **TURN ON** the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.

- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.
- In both cases keypad / HMI, the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter press **FWD/REV** button. Use the same button to stop the converter.
- Now the solar array simulator output voltage (600 V) is connected across the DC link capacitor between RSC and LSC to boost its voltage up to 600V once the MCB inside the simulator is switched ON.

3. DFIG STARTING PROCEDURE

DFIG and VFD are coupled together as shown in diagram. DFIG can be operated standalone / GRID mode based on selection.

a) Variable Frequency Drive (VFD):

- **TURN ON** the blower fan MCB supply.
- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display
- Go to **Frequent modes→ enter→Frequency Ref→enter→set the value→save it**.
- Now to **START** the VFD press **Start/stop** button, we can observe the machine will rotate as per the set frequency.
- We can observe the speed, voltage, current in keypad display.

STANDALONE MODE:

b) Rotor Side Converter (RSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- Before starting the RSC, we need to **pre-charge the DC bus of RSC** and **LSC**, For that we will pre-charge with the solar array emulator. Start the solar array emulator as usual and **TURN ON the MCB** provided in the **SOLAR ARRAY SIMULATOR** for Pre-charging of RSC and FEC.
- To operate the DFIG in standalone mode set the operation mode in standalone mode **→OPERATION_MODE→ENTER→REGULATION_MODE→ENTER→CHO-OSE WRIM STAND CTRL→SAVE it**
- Now press the **DC bus on button** we can observe the DC link voltage in keypad display as follows press **enter** in main page→**Go to** until **DC link voltage** appears→ here we can see the DC link voltage. If not check the fuses/fault conditions
- To **start** RSC press, **START/STOP button**. Here we can see the stator frequency, voltage, current of DFIG in keypad display. For e.g., if VFD is running at rated speed here we can see 50Hz,402V. If not displayed, please check for the fuses/fault conditions.
- To check the **rotor voltage** press, enter in **main page**→ go to until **Rotor voltage** appears→ here we can see the rotor voltage.

c) Line Side Converter (LSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- The pre-charging of LSC is already done because **RSC** and **LSC DC side** terminals are connected together.
- Press the DC bus on button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- DFIG stator voltage is already build-up and we can observe the DC bus voltage raised above the pre-charge level in LSC panel.
- Now **TURN OFF** the **MCB** provided in the **Solar array simulator** before starting the LSC.

- To **start** the LSC, press **Start/stop** button. Now we can see the VDC value in keypad display raised to set value which is **→Frequent modes→ enter→DC link volt ref**

Now this DFIG is connected to AC/ DC converter via 415/210V transformer. AC/ DC converter further connected to MAIN DC BUS.

5) AC/ DC CONVERTER (DFIG):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not, check the power supply.
- Press the DC bus ON button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- To start the AC/ DC converter, press Star/Stop button. Now AC/ DC converter is connected to DC bus
- We can inject the current to DC bus by varying **Active cur ref** **→Frequent modes→enter→Active cur ref→enter to change value**→esc/save
- We can observe power is drawn from the **DFIG** by **increasing** the **active cur ref** value which we can **observe** in **RSC** panel main page.
- Extracted power from DFIG will be pumped to DC bus, where bidirectional converter (Battery) is connected already so **battery** starts to **charging** that we can **observe** in **Bidirectional Converter (Battery) panel**.

6) THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- In this we can operate three level inverter in two modes GRID/STANDALONE mode

Grid mode:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220 / 415V).
- **Make sure close the all MCB's in Synchronizing panel**
- To select in Grid mode, go to **→Mode selection→enter→operation mode→enter→change it to grid mode→esc→save** it.
- In this Grid mode we have two options one is take the power from the grid other one is injecting power to the grid. If we select the **Master** mode, it'll **draw the power** from

the grid based on reference value. If we select the **slave** mode, it'll **inject power** to the grid based on the reference value.

- The selection as follows
  Goto→Mode selection→enter→parallel-mode→choose Master/Slave.

- The grid current reference value can be increases/decreases as follows
  Go to →Frequent modes→enter→Grid CUR Ref INC/DEC

- Choose the operation and parameters accordingly.

- Press the DC bus on button we can observe the DC bus voltage in keypad display and to **start** the inverter press **Start**/**Stop** button.

- To see the inverter **output voltage** in display, **press enter** in main page.

- If we are in master mode i.e., Draw the power from the grid the three-level inverter inject the power to the DC bus (330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battey) is connected to the DC bus(330/380V) we can observe the charging of battery (CC) in battery panel.

- If we are in slave mode i.e., inject the power to grid the three-level inverter draw the power from the DC bus(330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battery) is connected to the DC bus(330/380V) we can observe discharging of battery (DC) in battery panel.

- **To load** the three-level inverter, **TURN ON** the **MCB2** in **STATCOM** panel. Now it is connected to the load, vary the AC load accordingly.

Mode 1: DFIG based Wind source: Used to charging the battery and Injecting power to GRID:

Sl. No	Wind-AC/DC Converter	Battery	Injected Grid Current (A)		
	Active Current Ref. (%)	Charging Current (A)	R	Y	B

Mode 2 : Wind + Battery: Used to supplying AC load+ Injecting power to GRID

Sl.No	Wind-AC/ DC Converter	Battery	Load	AC Load Current (A)			Injected Grid Current (A)		
	Active Current Ref. (%)	Discharging Current (A)		R	Y	B	R	Y	B

Mode 3 : Wind + Grid: Supplying AC load and Charging Battery

Sl.No	Wind- AC/ DC Converter	Battery	Load	Load Current			Current drawn from the Grid (A)		
	Active Current Ref. (%)	Charging Current (A)		R	Y	B	R	Y	B

Mode 4: Battery as source to supplying AC load and injecting power to Grid

Sl.No	Battery Discharging Current (A)	Load	Load Current			Current Injected to Grid (A)		
			R	Y	B	R	Y	B

Mode 5: Grid as source to supplying AC load and charging the battery

Sl.No	Battery Charging Current (A)	Load	Load Current			Current drawn from the Grid (A)		
			R	Y	B	R	Y	B

Result:

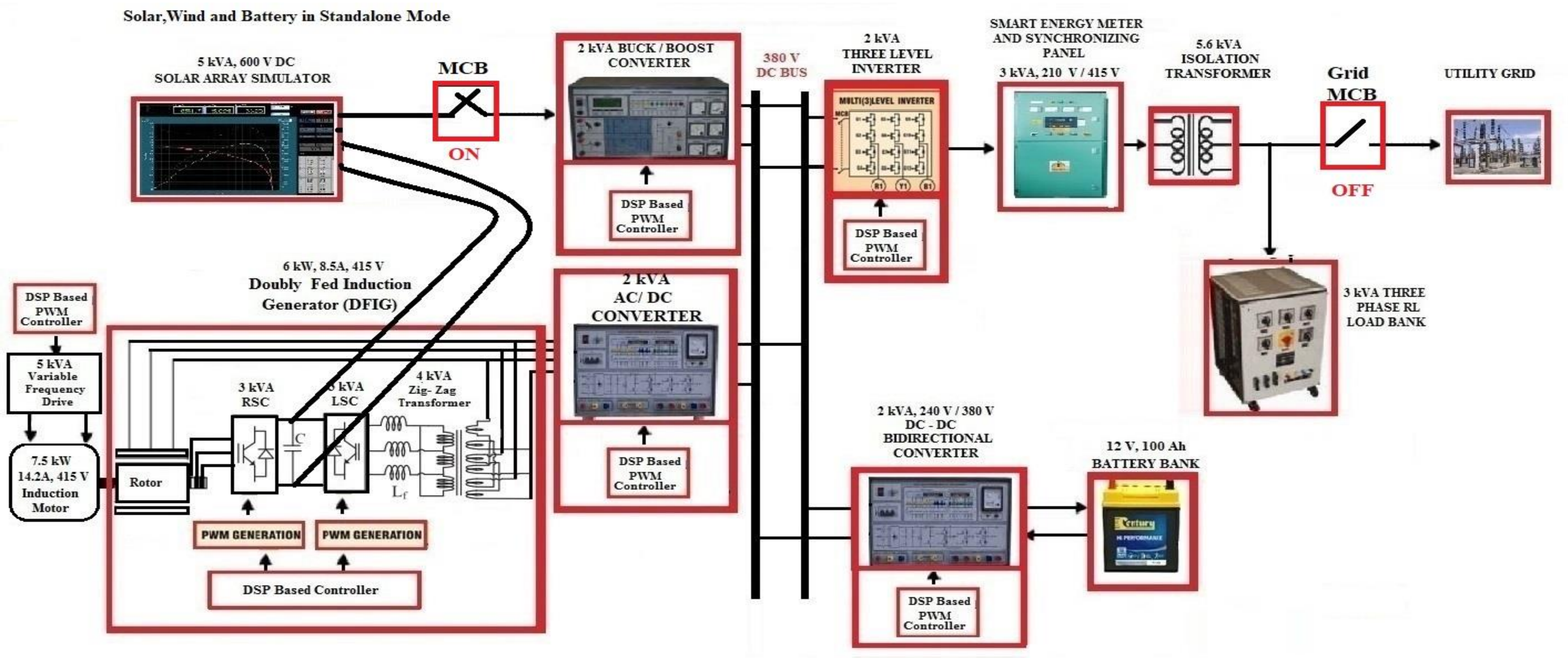
Expt. No : 6
Date :

Hybrid operation of solar, DFIG based wind and battery energy storage-based DC microgrid in standalone mode

Aim:

To study the coordinated operation of solar, DFIG based wind source and battery energy storage systems operated in standalone mode

Schematic diagram:



Operating Procedure Steps

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a micro-grid first, we need to start the bidirectional converter (Battery). To start the bidirectional Converter (Battery) panel, read the following steps carefully,

- Before turning on the power supply check the connections carefully, if everything is in normal condition **TURN ON** the control supply (push button) for the bidirectional converter (Battery) panel.
- After turning on the control supply keypad display will glow, this means control supply for the converter is on condition. If not check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON** the DC bus (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage check the fuses
- Before starting the converter, we need to set the DC bus voltage reference, for that go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. now set the DC bus volt ref value as per operation.
- Now to start the converter press **FWD/REV** button, we can see the output voltage (Vdc) as per the set value (DC bus volt Ref). use the same button to stop the converter.
- Now the battery bank is connected to the **DC bus**, we can Charge / Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR

Steps to operate the solar array simulator:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Solar array simulator consists of FEC and DC-DC converter. **TURN ON** the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.

- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.
- In both cases keypad/HMI the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter press **FWD/REV** button. Use the same button to stop the converter.
- Now the solar array simulator is connected to buck / boost converter.

3. BUCK / BOOST CONVERTER (SOLAR)

Buck / boost converter input is connected to the solar array emulator and output terminals connected to the DC bus.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display.
- Choose the max MPPT ref by pressing **→ PV MPPT para → MAX MPPT Ref**
- To **START** the converter, press **FWD/REV** button. Use the same button to stop it.
- Now the buck / boost converter is connected to the DC bus.

Now the battery is already connected to the DC bus and buck / boost converter also connected to the DC bus. Based on the PV parameters values, current will inject in to the battery bank via buck / boost converter and bidirectional converter (Battery). We can see the battery charging in battery panel **CC** in keypad and respective current value.

4. DFIG STARTING PROCEDURE

DFIG and VFD are coupled together as shown in diagram. DFIG can be operated standalone / GRID mode based on selection.

a) Variable Frequency Drive (VFD):

- **TURN ON** the blower fan MCB supply.
- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display
- Go to **Frequent modes→ enter→Frequency Ref→enter→set the value→save it**.
- Now to **START** the VFD press **Start/stop** button, we can observe the machine will rotate as per the set frequency.
- We can observe the speed, voltage, current in keypad display.

STANDALONE MODE:

b) Rotor Side Inverter (RSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- Before starting the RSC, we need to **pre-charge the DC bus of RSC** and **FEC**, For that we will pre-charge with the solar array emulator. Start the solar array emulator as usual and **TURN ON the MCB** provided in the **SOLAR ARRAY SIMULATOR** for Pre-charging of RSC and FEC.
- To operate the DFIG in standalone mode set the operation mode in standalone mode **→OPERATION_MODE→ENTER→REGULATION_MODE→ENTER→CHO-OSE WRIM STAND CTRL→SAVE it**
- Now press the **DC bus on button** we can observe the DC link voltage in keypad display as follows press **enter** in main page**→Go to** until **DC link voltage** appears→ here we can see the DC link voltage. If not check the fuses/fault conditions
- To **start** RSC press, **START/STOP button**. Here we can see the stator frequency, voltage, current of DFIG in keypad display. For e.g., if VFD is running at rated speed here we can see 50Hz,402V. If not displayed, please check for the fuses/fault conditions.
- To check the **rotor voltage** press, enter in **main page**→ go to until **Rotor voltage** appears→ here we can see the rotor voltage.

c) Line Side Converter (LSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- The pre-charging of LSC is already done because **RSC** and **LSC DC side** terminals are connected together.
- Press the DC bus on button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- DFIG stator voltage is already build-up and we can observe the DC bus voltage raised above the pre-charge level in LSC panel.
- Now **TURN OFF** the **MCB** provided in the **Solar array simulator** before starting the LSC.
- To **start** the LSC, press **Start/stop** button. Now we can see the VDC value in keypad display raised to set value which is **→Frequent modes→ enter→DC link volt ref**

Now this DFIG is connected to AC/ DC converter via 415/210V transformer. AC/ DC converter further connected to MAIN DC BUS.

5) AC/ DC CONVERTER (DFIG):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not, check the power supply.
- Press the DC bus ON button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- To start the AC/ DC converter, press Star/Stop button. Now AC/ DC converter is connected to DC bus
- We can inject the current to DC bus by varying **Active cur ref** **→Frequent modes→enter→Active cur ref→enter to change value**→esc/save
- We can observe power is drawn from the **DFIG** by **increasing** the **active cur ref** value which we can **observe** in **RSC** panel main page.
- Extracted power from DFIG will be pumped to DC bus, where bidirectional converter (Battery) is connected already so **battery** starts to **charging** that we can **observe** in **Bidirectional Converter (Battery) panel**.

6) THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- In this we can operate three level inverter in two modes GRID/STANDALONE mode

Stand-alone mode:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220/415V).
- Make sure close the all MCB’s in synchronizing panel.
- To select in Stand-alone mode, go to →**Mode selection**→**enter**→**operation mode**→**enter**→**change it to Stand-alone**→**esc**→**save** it.
- Choose the operation and parameters accordingly.
- Press the DC bus ON button. We can observe the DC bus voltage in keypad display and to **start** the inverter, press **Start**/**Stop** button.
- To see the inverter **output voltage** in display, **press enter** in main page.
- To load the three-level inverter, **TURN ON** the **MCB2** in STATCOM panel. Now it is connected to the load, vary the AC load accordingly.

Mode 1: PV and Wind sources: Used to charging the battery:

Sl. No	PV Module Profile	PV-Buck/ Boost Converter	Wind- AC/DC Converter	Battery
		Buck Current Ref. (A)	Active Current Ref. (%)	Charging Current (A)
	Voc:			
	Isc:			
	Operating Irradiance (W/m^2):			
	Operating Temp:			

Mode 2 : PV +Wind + Battery: Used to supplying AC load

Sl.No	PV Module Profile	PV-Buck / Boost Converter	Wind- AC/ DC Converter	Battery	Load	AC Load Current (A)		
		Buck Current Ref.(A)	Active Current Ref. (%)	Discharging Current (A)		R	Y	B
	Voc:							
	Isc:							
	Operating Irradiance (W/m^2):							
	Operating Temp:							

Mode 3 : PV +Wind : Supplying AC load and Charging Battery

Sl.No	PV Module Profile	PV-Buck / Boost Converter	Wind- AC/ DC Converter	Battery	Load	Load Current		
		Buck Current Ref.(A)	Active Current Ref. (%)	Charging Current (A)		R	Y	B
	Voc:							
	Isc:							
	Operating Irradiance (W/m^2):							
	Operating Temp:							

Mode 4: Battery as source to supplying AC load

Sl.No	Battery Discharging Current (A)	Load	Load Current		
			R	Y	B

Result:

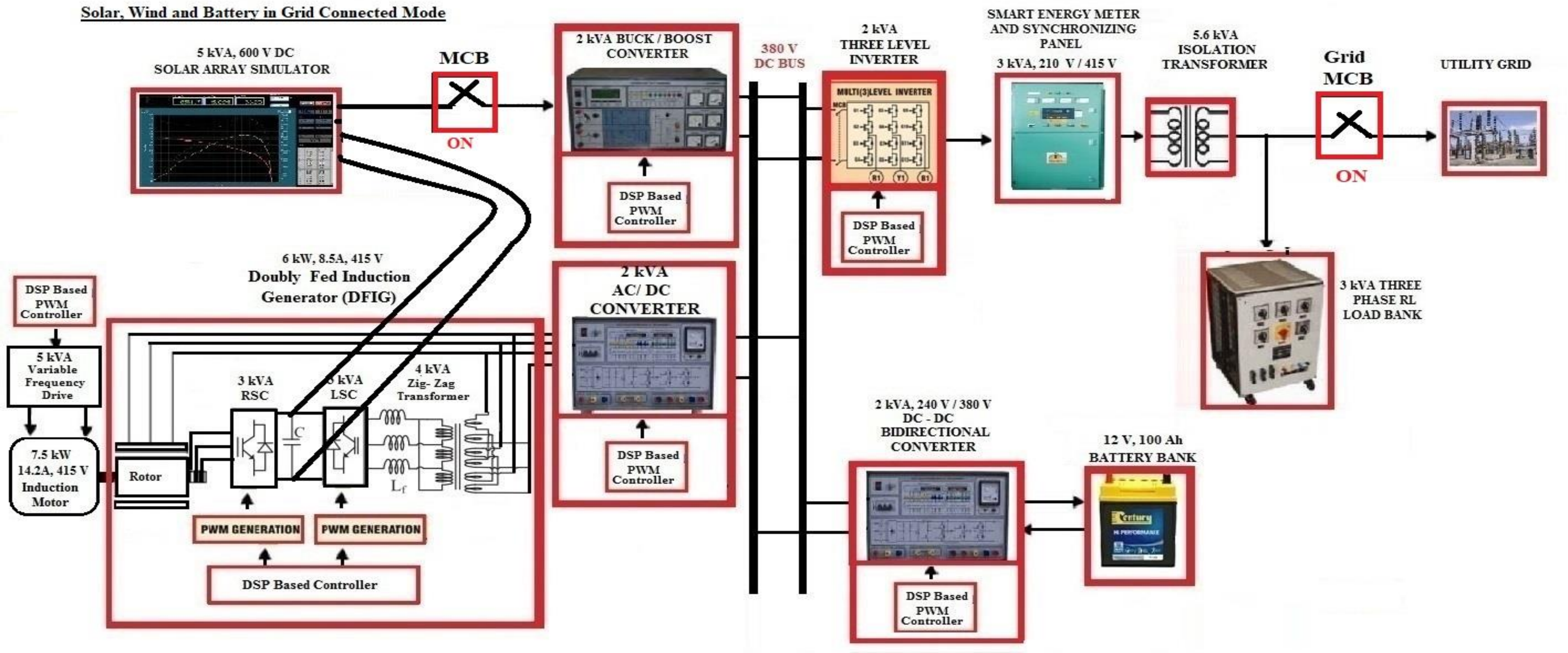
Expt. No : 7
Date :

Integration of solar, DFIG based wind and battery energy storage-based DC microgrid in grid connected mode of operation

Aim:

To study the coordinated operation of Solar, DFIG based wind source and battery energy storage to inject power to the AC grid

Schematic diagram:



Operating Procedure Steps

1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a micro-grid first, we need to start the bidirectional converter (Battery). To start the bidirectional Converter (Battery) panel, read the following steps carefully,

- Before turning on the power supply check the connections carefully, if everything is in normal condition **TURN ON** the control supply (push button) for the bidirectional converter (Battery) panel.
- After turning on the control supply keypad display will glow, this means control supply for the converter is on condition. If not check the power supply.
- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**.
- If battery voltage is showing in display, now **TURN ON** the DC bus (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage check the fuses
- Before starting the converter, we need to set the DC bus voltage reference, for that go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. now set the DC bus volt ref value as per operation.
- Now to start the converter press **FWD/REV** button, we can see the output voltage (Vdc) as per the set value (DC bus volt Ref). use the same button to stop the converter.
- Now the battery bank is connected to the **DC bus**, we can Charge / Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR

Steps to operate the solar array simulator:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Solar array simulator consists of FEC and DC-DC converter. **TURN ON** the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.

- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.
- In both cases keypad/HMI the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter press **FWD/REV** button. Use the same button to stop the converter.
- Now the solar array simulator is connected to buck / boost converter.

3. BUCK / BOOST CONVERTER (SOLAR)

Buck / boost converter input is connected to the solar array emulator and output terminals connected to the DC bus.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display.
- Choose the max MPPT ref by pressing **→ PV MPPT para → MAX MPPT Ref**
- To **START** the converter, press **FWD/REV** button. Use the same button to stop it.
- Now the buck / boost converter is connected to the DC bus.

Now the battery is already connected to the DC bus and buck / boost converter also connected to the DC bus. Based on the PV parameters values, current will inject in to the battery bank via buck / boost converter and bidirectional converter (Battery). We can see the battery charging in battery panel **CC** in keypad and respective current value.

4. DFIG STARTING PROCEDURE

DFIG and VFD are coupled together as shown in diagram. DFIG can be operated standalone / GRID mode based on selection.

a) Variable Frequency Drive (VFD):

- **TURN ON** the blower fan MCB supply.
- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display
- Go to **Frequent modes→ enter→Frequency Ref→enter→set the value→save it**.
- Now to **START** the VFD press **Start/stop** button, we can observe the machine will rotate as per the set frequency.
- We can observe the speed, voltage, current in keypad display.

STANDALONE MODE:

b) Rotor Side Inverter (RSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- Before starting the RSC, we need to **pre-charge the DC bus of RSC** and **FEC**, For that we will pre-charge with the solar array emulator. Start the solar array emulator as usual and **TURN ON the MCB** provided in the **SOLAR ARRAY SIMULATOR** for Pre-charging of RSC and FEC.
- To operate the DFIG in standalone mode set the operation mode in standalone mode **→OPERATION_MODE→ENTER→REGULATION_MODE→ENTER→CHO-OSE WRIM STAND CTRL→SAVE it**
- Now press the **DC bus on button** we can observe the DC link voltage in keypad display as follows press **enter** in main page→**Go to** until **DC link voltage** appears→ here we can see the DC link voltage. If not check the fuses/fault conditions
- To **start** RSC press, **START/STOP button**. Here we can see the stator frequency, voltage, current of DFIG in keypad display. For e.g., if VFD is running at rated speed here we can see 50Hz,402V. If not displayed, please check for the fuses/fault conditions.
- To check the **rotor voltage** press, enter in **main page**→ go to until **Rotor voltage** appears→ here we can see the rotor voltage.

c) Line Side Converter (LSC):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not check the power supply.
- The pre-charging of LSC is already done because **RSC** and **LSC DC side** terminals are connected together.
- Press the DC bus on button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- DFIG stator voltage is already build-up and we can observe the DC bus voltage raised above the pre-charge level in LSC panel.
- Now **TURN OFF** the **MCB** provided in the **Solar array simulator** before starting the LSC.
- To **start** the LSC, press **Start/stop** button. Now we can see the VDC value in keypad display raised to set value which is **→Frequent modes→ enter→DC link volt ref**

Now this DFIG is connected to AC/ DC converter via 415/210V transformer. AC/ DC converter further connected to MAIN DC BUS.

5) AC/ DC CONVERTER (DFIG):

- Press the control supply button to TURN ON the control supply. Keypad display will glow in front panel if not, check the power supply.
- Press the DC bus ON button, we can see the DC voltage in keypad display. If not displayed, please check for the fuses/fault conditions.
- To start the AC/ DC converter, press Star/Stop button. Now AC/ DC converter is connected to DC bus
- We can inject the current to DC bus by varying **Active cur ref** **→Frequent modes→enter→Active cur ref→enter to change value**→esc/save
- We can observe power is drawn from the **DFIG** by **increasing** the **active cur ref** value which we can **observe** in **RSC** panel main page.
- Extracted power from DFIG will be pumped to DC bus, where bidirectional converter (Battery) is connected already so **battery** starts to **charging** that we can **observe** in **Bidirectional Converter (Battery) panel**.

6) THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- In this we can operate three level inverter in two modes GRID/STANDALONE mode

Grid mode:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220 / 415V).

- **Make sure close the all MCB's in Synchronizing panel**

- To select in Grid mode, go to **→Mode selection→enter→operation mode→enter→change it to grid mode→esc→save** it.

- In this Grid mode we have two options one is take the power from the grid other one is injecting power to the grid. If we select the **Master** mode, it'll **draw the power** from the grid based on reference value. If we select the **slave** mode, it'll **inject power** to the grid based on the reference value.

- The selection as follows
  Goto→Mode selection→enter→parallel-mode→choose Master/Slave.

- The grid current reference value can be increases/decreases as follows
  Go to →Frequent modes→enter→Grid CUR Ref INC/DEC

- Choose the operation and parameters accordingly.

- Press the DC bus on button we can observe the DC bus voltage in keypad display and to **start** the inverter press **Start/Stop** button.

- To see the inverter **output voltage** in display, **press enter** in main page.

- If we are in master mode i.e., Draw the power from the grid the three-level inverter inject the power to the DC bus (330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battey) is connected to the DC bus(330/380V) we can observe the charging of battery (CC) in battery panel.

- If we are in slave mode i.e., inject the power to grid the three-level inverter draw the power from the DC bus(330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battery) is connected to the DC bus(330/380V) we can observe discharging of battery (DC) in battery panel.

- **To load** the three-level inverter, **TURN ON** the **MCB2** in **STATCOM** panel. Now it is connected to the load, vary the load accordingly.

<u>Mode 1: PV and Wind sources: Used to charging the battery and Injecting power to GRID:</u>

Sl. No	PV Module Profile	PV-Buck/ Boost Converter	Wind- AC/DC Converter	Battery	Injected Grid Current (A)		
		Buck Current Ref. (A)	Active Current Ref. (%)	Charging Current (A)	R	Y	B
	Voc:						
	Isc:						
	Operating Irradiance (W/m^2):						
	Operating Temp:						

<u>Mode 2 : PV +Wind + Battery: Used to supplying AC load+ Injecting power to GRID</u>

Sl.No	**PV Module Profile**	**PV-Buck / Boost Converter**	**Wind- AC/ DC Converter**	**Battery**	**Load**	**AC Load Current (A)**			**Injected Grid Current (A)**		
		Buck Current Ref.(A)	**Active Current Ref. (%)**	**Discharging Current (A)**		**R**	**Y**	**B**	**R**	**Y**	**B**
	Voc:										
	Isc:										
	Operating Irradiance (W/m^2):										
	Operating Temp:										

Mode 3 : PV +Wind + Grid: Supplying AC load and Charging Battery

Sl.No	PV Module Profile	PV-Buck / Boost Converter	Wind-AC/ DC Converter	Battery	Load	Load Current			Current drawn from the Grid (A)		
		Buck Current Ref.(A)	Active Current Ref. (%)	Charging Current (A)		R	Y	B	R	Y	B
	Voc:										
	Isc:										
	Operating Irradiance (W/m^2):										
	Operating Temp:										

Mode 4: Battery as source to supplying AC load and injecting power to Grid

Sl.No	Battery Discharging Current (A)	Load	Load Current			Current Injected to Grid (A)		
			R	Y	B	R	Y	B

Mode 5: Grid as source to supplying AC load and charging the battery

Sl.No	Battery Charging Current (A)	Load	Load Current			Current drawn from the Grid (A)		
			R	Y	B	R	Y	B

Result:

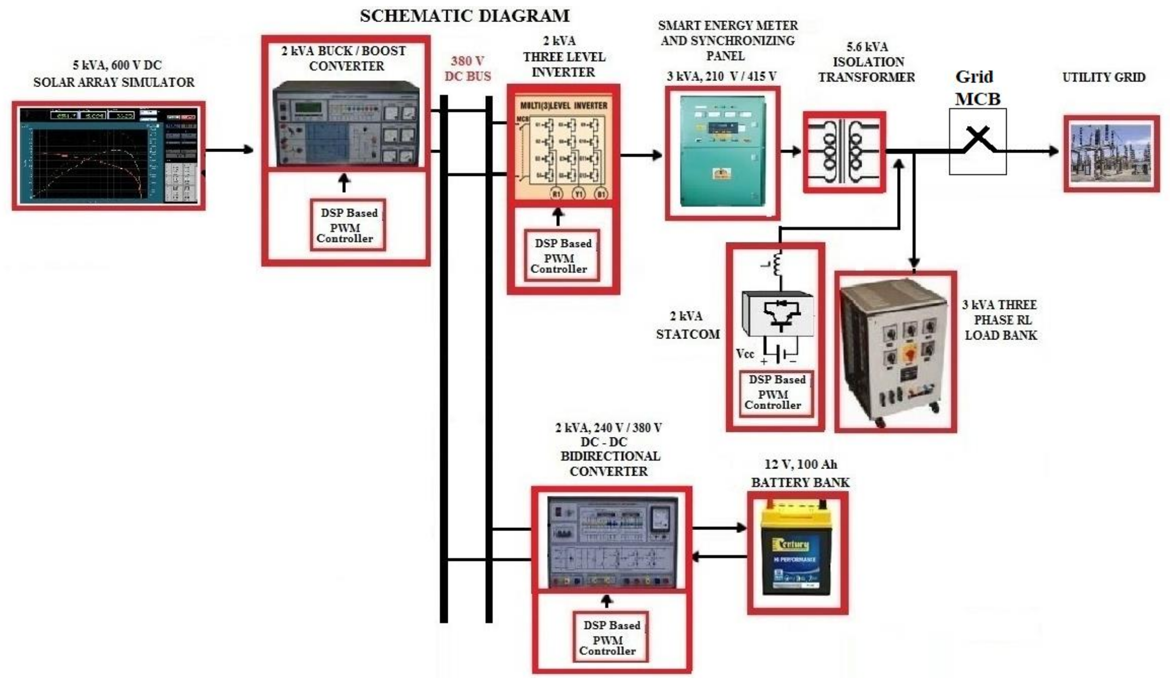
Expt. No :8
Date   :

Power quality improvement in DC microgrid using STATCOM controller

Aim:

To study the reactive power compensation using STATCOM controller in PV-BESS based DC microgrid

Schematic diagram:



1. BIDIRECTIONAL CONVERTER (BATTERY)

To form a micro-grid first, we need to start the bidirectional Converter (Battery). To start the bidirectional converter (Battery) panel read the following steps carefully,

- Before turning on the power supply check the connections carefully, if everything is in normal condition **TURN ON** the control supply (push button) for the bidirectional converter (Battery) panel.
- After turning on the control supply keypad display will glow, this means control supply for the converter is on condition. If not check the power supply.

- Now battery side terminals are connected to a battery bank, we can see the **battery voltage** in **keypad display**. If display is not working or not showing any parameters, please refer the in vector keypad troubleshooting manual.
- If battery voltage is showing in display, now **TURN ON** the **DC bus** (push button). We can see the output voltage (Vdc) as per the circuit diagram. If not showing any voltage check the fuses and refer the bidirectional converter (Battery) manual.
- Before starting the converter, we need to set the Dc bus voltage reference, for that go to the **Frequent modes → enter→ DC bus Volt Ref→ enter**. Now set the DC bus volt ref value as per operation.
- Now to start the converter press **FWD/REV** button, we can see the output voltage (Vdc) as per the set value (DC bus volt Ref). use the same button to stop the converter.
- Now the battery bank is connected to the **DC bus**, we can Charge/Discharge based on the operating procedure.

Note: In any case power supply interruption/disconnected please press the Emergency button provided in every panel.

2. SOLAR ARRAY SIMULATOR

To operate the solar array simulator individually read the solar array simulator manual.

- Press the control supply button to **TURN ON** the control supply. keypad display will glow in front panel if not check the power supply.
- Solar array simulator consists of FEC and DC-DC Converter. TURN ON the Grid supply for the FEC, Now the FEC will maintain the DC bus voltage. Observe the DC bus voltage in keypad display.
- Here the **PV parameters** can be set by keypad or HMI. Selection of this can be done in **keypad→Mode selection→ PV i/p Para sel→enter→HMI/Keypad** based upon choice.
- If we select as PV parameters in keypad mode, then choose the PV parameters in keypad **→PV_i/p_Para→select parameters Voc/Isc/irradiance/temp etc. → enter → change the value as per selection→save**.
- If we select as PV parameters in HMI, to enter PV parameter values in **HMI→ Go to HMI → press anywhere in HMI→ setting→enter Voc, Isc, irradiance, temp values → press graph→press load parameters**.

- In both cases keypad/HMI, the PV graph can be shown in HMI by pressing **GRAPH button**.
- To **START** the converter press **FWD/REV** button. Use the same button to stop the converter.
- Now the solar array simulator is connected to buck / boost converter.

3. BUCK / BOOST CONVERTER (SOLAR)

buck / boost converter input is connected to the solar array emulator and output terminals connected to the DC bus.

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- Press the DC bus button to **TURN ON** the DC bus. Observe the DC bus voltage in keypad display.
- Choose the max MPPT ref by pressing → **PV MPPT para → MAX MPPT Ref**
- To **START** the converter, press **FWD/REV** button. Use the same button to stop it.
- Now the buck / boost converter is connected to the DC bus.

Now the battery is already connected to the DC bus and buck / boost converter also connected to the DC bus. Based on the PV parameters values, current will inject to the battery bank via buck / boost converter and bidirectional converter (Battery). We can see the battery charging in battery panel **CC** in keypad and respective current value.

4) THREE LEVEL INVERTER:

- Press the control supply button to **TURN ON** the control supply. Keypad display will glow in front panel if not check the power supply.
- In this we can operate three level inverters in two modes GRID/STANDALONE mode

Grid Mode:

- Input of three level is connected DC bus (here it is 330/380V DC). Output is connected to synchronizing panel via transformer (220/415V).
- <u>Make sure close the all MCB's in synchronizing panel.</u>
- To select in Grid mode, go to **→Mode selection→enter→operation mode→enter→change it to grid mode→esc→save** it.

- In **Grid mode** we have two options one is take the power from the grid other one is inject power to the grid. If we select the **Master** mode, it'll **draw the power** from the grid based on reference value. If we select the **slave** mode, it'll **inject power** to the grid based on the reference value.
- The selection as follows

  Go to→Mode selection→enter→parallel-mode→choose Master/Slave.
- The grid current reference value can be increases/decreases as follows

  Go to →Frequent modes→enter→Grid CUR Ref INC/DEC
- Choose the operation and parameters accordingly.
- Press the DC bus on button we can observe the DC bus voltage in keypad display. And to **start** the inverter press **Start**/**Stop** button.
- To see the inverter **output voltage** in display, **press enter** in main page.
- If we are in master mode i.e., Draw the power from the grid the three-level inverter inject the power to the DC bus (330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battery) is connected to the DC bus(330/380V) we can observe the charging of battery (CC) in battery panel.
- If we are in slave mode i.e., inject the power to grid the three-level inverter draw the power from the DC bus(330/380V) based upon the reference value (**Grid CUR Ref**). if only bidirectional converter (Battery) is connected to the DC bus(330/380V) we can observe discharging of battery (DC) in battery panel.
- To load the three-level inverter, **TURN ON** the **MCB2** in **STATCOM** panel. Now it is connected to the load, vary the load accordingly.

PV and Battery as source to supply AC load and Injecting power to GRID with / without STATCOM

Sl. No	PV Module Profile	PV-Buck / Boost Converter	Battery	AC Load Current (RL Load)			Injected Grid Current (A)			STATCOM	Power Factor
		Buck Current Ref.(A)	Discharging Current (A)	R	Y	B	R	Y	B	ON/OFF Status	
	Voc:										
	Isc:										
	Operating Irradiance (W/m^2):										
	Operating Temp:										

Result:

Expt. No: 9

Date :

Battery Balancing and Parameter Estimation for Batteries

Aim:

To estimate the different parameters of the battery and achieve cell balancing

Software Required :

MATLAB R2024a with Simscape and Simulink

Theory

Cell Balancing

Customarily, every cell in a battery has somewhat different volumes and may be at dissimilar levels of state of charge (SOC). This is due to manufacturing discrepancies, assembly variances, for instance, cells from one production run mixed with others, and different histories experienced amongst the cells in a battery pack (e.g., charging/discharging, heat exposures, etc.), and this has to be accounted for to increase life and service of the specific battery pack in use. Every single battery pack will be, for these reasons, in a way different, so every balancing circuit must accommodate those differences.

Without balancing, the smallest capacity cell is a problem and potentially a serious one. It can be easily overcharged or over-discharged, whilst cells with higher capacities are only partially charged. The balance circuit should arrange for higher capacity cells to fully charge/discharge while smaller capacity cells are charged/ discharged suitably—which will be different. In a properly balanced battery pack, the cell with the largest capacity will be filled without overcharging any other (i.e., weaker, smaller) cell, and it can be discharged in use without over-discharging any other cell. Battery balancing is done by transferring energy from or to individual cells until the SOC of the cell with the lowest capacity is equal to the battery's SOC.

Concisely, the following reasons for the necessity for balancing a series connected battery pack:

- The foremost reason is safety. When lithium-ion cell voltage goes above 4.2V by a few hundred millivolts, it can encounter thermal runaway, melting the battery pack and the device it is powering, and it can even blow up.
- The second reason is longevity. If the maximal recommended charging voltage is exceeded even a little, it will cause much-accelerated degradation. Increasing the charging voltage from 4.2 to 4.25V causes the degradation rate to increase by 30%. For this reason, the faulty cell with a higher than its due voltage share will degrade faster.
- The third reason is the incomplete charging of the pack. Let us assume the protector circuit does its job and that charging stops when just one cell gets close to unsafe conditions. We have successfully prevented thermal runaway, but the other cells have lower voltages and are not fully charged. If we look at the pack voltage, it will be much less than 4.2V multiplied by the number of cells. Less pack voltage means less pack energy. (It also usually means less available capacity)

- The fourth reason is the incomplete use of pack energy. Instead of having too high a voltage, one cell could have too low a voltage compared to others when the pack is close to the end of discharge.

Simulation

Task 1: Passive Cell Balancing

Taks2: Building the model

Simscape components are used to model the behavior of a single battery cell, which is replicated to create a series connection for the simulation of a passive balancing circuit. A 3-RC + R equivalent circuit represents the electrical phenomena linked in turn to thermal effects via a thermal mass and the assumption of the Joule effect being the only heat source. Additionally, Simscape Electronics components provide the semiconductor devices responsible for the selective charge bleed, enabling balancing while charging. Temperature build-up is non-uniform because of the uneven current flow and

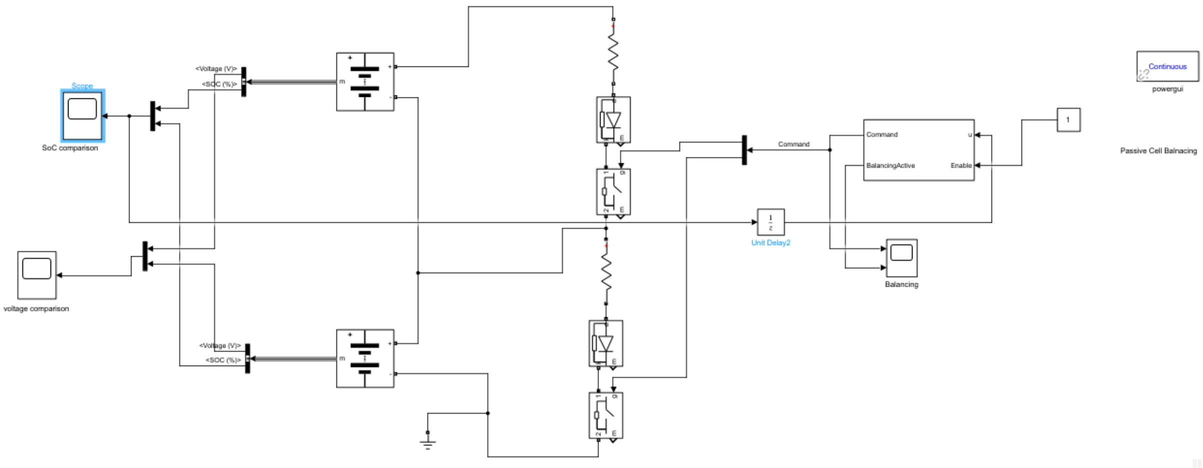


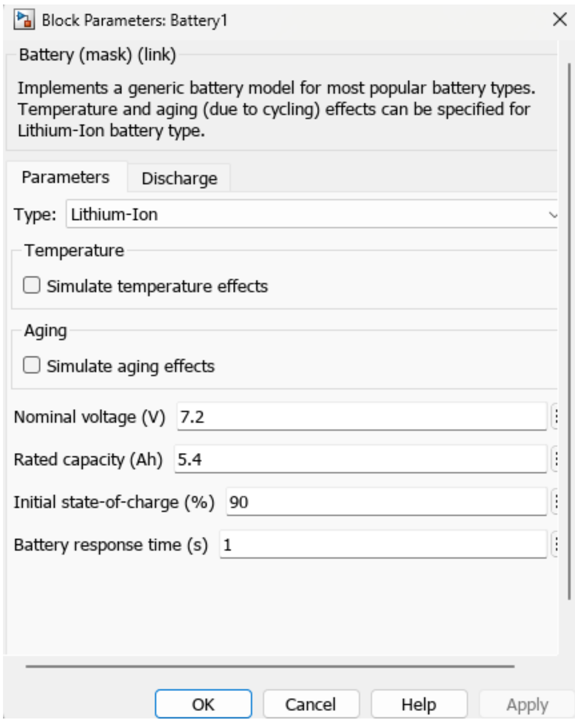
Figure 1 Circuit for passive cell balancing

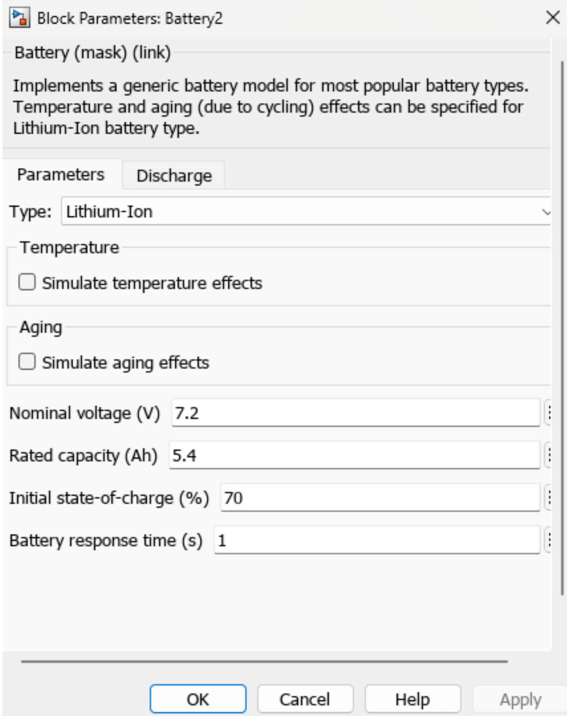
the non-symmetrical thermal design: insulation on one end and natural convection on the other. A supervisory logic strategy implemented in Stateflow establishes the moment and duration of the charging current bleeding. The steps are listed as follows:

1. Initially, build a two-cell series connected battery pack as shown in Figure 1
2. Include passive cell balancing and battery CC-CV block

Initialization

The following initialization was given to the simulation:





Simulation Results

After initialization, the simulation is executed to view the results. Based upon the initial charge of the batteries, the charging shall happen. The charging happening in the constant current (CC) and constant voltage (CV) is shown in Figure 2. Once the charging is completed, the cell balancing controller starts to regulate the cell SoC and after a definite period, the connected cells shall have the same SoC.

.

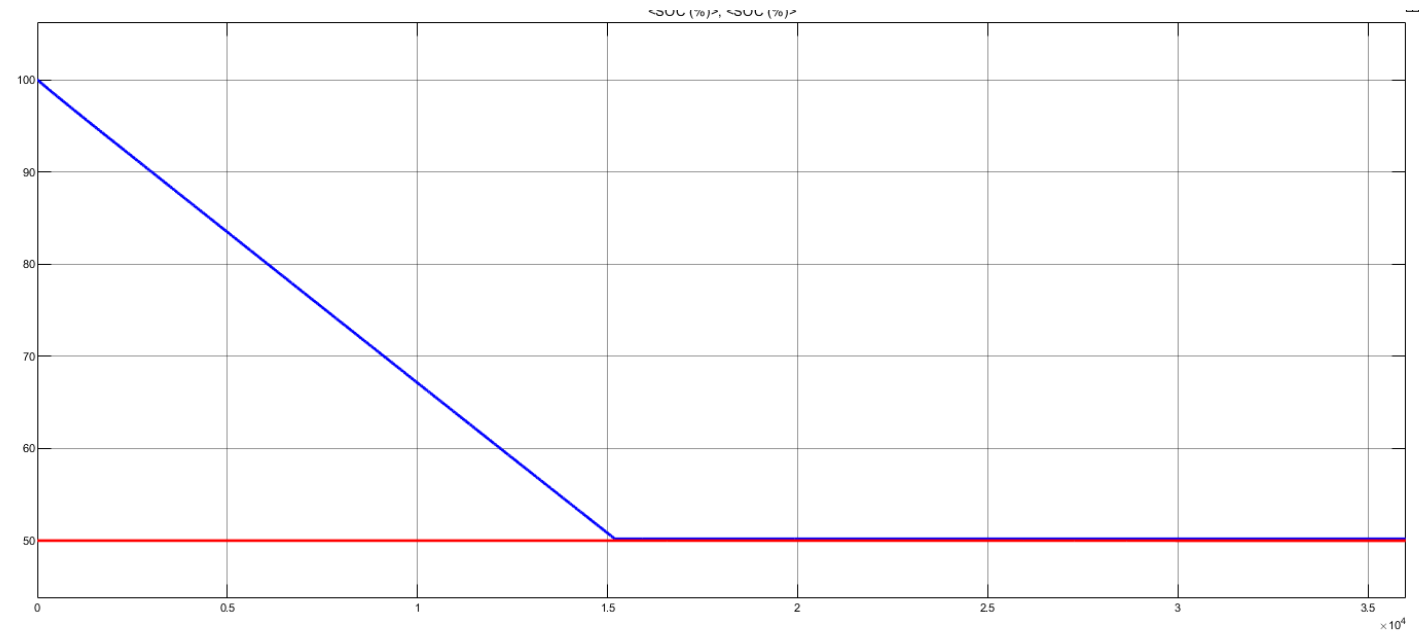


Figure 2 SOC of the Li-ion cells balance

Tabulation:

	SoC before balancing	SoC after balancing
Battery 1		
Battery 2		

Voltage details:

	Voltage before balancing	Voltage after balancing
Battery 1		
Battery 2		

Result :

Expt. No: 10

Date :

Thermal modelling of Li-ion batteries

Aim

To study the impact of temperature on a Lithium-Ion battery module in MATLAB

Software Required

MATLAB R2022a with Simscape and Simulink

Theory

Thermal management is a critical aspect of lithium-ion battery technology due to its direct impact on battery performance, safety, and lifespan. Accurate and reliable thermal modelling has become increasingly crucial as lithium-ion batteries continue to power a wide range of applications, including electric vehicles, portable electronics, and renewable energy storage systems.

Thermal modelling provides valuable insights into lithium-ion batteries' complex heat generation and dissipation processes. These batteries experience significant temperature variations during operation, affecting their performance and lifespan. Excessive heat generation can lead to thermal runaway, resulting in catastrophic battery failures and safety hazards. On the other hand, insufficient thermal management can lead to reduced battery efficiency, capacity degradation, and accelerated ageing. Accurate thermal modelling can contribute to developing enhanced battery designs, improved thermal management strategies, and identifying potential safety risks.

Simulation

Building the model

The significant component is the battery which can be imported from the Simulink library.

1. Import two battery models.
2. Use one model to simulate the temperature effects and another without temperature effects.
3. Run the simulation for 4000 seconds
4. Compare the performance on the scope.

5. A 'stair generator' block is used to build the temperature profile, as shown in Figure 1 .

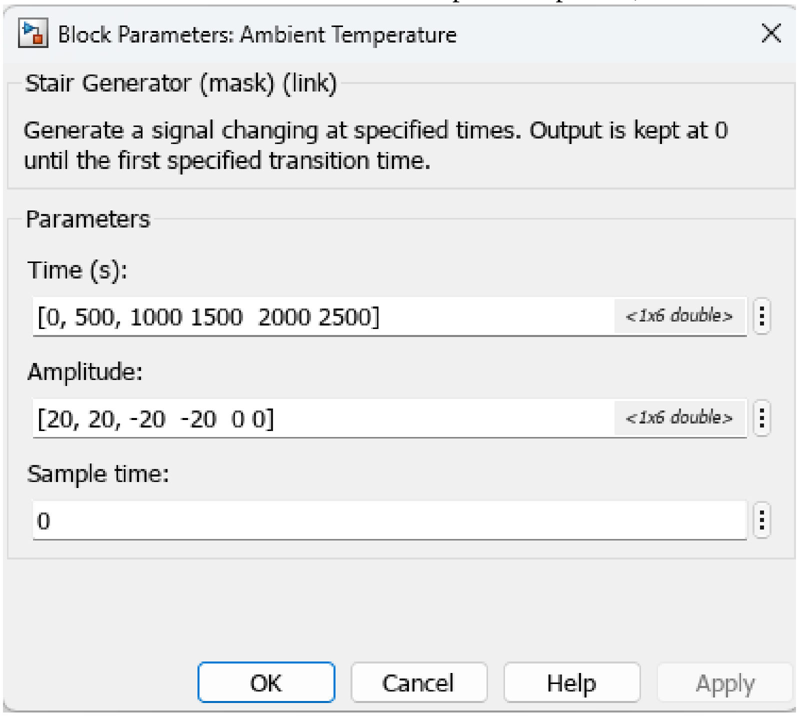


Figure 1 Temperature profile

6. the 'rate limiter' block is used to set the 'ramp rate' of the temperature profile, as shown in Figure 2.

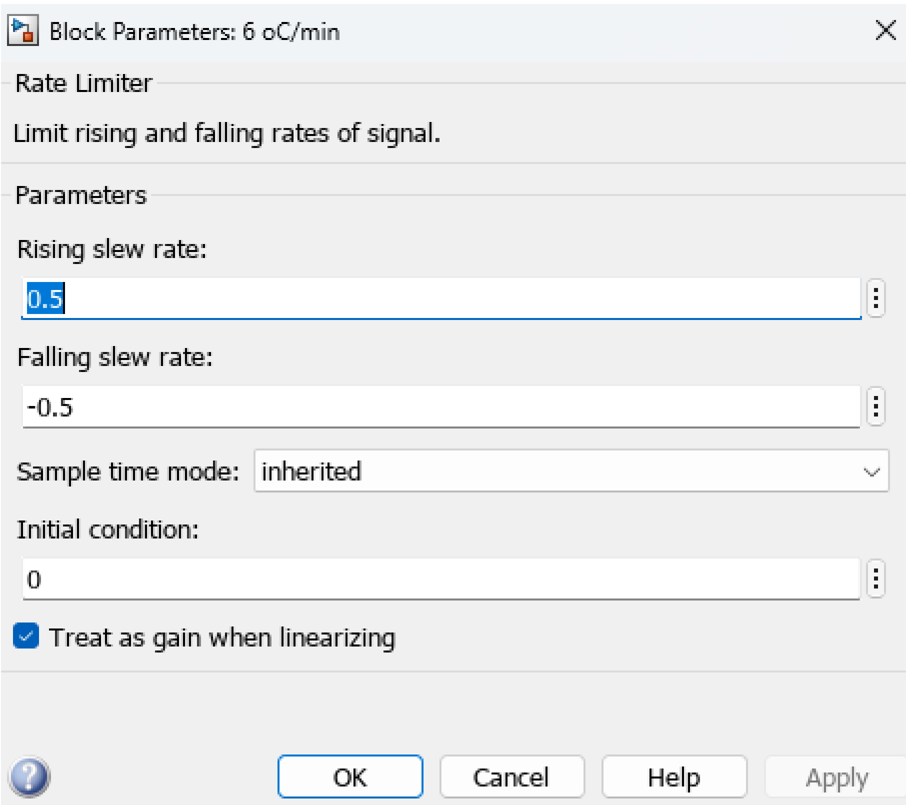


Figure 2 Ramp rate for temperature

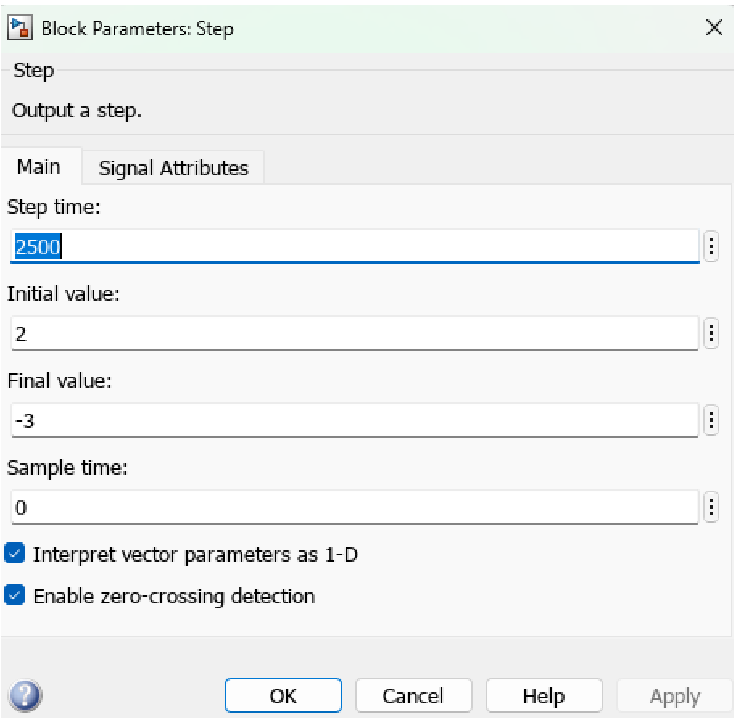


Figure 3 Step signal input

The final model is shown in Figure 4.

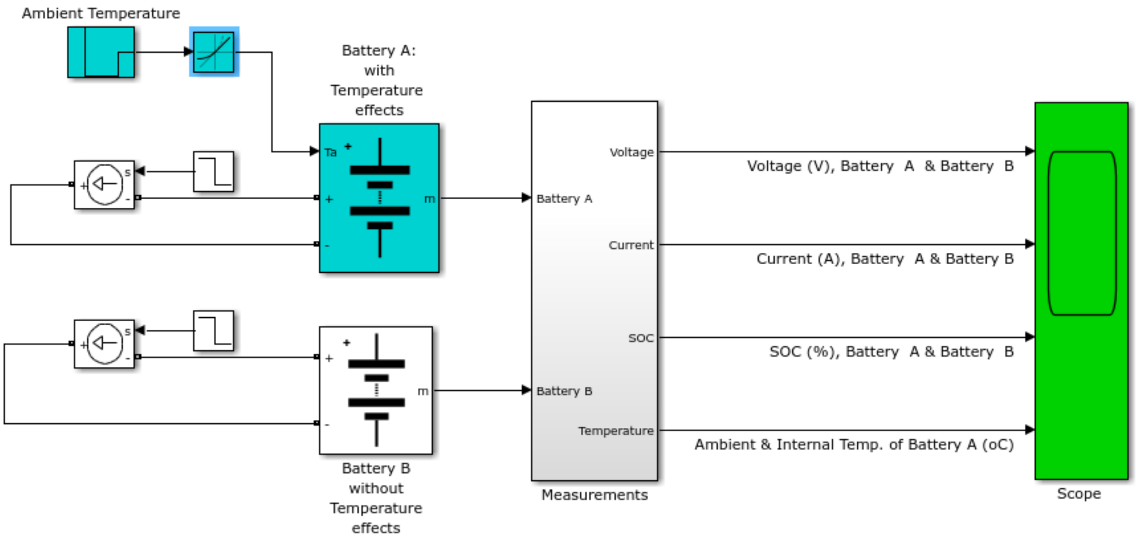


Figure 4 Simulation model

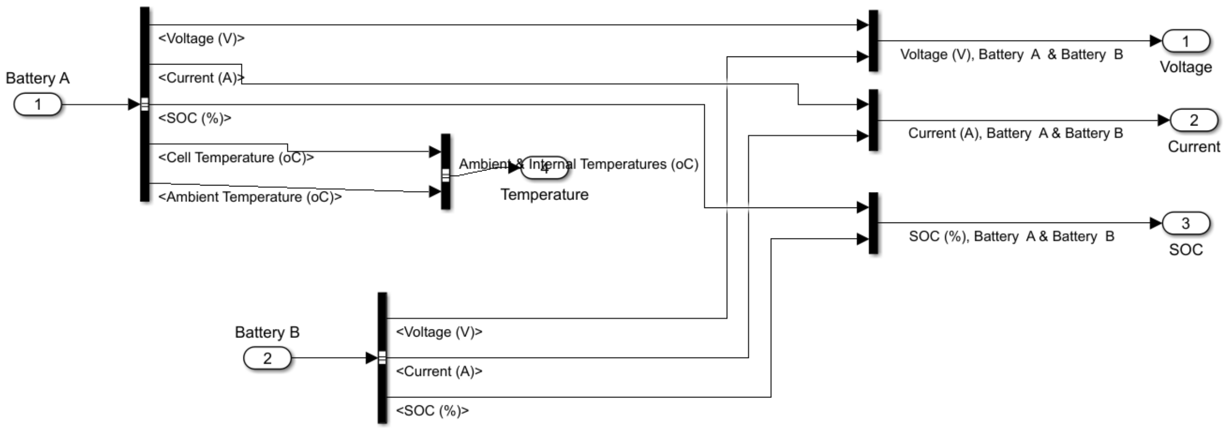


Figure 5 Measurement subsystem

Simulation Results

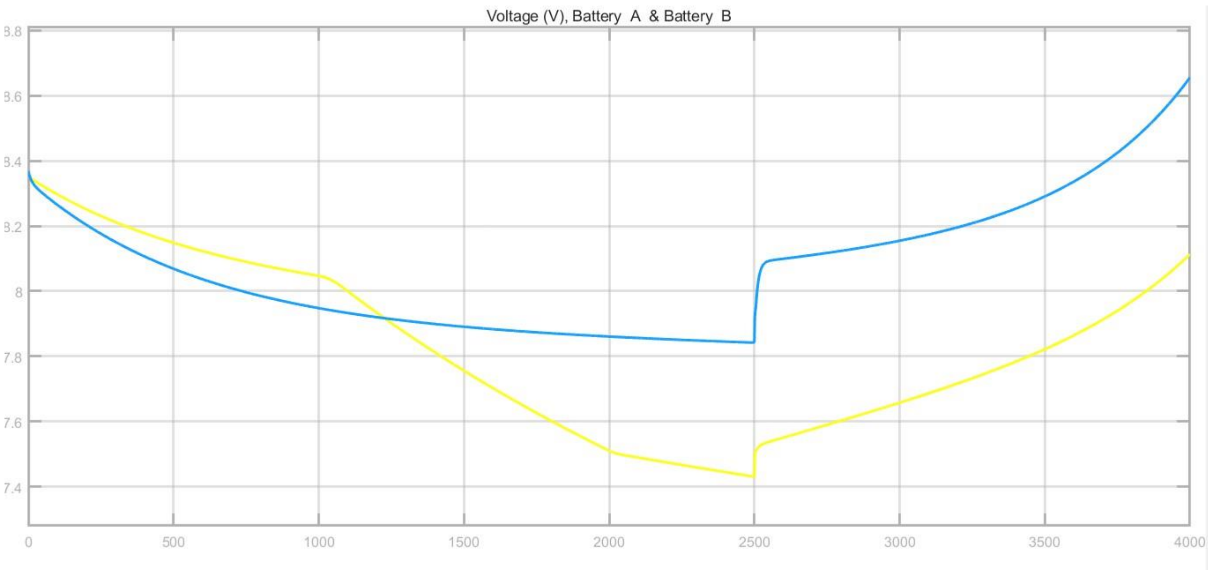


Figure 6 Temperature Impact on Voltage

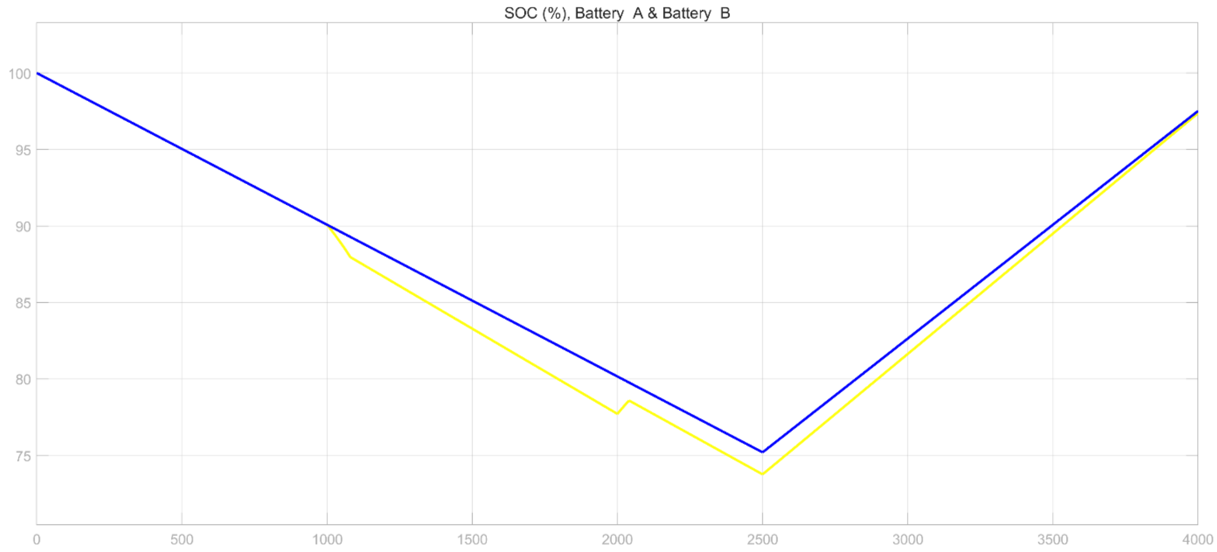


Figure 7 Impact of temperature on SoC

Result:

Expt. No: 11

Date :

Development of an enhanced self-correcting model of Li-ion battery and determination of its coulombic efficiency

Aim:

To characterize battery cell equivalent circuit parameters using the high pulse power characterization (HPPC)

Software Required :

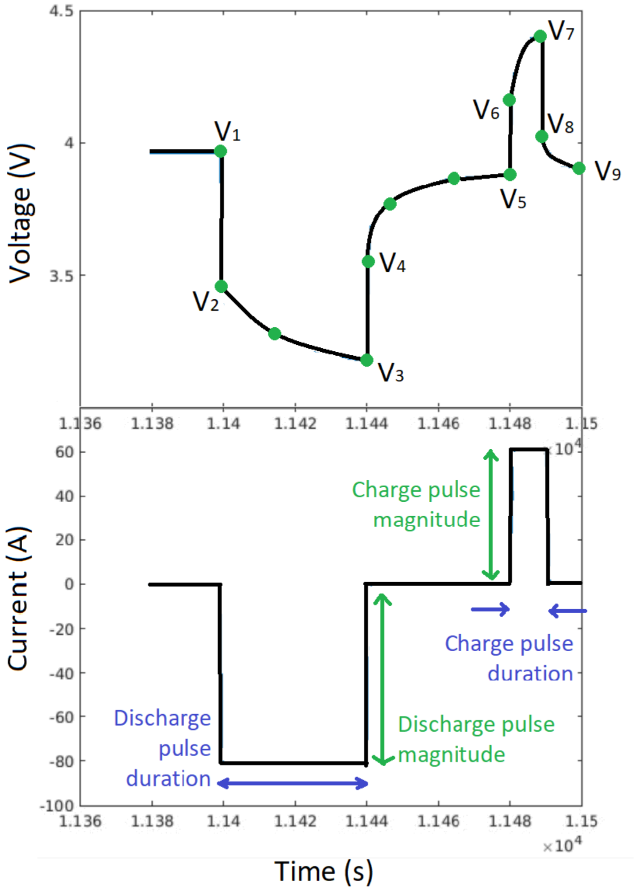
MATLAB R2022a with Simscape and Simulink

Theory :

Battery HPPC Test Data

A typical HPPC data is a set of discharge-charge pulses applied to a battery at different states of charge (SOC) and a given temperature. Typically, the test equipment is fully charged to undergo these pulse tests. At the end of every sequence, the SOC is discharged by a third of the C-rate. A long rest time of one hour is recommended for the cells to relax after every sequence of discharge-charge pulses. This process continues until it covers all points of interest in the SOC range.

This figure shows a typical discharge-charge profile.



Parameter Estimation Method

The Battery (Table-Based) block in Simscape Battery uses the equivalent circuit modelling approach. You can capture different physical phenomena of a cell by connecting multiple RC pairs in series. In Battery (Table-Based) block, you can select up to five RC pairs. You can derive the value of the resistance and time constant parameters from the HPPC test data.

The voltage response of a battery cell is equal to:

$$V = V_0 - I \times R_o - I \times \left(\sum R_i \left(1 - \exp\left(-\frac{t}{\tau_i} \right) \right) \right),$$

where

- V_0 is the cell open circuit potential.
- R_o is the cell ohmic resistance.
- R_i and τ_i are the cells *i*-th RC pair resistance and time constant values.
- I is the current passing through the cell.

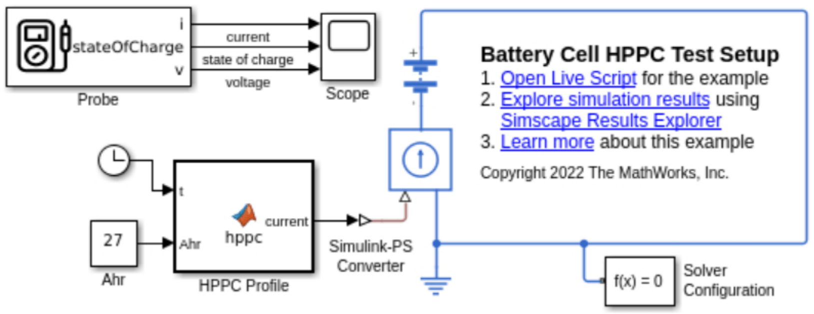
All parameters are a function of the SOC and cell temperature. Since HPPC tests are typically performed at constant temperatures, you can ignore the temperature dependence in the parameter estimation. In the figure above, the ohmic resistance is estimated from the sudden voltage change during discharge or charge pulses (V1 to V2 or V5 to V6). The RC pairs are fit based on the voltage relaxation profile just after the discharge or charge pulses.

The `ParameterEstimationLUTbattery` function estimates the battery parameters and:

1. Takes the HPPC profile over the entire SOC range as input.
2. Determines all the pulse locations and the points V1 - V9 in the above figure.
3. Calculates the ohmic resistance value.
4. Fits the RC parameters using MATLAB `fminsearch` or the Curve Fitting Toolbox™ (fminsearch or curvefit).
5. Calculates the cell open circuit potential (point V1, at a given SOC point, in the figure above).
6. Outputs all parameters to a workspace variable.

Generate Synthetic Test Data

Run the `CellCharacterizationHPPC` SLX file to generate the current and voltage data for the selected cell.



The HPPC Profile MATLAB function defines the discharge-charge protocols and the test method.

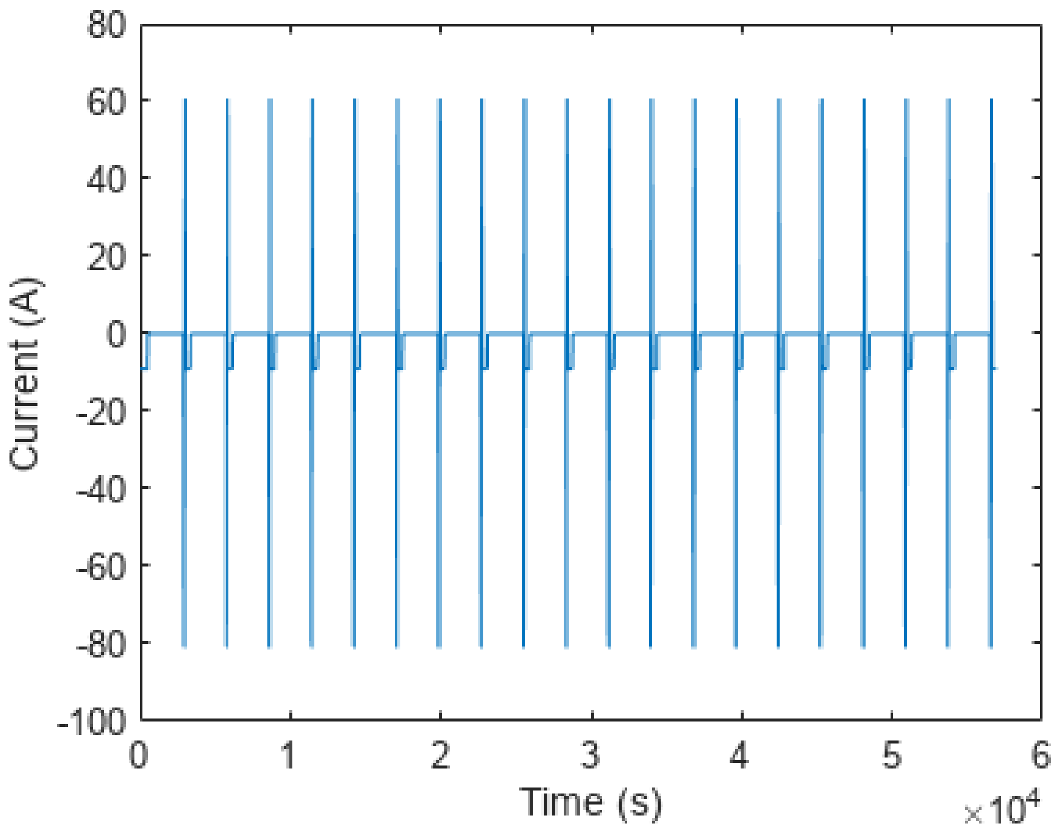
```
hppcSim = sim('CellCharacterizationHPPC.slx');
```

The `hppcSim` workspace variable contains the current and voltage data for the HPPC profile for battery cell parameter estimation.

Fit Parameters to Test Data

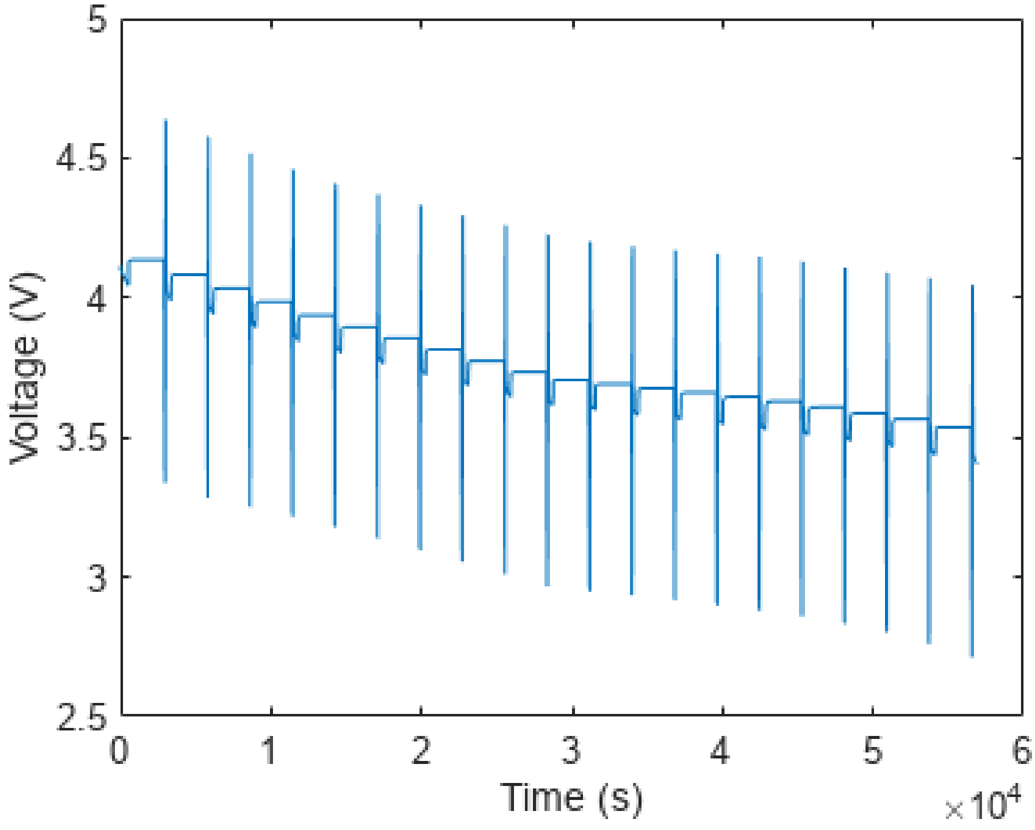
Load the HPPC data and plot the voltage and current values.

```
hppcTest = hppcSim.batteryHPPC_profile.extractTimetable;
time     = seconds(hppcTest.Time);
current  = hppcTest.current;
voltage  = hppcTest.voltage;

figure('Name','HPPC data - current pulses')
plot(time,current);
xlabel('Time (s)');ylabel('Current (A)')
```




```
figure('Name','HPPC data - voltage response')
```

```
plot(time,voltage);
xlabel('Time (s)');ylabel('Voltage (V)')
```



Define the cell capacity (Ahr) as during the HPPC tests and the initial SOC (0-1).

```
cellCapacity   = 27;
cellInitialSOC = 1;
cell_prop      = [cellCapacity; cellInitialSOC];
```

Define the pulse current magnitudes, in Amperes.

```
maxDischargeCurr  = 81;
maxChargeCurr     = 61;
constCurrSweepSOC = 9;
```

The `ParameterEstimationLUTbattery` function detects a pulse (sudden change in current) based on the value you specify for the `toleranceVal` variable. If the function detects a sudden change in discharge current, it compares this discharge current to the value of the `maxDischargeCurr` variable. If their difference is within the value of the `toleranceVal` variable, the function identifies the pulse. This process also applies to detecting the charge pulse (`maxChargeCurr`) and the SOC sweep (`constCurrSweepSOC`).

```
toleranceVal      = 1;
hppc_protocol     = [maxDischargeCurr;...
                     maxChargeCurr;...
                     constCurrSweepSOC;...
                     toleranceVal];
```

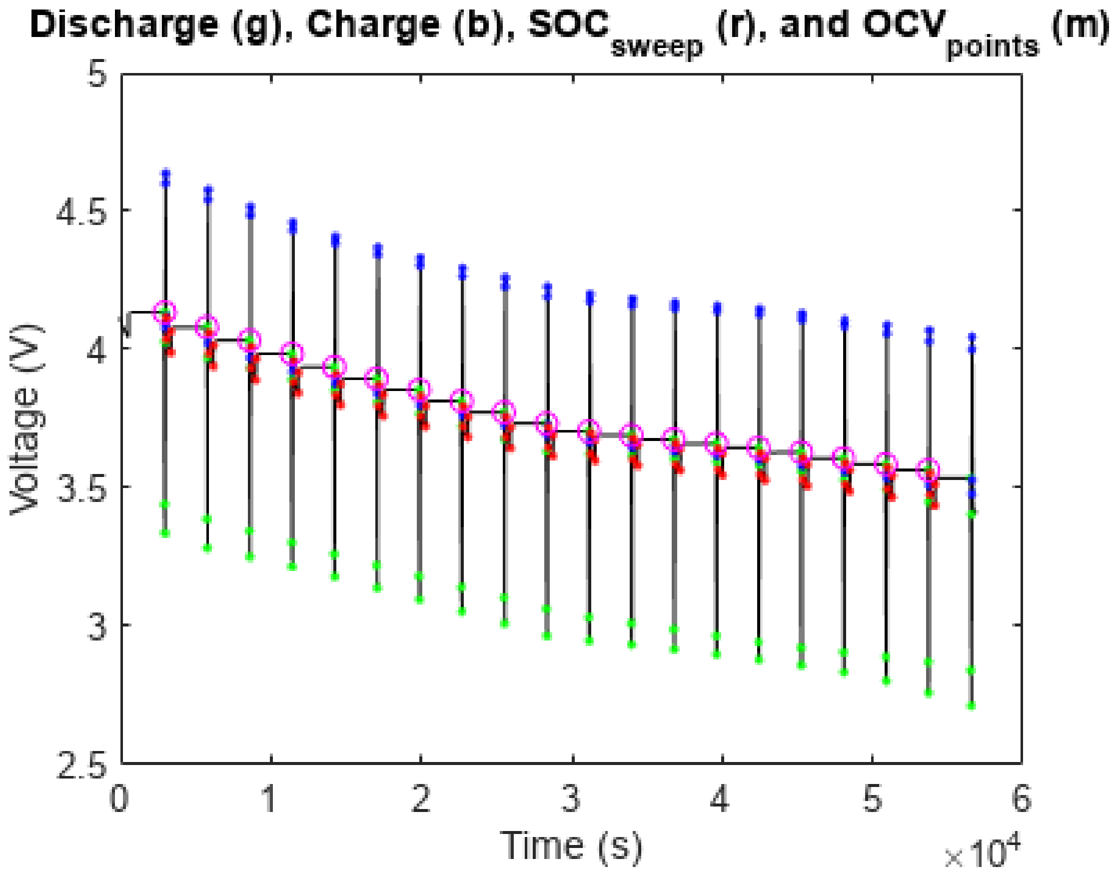
Define the number of RC pairs to consider, the initial guess for resistance, and the time constant values.

```
numRCpairs     = 1;
initialGuess_RC = [1e-3 20]; % [R1, Tau1, R2, Tau2 ....]

result=batt_BatteryCellCharacterization.ParameterEstimationLUTbattery(...
                                     [time, current, voltage],...
```

```
                                                     cell_prop,...
                                                     hppc_protocol,...
                                                     numRCpairs,...
                                                     initialGuess_RC,...
                                                     "fminsearch");
Read input data
*** Number of discharge pulses =20
*** Number of charge pulses    =20
*** Number of SOC sweep pulses =19
Extracted pulse data from input data
Calculated ohmic resistance
*** Calculated RC parameters for discharge
*** Calculated RC parameters for charge
*** Calculated rmse for the fit
Calculated RC parameters
Completed OCV data extraction
% To use curvefit toolbox for data fit, type "curvefit"
% instead of "fminsearch". The curvefit function requires
% the Curve Fitting Toolbox license.
```

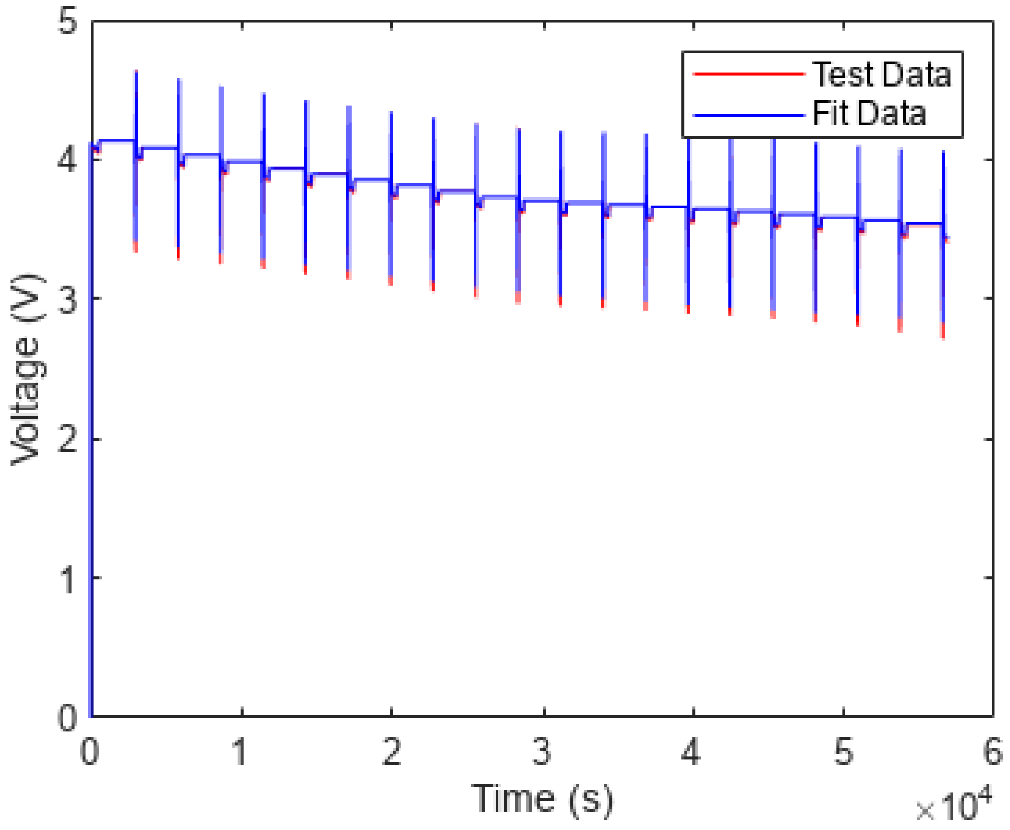
To check if the function identified the correct pulses, at a MATLAB Command Window, enter:

```
plotAndVerifyPulseData(result);
```



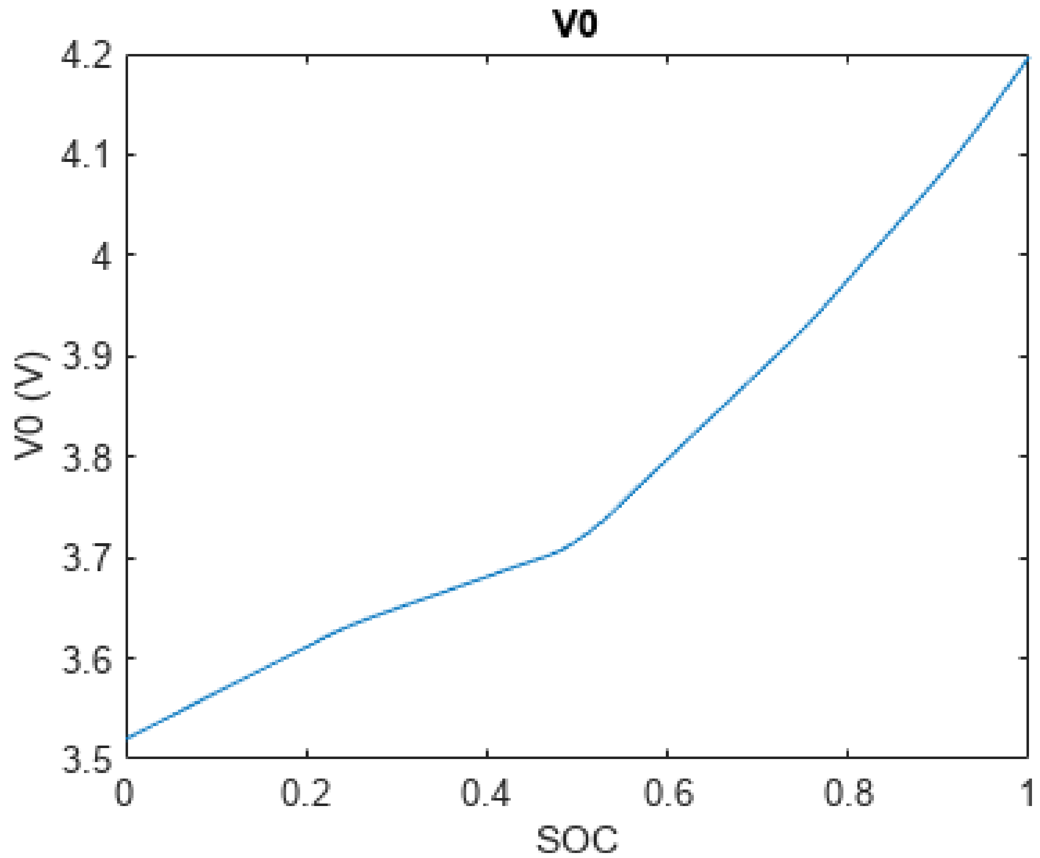
To verify the fit, at a MATLAB Command Window, enter:

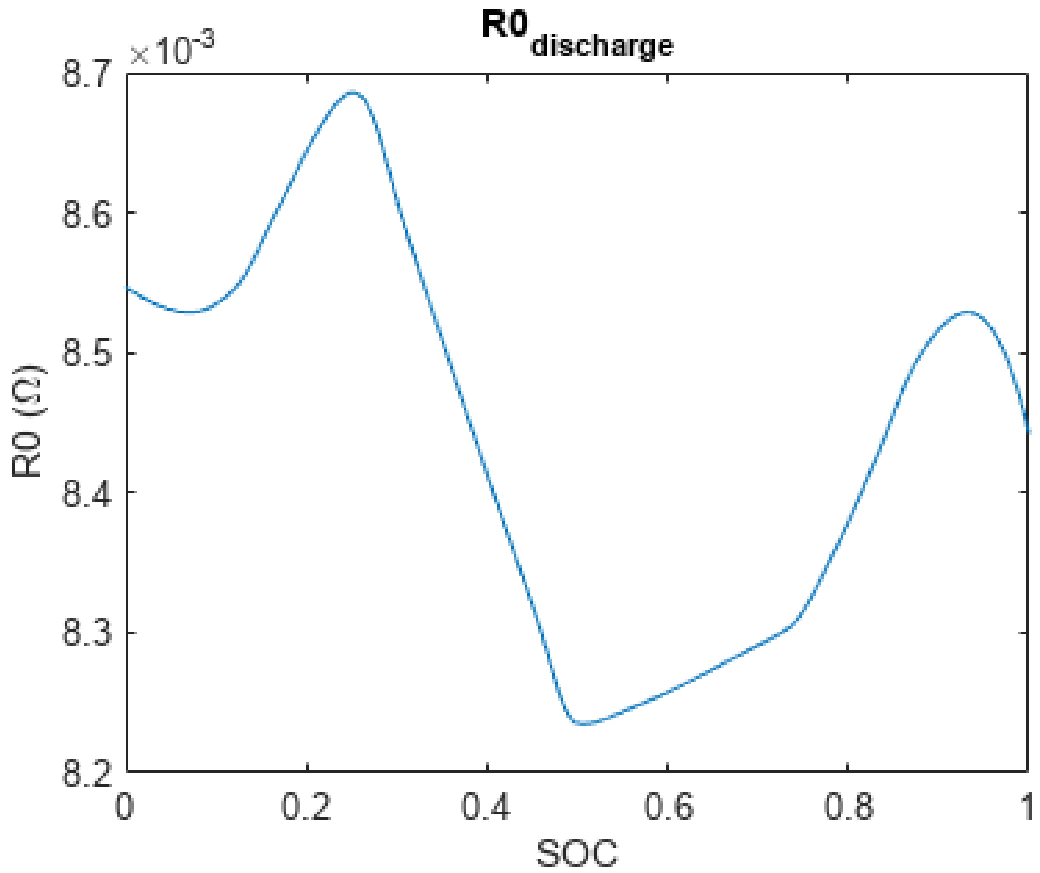
```
fitDataEverySOCval = 0.001;
fitDataForSOCpts = 0:fitDataEverySOCval:1;
verifyDataFit(result,fitDataEverySOCval,1);
```

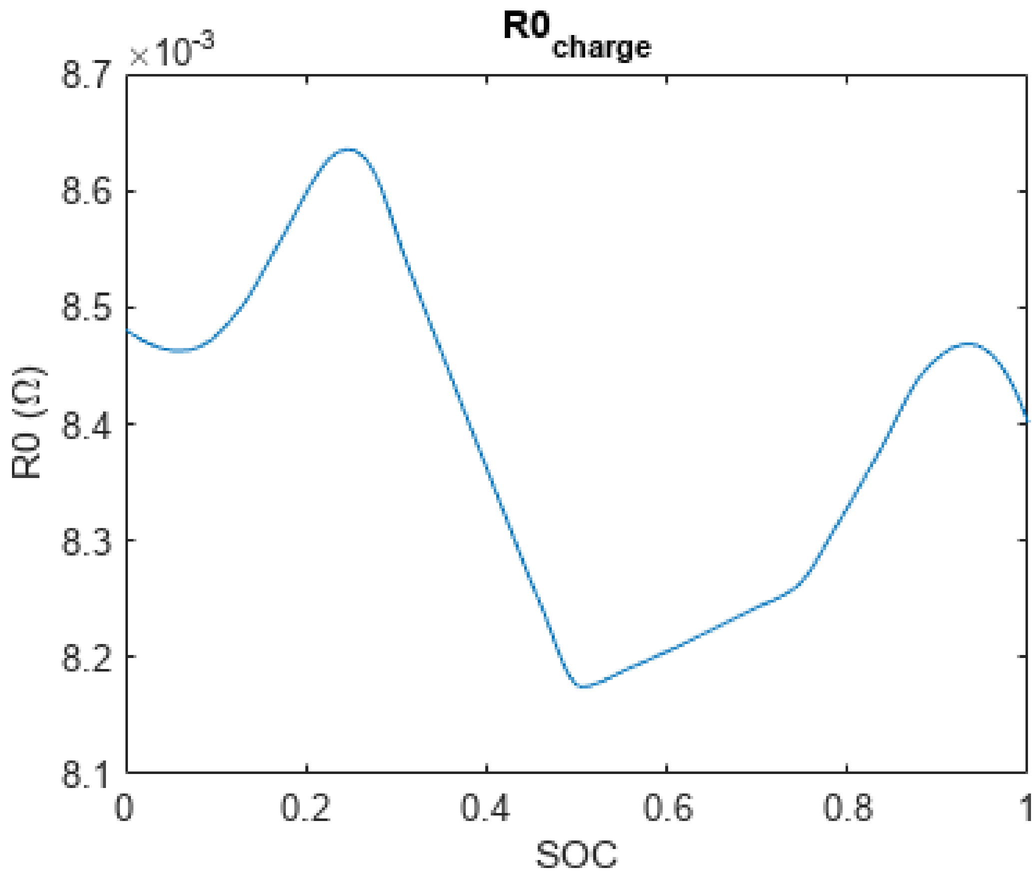


To save the parameters, enter:

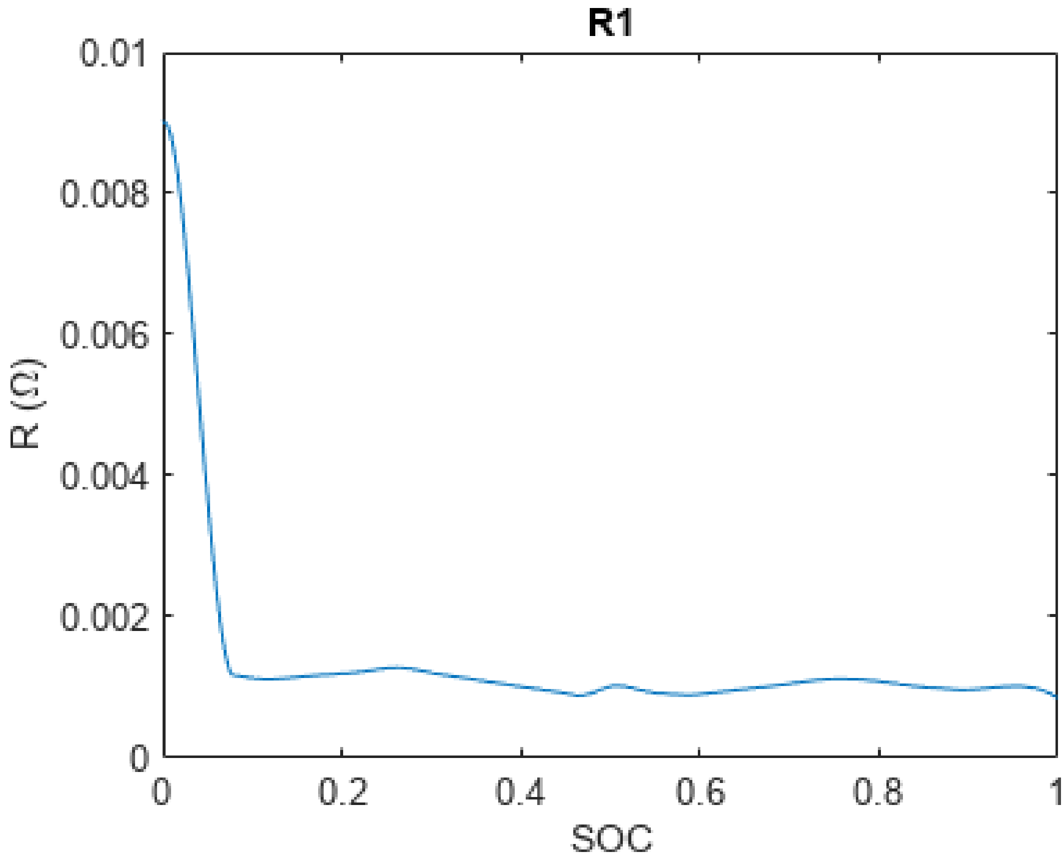
```
cellParameters = exportResultsForLib(result,...
                 fitDataForSOCpts);
```


V0
V0 (V)
4.2
4.1
4
3.9
3.8
3.7
3.6
3.5
0
0.2
0.4
0.6
0.8
1
SOC


R0discharge
×10-3
R0 (Ω)
8.7
8.6
8.5
8.4
8.3
8.2
0
0.2
0.4
0.6
0.8
1
SOC



R0 charge
×10^-3
8.7
8.6
8.5
8.4
8.3
8.2
8.1
R0 (Ω)
0
0.2
0.4
0.6
0.8
1
SOC



R1
0.01
0.008
0.006
0.004
0.002
0
R (Ω)
0
0.2
0.4
0.6
0.8
1
SOC

To save the generated parameters in a file, at the MATLAB Command Window, run:

```
save batt_BatteryCellCharacterizationResults.mat cellParameters
```

This example uses parameters stored in `batt_BatteryCellCharacterizationResults` MAT file to verify the accuracy of the fit. If the estimated parameters do not look reasonable, try fitting them with more RC pairs or try a different initial guess.

Result:

Expt. No: 12

Date :

Modelling and analysis of a hybrid electric vehicle drivetrain with a modified Indian driving cycle

Aim:

To analyze the provided hybrid electric vehicle powertrain with drive cycle data.

Software Required :

MATLAB R2022a with Simscape and Simulink.

Theory:

The hybrid electric vehicle (HEV) P3 reference application represents a full HEV model with an internal combustion engine, transmission, battery, motor, and associated powertrain control algorithms. By default, the HEV P3 reference application is configured with:

- Lithium-ion battery pack
- Mapped electric motor
- Mapped spark-ignition (SI) engine

Use the command "`autoblkHevP3Start`" to start the reference project.

The table below describes the blocks and subsystems in the reference application, indicating which subsystems contain variants.

Reference Application Element	**Description**	**Variants**
Analyze Power and Energy	Double-click **Analyze Power and Energy** to open a live script. Run the script to evaluate and report power and energy consumption at the component- and system level.	*NA*
Drive Cycle Source block — FTP75 (2474 seconds)	Generates a standard or user-specified drive cycle velocity versus time profile. Block output is the selected or specified vehicle longitudinal speed.	✓
Environment subsystem	Creates environment variables, including road grade, wind velocity, and atmospheric temperature and pressure.	
Longitudinal Driver subsystem	Uses the Longitudinal Driver or Open Loop variant to generate normalized acceleration and braking commands. • Longitudinal Driver variant implements a driver model that uses vehicle target and reference velocities.	✓

Reference Application Element	Description	Variants
	• Open Loop variant allows you to configure the acceleration, deceleration, gear, and clutch commands with constant or signal-based inputs.	
Controllers subsystem	Implements a powertrain control module (PCM) containing a P3 hybrid control module (HCM), an engine control module (ECM), and a transmission control module (TCM).	✓
Passenger Car subsystem	Implements a hybrid passenger car that contains a drivetrain, electric plant, and engine subsystems. To model the drivetrain, use the **Toggle To Simscape Drivetrain** button to switch between Simscape™ and Powertrain Blockset™ variants of the drivetrain subsystem. By default, the reference application uses the Powertrain Blockset variant. The Simscape variant incorporates physical connections to provide a flexible way to assemble components.	✓
Visualization subsystem	Displays vehicle-level performance, battery state of charge (SOC), fuel economy, and emission results useful for powertrain matching and component selection analysis.	

Simulation:
Evaluate and Report Power and Energy

Double-click **Analyze Power and Energy** to open a live script. Run the script to evaluate and report power and energy consumption at the component- and system level.

The script provides:

- An overall energy summary that you can export to an Excel® spreadsheet.
- Engine plant, electric plant, and drivetrain plant efficiencies, including an engine histogram of time spent at the different engine plant efficiencies.
- Data logging allows you to use the Simulation Data Inspector to analyze the powertrain efficiency and energy transfer signals.

Drive Cycle Source

The Drive Cycle Source block generates a target vehicle velocity for a selected or specified drive cycle. The reference application has these options.

Timing	Variant	Description
Output sample time	Continuous (default)	Continuous operator commands
	Discrete	Discrete operator commands

Longitudinal Driver

The Longitudinal Driver subsystem generates normalized acceleration and braking commands. The reference application has these variants.

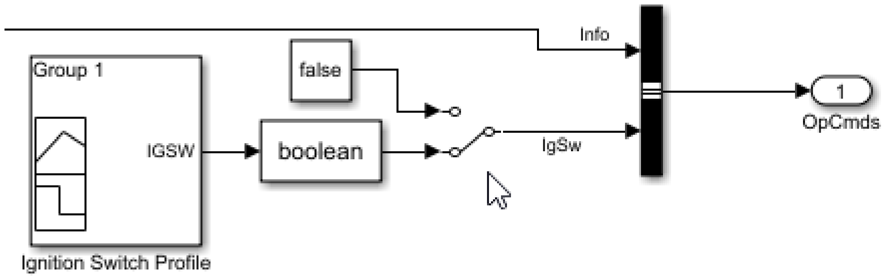
Block Variants			Description
Longitudinal Driver (default)	Control	Mapped	PI control with tracking windup and feed-forward gains that are a function of vehicle velocity.
		Predictive	Optimal single-point preview (look ahead) control.
		Scalar	Proportional-integral (PI) control with tracking windup and feed-forward gains.
	Low-pass filter (LPF)	LPF	Use an LPF on target velocity error for smoother driving.
		pass	Do not use a filter on velocity error.
	Shift	Basic	Stateflow® chart models reverse, neutral, and drive gear shift scheduling.
		External	Input gear, vehicle state, and velocity feedback generate acceleration and braking commands to track forward and reverse vehicle motion.
		None	No transmission.
		Scheduled	Stateflow chart models reverse, neutral, park, and N-speed gear shift scheduling.
Open Loop			Open-loop control subsystem. You can configure the acceleration, deceleration, gear, and clutch commands in the subsystem with constant or signal-based inputs.

To idle the engine at the beginning of a drive cycle and simulate catalyst light-off before moving the vehicle with a pedal command, use the Longitudinal Driver variant. The Longitudinal Driver subsystem includes an ignition switch signal profile, IgSw. The engine controller uses the ignition switch signal and a catalyst light-off timer to start the engine.

The catalyst light-off timer overrides the engine stop-start (ESS) stop function control while the catalyst light-off timer is counting up. During the simulation, regular ESS operation resumes after the IgSw down-edge time reaches the catalyst light-off time CatLightOffTime. If there is no torque command before the simulation reaches the EngStopTime, the ESS shuts down the engine.

To control ESS and catalyst light-off:

- In the Longitudinal Driver Model subsystem, set the ignition switch profile IgSw to 'on'.



- In the engine controller model workspace, set these calibration parameters:
  - EngStopStartEnable — Enables ESS. To disable ESS, set the value to false.
  - CatLightOffTime — Engine idle time from engine start to catalyst light-off.
  - EngStopTime — ESS engine run time after driver model torque request cut-off.

Controllers

The Controller subsystem has a PCM containing an ECM, HCM, and TCM. The controller has these variants.

Controller	Variant	Description
ECM	SiEngineController (default)	Implements the SI Controller
	CiEngineController	Implements the CI Controller
HCM	ECMS	Implements the Equivalent Consumption Minimization Strategy
TCM	TransmissionController	Implements the transmission controller

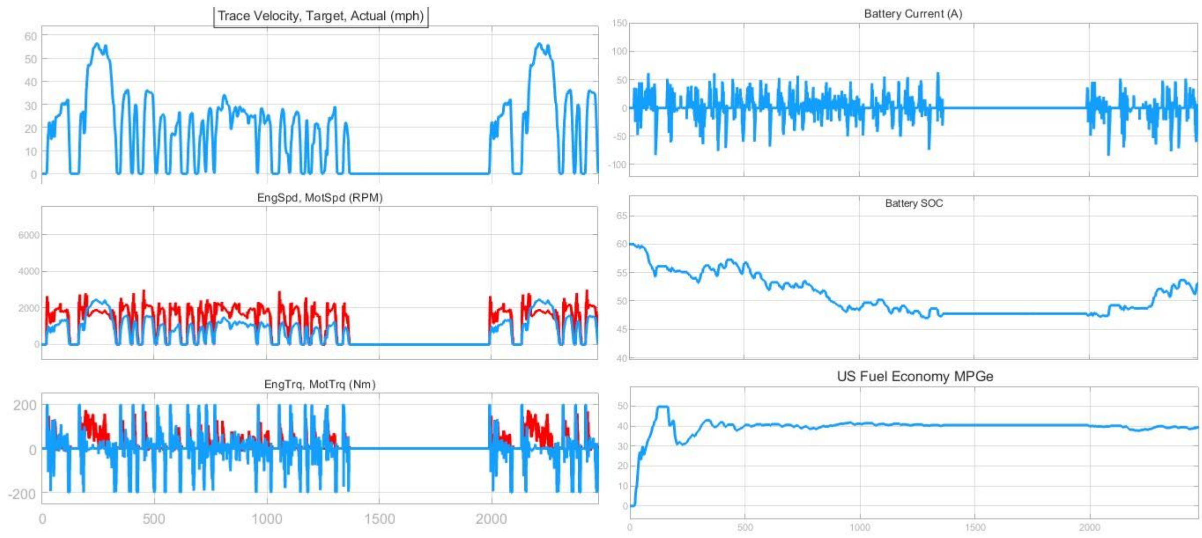
Passenger Car

The Passenger Car subsystem contains a drivetrain, electric plant, and engine subsystems to implement a passenger car. Use the CI and SI engine project templates to create your own engine variants for the reference application. The reference application has these subsystem variants.

Simulation Results:

Click Run to create an "`autoblks.pwr.PlantInfo`" object that analyzes the model energy consumption. Use the PwrUnits and EnrgyUnits properties to set the units.

After you run the simulation, the live script provides the energy summary. One can use the results to analyze energy and power losses at the component and system level.


Trace Velocity, Target, Actual (mph)
Battery Current (A)
EngSpd, MotSpd (RPM)
Battery SOC
EngTrq, MotTrq (Nm)
US Fuel Economy MPGe

Result:

Expt. No: 13

Date :

Development of supervisory control algorithms for battery management systems

Aim:

To use a constant current and constant voltage algorithm to charge and discharge a battery

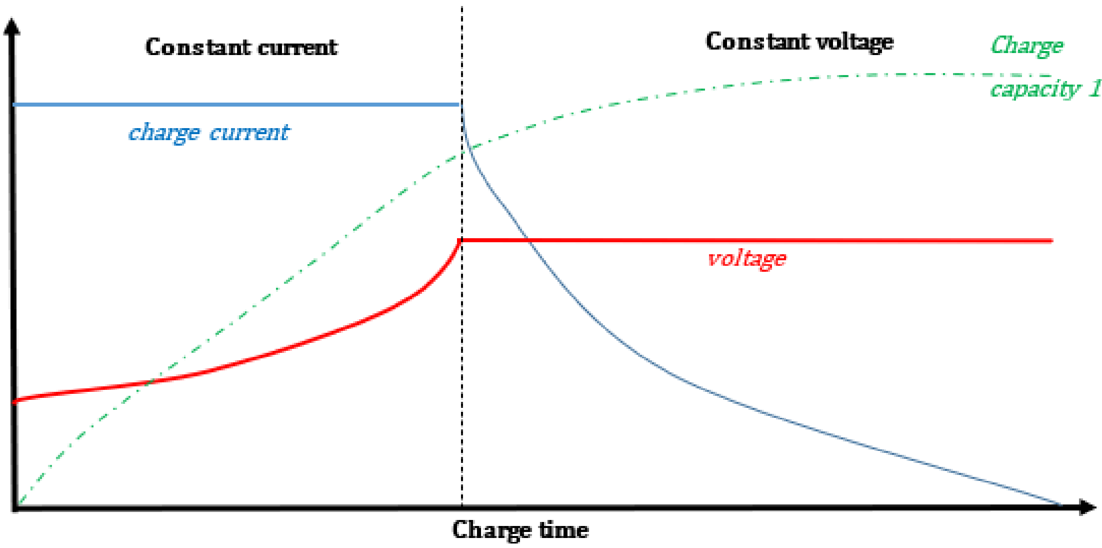
Software Required :

MATLAB R2022a with Simscape and Simulink.

Theory:

Equations

This model implements the CC-CV algorithm in constant-current and constant-voltage modes. This figure shows the operation of these modes:



This equation defines the battery reference current that the block outputs:

$$
Current = \begin{cases} Maximum\ charge\ current, & if\ battery\ is\ charging\ and\ v_{meas} < v_{\max} \\ \left(K_p + K_i \frac{1}{s}\right)(v_{\max} - v_{meas}), & if\ battery\ is\ charging\ and\ v_{meas} \geq v_{\max} \\ Maximum\ discharge\ current, & if\ battery\ is\ discharging \end{cases}
$$

where

- v_{max} is the value of the **Maximum cell voltage (V)** parameter.
- v_{meas} is the voltage of the highest cell.
- K_p and K_i are the values of the **Controller proportional gain** and **Controller integral gain** parameters.

The CC-CV is available as a block in the Simscape library. This block implements a constant-current (CC), constant-voltage (CV) charging algorithm for a battery. For a discharging battery, the block uses the value of the **CurrentWhenDischarging** input port. This diagram illustrates the overall structure of the block:

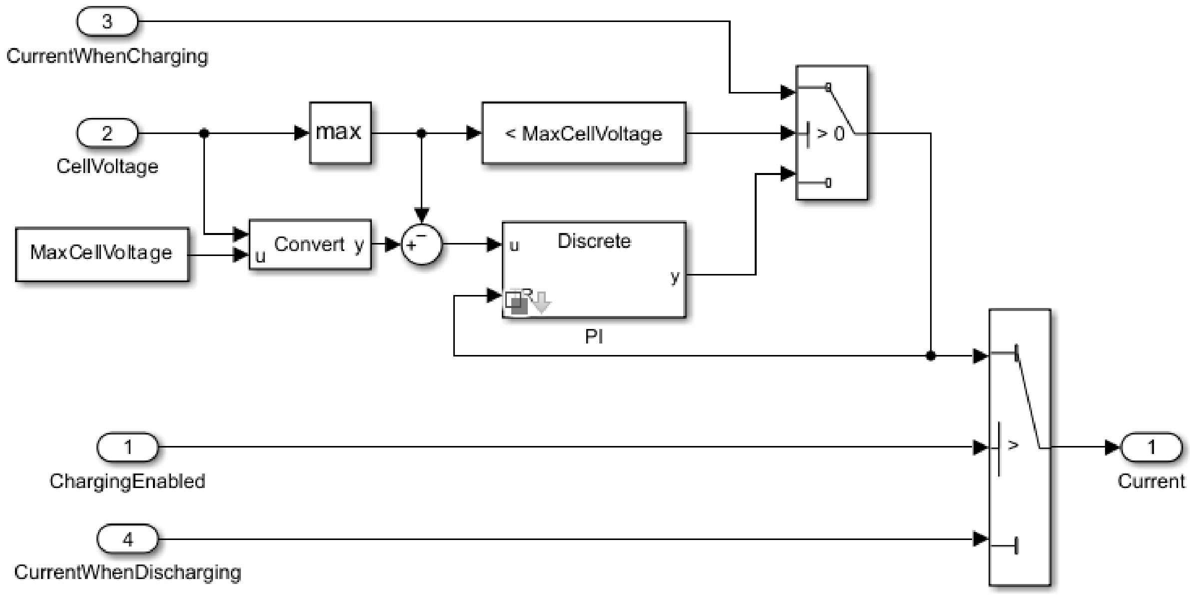


Figure 1 CC-CV subsystem – Look under mask

Model Development:

The Battery CC-CV block is charging and discharging the battery for 10 hours. The initial state of charge is equal to 0.3. When the battery is charging, the current is constant until the battery reaches the maximum voltage, and the current decreases towards 0. When the battery is discharging, a constant current is used.

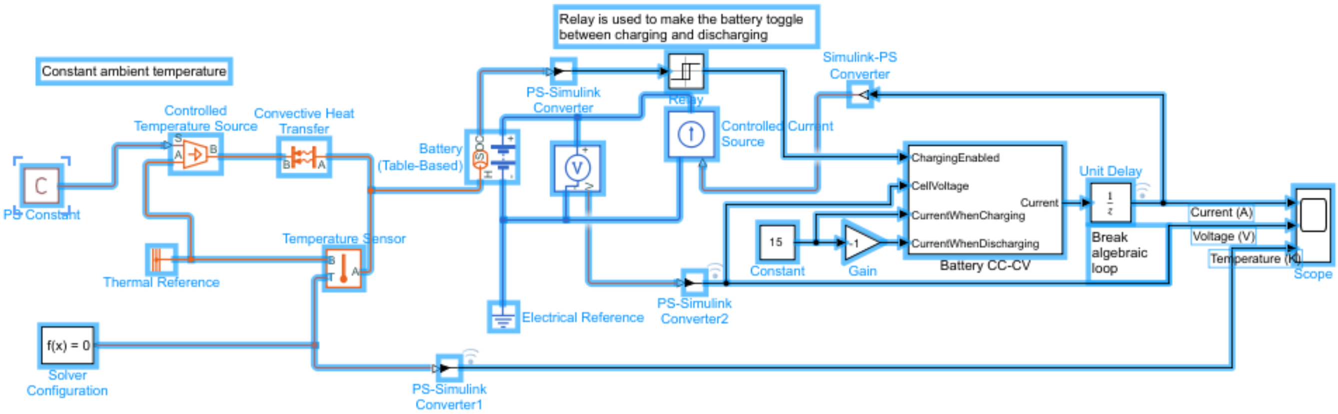


Figure 2 Simulation model

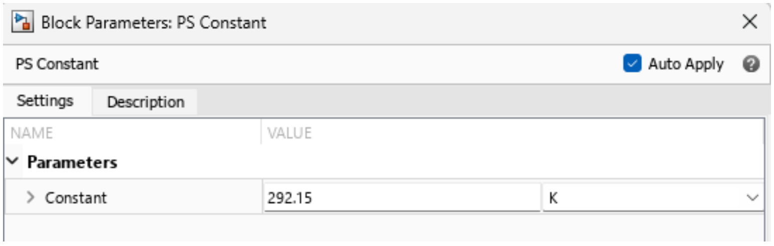


Figure 3 PS Constant

Simulation Results

The plot below shows the battery's current, voltage, and temperature under test.

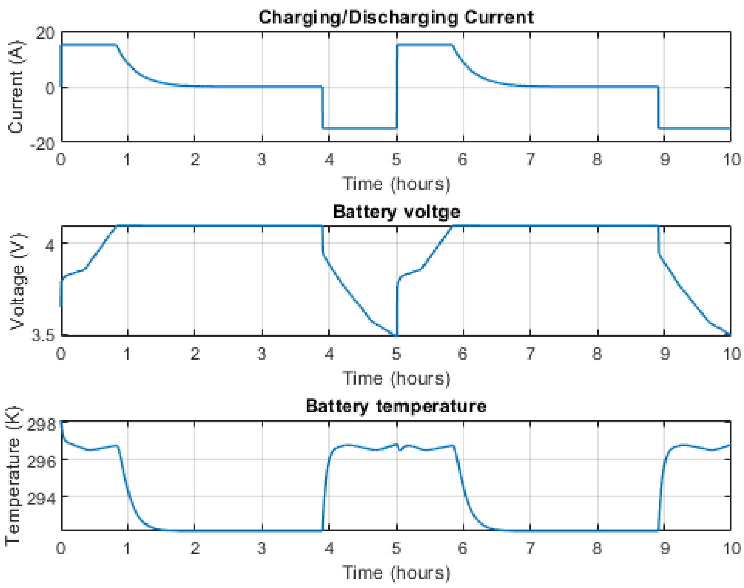


Figure 4 Battery characteristics

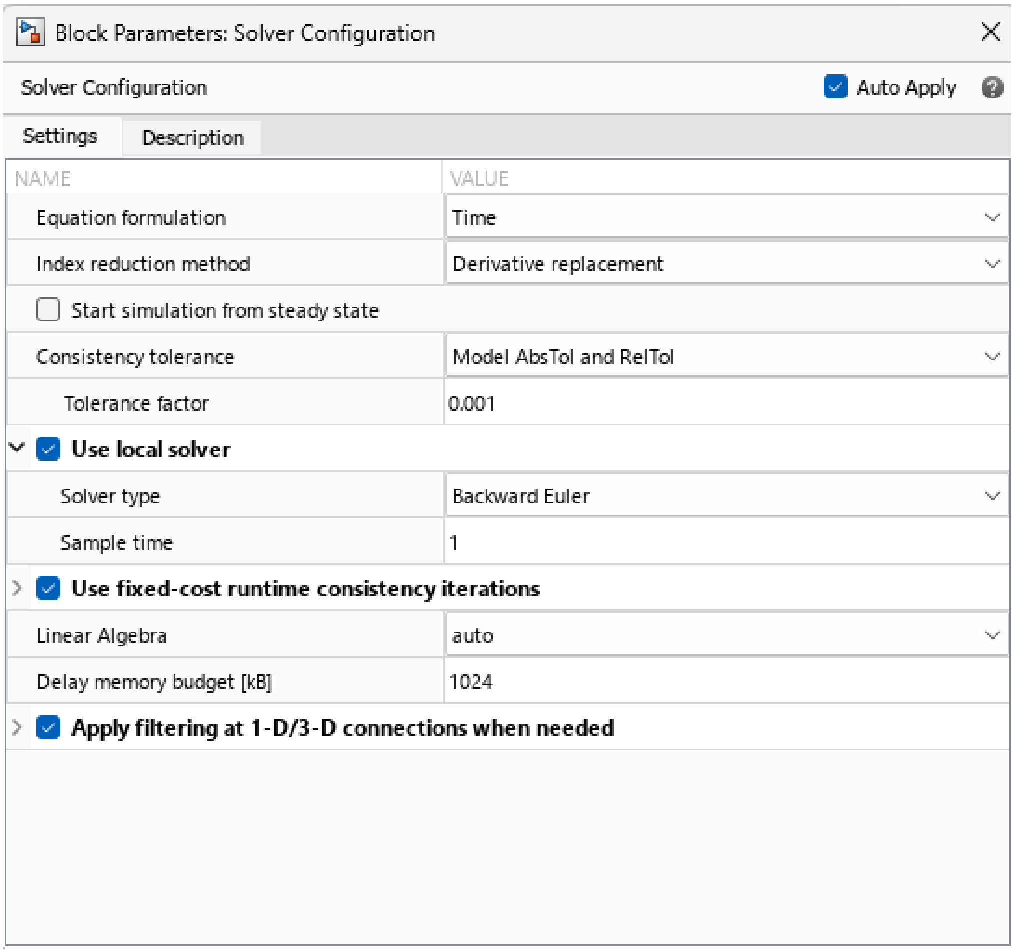


Figure 5 Solver Configuration

Battery data

Parameter	Unit	Values
Battery capacity	Ah	27
Temperature vector	K [1×3] vector	278 293 313
State of charge	% [1× 7] vector	0 0.1000 0.2500 0.5000 0.7500 0.9000 1.0000
Terminal voltage	V [7× 3] vector	3.4900 3.5000 3.5100 3.5500 3.5700 3.5600 3.6200 3.6300 3.6400 3.7100 3.7100 3.7200 3.9100 3.9300 3.9400 4.0700 4.0800 4.0800 4.1900 4.1900 4.1900
Battery charging current	A	+15
Battery discharging current	A	-15
Battery terminal resistance	Ohm [7× 3] vector	0.0117 0.0085 0.0090 0.0110 0.0085 0.0090 0.0114 0.0087 0.0092 0.0107 0.0082 0.0088 0.0107 0.0083 0.0091 0.0113 0.0085 0.0089 0.0116 0.0085 0.0089

Constant ambient temperature

Parameter	Unit	Values
Constant	K	292.15

Relay block

Parameter	Unit	Values
Switch ON point	SoC %	0.9
Switch OFF point	SoC %	0.3
Output when ON	No unit	0
Output when OFF	No unit	1

Battery CC-CV block

Parameter	Unit	Values
Controller constant	Kp	100
Controller constant	Ki	10
Maximum cell voltage	V	4.1000
Controller constant	Kaw	1
Sampling time	Second	1

Result:

Expt. No: 14

Date   :

Analysis of the state of charge estimation algorithm using the extended Kalman Filter and Unscented Kalman Filter

Aim:

To estimate the battery state-of-charge (SOC) by using a Kalman filter

Software Required :

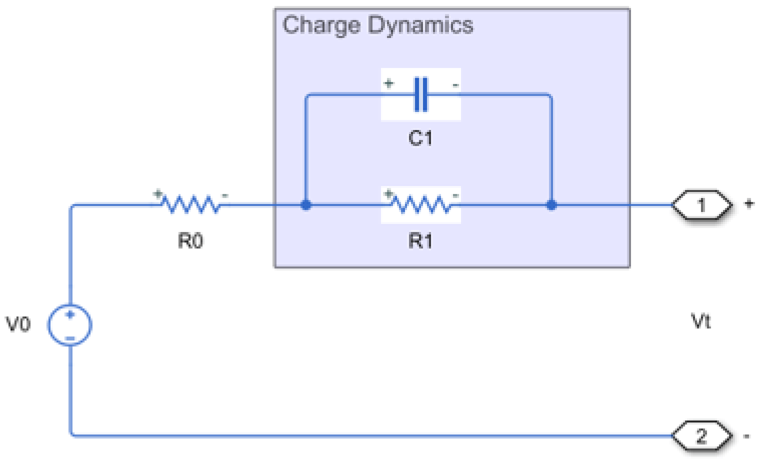
MATLAB R2022a with Simscape and Simulink.

Theory:

The SOC is defined as the ratio of the released capacity $C_{releasable}$ to the rated capacity C_{rated}. Manufacturers provide the value of the rated capacity of each battery, which represents the maximum amount of charge in the battery:

$$SOC = \frac{C_{relesable}}{C_{rated}}.$$

For SoC estimation, the equivalent circuit of the battery is used. This figure shows the equivalent circuit for a battery with one-time-constant dynamics:



The equations for the equivalent circuit, with the terminal resistance R_0 as an additional state, are:

$$\frac{dSOC}{dt} = -\frac{i}{3600AH(T)}$$

$$\frac{dV_1}{dt} = \frac{i}{C_1(SOC,T)} - \frac{V_1}{R_1(SOC,T)C_1(SOC,T)}$$

$$V_t = V_0(SOC,T) - iR_0 - V_1$$

where

- SOC is the state of charge.

- i is the current.
- V_0 is the no-load voltage.
- V_t is the terminal voltage.
- AH is the ampere-hour rating.
- R_1 is the first polarization resistance.
- C_1 is the parallel RC capacitance.
- T is the temperature.

A time constant, τ_1, for the parallel section relates the first polarization resistance R_1 and the parallel RC capacitance C_1 using the relationship $C1=\tau1/R1$.

For the Kalman filter algorithms, the block uses this state and these process and observation functions:

$$x = \begin{bmatrix} SOC & V_1 \end{bmatrix}^T$$

$$f(x,i) = \begin{bmatrix} -\dfrac{i}{3600AH(T)} \\ \dfrac{i}{C_1(SOC,T)} - \dfrac{V_1}{R_1(SOC,T)C_1(SOC,T)} \end{bmatrix}$$

$$h(x,i) = V_0(SOC,T) - iR_0 - V_1$$

Extended Kalman Filter

The EKF technique relies on linearization to approximate the nonlinear system at every time step. To linearize at every time step, the algorithm computes these Jacobians online:

$$F = \frac{\partial f}{\partial x}$$

$$H = \frac{\partial h}{\partial x}$$

The EKF is a discrete-time algorithm. After the discretization, the Jacobians for the SOC estimation of the battery are:

$$\mathbf{F}_d = \begin{bmatrix} 1 & 0 \\ 0 & e^{\frac{-T_S}{R_1 C_1}} \end{bmatrix}$$

$$\mathbf{H}_d = \begin{bmatrix} \dfrac{\partial V_{OC}}{\partial SOC} & -1 \end{bmatrix}$$

where TS is the sample time.

The EKF algorithm comprises these phases:

- **Initialization**
  - $\hat{x}(0|0)-$ State estimate at time step 0 using measurements at time step 0.
  - $\hat{P}(0|0)-$ State estimation error covariance matrix at time step 0 using measurements at time step 0.
- **Prediction**

- Project the states ahead (*a priori*):

$$\hat{\mathbf{x}}(k+1|k) = f(\hat{\mathbf{x}}(k|k), i).$$

- Project the error covariance ahead:

$$\hat{\mathbf{P}}(k+1|k) = \mathbf{F}_d(k)\hat{\mathbf{P}}(k|k)\mathbf{F}_d^T(k) + \mathbf{Q},$$

- where $\mathbf{Q}$ is the covariance of the process noise.

- **Correction**
  - Compute the Kalman gain:

$$\mathbf{K}(k+1) = \hat{\mathbf{P}}(k+1|k)\mathbf{H}_d^T(k)(\mathbf{H}_d(k)\hat{\mathbf{P}}(k+1|k)\mathbf{H}_d^T(k) + \mathbf{R})^{-1},$$

  - where R is the covariance of the measurement noise.
  - Update the estimate with the measurement y(k) (*a posteriori*):

$$\hat{\mathbf{x}}(k+1|k+1) = \hat{\mathbf{x}}(k+1|k) + \mathbf{K}(k+1)(V_t(k) - h(\hat{\mathbf{x}}(k|k), i)).$$

  - Update the error covariance:

$$\hat{\mathbf{P}}(k+1|k+1) = (\mathbf{I} - \mathbf{K}(k+1)\mathbf{H}_d)\hat{\mathbf{P}}(k+1|k).$$

Building the model:

The initial SOC of the battery is equal to 0.5. The estimator uses an initial condition for the SOC equal to 0.8. The battery keeps charging and discharging for 6 hours. The extended Kalman filter estimator converges to the real value of the SOC in less than 10 minutes and then follows the real SOC value. To use a different Kalman filter implementation, in the SOC Estimator (Kalman Filter) block, set the Filter type parameter to the desired value.

Model

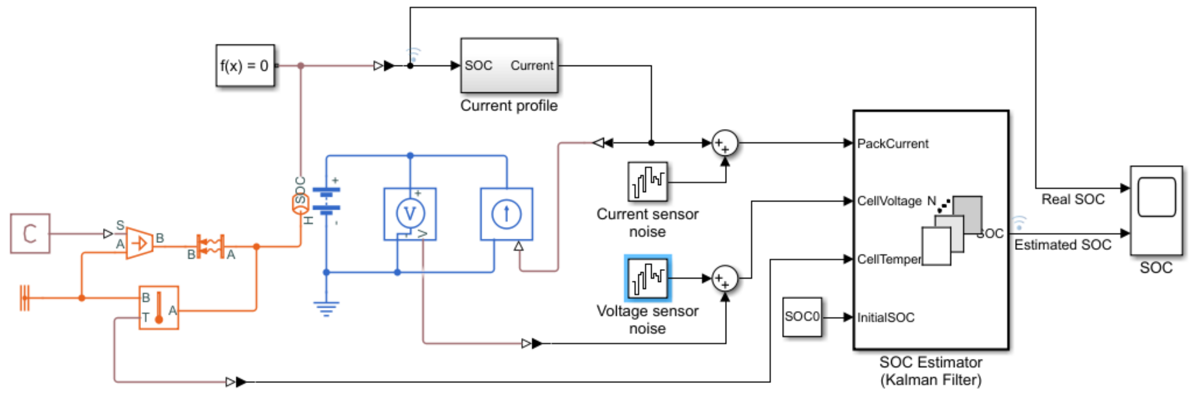


Figure 1 Simulation Model

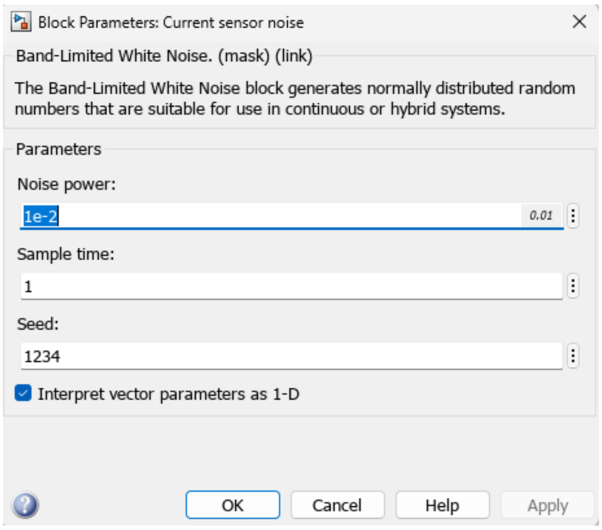


Figure 2 Current sensor noise

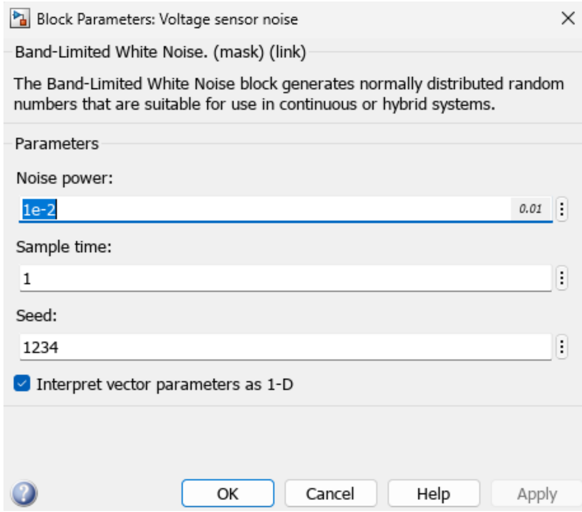


Figure 3 Voltage sensor noise

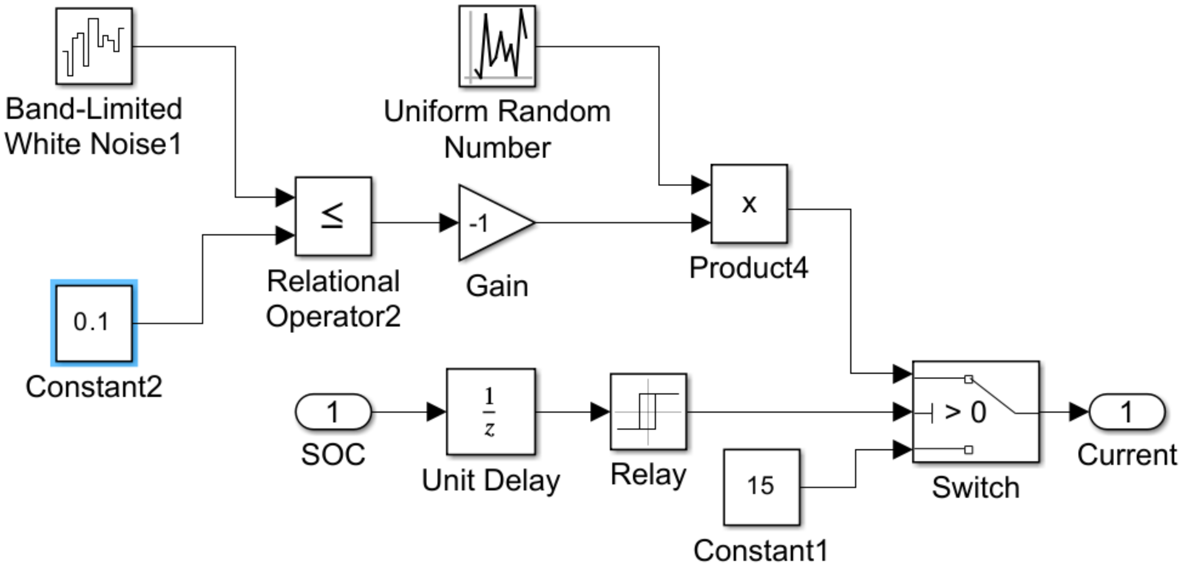
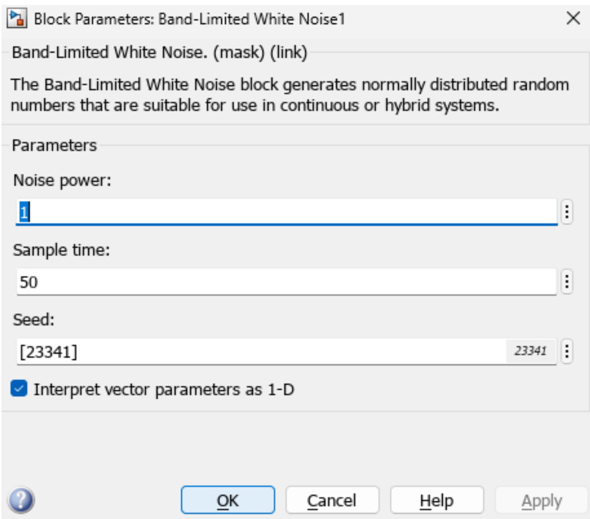
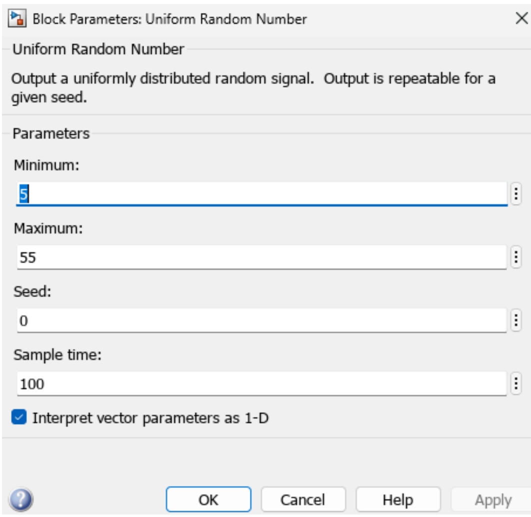
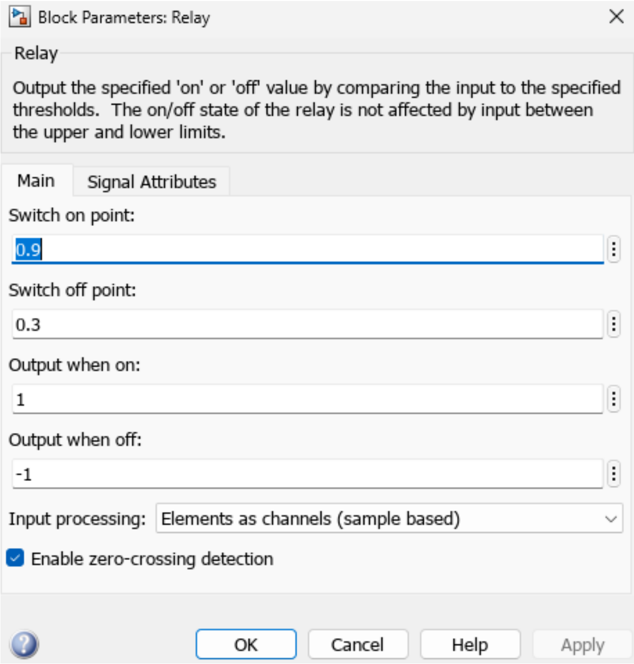


Figure 4 Current profile subsystem





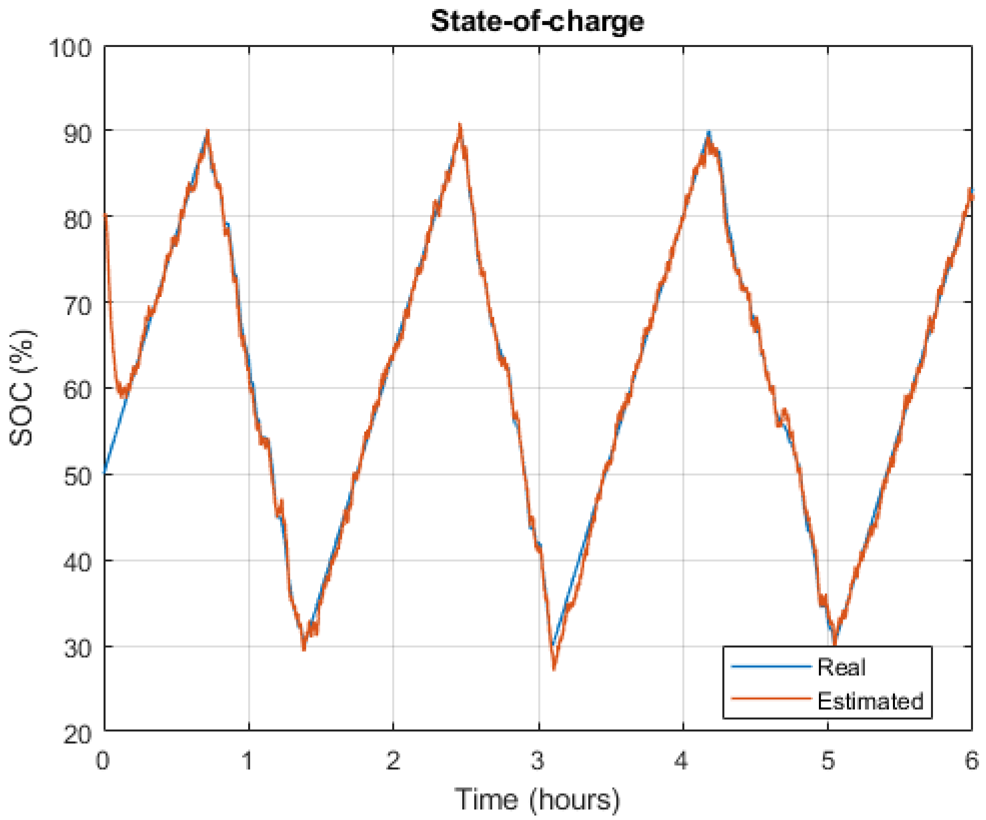


Simulation Data:

```
%% Parameters for Battery State-of-Charge Estimation
% using a Kalman filter. The initial SOC of the battery is equal to 0.5.
% The estimator uses an initial condition for the SOC equal to 0.8
%% System Parameters
SOC_vec = [0, .1, .25, .5, .75, .9, 1]; % Vector of state-of-charge values, SOC
T_vec   = [278, 293, 313];              % Vector of temperatures, T, (K)
AH      = 27;                           % Cell capacity, AH, (A*hr)
thermal_mass = 100;                     % Thermal mass (J/K)
initialSOC = 0.5;                       % Battery initial SOC
V0_mat  = [3.49, 3.5, 3.51; 3.55, 3.57, 3.56; 3.62, 3.63, 3.64;...
    3.71, 3.71, 3.72; 3.91, 3.93, 3.94; 4.07, 4.08, 4.08;...
    4.19, 4.19, 4.19];                          % Open-circuit voltage, V0(SOC,T),
(V)
R0_mat  = [.0117, .0085, .009; .011, .0085, .009;...
    .0114, .0087, .0092; .0107, .0082, .0088; .0107, .0083, .0091;...
    .0113, .0085, .0089; .0116, .0085, .0089];  % Terminal resistance, R0(SOC,T),
(ohm)

R1_mat  = [.0109, .0029, .0013; .0069, .0024, .0012;...
    .0047, .0026, .0013; .0034, .0016, .001; .0033, .0023, .0014;...
    .0033, .0018, .0011; .0028, .0017, .0011];  % First polarization resistance,
R1(SOC,T), (ohm)
tau1_mat = [20, 36, 39; 31, 45, 39; 109, 105, 61;...
    36, 29, 26; 59, 77, 67; 40, 33, 29; 25, 39, 33]; % First time constant,
tau1(SOC,T), (s)

cell_area = 0.1019; % Cell area (m^2)
h_conv    = 5;      % Heat transfer coefficient (W/(K*m^2))

%% Kalman Filter
Q    = [1e-4 0; 0 1e-4]; % Covariance of the process noise, Q
R    = 0.7;              % Covariance of the measurement noise, R
P0   = [1e-5 0; 0 1];    % Initial state error covariance, P0
SOC0 = 0.8;              % Initial SOC for estimator
Ts   = 1;                % Sample time
```

Simulation Results

The plot below shows the real and estimated battery state of charge.



Result: