ELECTRIC VEHICLE LAB MANUAL

Subject: Electric Vehicle lab

Department of Electrical Engineering
J. C. Bose University of Science and Technology
YMCA, Faridabad-121 006

DEPARTMENT OF ELECTRICAL ENGINEERING

VISION OF THE DEPARTMENT

Electrical Engineering Department congregates the challenges of new technological advancements to provide comprehensively trained, career-focused, morally strong accomplished graduates, cutting-edge researchers by experimental learning which contribute to ever-changing global society and serve as competent engineers.

MISSION OF THE DEPARTMENT

- To commit excellence in imparting knowledge through incubation and execution of high-quality innovative educational programs.
- To develop the Research-oriented culture to build national capabilities for excellent power management.
- To inculcate and harvest the moral values and ethical behavior in the students through exposure of self -discipline and personal integrity.
- To develop a Centre of Research and Education generating knowledge and technologies which lay ground work in shaping the future in the field of electrical engineering.

PROGRAM OUTCOMES (POs)

Graduates of the Electrical Engineering program at JCBUST, YMCA will be able to:

PO1. Apply knowledge of mathematics, science, engineering fundamentals, and electrical engineering specialization to the solution of engineering problems.

PO2. Identify, formulate, review literature, and analyze electrical engineering problems to design, conduct experiments, analyze data, and interpret data.

PO3. Design solutions for electrical engineering problems and design system components of processes that meet the desired needs with appropriate consideration for public health and safety and cultural, societal, and environmental considerations.

PO4. Use research-based knowledge and research methods including design of experiments, analysis and interpretation of data, and synthesis of the information to provide valid conclusions in electrical engineering.

PO5. Create, select, and apply appropriate techniques, resources, and modern engineering and IT tools including prediction and modeling to electrical engineering activities with an understanding of the limitations.

PO6. Apply reasoning informed by contextual knowledge to assess societal, health, safety, legal, and cultural issues and the consequent responsibilities relevant to professional engineering practice.

PO7. Understand the impact of electrical engineering solutions in societal and environmental contexts, and demonstrate the knowledge and need for sustainable development.

PO8. Apply ethical principles and commit to professional ethics and responsibilities and norms of the engineering practice.

PO9. Function effectively as an individual, and as a member or leader in diverse teams, and in multidisciplinary settings.

PO10. Communicate effectively on complex engineering activities with the engineering committee and with society at large, such as being able to comprehend and write effective reports and design documentation, and make effective presentations in electrical engineering.

PO11. Demonstrate knowledge and understanding of the engineering principles and management principles and apply these to one‘s own work, as a member and leader in a team, to manage projects and in multidisciplinary environments.

PO12. Recognize the need for, and the preparation and ability to engage in independent research and lifelong learning in the broadest context of technological changes in electrical engineering.

PROGRAM SPECIFIC OUTCOMES (PSOs)

PSO1. To apply state-of-the-art knowledge in analysis design and complex problem solving with effective implementation in the multidisciplinary area of Electrical Engineering with due regard to environmental and social concerns.

PSO2. To prepare graduates for continuous self-learning to apply technical knowledge and pursue research in advanced areas in the field of Electrical Engineering for a successful professional career to serve society ethically.

PROGRAM EDUCATIONAL OBJECTIVES (PEOs)

PEO1. To produce competent electrical engineering graduates with a strong foundation design, analytics and problem solving skills for successful professional careers in industry, research and public service.

PEO2. To provide a stimulating research environment so as to motivate the students for higher studies and innovation in the specific and allied domains of electrical engineering.

PEO3. To encourage the graduates to practice the profession following ethical codes, social responsibility and accountability.

PEO4. To train students to communicate effectively in multidisciplinary environment.

PEO5. To imbibe an attitude in the graduates for life-long learning process.

Syllabus

Electrical vehicle lab

L-T-P	**Internal Marks-15**
0-0-4	**ExternalMarks-35**
	Total-50

List of Experiments

1 Introduction to power electronics based electric vehicle system

2 Constant current mode of discharging/charging of EV Battery to the three-phase grid (Vehicle to Grid) and (Grid to Vehicle).

3 Open loop and close loop speed control of EV induction motor drive(V/F) in both clockwise and anti-clockwise direction.

4 Field oriented control of EV PMSM motor drive in both clockwise and anti-clockwise direction.

5 Create your own speed profile and run the propulsion motor (EV IM and EV PMSM) and analyse the speed profile, voltage, current, and power of the motor.

6 Run the propulsion motor by throttle paddle and analyse the speed, voltage, current, power of the system.

7. Testing and analysis and propulsion motor loading at different speed and torque condition.

a) Constant speed VS constant torque

b) Constant speed VS variable torque

c) Changing speed VS constant torque

8. Study of four quadrant operation of propulsion motor and analyse all the parameters like voltage, current, speed, toque, and power flow.

a)Forward motoring mode

b)Forward braking mode

c)Reverse motoring mode

d) Reverse braking mode

9. Study of grid side converter operation and analyse the active power flow and reactive power compensation.

COURSE OBJECTIVES & OUTCOMES

Course objectives:

1. **Improve the skills** related to fundamental knowledge and concept of electric vehicle.
2. **Gain the brief knowledge** about the charging and discharging of electric vehicles
3. **Understand the in-depth knowledge** of the field oriented control of EV PMSM motor drive
4. **Attain and analyze the working** of the propulsion motor under the various loading conditions in variable speed and torque conditions.
5. **Analyse the** four quadrant operation of propulsion motor.

Course outcome:

CO1	To understand the basic concept of electric vehicles and power electronics converter devices
CO2	To observe and analyze the charging and discharging of electric vehicle for constant current mode.
CO3	To analyze the field oriented control of EV PMSM motor drive
CO4	To test and analysis the propulsion motor loading under variable speed and torque condition
CO5	To analyze the four quadrant operation of propulsion motor.

Mapping of Course Outcomes (COs) with POs and PSOs

COs	PO1	PO2	PO3	PO4	PO5	PO6	PO7	PO8	PO9	PO10	PO11	PO12	PSO1	PSO2
CO1	3	3	2	3	3	1	2	1	3	3	2	2	3	3
CO2	3	3	3	3	3	1	2	1	3	3	2	2	3	3
CO3	3	3	3	3	3	1	2	1	3	3	2	2	3	3
CO4	3	3	3	3	3	1	2	1	3	3	2	2	3	3
CO5	3	3	3	3	3	1	2	1	3	3	2	2	3	3

Justification:

1. **CO1** aligns strongly with fundamental knowledge and introduction (PO1, PO2, PO4,PO5,PO9,PO10), while it moderately aligns with design and analysis (PO3, PO7,PO10,PO11). It supports PSO1,PSO2 significantly through hands-on analysis, testing, and problem-solving in motors.
2. **CO2** contributes highly to the charging and discharging of electric vehicle (PO1, PO2, PO4,PO5,PO9,PO10)and moderately to experimentation and analysis (PO3, PO7,PO10,PO11). The practical experience and performance analysis contribute to PSO1 and PSO2, reflecting real-world skills.
3. **CO3** involves field oriented method of electric vehicle, contributing significantly to all relevant POs, especially in experimentation and design (PO1, PO2, PO4,PO5,PO9,PO10) and advanced problem-solving (PSO1, PSO2).
4. **CO4** emphasizes complex analysis and machine characteristics, aligning closely with research and experimentation (PO1, PO2, PO4,PO5,PO9,PO10)along with its application to real-world problems (PO3, PSO1). The course outcome also encourages continuous learning (PSO1, PSO2).
5. **CO5** focus on the quadrant operation of electric vehicle which strongly map the (PO1, PO2, PO4,PO5,PO9,PO10) and (PSO1, PSO2).

||General Instructions||

1. Students should come well-prepared for the experiment they will be conducting.
2. Usage of mobile phones in the laboratory is strictly prohibited.
3. In the lab, wear shoes and avoid loose-fitting clothes.
4. Read and understand the experiment manual thoroughly before starting the experiment. Know the objectives, procedures, and safety precautions.
5. Before starting the experiment, check the condition of the equipment, wiring, and connections. Report any damaged or malfunctioning equipment to the lab instructor immediately.
6. Ensure all connections are made as per the circuit diagram. Double-check all connections before powering the equipment.
7. Do not switch on the power supply until the instructor has approved your setup. Always start with the minimum voltage/current required and gradually increase as needed.
8. Do not overload machines beyond their rated capacity. Overloading can damage the equipment and pose safety risks.
9. Familiarize yourself with the lab's emergency shutdown procedures, including the location of emergency switches and fire extinguishers.
10. Do not bring food or drinks into the lab to avoid accidental spills, which can lead to electrical hazards.
11. Stay attentive during the experiment. Avoid distractions like mobile phones, and do not engage in unnecessary conversation during lab work.
12. Accurately record all measurements and observations during the experiment. Ensure that all data is properly noted in your lab report.
13. If you are unsure about any procedure or face difficulties during the experiment, do not hesitate to ask the lab instructor for guidance.
14. After completing the experiment, switch off the power supply, disconnect the setup, and return all equipment to its proper place. Ensure the workspace is clean and organized.

Electrical vehicle lab

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Exp. No.	Experiment
1.	Introduction to power electronics based electric vehicle system
2.	Constant current mode of discharging/charging of EV Battery to the three-phase grid (Vehicle to Grid) and (Grid to Vehicle).
3.	Open loop and close loop speed control of EV induction motor drive(V/F) in both clockwise and anti-clockwise direction.
4.	Field oriented control of EV PMSM motor drive in both clockwise and anti-clockwise direction.
5.	Create your own speed profile and run the propulsion motor (EV IM and EV PMSM) and analyse the speed profile, voltage, current, and power of the motor.
6.	Run the propulsion motor by throttle paddle and analyse the speed, voltage, current, power of the system.
7.	Testing and analysis and propulsion motor loading at different speed and torque condition. a) Constant speed VS constant torque b) Constant speed VS variable torque c) Changing speed VS constant torque
8.	Study of four quadrant operation of propulsion motor and analyse all the parameters like voltage, current, speed, toque, and power flow. a)Forward motoring mode b)Forward braking mode c)Reverse motoring mode d) Reverse braking mode
9.	Study of grid side converter operation and analyse the active power flow and reactive power compensation.

Experiment No.1

Aim: - 1. Introduction to power electronics based electric vehicle system

Hardware and software used: - Hardware model interfaced with MATLAB Simulink model

Theory: -

Electric vehicle (EV) battery charging setups integrated with renewable energy sources represent a significant advancement in sustainable transportation and energy management. This integration involves using renewable energy, such as solar, wind, or hydropower, to power the charging infrastructure for EVs, reducing reliance on fossil fuels and minimizing carbon emissions.

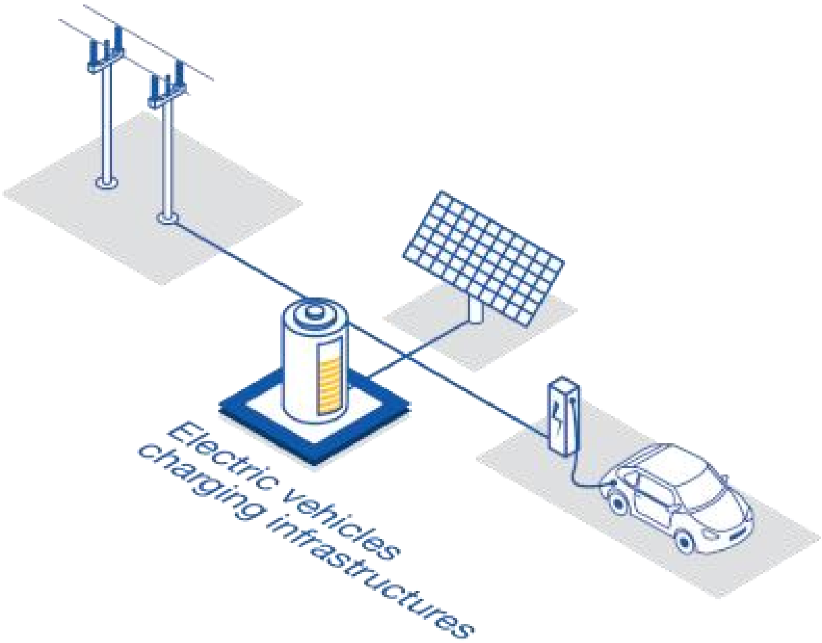


Figure 1: Renewable Energy based EV Charging.

The setup typically includes several key components: renewable energy generation systems, energy storage solutions, and smart charging infrastructure. Solar panels are often installed on residential or commercial properties, converting sunlight into electricity that can be used immediately or stored in batteries for later use. Wind turbines can also be employed, especially in regions with consistent wind patterns, to generate electricity that can be directed towards EV charging stations. Hydropower, where feasible, provides a continuous and reliable source of renewable energy for large-scale EV charging networks.

Electric Vehicle Battery Charging Setup:
This EV battery charging architecture can vary based on the number of renewable resources used. To replicate the functionality and integrity of different renewable sources, to Charge or discharge the

battery the below mentioned configuration has been designed. The resources are grid tied using Grid Side Converter, which maintains a constant DC bus Voltages for the integration of other renewable resources and EV battery.

The Setup consists of a Bi-directional power supply with bi-directional buck boost converter and EV Battery Setup with interleaved buck boost converter to charge or discharge the battery from the grid.

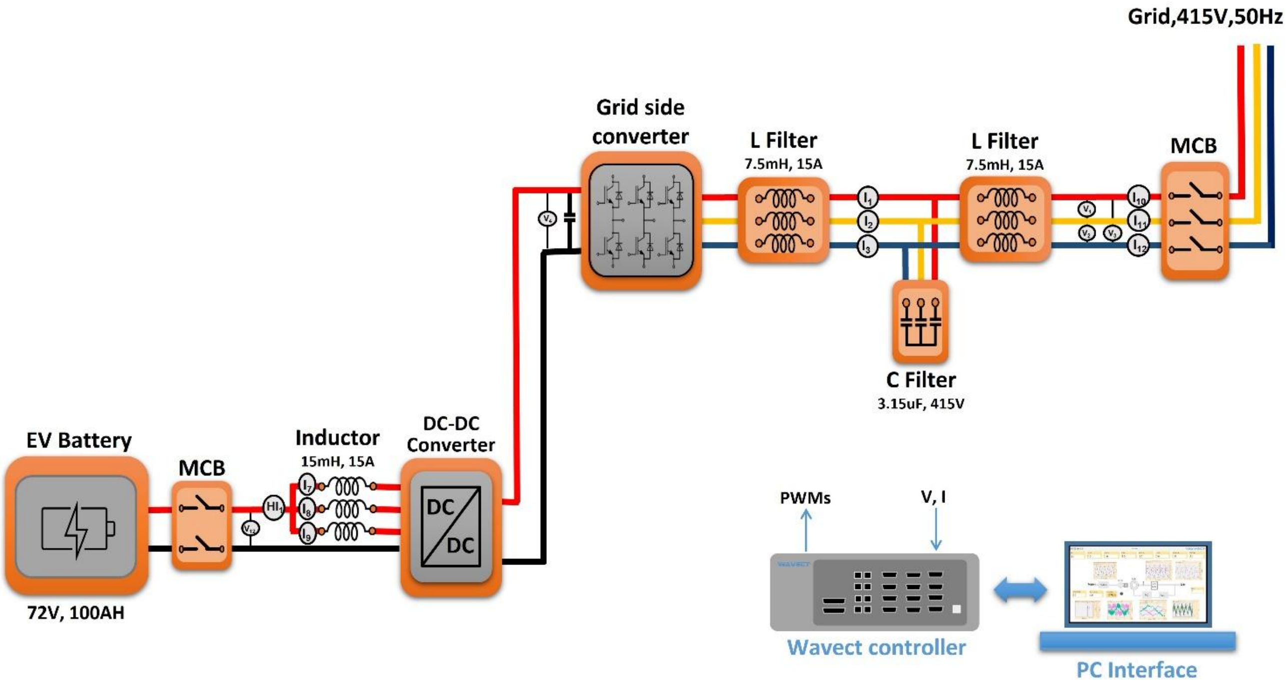


Figure 2: Architecture of WAVECT Based EV Charging/discharging Setup.

Grid Side Converter:

The function of the grid-side converter is to keep the dc-link voltage constant regardless of power flow. If a vector control method is applied, with a reference frame oriented along the grid voltage vector position, an independent control of the active and reactive power for the grid-side is guaranteed.

Connection Diagram:

The Grid side converter is connected to three phase grid via line reactor (LCL filter) to filter out the THD in the grid current by measuring the grid voltage and grid current as per the connection diagram.

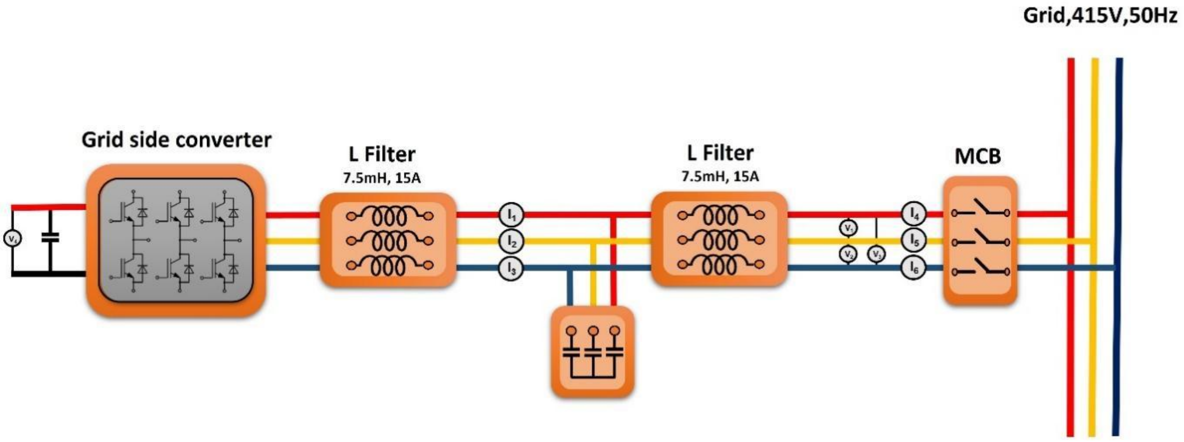


Figure 3: Connection Diagram of Grid Side Converter.

Control Algorithm:

we have implemented vector control for control active and reactive power independently in Grid side converter (GSC). Depending on the DC bus voltage the GSC will decide whether it needs to take power from the grid or needs to be sent to the grid.

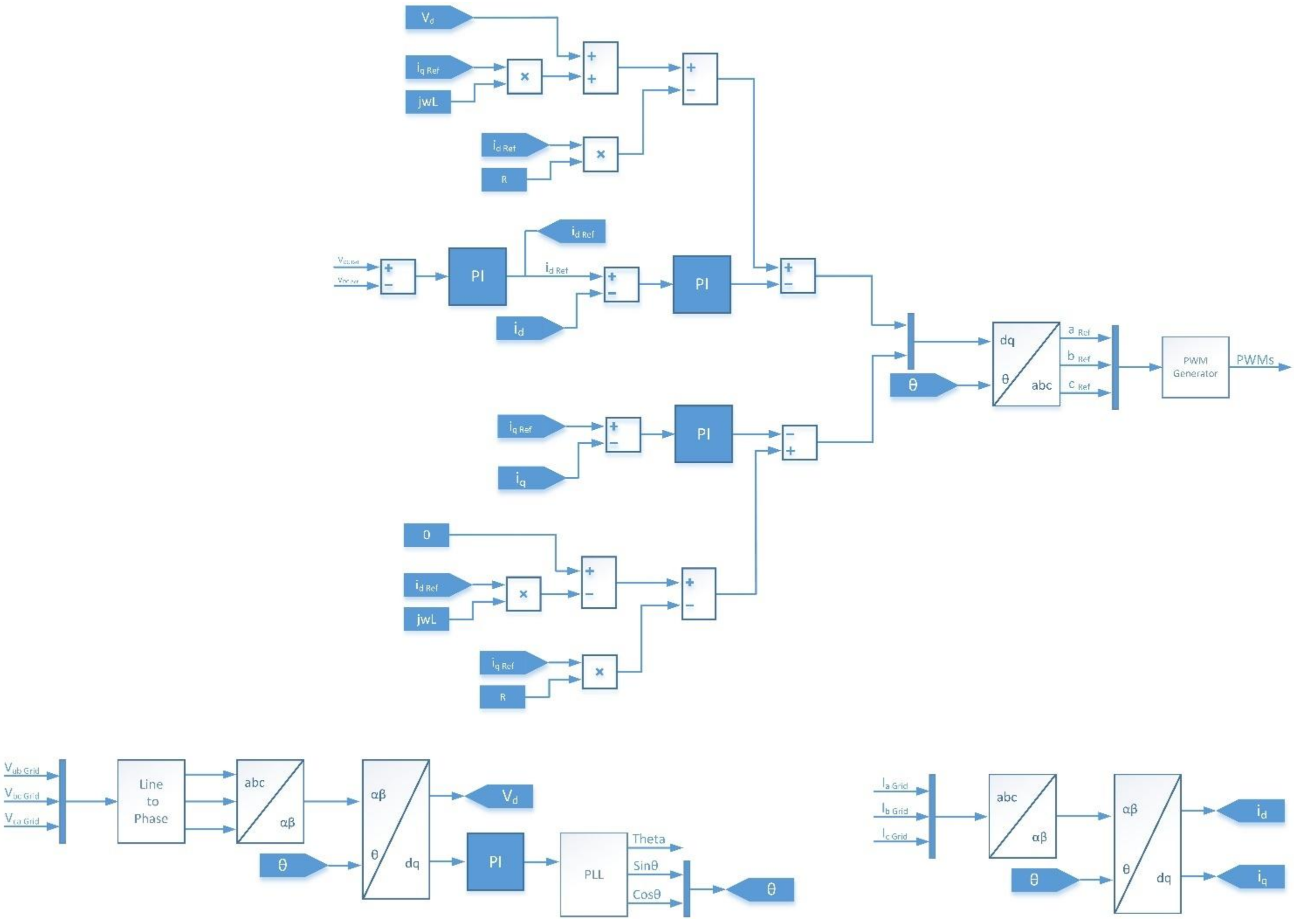


Figure 4: Control Algorithm for Grid Side Converter.

Working:
The PWM converter is current-regulated, with the q-axis current used to regulate the dc-link voltage and the d-axis current component control of grid-side PWM converter used to regulate the reactive power. The Basic component of the Grid Side Converters are as follows

- Transformations from time variant quantities to time invariant quantities and vice versa
- Phase locking loop for Grid Synchronization
- PI Controllers for current control and fixed DC Voltage level maintenance

A brief explanation of the modelling for the above-mentioned parts are as given below.

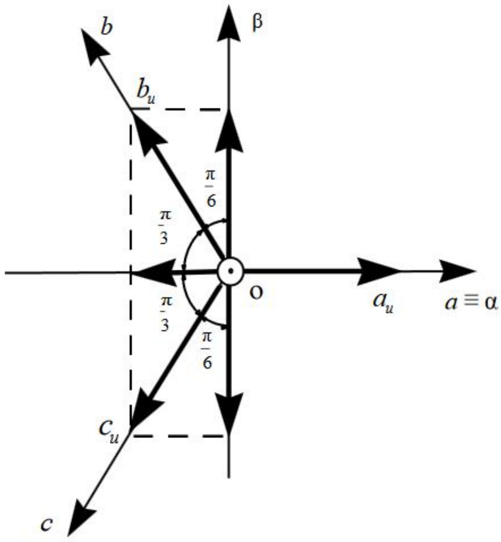
1. Transformation

Transformation is used for simplifying a complex multi-phase time invariant system into 2 phase time invariant quantity and vice versa. This helps the modelling of control systems much easier when compared considering raw data.

There are majorly two types of Transformation and its inverses namely

- abc to αβ transform
- αβ to dq transform

A transformation from the three-phase stationary coordinate system to the two phase, so called αβ,



$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = 2/3\begin{pmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{pmatrix}\begin{pmatrix}a\\ b\\ c\end{pmatrix}$$

Figure 5: abc to αβ Transformation.

stationary coordinate system. The transformation is also called as Clarkes transform.

A transformation from the two-phase stationary coordinate system to the dq synchronous reference frame. The transformation is also called a Parks transform. There are two variants of parks transform, Parks and Modified Parks transform. In modified Parks transform the d axis is consider 90 degrees behind the A phase

2.Phase Locking Loop

A phase-locked loop (PLL) is a closed-loop system in which an internal oscillator is controlled to keep the time of some external periodical signal by using the feedback loop. Synchronous Frame PLL (SF- PLL) is widely used in three-phase systems.

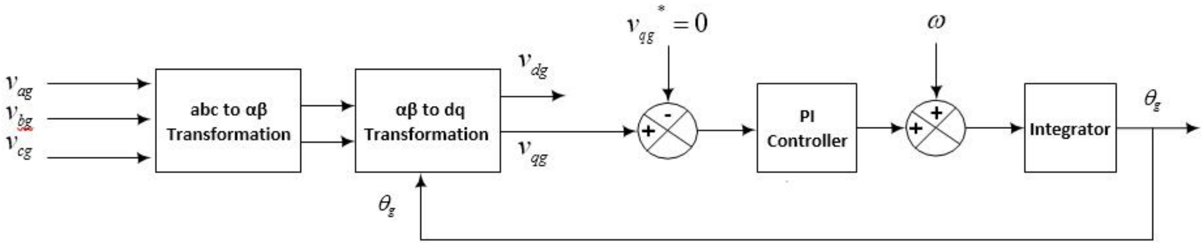
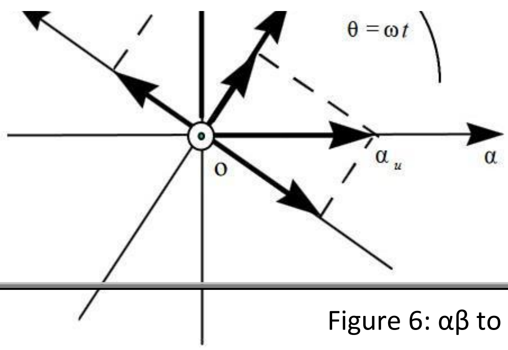


Figure 7: Synchronous Reference Frame PLL.



$$\begin{bmatrix}d\\ q\end{bmatrix} = \begin{pmatrix}\cos(\theta) & \sin(\theta)\\ -\sin(\theta) & \cos(\theta)\end{pmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix}$$

Figure 6: αβ to dq Transformation

The block diagram of SF-PLL is illustrated in above figure, where the instantaneous phase angle is detected by synchronizing the PLL rotating reference frame to the utility voltage vector. The PI controller sets the quadrature axis reference voltage Vq to zero, which results in the reference being locked to the utility voltage vector phase angle. In addition, the voltage frequency f and amplitude Vm can be obtained as the by- products. Under ideal utility conditions without any harmonic distortions or unbalance, SRF-PLL with a high bandwidth can yield a fast and precise detection of the phase and amplitude of the utility voltage vector.

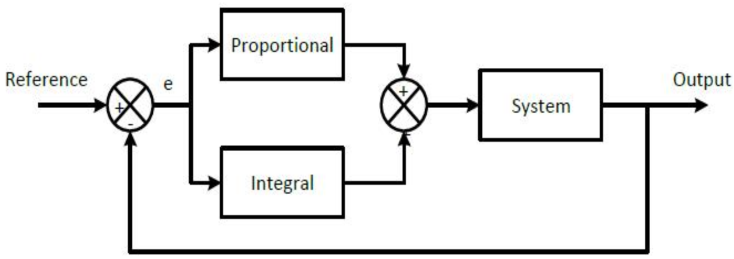
3.PI Controller

A proportional–integral (PI controller) is a control loop feedback mechanism (controller) commonly used in control systems. It includes two components (Integral and Proportional).

The proportional term (P) gives a system control input proportional with the error. Using only P control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value. In the figure below the stationary error in the system process value appears after a change in the desired value (ref). Using a too large P term gives an unstable system. Digital implementation of proportional term consists a multiplier.

The integral term (P) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value and these results in no stationary error when the reference is stable. The most common use of the I term is normally together with the P term, called a PI controller. Using only the I term gives slow response and often an oscillating system. The figure below shows the step responses to an I and PI controller. As seen the PI controller response have no stationary error and the I controller response is very slow. A block representation of digital integrator is shown below. Practical Digital Integrators are implemented based on numerical integration methods. A normal implementation is shown below It is Time domain Input-output relation is given by

$$y[n] = y[n-1] + x[n]$$



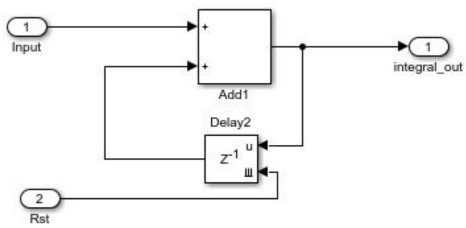


Figure 8:PI Controller and Integrator model.

ADDITIONAL NOTES

1. While connecting the system take special care that the Grid is turned off
2. Ensure that the connections are tight and firm or it may cause sparking at the terminals.
3. The Current measurement for the filters should be done just before they enter the filter reactors. This is because the control algorithm uses only filter current.
4. Ensure that the voltage is measured at the grid end and not after inductor to avoid voltage drop for the measured voltage.
5. Ensure the PWM are connected to the correct phases as per the algorithm model.
6. Verify Grid Synchronization (PLL) before turning on GSC. Turn on the system only if the Theta of the Grid is a rising ramp signal. Else, interchange the phases from the grid side connection (ie. RBY instead of RYB etc.)

Experiment No. 2

Aim: Constant current mode of discharging/charging of EV Battery to the three-phase grid (Vehicle to Grid) and (Grid to Vehicle).

Apparatus Required: MATLAB/SIMULINK installed on PC.

Theory:

EV Battery Charging Discharging Setup:

A constant current charger is implemented for the Battery Pack using a bi-directional DC to DC Converter which will convert battery voltage level to DC link Voltage level as shown.

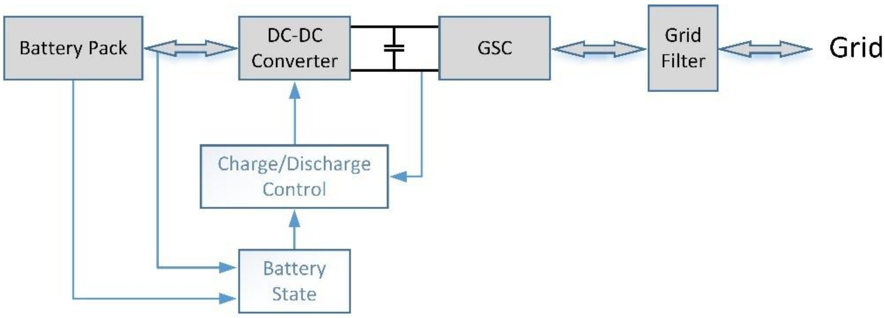


Figure 9: Architecture of EV Battery Charging Setup.

Constant current chargers vary the voltage they apply to the battery to maintain a constant current flow, switching off when the voltage reaches the level of a full charge. A simple PI controller is used to control the battery current.

Connection Diagram:

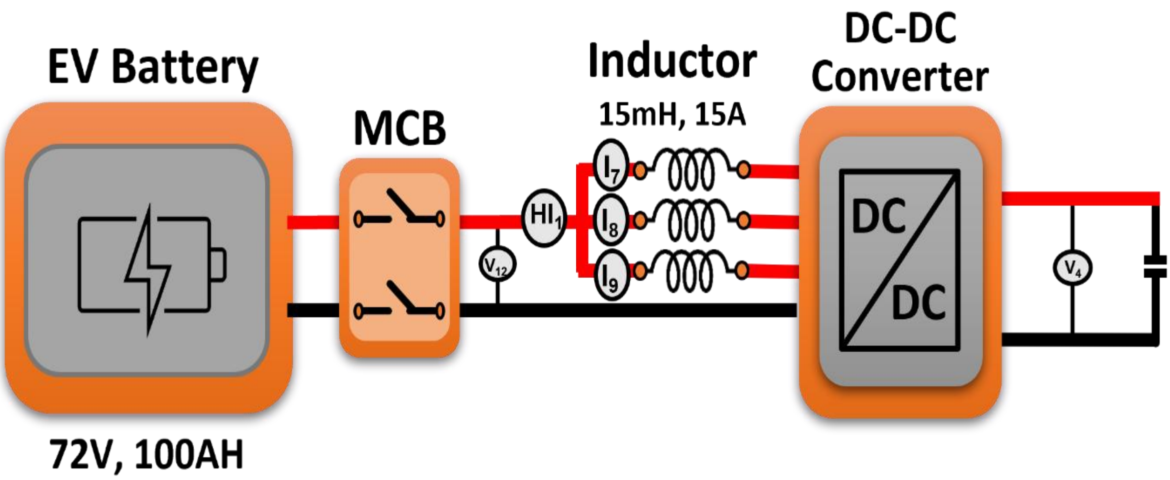


Figure 10: Connection Diagram of EV Battery Charging Setup.

Control Algorithm:

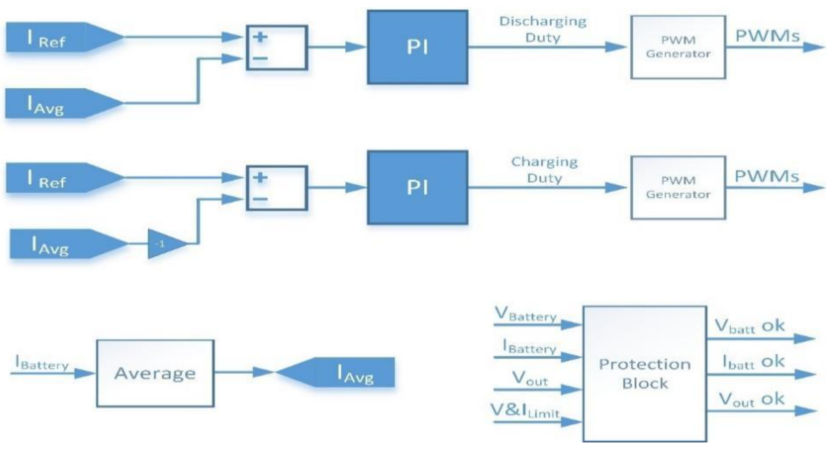


Figure 11: Control Algorithm of EV Battery Charging.

Additional Notes:

1. Additional DC Capacitor can be added at the Battery end to have a better filtered charging voltage.
2. Ensure that the polarity of the battery is properly considered.

Hardware Ratings:

Grid Specifications/ratings

- 3 Phase, Line to Line Voltage 415V, 50Hz

Grid Side Converter

- IGBT based Power Converter
    - Power Converter Configuration: Rectifier + Brake Chopper + Inverter
    - Rectifier: 415VAC Input, 560VDC Output, 45 Amps
    - Chopper: 600VDC Input, 300VDC Output, 30 Amps at 2 KHz
    - Inverter: 600V DC Link, 415VAC Output, 30 Amps at 2 KHz
    - Max Switching Frequency: Up to 20 kHz
    - Fundamental Frequency: 50 Hz
    - Type of Cooling: Forced Air
    - Ambient Temp: 40 Deg
    - Power Converter consists of 1 x SKD 160/18 module, 4 x SKM75GB12T4 IGBT modules, MD-P3 heatsink, 4 x SKYPER 32 R drivers, Electrolytic capacitor, Busbar, IGBT snubbers, fan, and thermal trip etc. All are encapsulated in polycarbonate box with Elcom knobs on it etc.

Grid Side LCL Filter

- Inductive Filter- 7.5mH/Phase, 15A
- Capacitive Filter- 3.15uF/Phase, 415V

Bidirectional DC-DC Converter for Battery:

- IGBT based Power Converter
    - Power Converter Configuration: Rectifier + Brake Chopper + Inverter
    - Rectifier: 415VAC Input, 560VDC Output, 45 Amps
    - Chopper: 600VDC Input, 300VDC Output, 30 Amps at 2 KHz
    - Inverter: 600V DC Link, 415VAC Output, 30 Amps at 2 KHz
    - Max Switching Frequency: Up to 20 kHz
    - Fundamental Frequency: 50 Hz
    - Type of Cooling: Forced Air
    - Ambient Temp: 40 Deg
    - Power Converter consists of 1 x SKD 160/18 module, 4 x SKM75GB12T4 IGBT modules, MD-P3 heatsink, 4 x SKYPER 32 R drivers, Electrolytic capacitor, Busbar, IGBT snubbers, fan, and thermal trip etc. All are encapsulated in polycarbonate box with Elcom knobs on it etc.

Buck-Boost Switching Inductor:

- EV Battery side inductor- 15mH, 15A.

Li-Ion Battery:

- The Li-ion Battery Setup of 7.3Kwh, 100Ah, 73.6V with BMS

Procedure: -

Notes before turning on the hardware:

1. The system is designed to operate EV battery charging and discharging in grid tied mode.
2. The flow of power in both directions at GSC can be observed.
3. The maximum current rating of Grid side LCL filter is 15A.
4. Battery can charge or discharge based on input command. The ref current command is given by the user. The maximum current for charge or discharge of the battery is 30A.

Modes of Operation:

Modes of operation can be performed with this setup is mentioned below:

- Power flow from EV Battery to the Grid. (Discharging).
- Power flow from the Grid to EV Battery. (Charging).

Procedure to Operate:

GSC Operation:

1. Make sure all the connections were firm as per the connection diagram.
2. Ensure that PWM's 9-10 are connected to the R phase, 11-12 are connected to the Y phase and 13-14 are connected to the B phase to the Grid Side Converter (GSC) as per the algorithm model.

3. First turn on the Grid side MCB then turn ON the MCB provided in the In-rush Current limiting box. This will help the capacitors (DC link) to slowly charge with the help of power resistors which are connected parallelly across the contactor terminals, a timer relay is placed to energize the contactor once the capacitor is charged enough to limit the in-rush current.
4. Check the Phase voltages and turn ON PWM_en, then turn on PLL (PLL_en=1) and check the Grid synchronization (Theta). If the Theta of the Grid is a rising ramp signal, then move further or else, turn off the grid and interchange the phases from the grid side connection (I.e.. RBY instead of RYB etc.)
5. Observe the DC link voltage.
6. Enter Vdc_ref 20-30V more than DC-link actual voltage and turn ON GSC. Check whether the DC link voltage is following the reference voltage and parallelly observe the grid currents and GSC currents.

EV Battery Operation:

1. Once the GSC is functioning properly, move onto Battery charging and discharging operation.
2. Turn ON MCB 1 and MCB 3 at the Battery side. Observe the voltage across the battery and charge or discharge the battery accordingly.
3. Make sure that PWM 1-2 are connected to R phase, PWM 3-4 are connected to Y phase and PWM 4-6 are connected to B phase of the Battery Side Buck-Boost Converter.
4. Enter V_{max} = 90 and V_{min} =70 to limit according to battery input voltage level.
5. Then enter current limit and reference current at which rate you want to charge the battery (Battery_I_limit and Battery_ref_I) positive value (maximum reference current is 30A).
6. Ensure that the Battery current limit is always 5A more than the Battery reference current.
7. For discharging, enable bat_En and observe the power flow form battery to grid and make sure that the actual current is matching with the reference current entered.
8. For Charging enter the current reference (Positive value).
9. Then first turn on ch_DIS and then bat_En. Observe the power flow from grid to battery by entering different current values.
10. Since the Battery is rated for higher current, it is connected to High Current sensor 1 and in turn mapped with ADC 5 with the controller. User must continuously monitor the Actual current of the Battery during both Charging and Dis-charging conditions.

Once the operation is complete, Turn OFF the Battery charging/discharging, turn off GSC, Turn OFF PLL_en and Turn OFF PWM_en. Turn OFF the GRID MCB and turn OFF MCB 1 and MCB 3 at the Battery side.

NOTE – Even if all the Mains are turned OFF; the DC link will be still charged and will discharge slowly by the power resistors connected across them. So, make sure that you monitor the DC link voltage and ensure that it is completely discharged before leaving the setup.

Result:

Hardware Results:

Grid Sive Converter:

Figure 12: Grid Side Converter Panel.

From the above figure we can see that after turning on the PLL grid theta matches with ‘R’ phase voltage. And depending on the reference voltage given by the user the GSC maintains the reference voltage.

EV Battery Operation:

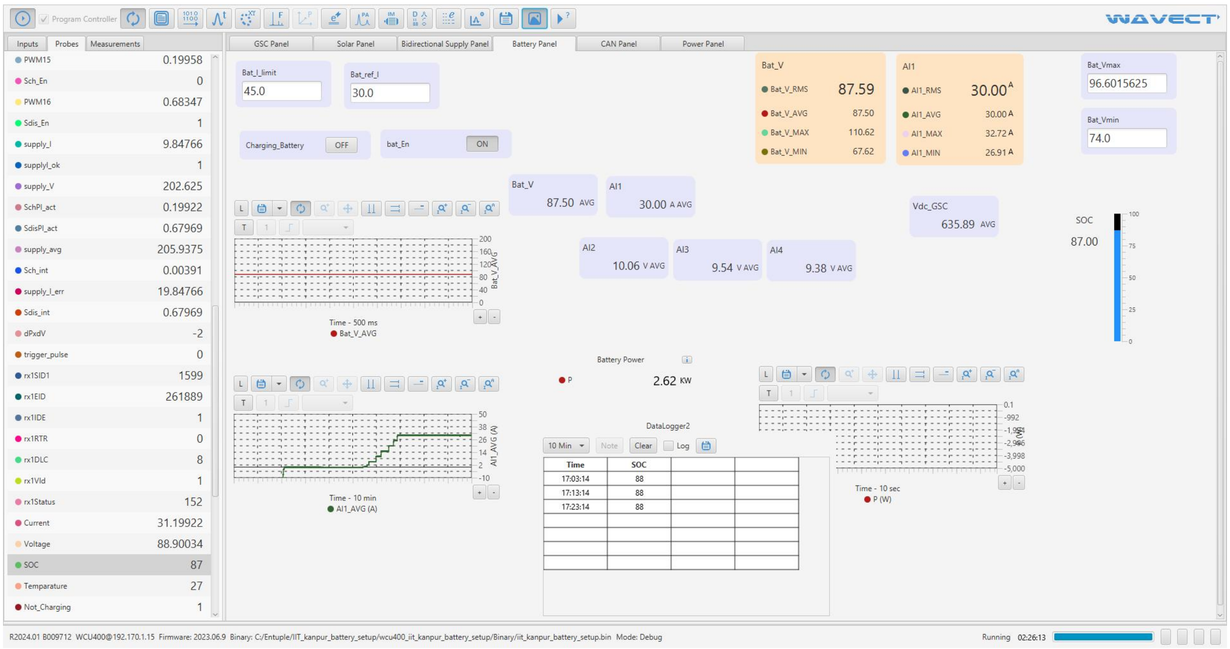


Figure 13: EV Battery Charging Discharging Panel.

Power Measurement:

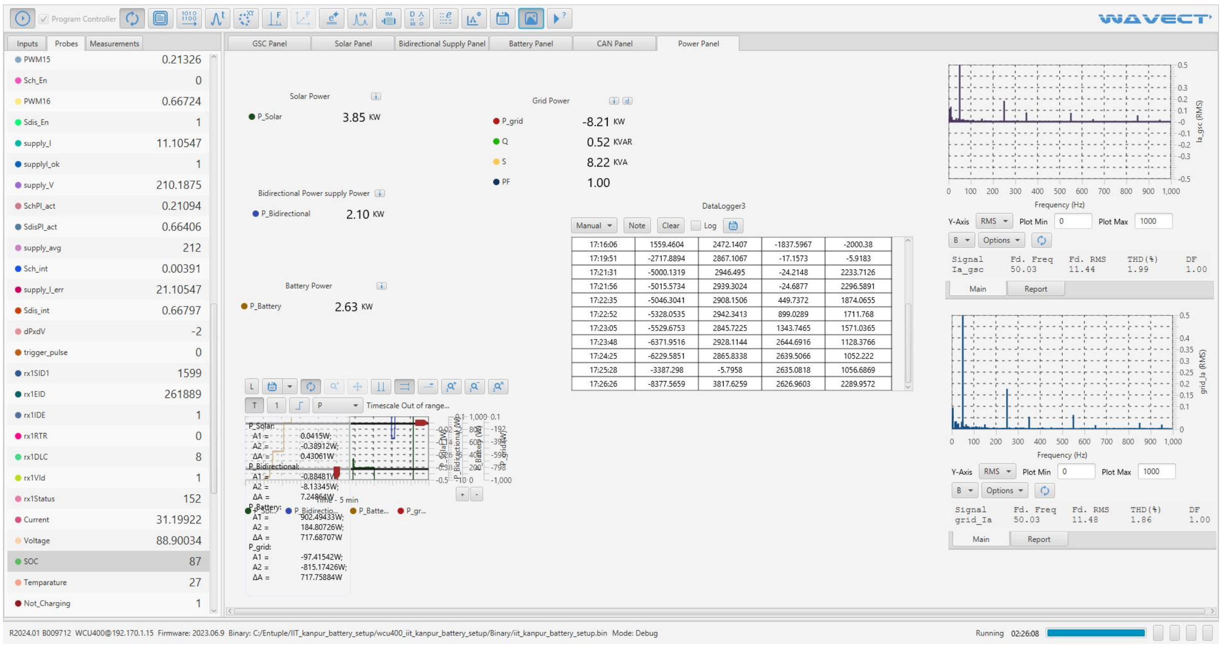


Figure 14: Power Measurement panel.

Experiment No. 3

Aim: Open loop and close loop speed control of EV induction motor drive(V/F) in both clockwise and anti-clockwise direction.:

Apparatus: Hardware set up

Theory:

The EV Induction Motor drive consists of Li-ion Battery, DC-DC converter, Converter for IM motor drive and EV IM motor of 3KW, 3000RPM.The Li-ion battery of 73.6V,100AH is used as a source for the IM drive. The Battery pack has BMS along with CAN communication. By using CAN, we can read battery data like voltage, current, SOC, Charging status and cell level voltage etc.DC-DC converter is used for bidirectional loading of EV IM (i, e. Motoring and regeneration). Since the motor is of 60V and the battery is of 73.6V, during motoring mode the DC-DC converter is in Buck mode and in regeneration mode it is in Boost mode (Charge the battery from regeneration power). Speed control of IM motor is done using V/F operation where we can maintain the stator flux constant (Detailed explanation is there below). The 2 level 3 leg IGBT based converter of high current and low voltage is used for this.

Working of Induction Motor

Induction motors derive their name from the way the rotor magnetic field is created. The bars forming the conductors along the rotor axis are connected by a thick metal ring at the ends, resulting in a short circuit. The sinusoidal stator phase currents fed in the stator coils create a magnetic field rotating at the speed of the stator frequency (ωs). The rotating stator magnetic field induces currents in the short-circuited rotor. These currents produce the rotor magnetic field, which interacts with the stator magnetic field, and produces torque, which is the useful mechanical output of the machine.

Since the induction mechanism needs a relative difference between the motor speed and the stator flux speed, the induction motor rotates at a frequency near, but less than that of the synchronous speed. This slip must be present, even when operating in a field-oriented control. The rotor in an induction motor is not externally excited. This means that there is no need for slip rings and brushes. This makes the induction motor robust, inexpensive and requires less maintenance. Torque production is governed by the angle formed between the rotor and the stator magnetic fluxes.

V/F Control of IM

Another major advantage of the Induction Motor over other motors is the ease with which its speed can be controlled. There are various methods for the speed control of an Induction Motor. V/f Control is the most popular and has found widespread use in industrial and domestic applications because of its ease-of-implementation.

However, it has inferior dynamic performance compared to vector control. Thus, in areas where precision is required, V/f Control are not used. The various advantages of V/f Control are as follows:

i. It provides good range of speed.

ii. It gives good running and transient performance.

iii. It has low starting current requirement.

iv. It has a wider stable operating region.

v. Voltage and frequencies reach rated values at base speed.

vi. The acceleration can be controlled by controlling the rate of change of supply frequency.

vii. It is cheap and easy to implement.

Synchronous speed can be controlled by varying the supply frequency. Voltage induced in the stator is $E_1 \propto \varphi f$ where φ is the air-gap flux and f is the supply frequency. As we can neglect the stator voltage drop, we obtain terminal voltage $V_1 \propto \varphi f$.

Any reduction in the supply frequency without a change in the terminal voltage causes an increase in the air gap flux which will cause magnetic saturation of motor. Also, the torque capability of motor is decreased. Hence while controlling a motor with the help of VFD or Variable Frequency Drive we always keep the V/f ratio constant.

However, the frequency (or synchronous speed) is not the real speed because of a slip as a function of the motor load. At no-load torque, the slip is very small, and the speed is nearly the synchronous speed. Thus, the simple open-loop Vs/f (or V/Hz) system cannot precisely control the speed with a presence of load torque. The slip compensation can be simply added in the system with the speed measurement.

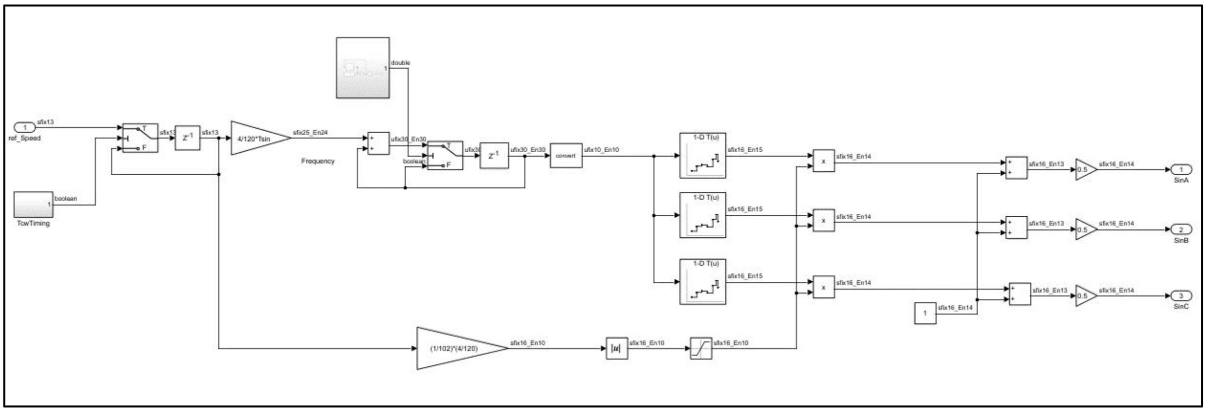


Figure 15: V/F control of induction motor.

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$V_2 = \frac{N_2}{N_1} \times V_1$$

$$V_2 = \frac{V_1 \times P}{120 f_1} \cdot N_2$$

$$V_2 = \frac{P}{120 f_1} \cdot V_1 \cdot N_2$$

$$V_2 = \frac{4}{120 \times 102} \cdot V_1 \cdot N_2$$

$$V_2 = \frac{4}{120 \times 102} \times 1 \cdot N_2$$

Where,

N1= Synchronous speed (3000 rpm)

f1= Stator frequency (102 Hz)

P= Number of poles (4)

V1= Rated stator voltage (V1=1 for modulation index)

Since the stator flux is constantly maintained (independent of the change in supply frequency), the torque developed depends only on the slip speed. By regulating the slip speed, the torque and speed of an AC induction motor can be controlled with the constant V/Hz principle through regulation of slip speed where a PI controller is employed to regulate the slip speed of the motor to keep the motor speed at its set value.

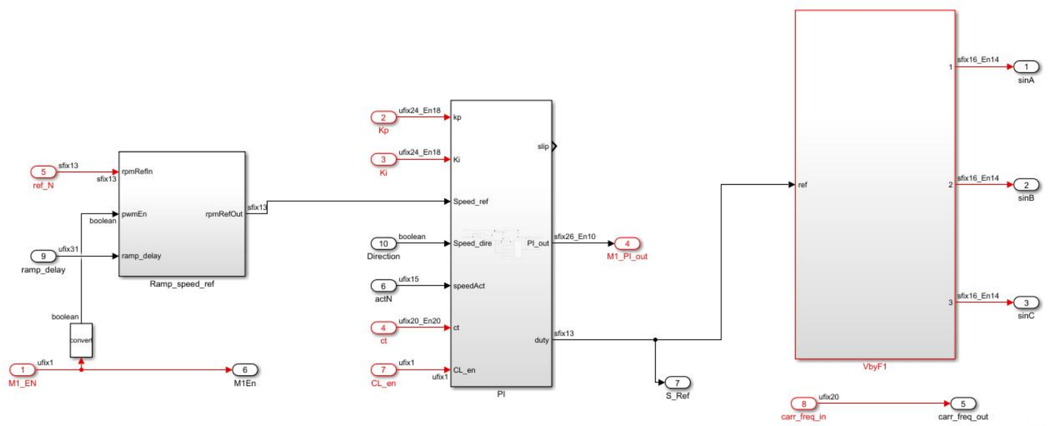


Figure 16: Close loop V/F control.

PI Controller

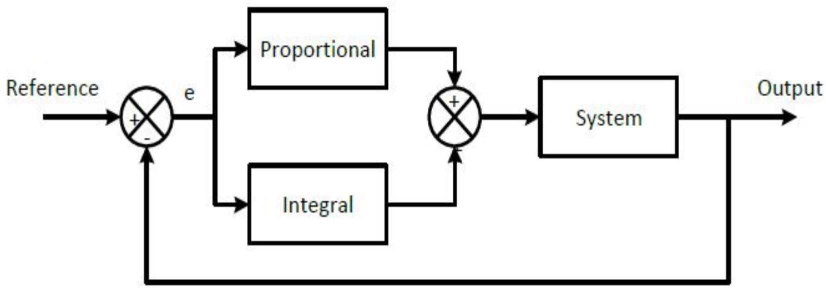
A proportional–integral (PI controller) is a control loop feedback mechanism (controller) commonly used in control systems. It includes two components (Integral and Proportional).

The proportional term (P) gives a system control input proportional with the error. Using only P control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value. In the figure below the stationary error in the system process value appears after a change in the desired value (ref). Using a too large P term gives an unstable system. Digital implementation of proportional term consists of a multiplier.

The integral term (I) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value and these results in no stationary error when the reference is stable. The most common use of the I term is normally together with the P term, called a PI controller. Using only the I term gives slow response and often an oscillating system. The figure below shows the step responses to an I and PI controller. As seen the PI controller response have no stationary error and the I controller response is very slow. A block representation of digital integrator is shown below. Practical Digital Integrators are implemented based on numerical integration methods. A normal implementation is shown below.

It is Time domain Input-output relation is given by.

$$y[n] = y[n-1] + x[n]$$



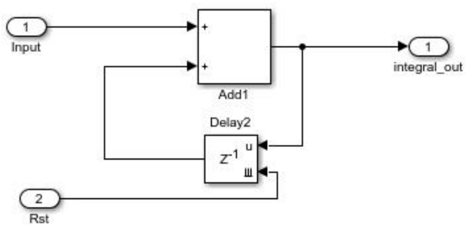


Figure 17: PI controller and integrator model.

Load Emulator:
Load Emulator (called as AC dynamometer) is consisting of load side converter, Front end converter, Torque sensor, Induction machine and filters etc.

Load side converter is used to control the slip of the loading Induction machine depending on the torque reference/profile given by the user.

Front end converter is a bidirectional converter, and its main function is to maintain the DC link voltage regardless of power flow.Torque sensor is used to sense the actual torque of the load.Induction motor is used to load the propulsion motor for different load profiles. Depending on the slip given the IM will operate in motoring and regeneration mode there by it can load propulsion motor for all four quadrants. Front-End Converter: Bidirectional DC-AC Converter

The function of the Front-end converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. If a vector control method is applied, with a reference frame oriented along the grid voltage vector position, an independent control of the active and reactive power for the grid-side is guaranteed. The PWM converter is current-regulated, with the d-axis current used to regulate the dc-link voltage and the q-axis current component control of grid-side PWM converter used to regulate the reactive power. The Basic component of the Grid Side Converters are as follows.

- Transformations from time variant quantities to time invariant quantities and vice versa (Explained above)
- PI Controllers for current control and fixed DC Voltage level maintenance (Explained above)
- Phase locking loop for Grid Synchronization. A brief explanation of the modelling is given below.

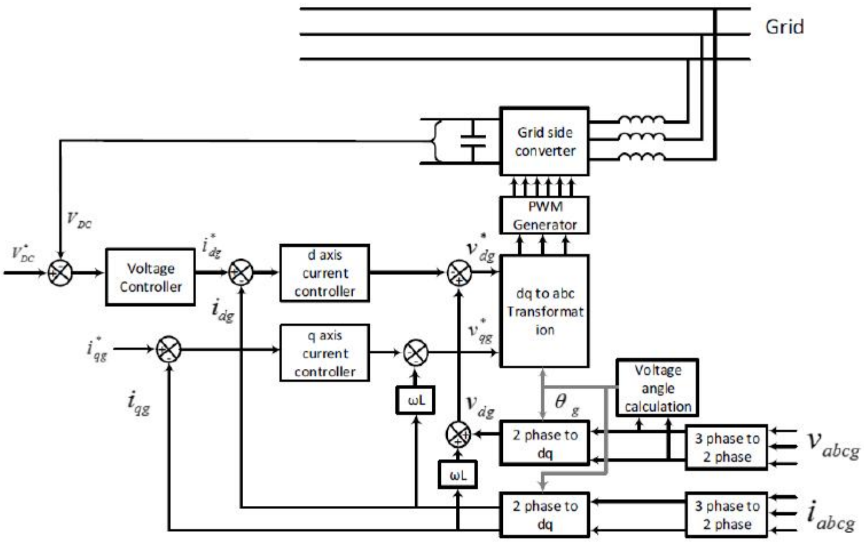


Figure 18: Control algorithm for Front-End Converter.

Phase Locking Loop

A phase-locked loop (PLL) is a closed-loop system in which an internal oscillator is controlled to keep the time of some external periodical signal by using the feedback loop. Synchronous Frame PLL (SF- PLL) is widely used in three-phase systems.

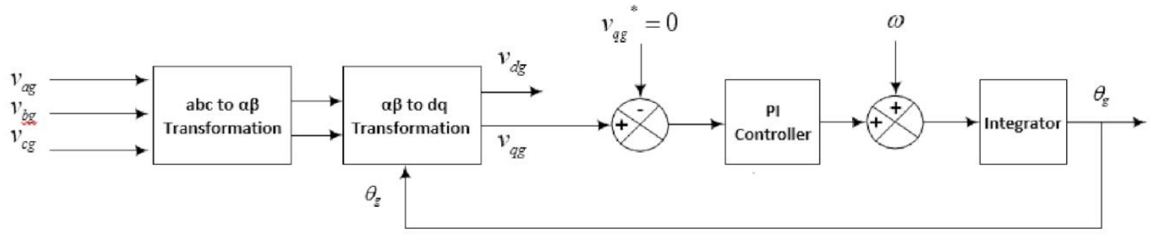


Figure 19: Synchronous reference frame PLL

The block diagram of SF-PLL is illustrated in above figure, where the instantaneous phase angle is detected by synchronizing the PLL rotating reference frame to the utility voltage vector. The PI controller sets the quadrature axis reference voltage Vq to zero, which results in the reference being locked to the utility voltage vector phase angle. In addition, the voltage frequency f and amplitude Vm can be obtained as the by- products. Under ideal utility conditions without any harmonic distortions or unbalance, SRF-PLL with a high bandwidth can yield a fast and precise detection of the phase and amplitude of the utility voltage vector.

Loading Side Converter:

Load side converter is the one who controls the Induction Machine to load the propulsion motor for different loads.We are sensing actual torque from the torque sensor and comparing with torque reference/profiles and obtaining slip speed. The slip speed is added with reference speed which is given to the propulsion motor and that speed is the reference to the Loading IM. Here we are employing V/F control to operate the IM for different slip operation. Depending on the positive and negative slip, the induction machine will go to motoring and regeneration mode.

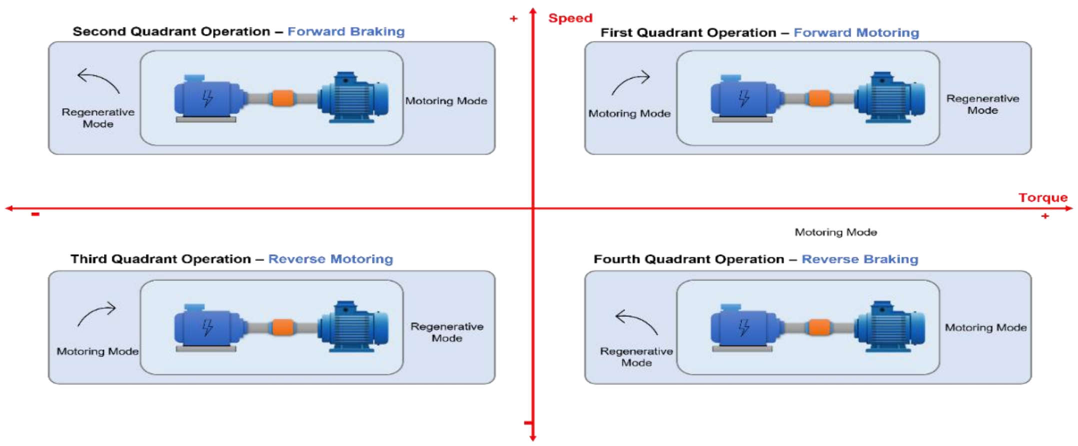


Figure 20: Four quadrant operation of induction motor.

- When slip is negative, the induction machine will go to regeneration mode there by propulsion motor will get loaded and the regeneration power from the loading machine is sent to the grid by using FEC.
- When slip is positive, the induction machine will go to motoring mode there by the propulsion motor will go to regeneration mode and the regeneration power from the propulsion motor will be sent to the battery by using DC-DC converter.
- Same will applied during reverse motoring and breaking.

Speed Profiles and Torque Profiles:
By using this set up we can test our propulsion motor for different speed and torque profiles in real time and, we can test motor for different road condition for long duration to check the thermal and physical stability of the motor.

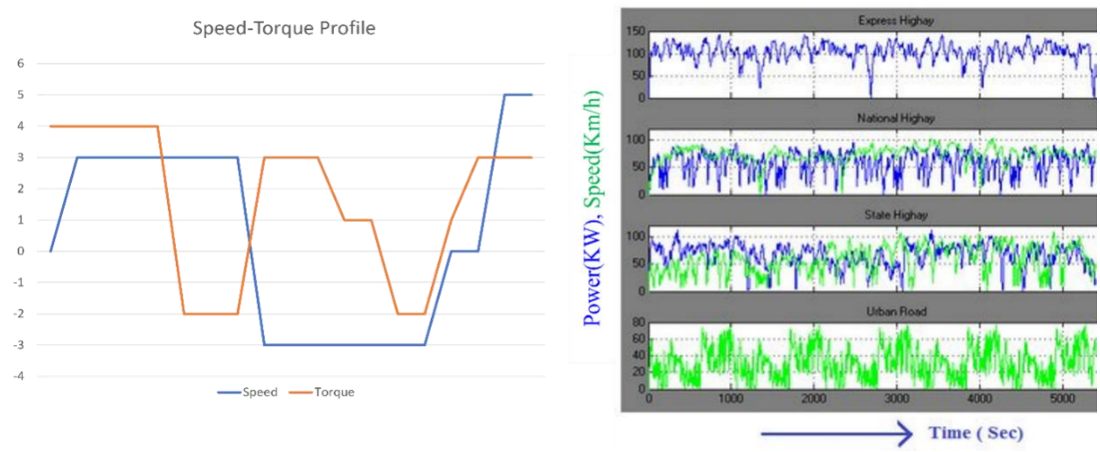


Figure 21: Speed profile and torque profile.

The Profiles will be given in real time by using WAVECT. We can create different speed and torque profiles for different road conditions in CSV format and load those by using itable. itable is the WAVECT IO library where we can load array of data in real time. The speed and torque profile are as shown above.

Hardware ratings:

Battery Specifications/ Ratings
The Li-ion Battery Setup of 7.3Kwh, 100Ah, 73.6V with BMS

Propulsion Motor Specifications/Ratings
3KW, 3000 RPM, 60V IM

Red, white, and black are the motor phases

Propulsion Drive

Bidirectional DC-DC Converter for Battery 6KW

- Input voltage: 200-100VDC,

- Output voltage: 100-200 VDC, 60 Amps (Buck), 30 Amps (Boost)
- Inductor of rating 2.3mH,50A

The propulsion drive supports bi-directional power flow.

- Supports bi-directional power flow.
- Voltage In: 200VDC,
- Voltage Out: 72VAC, 100Amps
- Forced Air Cooling

Load Emulator

The load emulator consists of below components:

- Induction Motor – 3KW, 415V, 3000 RPM (ABB/reputed make)
- Torque Sensor – 20Nm
- Converter for loading motor and Front-end converter (Ratings are as below).
- IGBT based Power Converter (FEC and Loading side Converter)
    - Power Converter Configuration: Rectifier + Brake Chopper + Inverter
    - Rectifier: 415VAC Input, 560VDC Output, 45 Amps
    - Chopper: 600VDC Input, 300VDC Output, 30 Amps at 2 KHz
    - Inverter: 600V DC Link, 415VAC Output, 30 Amps at 2 KHz
    - Max Switching Frequency: Up to 20 kHz
    - Fundamental Frequency: 50 Hz
    - Type of Cooling: Forced Air
    - Ambient Temp: 40 Deg
    - Power Converter consists of 1 x SKD 160/18 module, 4 x SKM75GB12T4 IGBT modules, MD-P3 heatsink, 4 x SKYPER 32 R drivers, Electrolytic capacitor, Busbar, IGBT snubbers, fan, and thermal trip etc. All are encapsulated in polycarbonate box with Elcom knobs on it etc.
- LCL Filter for Grid Side Converter
    - Inductive Filter- 7.5mH/phase
    - Capacitor Bank- 3.15uF,415V Star Connected

Operation Method:

Notes before turning on the hardware

1. Make sure all the connections were firm and turn ON Battery MCB and Grid MCB. Run the propulsion motor and note down the direction of rotation. Turn off the propulsion motor and enable loading motor and check the direction of rotation. If both motors direction of rotation is same, it indicates that phase sequence is correct. If not interchange any two phases of loading motor to get same direction of rotation.
2. Turn on the grid and check the voltage and currents.
3. Turn on supply to the Torque sensor signal conditioner. Check is there any offset in the Actual torque value. if it is there, adjust the ZERO knob in signal conditioner and make the torque zero).
4. The system is designed to operate for 3KW capacity of EV motors (generally 2-wheeler and 3-wheeler).
5. Close loop V/F is employed for the IM drive (User can implement other control topologies as per their application).
6. Since the propulsion drive converters were working at high current, recommended to operate the converters with Fan/Blower.
7. Before turning on the set up, check all the hardware connections.
8. Check the supply to Torque sensor conditioner. It must be 9V DC supply (It may vary for different Torque sensors).
9. Without grid we cannot load the propulsion motor and the algorithm tested with grid connected mode only.
10. The flow of power in both directions at Battery and Grid can be observed during four quadrant operation.

Connection Diagram

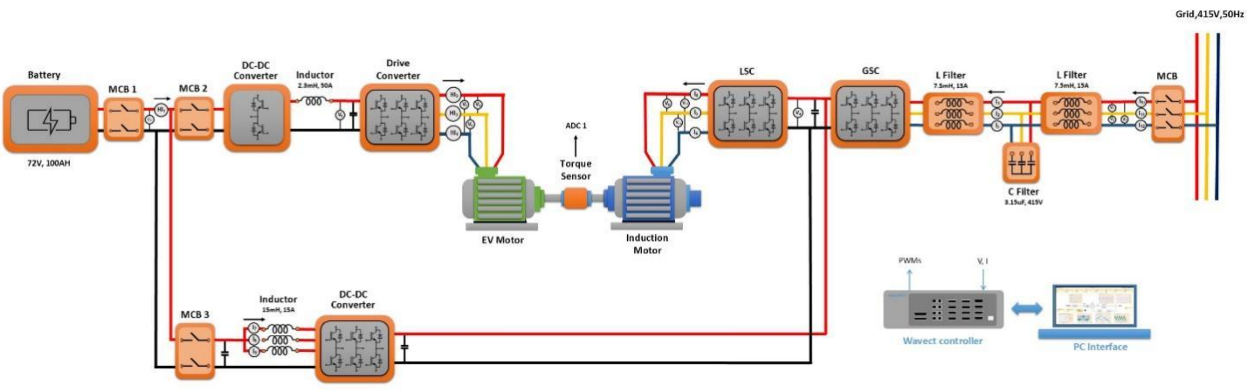


Figure 22: Connection diagram of EV load emulator setup.

Signal and PWM connection

1. Make sure all the pwm and ADC connections were firm.
2. EV Propulsion Motor PWM Connection.
   - Pwm 1..2 – Propulsion motor (R-Phase)
   - Pwm 3..4 – Propulsion motor (Y- Phase)
   - Pwm 5..6 – Propulsion Motor (B- Phase)
3. GSC PWM connection.
   - Pwm 9..10 – GSC (R- Phase)
   - Pwm 11..12 – GSC (Y- Phase)
   - Pwm 13..14 – GSC (B- Phase)
4. Loading side converter PWM connection.
   - Pwm 17..18 – LSC (R- Phase)
   - Pwm 19..20 – LSC (Y- Phase)
   - Pwm 21..22 – LSC (B- Phase)
5. EV Buck Boost converter PWM connection.
   - Pwm 23..24 – EV buck boost
6. ADC Connection.
   - ADC 1 – Torque sensor signal conditioner output (BNC Cable).
   - ADC 2 – Throttle Padel output (BNC Cable).
   - ADC 5 – Battery current (HCS 1 BNC cable)
   - ADC 6 – R phase propulsion motor current (HCS 2 BNC cable).
   - ADC 7 – Y phase propulsion motor current (HCS 3 BNC cable).
   - ADC 8 – B phase propulsion motor current (HCS 4 BNC cable).
7. Encoder connection for speed sensing
   - Encoder 1 – Enc 1
   - Encoder 2 – Enc 2

Procedure to Operate

1. Make sure all the connections were firm as per the connection diagram.
2. Turn on Battery MCB 1 and MCB 2 then Check the battery voltage at V12 voltage sensor.
3. Enter Buck reference (Buck_ref=60) and enable gPwmen and Bidirectional converter (Bi_dir=1), check the voltage at V8 sensor, it is tracking reference or not (if not tune the Kp and Ki values for buck operation).
4. Enter speed reference and other inputs to the propulsion motor.
   - speed_ref_M1=1500(maximum up to 3000RPM)
5. Enable the PWMs for propulsion motor(M1pwmEn=1). Then enable close loop (CL_En_M1).
6. Enter different reference speed and observe the actual speed (It will slowly increase as soft start was implemented in the logic), it will track the reference speed.
7. If we give positive speed Motor will run in CCW direction and if we give negative speed it will run in CW direction.

8. Disable M1pwmEn, enter speed select to 2 and speed step time to 10(we can vary in terms of seconds).
9. Go to itable section load the csv file which we created for different speed and enable the M1pwmEn. Observe the actual speed is tracking as per the profile speed.
10. Then run the propulsion motor at constant speed. Turn on grid MCB and observe the grid voltages and currents.
11. Enable PLL(PLL_en=1) and check whether the grid theta (raising ramp) is locking with A phase voltage of grid.
12. If not, turn off the grid and interchange any two phases at the grid side and repeat 11th step to check the grid synchronization.
13. If LCL filter is connected, make sure to identify the grid side currents and GSC currents separately.
14. The model uses V1, V2, V3 as Grid Voltages input to GSC Algorithm, and I1, I2, I3 as GSC Currents.
15. Give Vdc_Ref 20 or 35V more than VDC voltage (620V) and turn ON GSC. We can observe that the Vdc voltage is maintained as per the reference.
16. Turn on supply to the Torque sensor signal conditioner.
17. Now to load the propulsion motor we have to give torque reference to the loading side motor.
18. Enter positive Torque reference (T_ref= 2) and enable Induction motor PWMs (M2pwmEn=1)
19. We can observe that the actual torque will track the reference torque. The Propulsion motor will get loaded and the Induction machine (loading side machine) will be in regeneration mode and the regeneration power is sent to the grid (observe the negative power in grid power panel and positive power in Battery and Propulsion motor power panel).
20. Change the torque reference values to other negative value, observe that the propulsion motor will ger loaded more and the regenerating power form the loading side motor is also increased (you can load up to 3KW as the propulsion motor is rated for 3KW, 9,.5 Nm at 3000 RPM).
21. Now for regenerative braking mode, propulsion motor torque has to be negative.
22. Enter negative Torque reference (T_ref= -2).
23. We can observe that the Propulsion motor will go to regeneration and the Induction machine (loading machine) will go to motoring mode and the power is taken by the grid to drive the Induction machine (observe the positive power in grid power panel and negative power in Battery and Propulsion motor power panel).
24. Increase the torque reference values and observe that the Propulsion motor will generate more power and the power taken from the grid is also more to drive the Induction machine (You can load up to 3KW as the Induction Machine is rated for 3KW,9Nm at 3000RPM).
25. Change the speed for constant Torque, Torque for constant speed and observe the dynamic behaviour of the propulsion motor for these operations.
26. Disable M2pwmEn and M1pwmEn.
27. Enter negative speed for the reverse motoring and breaking operation. We can Observe that the motor will run in opposite direction.
28. Repeat the steps from 18 to 25 to operate the set up for reverse motoring and breaking.

29. Disable M2pwmEn and enter torque select to 2(torqueselect=2) to load the different torque profile. Enter torque step time (in terms of sec).
30. Go to itable section load the csv file which we have created for different torque profiles and enable M2pwmEn. We can observe that the actual torque will track the profile torque and accordingly the propulsion motor will get loaded for mooting and regeneration and the power flow can be observed by using grid and battery power panels.
31. Repeat the above 2 steps for reverse direction and observe the power flow.
32. To turn off the setup disable M2pwmEn -> GSC_en -> PLL_en -> CL_En-> M1pwmEn -> Bidir_en -> gPwmEn.
33. Turn off grid MCB, Battery MCB and Torque sensor conditioner supply.

Hardware Results:

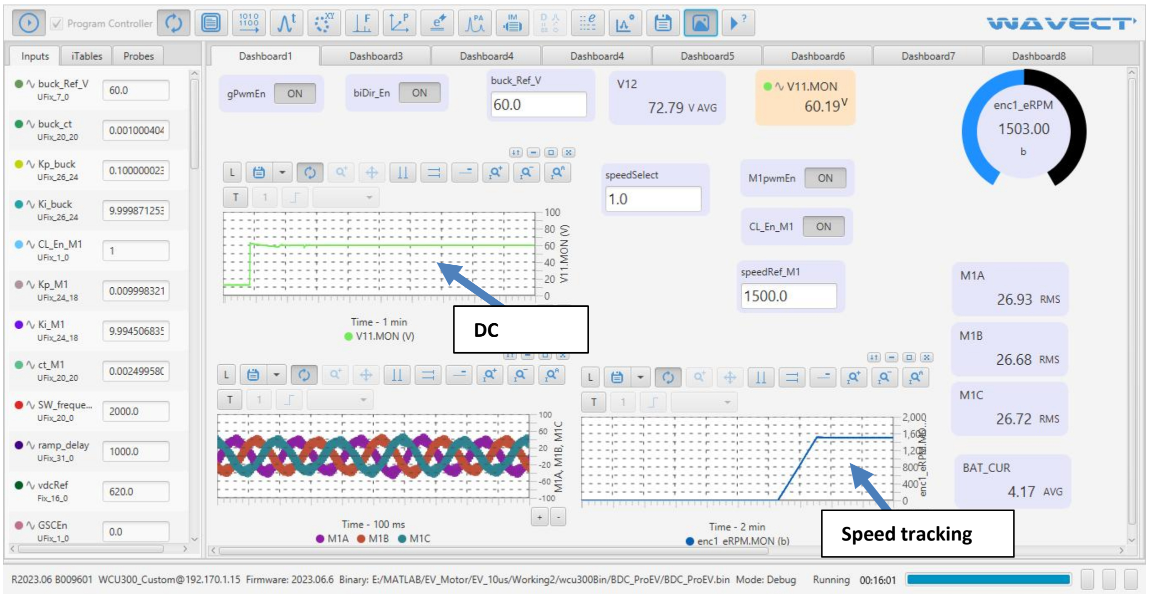


Figure 23: Dashboard for Propulsion motor drive.

Propulsion input voltage reference (60V) is given by the user and the voltage is maintained by the voltage loop. After that Speed reference given manually, we can observe the soft starting is employed and the speed is maintaining as per the reference.

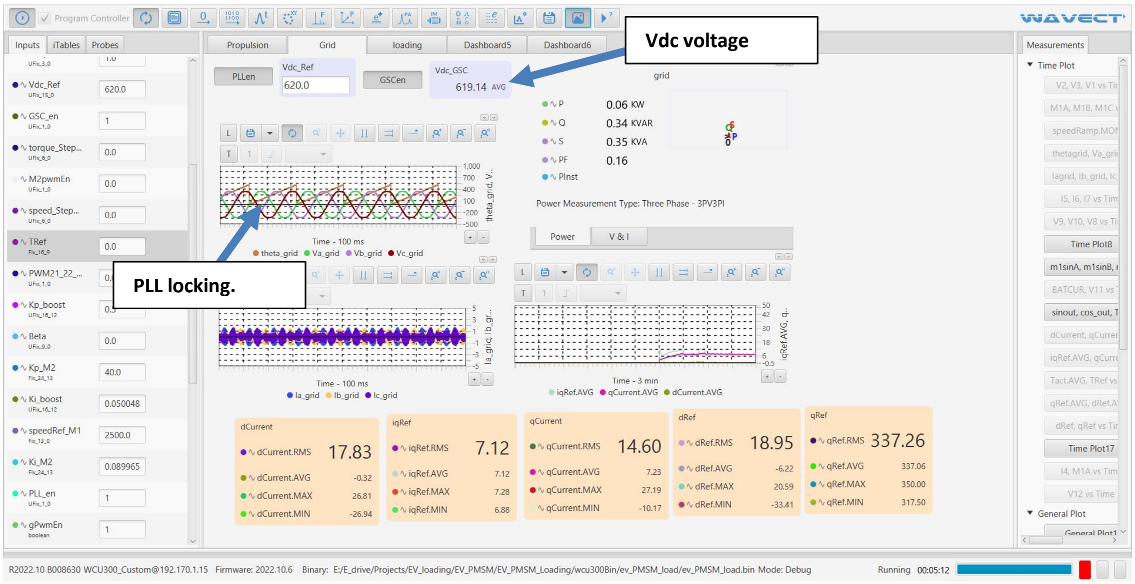


Figure 24: Dashboard for Front-End converter.

We can observe grid voltages and currents in the above image. When we turned on the PLL, grid theta is matching with Phase a of grid voltage. Also, we can observe that the Vdc voltage is maintaining as per the reference.

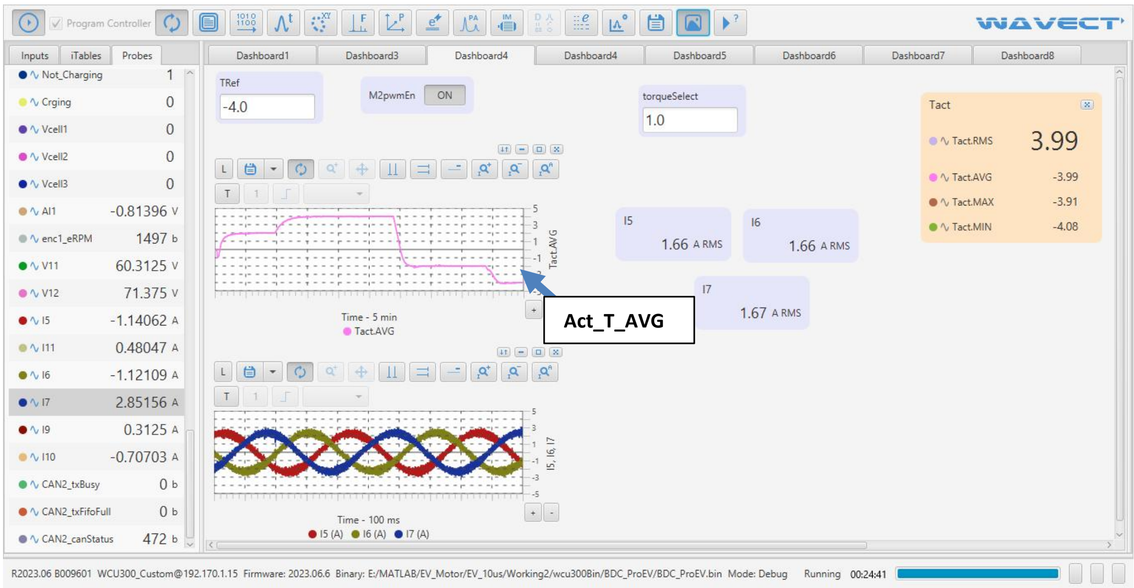


Figure 25: Dashboard for loading side motor.

The actual torque is tracking as per the reference accordingly, propulsion motor will get loaded and regeneration power sent to the grid.

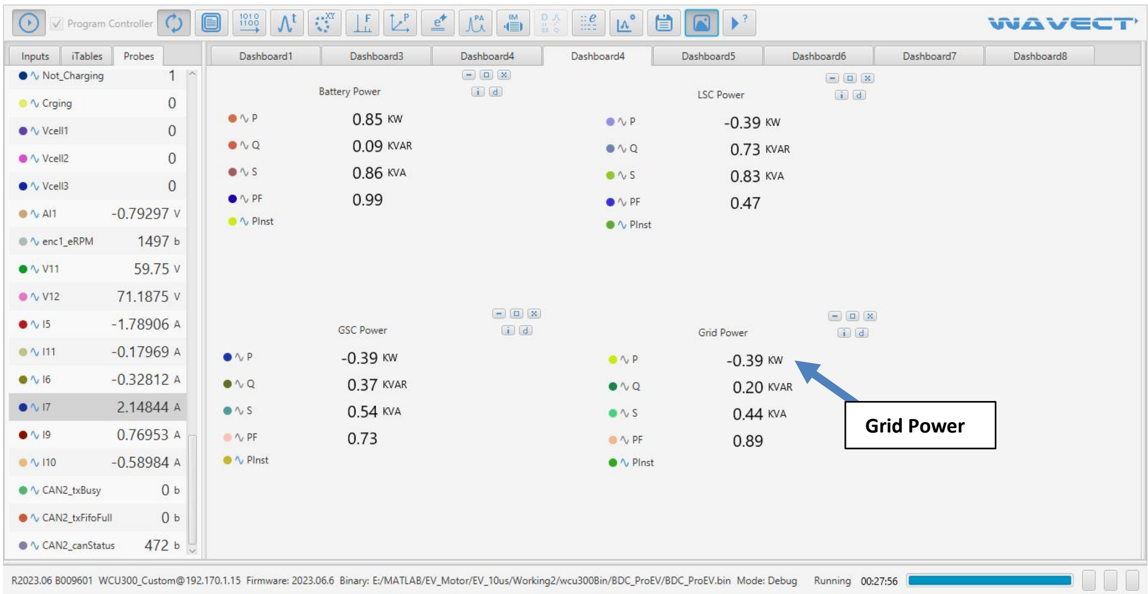


Figure 26: Dashboard for power panel measurement (Forward Motoring Mode).

During forwarding motoring mode, we can observe from the above dashboard, battery is feeding power to drive the propulsion motor and at the loading side the regenerative power is feeding to the grid.

During forward braking mode (the regeneration mode), the propulsion motor the power is taken from the grid to drive the Induction machine (Motoring). From the below image we can observe the power from the grid and the regeneration power from the propulsion machine is sent to the battery (charging using regeneration power).

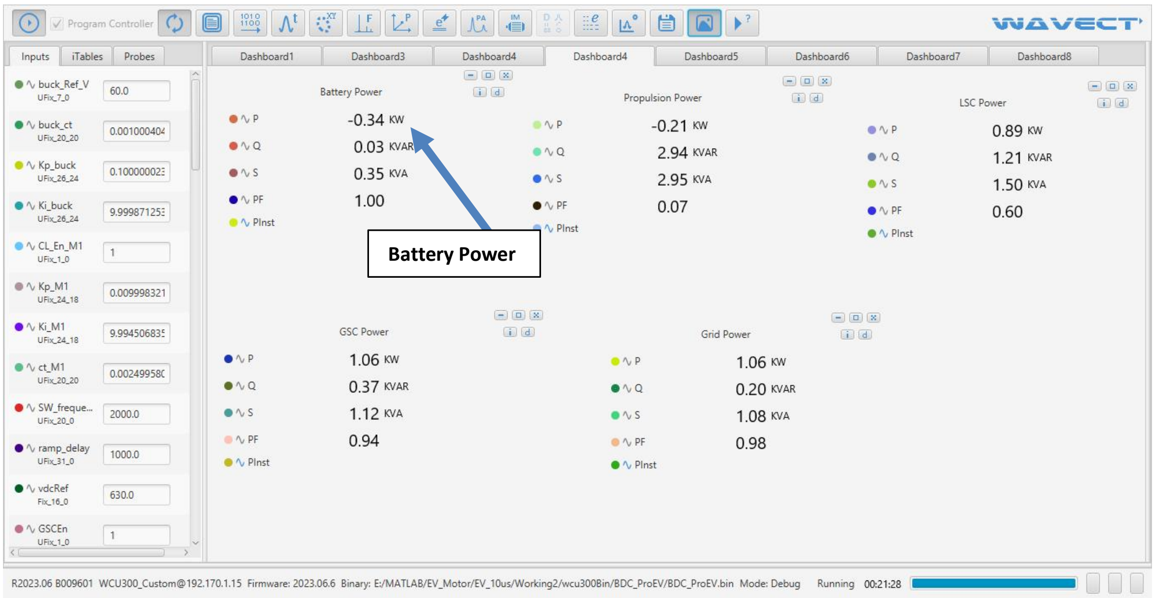


Figure 27: Dashboard for power panel measurement (Forward Braking Mode).

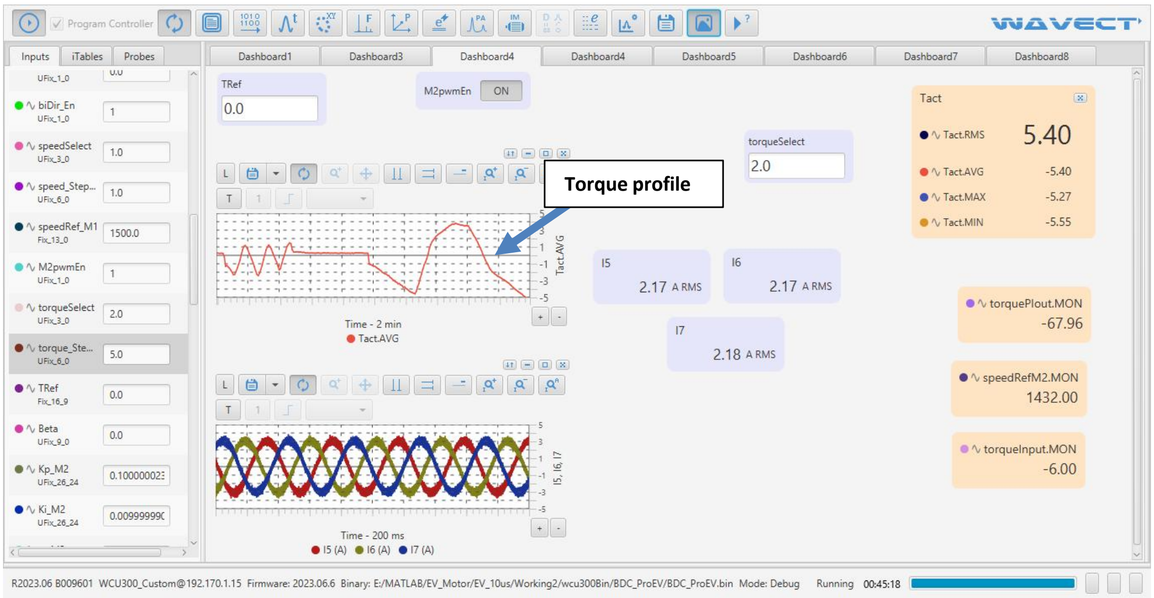


Figure 28: Torque profile implementation for loading the motor.

In the image we can observe the torque profile. Depending on the different profile the motor will get loaded.

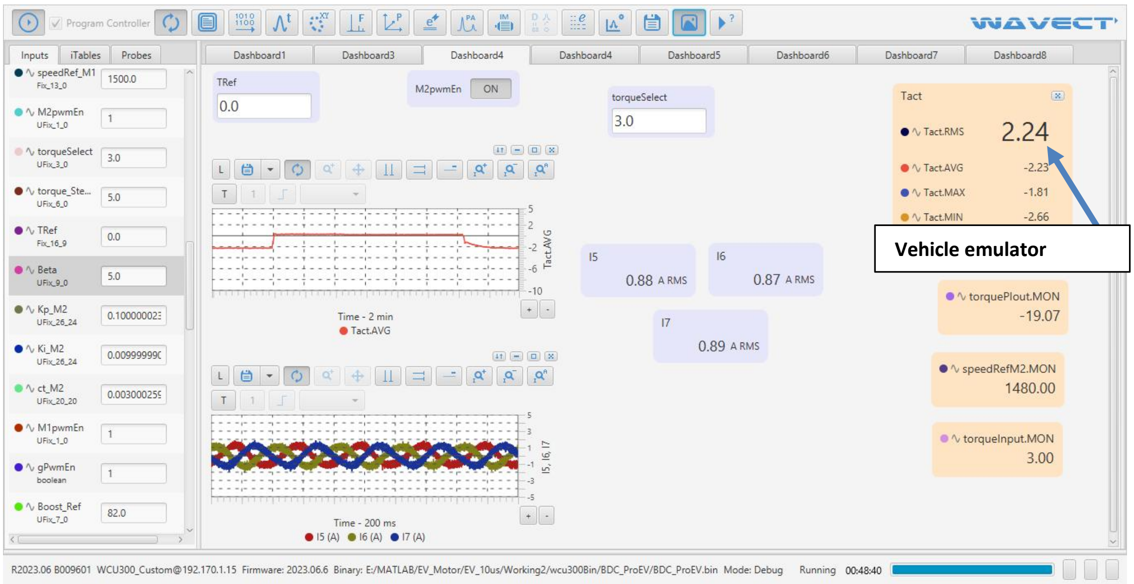


Figure 29: Car physics emulated torque to load the propulsion motor.

In this image the calculated torque from the vehicle emulator is given to loading motor. We can observe that 2.24Nm torque is given to the motor and propulsion motor is getting loaded accordingly.

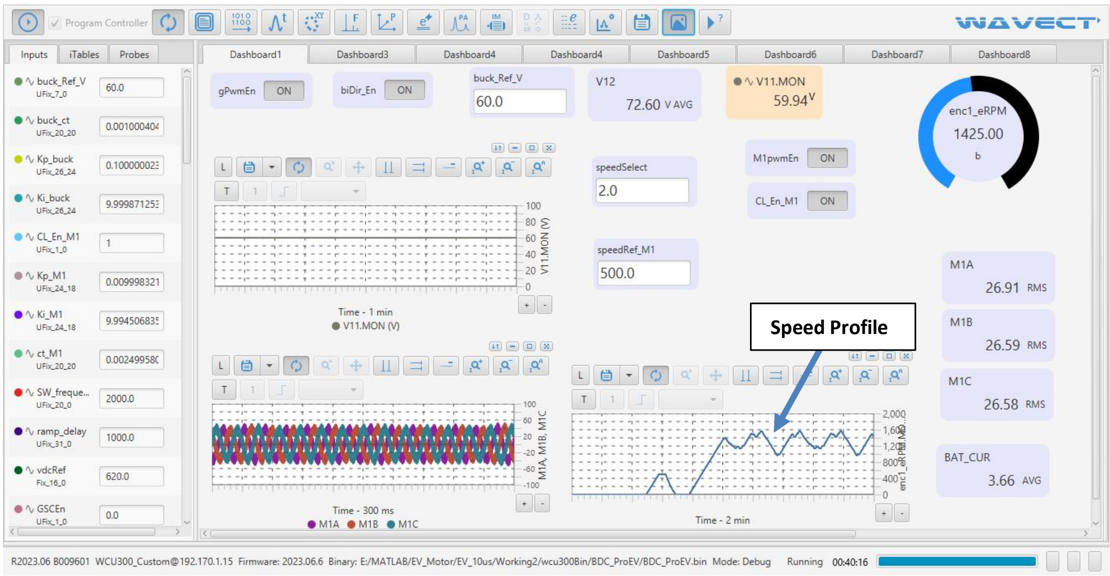


Figure 30: Torque profile implementation for propulsion motor.

In the below image we can see the speed profile. The actual speed of the motor is maintaining as per the speed profile given.

Experiment no. 4

Aim: Field oriented control of EV PMSM motor drive in both clockwise and anti-clockwise direction.

Apparatus Required:

Theory : The EV PMSM drive consists of Li-ion Battery, DC-DC converter, Converter for PMSM motor and EV PMSM motor with Resolver of 3KW, 3000RPM.

The Li-ion battery of 73.6V,100AH is using as a source for the PMSM drive. The Battery pack is having BMS along with CAN communication. By using CAN, we can read battery data like voltage, current, SOC, Charging status and cell level voltage etc.

DC-DC converter is used for bidirectional loading of EV PMSM (i, e. Motoring and regeneration). Since the motor is of 72V and the battery is of 73.6V, during motoring mode the DC-DC converter is in Buck mode and in regeneration mode it is in Boost mode (Charge the battery from regeneration power).

Speed control of PMSM is done using FOC operation where we can control flux and torque independently (Detailed explanation is there below). The 2 level 3 leg IGBT based converter of high current and low voltage is used for this.

Working of Resolver

A resolver is an electromechanical device like an encoder and the main function of this device is to change the mechanical motion to an electronic signal. It is a rotating transformer including three windings namely one primary and two secondary and phased with 90 degrees. These are used in brushless AC servo motors with a permanent magnet, aerospace, and military applications. The resolver works on the principle of an electrical transformer. These transformers use copper windings in stator and rotor. Based on the rotor's angular position, the inductive coupling of the windings will be changed. The resolver energizes by using an DC signal and the output of this can be measured to provide an electrical signal.

The Output of resolver will be cos and sin functions, depending on the rotor position we will get cos and sine functions. If we compute those with atan2 function, we will get rotor angle (direct theta) which is in-phase with phase A.

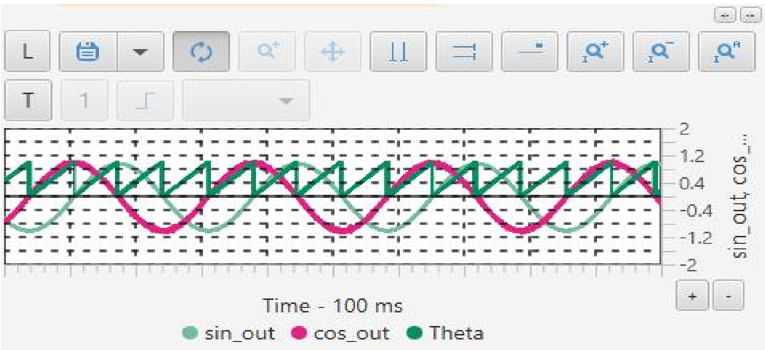


Fig.31 Resolver output

Voltage Control of PMSM

There are different control schemes for PMSM motor namely Two phase excitation, Voltage control and Field oriented control.

In voltage control of PMSM, three reference signals of 120 degrees can generate by using rotor angle (estimated by Resolver) to run the motor in voltage control mode. The reference signals with 90^0 lead and lag with respect to rotor angle to get maximum Torque.

To get maximum torque the stator flux and rotor flux must be 90^0 apart. The problem with voltage control is we are making voltage to be lead/lag by 90^0 but the stator flux and rotor flux won't be 90^0 due to lagging of current so, motor will draw more current to overcome the magnetic field from the rotor.

Observations

Tested the motor with voltage control scheme, observed that the motor was drawing 20A of current (0.26KW active power and 1.2KVAr of reactive power) during counter-clockwise direction and in other direction it was drawing 40A of current (0.26KW active power and 2.68KVAr of reactive power).

Changed the lag and lead angle to more than 90^0 and less than 90^0 to make stator flux and rotor flux exact 90 degrees, found that the motor was drawing huge current (around 45A at half speed).

We conclude that voltage control is not a good method to test the PMSM motor so, we moved on to FOC control.

FOC of PMSM

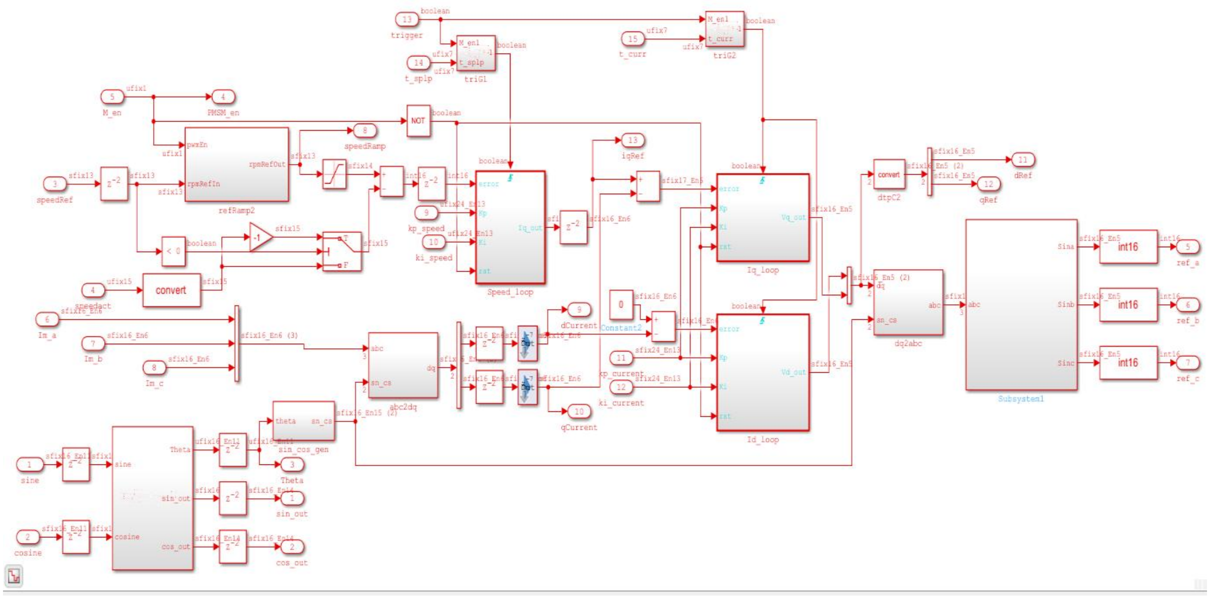


Fig.32 FOC model of PMSM

Field Oriented Control (FOC) is the most common control method used for PMSM control where we can control Torque and Flux independently. Also, we can operate the motor beyond the rated speed by flux weakening. The main aim is to run the AC motor like DC motor where we can control Torque and flux independently.

In any AC machines Flux and torque components coupled in the form of three phase AC currents (time variant quantities). In FOC by applying vector control three phase AC currents decoupled into Id and Iq (Flux and Torque components) where we can torque, flux of the machine can be independently controlled.

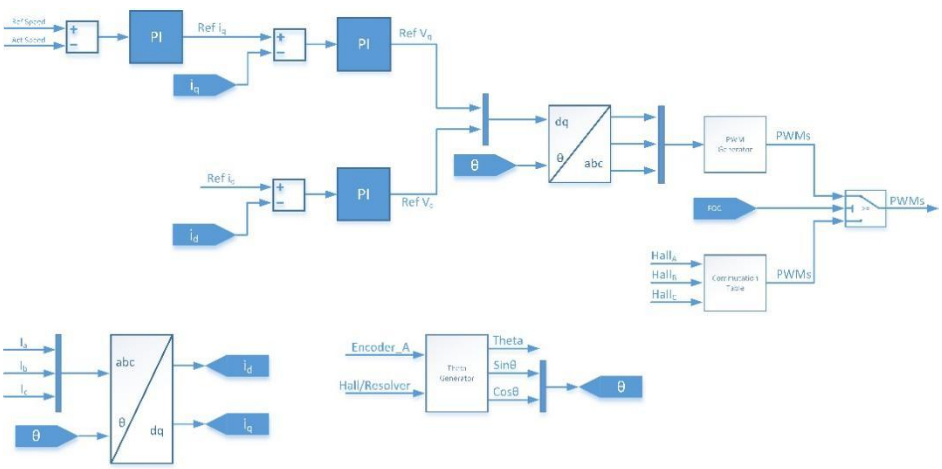


Fig.33 Control logic of FOC of PMSM motor drive.

There are three loops in FOC namely Speed loop (PI output is Iq ref), Iq loop and Id loop. Measured motor currents Ia, Ib and Ic, converted to dq components by using rotor angle (Rotor theta). The Iq ref taken from the Speed loop and compared with actual Iq and we will get Vq. Id ref is given as '0' to make flux constant and compared with actual Id and we will get Vd. Vd and Vq are converted into ABC references and compared with the carrier signal to generate PWM and fed to the Converter.

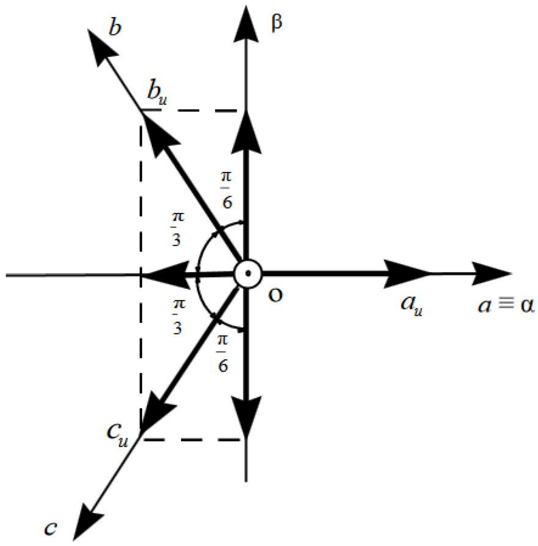
Transformation

Transformation is used for simplifying a complex multi-phase time invariant system into 2 phase time invariant quantity and vice versa. This helps the modelling of control system much easier when compared considering raw data.

There are majorly two types of Transformation and its inverses namely.

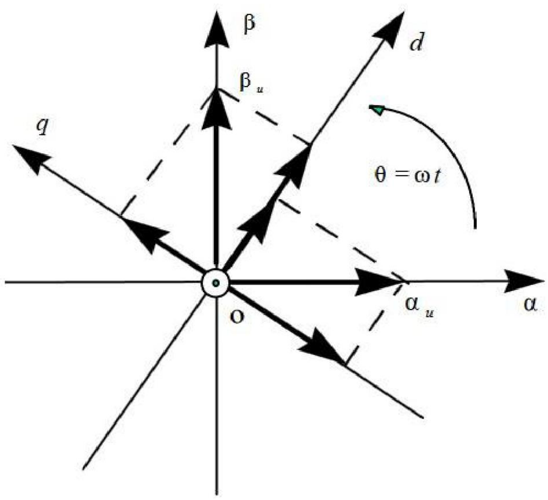
- ABC to αβ transform.
- αβ to dq transform.

A transformation from the three-phase stationary coordinate system to the two phases, so called αβ, stationary coordinate system. The transformation is also called as Clarkes transform.



$$\begin{pmatrix}\alpha\\ \beta\end{pmatrix} = 2/3\begin{pmatrix}1 & -1/2 & -1/2\\ 0 & \sqrt{3}/2 & -\sqrt{3}/2\end{pmatrix}\begin{pmatrix}a\\ b\\ c\end{pmatrix}$$

Fig.34 abc to αβ transformation



$$\begin{bmatrix}d\\ q\end{bmatrix} = \begin{pmatrix}\cos(\theta) & \sin(\theta\\ -\sin(\theta) & \cos(\theta)\end{pmatrix}\begin{bmatrix}\alpha\\ \beta\end{bmatrix}$$

Fig.35 αβ to dq transformation

A transformation from the two-phase stationary coordinate system to the dq synchronous reference frame. The transformation is also called a Parks transform. There are two variants of parks transform, Parks and Modified Parks transform. In modified Parks transform the d axis is consider 90 degrees behind the A phase.

PI Controller

A proportional–integral (PI controller) is a control loop feedback mechanism (controller) commonly used in control systems. It includes two components (Integral and Proportional).

The proportional term (P) gives a system control input proportional with the error. Using only P control gives a stationary error in all cases except when the system control input is zero and the system process value equals the desired value. In the figure below the stationary error in the system process value appears after a change in the desired value (ref). Using a too large P term gives an unstable system. Digital implementation of proportional term consists of a multiplier.

The integral term (I) gives an addition from the sum of the previous errors to the system control input. The summing of the error will continue until the system process value equals the desired value and these results in no stationary error when the reference is stable. The most common use of the I term is normally together with the P term, called a PI controller. Using only the I term gives slow response and often an oscillating system. The figure below shows the step responses to an I and PI controller. As seen the PI controller response have no stationary error and the I controller response is very slow. A block representation of digital integrator is shown below. Practical Digital Integrators are implemented based on numerical integration methods. A normal implementation is shown below.
It is Time domain Input-output relation is given by.

$$y[n] = y[n-1] + x[n]$$

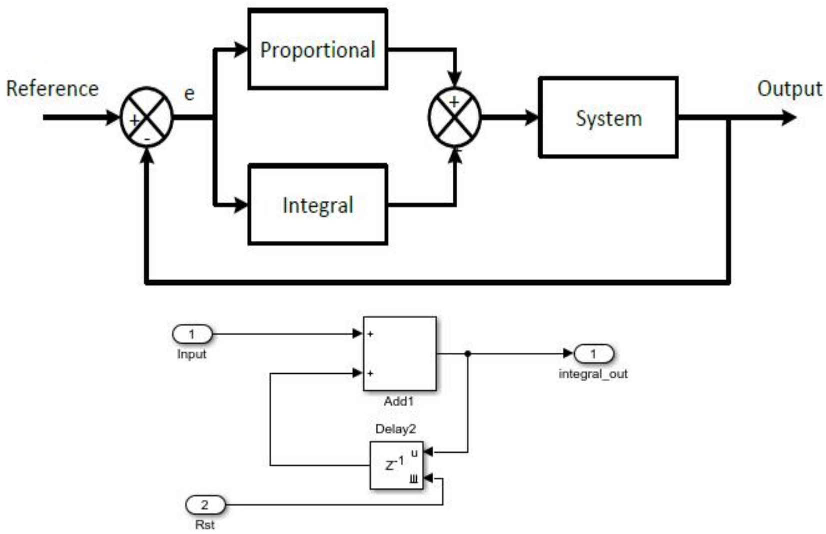


Fig.36 PI Controller and Integrator model

Experiment No. 5

Aim: Create your own speed profile and run the propulsion motor (EV IM and EV PMSM) and analyse the speed profile, voltage, current, and power of the motor.

Apparatus Required: Hardware and software set up

Theory:

Load Emulator

Load Emulator (called as AC dynamometer) is consisting of load side converter, Front end converter, Torque sensor, Induction machine and filters etc.

Load side converter is used to control the slip of the loading Induction machine depending on the torque reference/profile given by the user.

Front end converter is a bidirectional converter, and its main function is to maintain the DC link voltage regardless of power flow.

Torque sensor is used to sense the actual torque of the load.

Induction motor is used to load the propulsion motor for different load profiles. Depending on the slip given the IM will operate in motoring and regeneration mode there by it can load propulsion motor for all four quadrants.

Front-End Converter: Bidirectional DC-AC Converter

The function of the Front-end converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. If a vector control method is applied, with a reference frame oriented along the grid voltage vector position, an independent control of the active and reactive power for the grid-side is guaranteed.

The PWM converter is current-regulated, with the d-axis current used to regulate the dc-link voltage and the q-axis current component control of grid-side PWM converter used to regulate the reactive power. The Basic component of the Grid Side Converters are as follows.

- Transformations from time variant quantities to time invariant quantities and vice versa (Explained above)
- PI Controllers for current control and fixed DC Voltage level maintenance (Explained above)
- Phase locking loop for Grid Synchronization. A brief explanation of the modelling is given below.

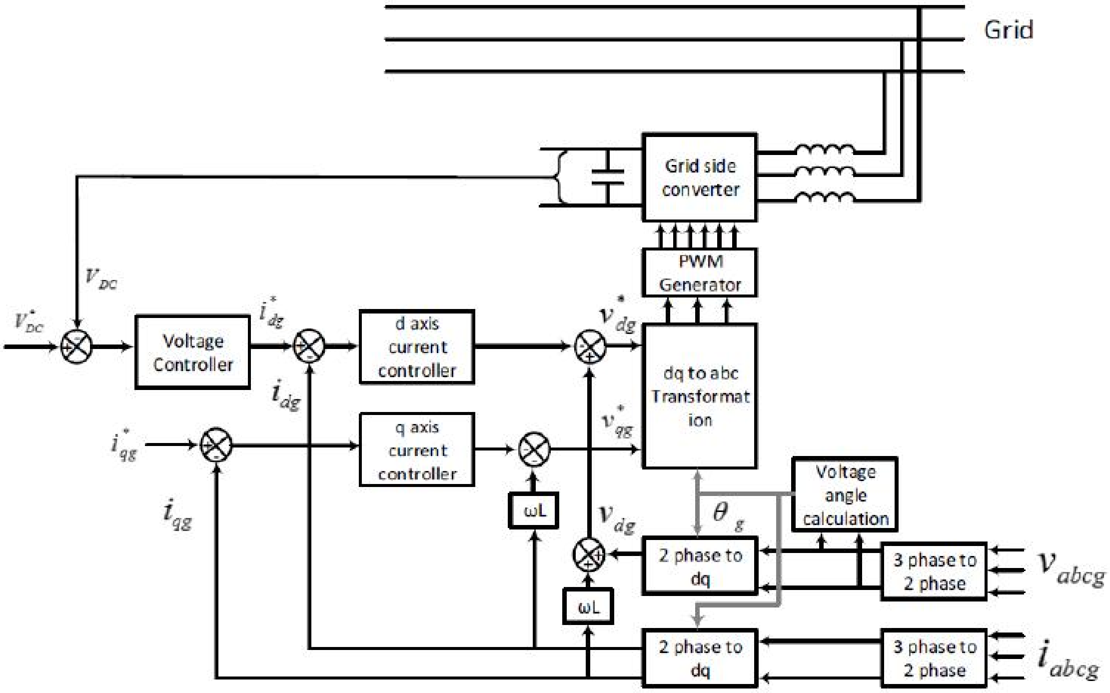


Fig.37 Control algorithm for Grid Side Converter

Hardware Ratings

Battery Specifications/ratings

The Li-ion Battery Setup of 7.3Kwh, 100Ah, 73.6V with BMS

Propulsion Motor Specifications/ratings

3.5/3KW,3000RPM,72V PMSM motor with Resolver (also known as Cos-Sin Encoder) for rotor position sensing.

R(Blue), Y(Yellow) and B(Green) are the Motor Phases (written in marker).

Resolver Connection:

- Red- Supply (5V dc)
- Black- Ground
- Green- cos
- Yellow- sin
- Shield- Signal ground
- White- NC/Ground

Propulsion Drive

Bidirectional DC-DC Converter for Battery 6KW

- Input voltage: 200-100VDC,
- Output voltage: 100-200 VDC, 60 Amps (Buck), 30 Amps (Boost)
- Inductor of rating 2.3mH,50A

The propulsion drive supports bi-directional power flow.

- Supports bi-directional power flow.
- Voltage In: 200VDC,
- Voltage Out: 72VAC, 100Amps
- Forced Air Cooling

Load Emulator

The load emulator consists of below components:

- Induction Motor – 3KW, 415V, 3000 RPM (ABB/reputed make)
- Torque Sensor – 20Nm
- Converter for loading motor and Front-end converter (Ratings are as below).
- IGBT based Power Converter (FEC and Loading side Converter)
  - Power Converter Configuration: Rectifier + Brake Chopper + Inverter
  - Rectifier: 415VAC Input, 560VDC Output, 45 Amps
  - Chopper: 600VDC Input, 300VDC Output, 30 Amps at 2 KHz
  - Inverter: 600V DC Link, 415VAC Output, 30 Amps at 2 KHz
  - Max Switching Frequency: Up to 20 kHz
  - Fundamental Frequency: 50 Hz
  - Type of Cooling: Forced Air
  - Ambient Temp: 40 Deg
  - Power Converter consists of 1 x SKD 160/18 module, 4 x SKM75GB12T4 IGBT modules, MD-P3 heatsink, 4 x SKYPER 32 R drivers, Electrolytic capacitor, Busbar, IGBT snubbers, fan, and thermal trip etc. All are encapsulated in polycarbonate box with Elcom knobs on it etc.

- LCL Filter for Grid Side Converter
  - Inductive Filter- 7.5mH/phase
  - Capacitor Bank- 1.5uF,415V Star Connected

OPERATION METHOD

Notes before turning on the set up

1. Make sure all the connections were firm as per the connection diagram.
2. Then turn ON Battery MCB1 and MCB 2 and check the battery voltage in wavect suite.
3. Then run the propulsion motor(as per the operating procedure) and note down the direction of rotation of motor. Turn off the propulsion motor and enable loading motor and check the direction of rotation. If both motors direction of rotation is same, it indicates that phase sequence is correct. If not interchange any two phases of loading motor to get same direction of rotation.
4. Turn on the grid and check the voltage and currents.
5. Turn on supply to the Torque sensor signal conditioner. Check is there any offset in the Actual torque value. if it is there, adjust the ZERO knob in signal conditioner and make the torque zero).
6. The system is designed to operate for 3KW capacity of EV motors (generally 2-wheeler and 3-wheeler).
7. FOC is employed for the PMSM drive (User can implement other control topologies as per their application).
8. Since the propulsion drive converters were working at high current, recommended to operate the converters with Fan/Blower.
9. Before turning on the set up, check all the hardware connections.
10. Check the supply to Torque sensor conditioner. It must be 9V DC supply (It may vary for different Torque sensors).
11. 5V DC supply must be given to the resolver.
12. Without grid we cannot load the propulsion motor and the algorithm tested with grid connected mode only.
13. The flow of power in both directions at Battery and Grid can be observed during four quadrant operation.

Connection Diagram

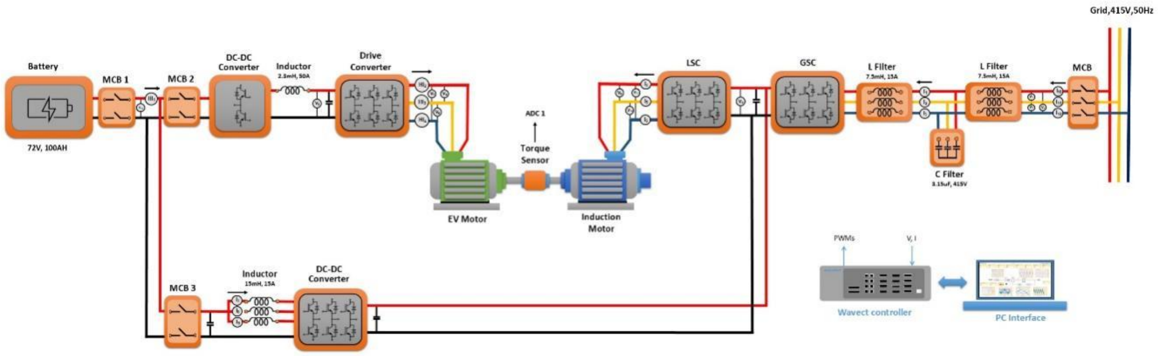


Fig.38 Connection Diagram of EV Setup

Signal and PWM connection

1. **Make sure all the pwm and ADC connections were firm.**
2. EV Propulsion Motor PWM Connection.

- Pwm 1..2 – Propulsion motor (R-Phase)
- Pwm 3..4 – Propulsion motor (Y- Phase)

- Pwm 5..6 – Propulsion Motor (B- Phase)

3. GSC PWM connection.

- Pwm 9..10 – GSC (R- Phase)
- Pwm 11..12 – GSC (Y- Phase)
- Pwm 13..14 – GSC (B- Phase)

4. Loading side converter PWM connection.

- Pwm 17..18 – LSC (R- Phase)
- Pwm 19..20 – LSC (Y- Phase)
- Pwm 21..22 – LSC (B- Phase)

5. EV Buck Boost converter PWM connection.

- Pwm 23..24 – EV buck boost

6. ADC Connection.

- ADC 1 – Torque sensor signal conditioner output (BNC Cable).
- ADC 2 – Throttle Padel output (BNC Cable).
- ADC 3 – Resolver sin signal.
- ADC 4 – Resolver cos signal.
- ADC 5 – Battery current (HCS 1 BNC cable)
- ADC 6 – R phase propulsion motor current (HCS 2 BNC cable).
- ADC 7 – Y phase propulsion motor current (HCS 3 BNC cable).
- ADC 8 – B phase propulsion motor current (HCS 4 BNC cable).

7. Encoder connection for speed sensing

- Encoder 1 – Enc 1
- Encoder 2 – Enc 2

Procedure to Operate

1. Make sure all the connections were firm as per the connection diagram.
2. Turn on Battery MCB1 and MCB 2. Then Check the battery voltage at V_{12} voltage sensor in wavect suite.
3. Enter Buck reference (Buck_ref=72) and enable gPwmen and Bidirectional converter (Bi_dir=1), check the voltage at V_8 sensor, it is tracking reference or not (if not tune the Kp and Ki values for buck operation).
4. Enter speed reference to the propulsion motor.
   - speed_ref_M1=1500(maximum up to 2800RPM)
5. Enable the PWMs for propulsion motor(m1_en=1).
6. Enter different reference speed and observe the actual speed (It will slowly increase as soft start was implemented in the logic), it will track the reference speed. Also observe the Iq of the PMSM machine.
7. If we give positive speed Motor will run in CCW direction and if we give negative speed it will run in CW direction.
8. Disable M1_en, enter speed select to 2 and speed step time to 10(we can vary in terms of seconds).
9. Go to itable section load the csv file which we created for different speed and enable the m1_en. Observe the actual speed is tracking as per the profile speed.

10. Run the propulsion motor at constant speed. Turn on grid MCB and observe the grid voltages and currents.
11. Enable PLL(PLL_en=1) and check whether the grid theta (raising ramp) is locking with A phase voltage of grid.
12. If not, turn off the grid and interchange any two phases at the grid side and repeat 11th step to check the grid synchronization.
13. If LCL filter is connected, make sure to identify the grid side currents and GSC currents separately.
14. The model uses V1, V2, V3 as Grid Voltages input to GSC Algorithm, and I1, I2, I3 as GSC Currents.

Experiment No. 6

Aim: Run the propulsion motor by throttle paddle and analyse the speed, voltage, current, power of the system

Apparatus Required: Hardware and software set up

Theory:

Theory discussed in the previous section is almost same. By using this set up we can test our propulsion motor for different speed and torque profiles in real time and, we can test motor for different road condition for long duration to check the thermal and physical stability of the motor.

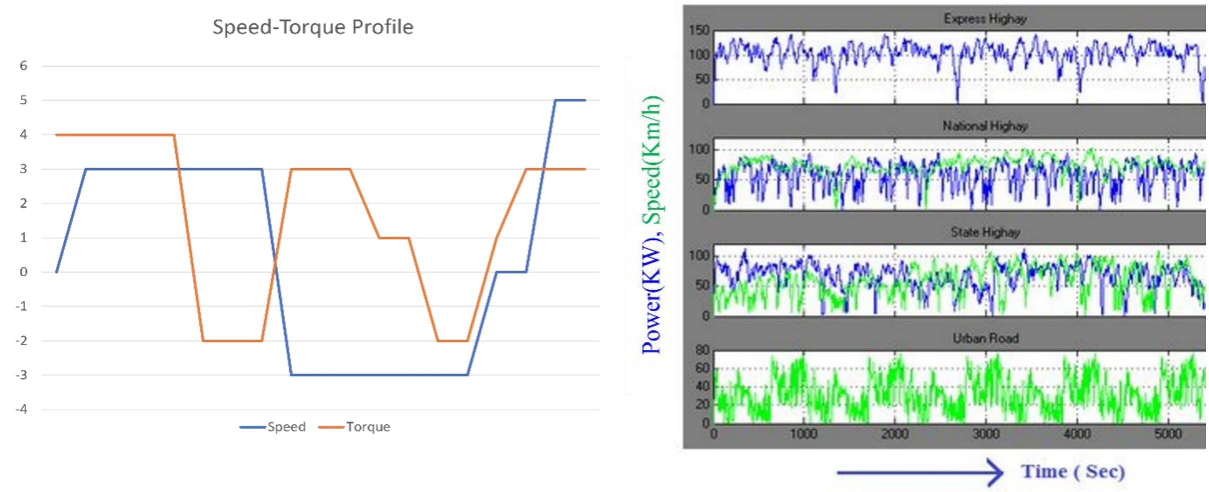


Fig.39: Speed and Torque Profile

The Profiles will be given in real time by using WAVECT. We can create different speed and torque profiles for different road conditions in CSV format and load those by using itable. itable is the WAVECT IO library where we can load array of data in real time. The speed and torque profile are as show above.

Procedure to Operate

1. Make sure all the connections were firm as per the connection diagram.

2. Turn on Battery MCB1 and MCB 2. Then Check the battery voltage at V12 voltage sensor in wavect suite.

3. Enter Buck reference (Buck_ref=72) and enable gPwmen and Bidirectional converter (Bi_dir=1), check the voltage at V8 sensor, it is tracking reference or not (if not tune the Kp and Ki values for buck operation).

4. Enter speed reference to the propulsion motor.

o speed_ref_M1=1500(maximum up to 2800RPM)

5. Enable the PWMs for propulsion motor(m1_en=1).

6. Enter different reference speed and observe the actual speed (It will slowly increase as soft start was implemented in the logic), it will track the reference speed. Also observe the Iq of the PMSM machine.

7. If we give positive speed Motor will run in CCW direction and if we give negative speed it will run in CW direction.

8. Disable M1_en, enter speed select to 2 and speed step time to 10(we can vary in terms of seconds).

9. Go to itable section load the csv file which we created for different speed and enable the m1_en. Observe the actual speed is tracking as per the profile speed.

10. Run the propulsion motor at constant speed. Turn on grid MCB and observe the grid voltages and currents.

11. Enable PLL(PLL_en=1) and check whether the grid theta (raising ramp) is locking with A phase voltage of grid.

12. If not, turn off the grid and interchange any two phases at the grid side and repeat 11th step to check the grid synchronization.

13. If LCL filter is connected, make sure to identify the grid side currents and GSC currents separately.

14. The model uses V1, V2, V3 as Grid Voltages input to GSC Algorithm, and I1, I2, I3 as GSC Currents.

15. Give Vdc_Ref 20 or 35V more than VDC voltage and turn ON GSC. We can observe that the Vdc voltage maintain as per the reference.

16. Turn on supply to the Torque sensor signal conditioner.

17. Enter positive Torque reference (T_ref= 2) and enable Induction motor PWMs(m2_en=1).

18. We can observe that the actual torque will track the reference (Motor torque (Tm) and load torque (Tl) will be opposite). The Propulsion motor will get loaded and the Induction machine (loading machine) will be in regeneration mode and the regeneration power is sent to the grid (observe the negative power in grid power panel and positive power in Battery and Propulsion motor power panel).

Experiment No. 7

Aim: Testing and analysis and propulsion motor loading at different speed and torque condition.

a) Constant speed VS constant torque

b) Constant speed VS variable torque

c) Changing speed VS constant torque

Apparatus Required: Hardware and software set up

Procedure to Operate

1. Make sure all the connections were firm as per the connection diagram.
2. Turn on Battery MCB1 and MCB 2. Then Check the battery voltage at V12 voltage sensor in wavect suite.
3. Enter Buck reference (Buck_ref=72) and enable gPwmen and Bidirectional converter (Bi_dir=1), check the voltage at V8 sensor, it is tracking reference or not (if not tune the Kp and Ki values for buck operation).
4. Enter speed reference to the propulsion motor.
   - o speed_ref_M1=1500(maximum up to 2800RPM)
5. Enable the PWMs for propulsion motor(m1_en=1).
6. Enter different reference speed and observe the actual speed (It will slowly increase as soft start was implemented in the logic), it will track the reference speed. Also observe the Iq of the PMSM machine.
7. If we give positive speed Motor will run in CCW direction and if we give negative speed it will run in CW direction.
8. Disable M1_en, enter speed select to 2 and speed step time to 10(we can vary in terms of seconds).
9. Go to itable section load the csv file which we created for different speed and enable the m1_en. Observe the actual speed is tracking as per the profile speed.
10. Run the propulsion motor at constant speed. Turn on grid MCB and observe the grid voltages and currents.
11. Enable PLL(PLL_en=1) and check whether the grid theta (raising ramp) is locking with A phase voltage of grid.
12. If not, turn off the grid and interchange any two phases at the grid side and repeat 11th step to check the grid synchronization.
13. If LCL filter is connected, make sure to identify the grid side currents and GSC currents separately.
14. The model uses V1, V2, V3 as Grid Voltages input to GSC Algorithm, and I1, I2, I3 as GSC Currents.
15. Give Vdc_Ref 20 or 35V more than VDC voltage and turn ON GSC. We can observe that the Vdc voltage maintain as per the reference.
16. Turn on supply to the Torque sensor signal conditioner.
17. Enter positive Torque reference (T_ref= 2) and enable Induction motor PWMs(m2_en=1).

18. We can observe that the actual torque will track the reference (Motor torque (Tm) and load torque (Tl) will be opposite). The Propulsion motor will get loaded and the Induction machine (loading machine) will be in regeneration mode and the regeneration power is sent to the grid (observe the negative power in grid power panel and positive power in Battery and Propulsion motor power panel).

19. Change the torque reference values to other and we can observe that the Propulsion motor will get loaded more and the regeneration power from the Induction motor is also more (You can load up to 3KW, 60A as the propulsion motor is rated for 3KW,9Nm at 3000RPM).

20. Enter negative Torque reference (T_ref= -2).

21. We can observe that the Propulsion motor will go to regeneration and the Induction machine (loading machine) will go to motoring mode and the power is taken by the grid to drive the Induction machine (observe the positive power in grid power panel and negative power in Battery and Propulsion motor power panel).

22. Change the torque reference values to other and we can observe that the Propulsion motor will generate more power and the power taken from the grid is also more to drive the Induction machine (You can load up to 3KW as the Induction Machine is rated for 3KW,9Nm at 3000RPM).

23. Change the speed for constant Torque, Torque for constant speed and observe the dynamic behaviour of the propulsion motor for these operations.

Results:

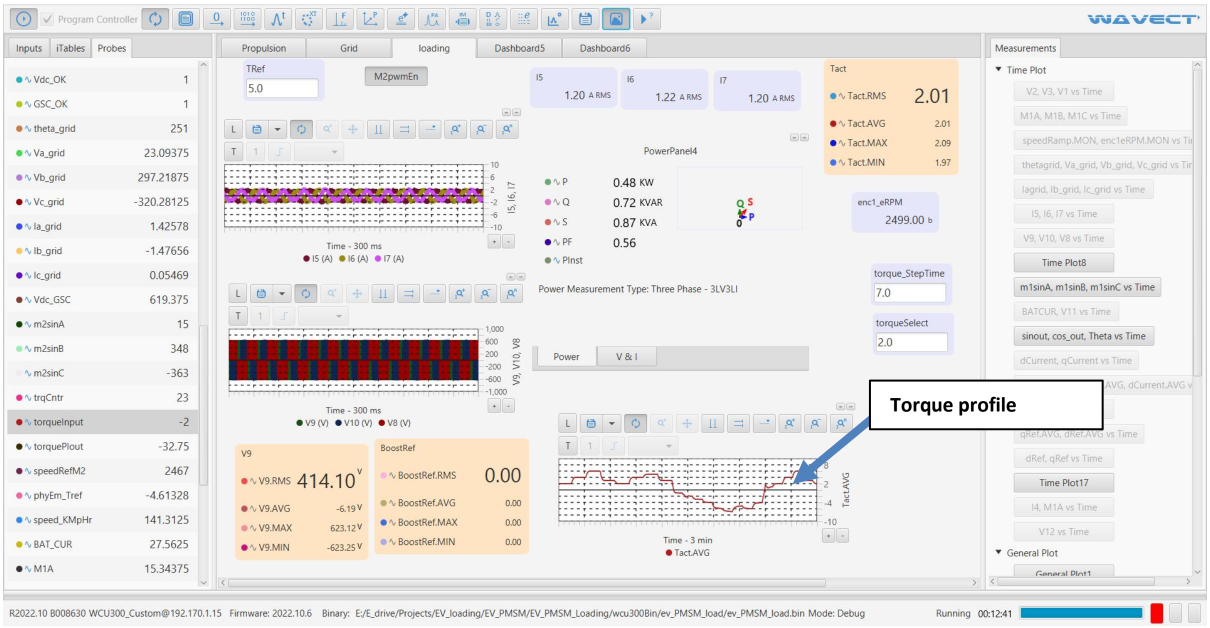


Fig.40 various characteristics and torque profile

In the image we can observe the torque profile. Depending on the different profile the motor will get loaded.

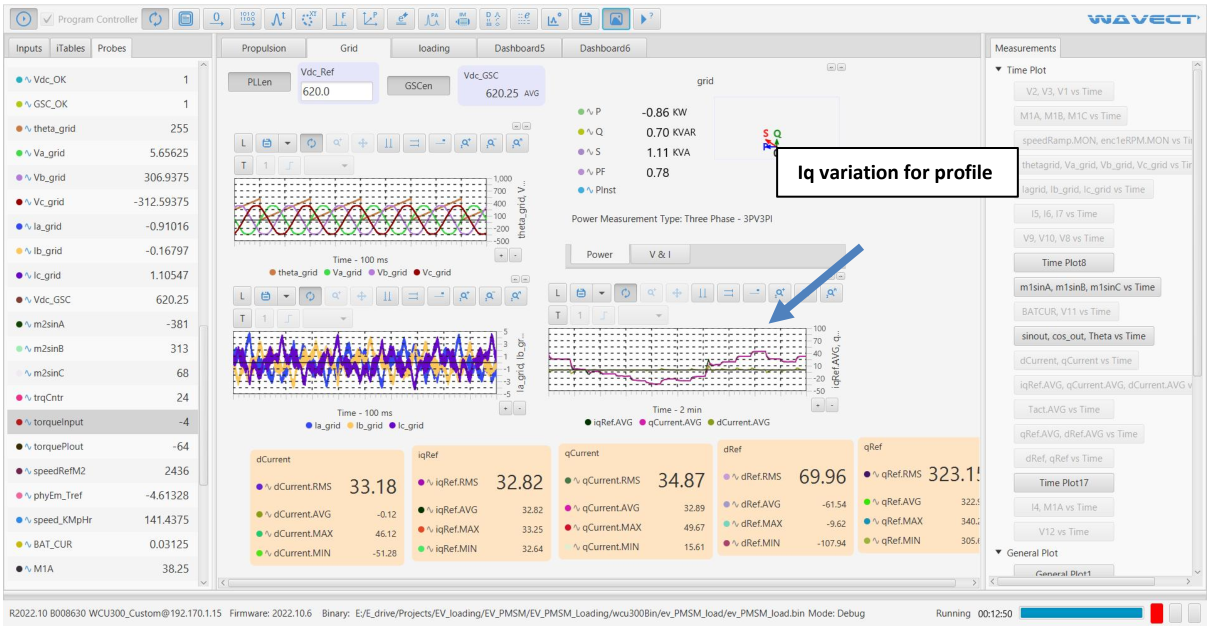


Fig.41 various characteristics and Iq variation

In the above image we can see that the variation of PMSM Iq (torque component) for different load profile.

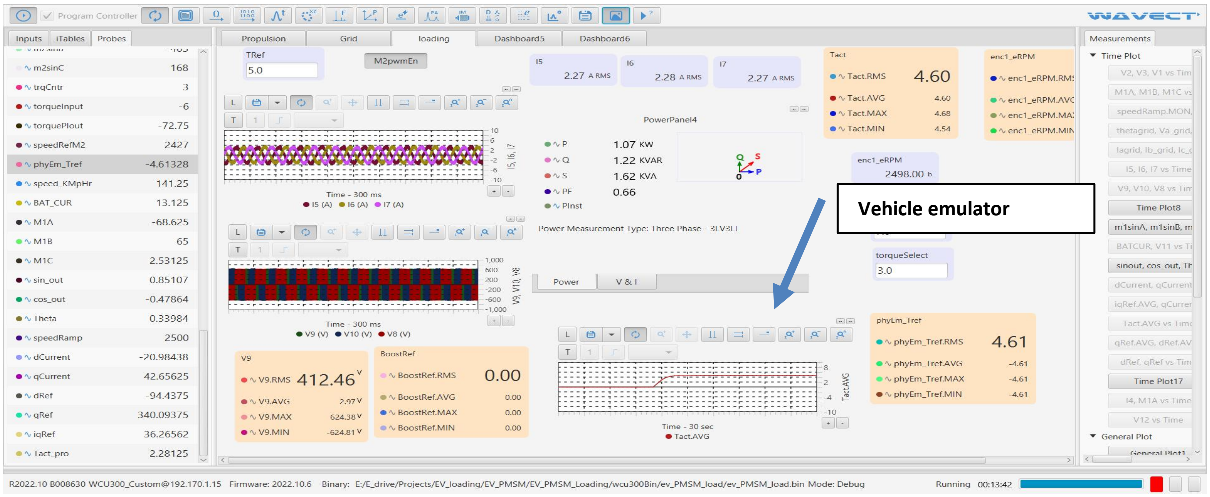


Fig.42 various characteristics and vehicle emulator profile

In this image the calculated torque from the vehicle emulator given to loading motor. We can observe that 4.61Nm torque is given to the motor and propulsion motor is get loaded accordingly. The propulsion motor power can be observed in the below image.

Experiment No. 8

Aim: Study of four quadrant operation of propulsion motor and analyse all the parameters like voltage, current, speed, toque, and power flow.

a)Forward motoring mode

b)Forward braking mode

c)Reverse motoring mode

d) Reverse braking mode

Apparatus Required: Hardware and software set up

Theory:

Load side converter is the one who controls the Induction Machine to load the propulsion motor for different loads.
We are sensing actual torque from the torque sensor and comparing with torque reference/profiles and obtaining slip speed. The slip speed is added with reference speed which is given to the propulsion motor and that speed is the reference to the Loading IM. Here we are employing V/F control to operate the IM for different slip operation. Depending on the positive and negative slip, the induction machine will go to motoring and regeneration mode.

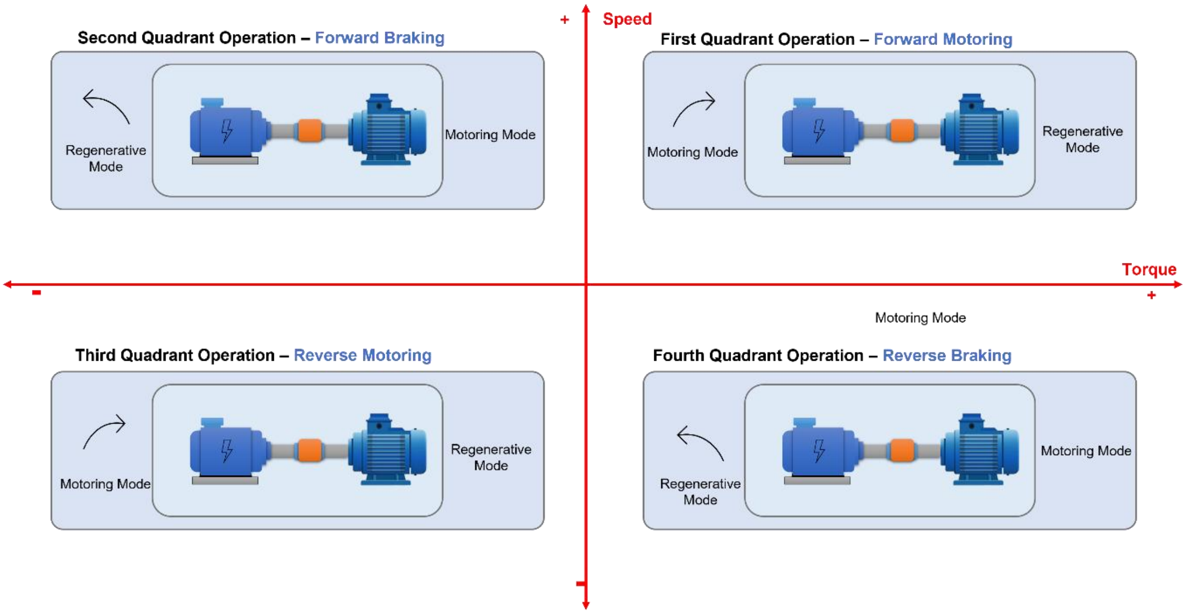


Fig.43: Four quadrant operation

- When slip is negative, the induction machine will go to regeneration mode there by propulsion motor will get loaded and the regeneration power from the loading machine is sent to the grid by using FEC.

- When slip is positive, the induction machine will go to motoring mode there by the propulsion motor will go to regeneration mode and the regeneration power from the propulsion motor will be sent to the battery by using DC-DC converter.
- Same will applied during reverse motoring and breaking.

Signal and PWM connection

1. Make sure all the pwm and ADC connections were firm.
2. EV Propulsion Motor PWM Connection.
   - Pwm 1..2 – Propulsion motor (R-Phase)
   - Pwm 3..4 – Propulsion motor (Y- Phase)
   - Pwm 5..6 – Propulsion Motor (B- Phase)
3. GSC PWM connection.
   - Pwm 9..10 – GSC (R- Phase)
   - Pwm 11..12 – GSC (Y- Phase)
   - Pwm 13..14 – GSC (B- Phase)
4. Loading side converter PWM connection.
   - Pwm 17..18 – LSC (R- Phase)
   - Pwm 19..20 – LSC (Y- Phase)
   - Pwm 21..22 – LSC (B- Phase)
5. EV Buck Boost converter PWM connection.
   - Pwm 23..24 – EV buck boost
6. ADC Connection.
   - ADC 1 – Torque sensor signal conditioner output (BNC Cable).
   - ADC 2 – Throttle Padel output (BNC Cable).
   - ADC 3 – Resolver sin signal.
   - ADC 4 – Resolver cos signal.
   - ADC 5 – Battery current (HCS 1 BNC cable)
   - ADC 6 – R phase propulsion motor current (HCS 2 BNC cable).
   - ADC 7 – Y phase propulsion motor current (HCS 3 BNC cable).
   - ADC 8 – B phase propulsion motor current (HCS 4 BNC cable).
7. Encoder connection for speed sensing
   - Encoder 1 – Enc 1
   - Encoder 2 – Enc 2

Procedure to Operate

1. Make sure all the connections were firm as per the connection diagram.
2. Turn on Battery MCB1 and MCB 2. Then Check the battery voltage at V12 voltage sensor in wavect suite.
3. Enter Buck reference (Buck_ref=72) and enable gPwmen and Bidirectional converter (Bi_dir=1), check the voltage at V8 sensor, it is tracking reference or not (if not tune the Kp and Ki values for buck operation).
4. Enter speed reference to the propulsion motor.
   - o speed_ref_M1=1500(maximum up to 2800RPM)
5. Enable the PWMs for propulsion motor(m1_en=1).

6. Enter different reference speed and observe the actual speed (It will slowly increase as soft start was implemented in the logic), it will track the reference speed. Also observe the Iq of the PMSM machine.
7. If we give positive speed Motor will run in CCW direction and if we give negative speed it will run in CW direction.
8. Disable M1_en, enter speed select to 2 and speed step time to 10(we can vary in terms of seconds).
9. Go to itable section load the csv file which we created for different speed and enable the m1_en. Observe the actual speed is tracking as per the profile speed.
10. Run the propulsion motor at constant speed. Turn on grid MCB and observe the grid voltages and currents.
11. Enable PLL(PLL_en=1) and check whether the grid theta (raising ramp) is locking with A phase voltage of grid.
12. If not, turn off the grid and interchange any two phases at the grid side and repeat 11th step to check the grid synchronization.
13. If LCL filter is connected, make sure to identify the grid side currents and GSC currents separately.
14. The model uses V1, V2, V3 as Grid Voltages input to GSC Algorithm, and I1, I2, I3 as GSC Currents.
15. Give Vdc_Ref 20 or 35V more than VDC voltage and turn ON GSC. We can observe that the Vdc voltage maintain as per the reference.
16. Turn on supply to the Torque sensor signal conditioner.
17. Enter positive Torque reference (T_ref= 2) and enable Induction motor PWMs(m2_en=1).
18. We can observe that the actual torque will track the reference (Motor torque (Tm) and load torque (Tl) will be opposite). The Propulsion motor will get loaded and the Induction machine (loading machine) will be in regeneration mode and the regeneration power is sent to the grid (observe the negative power in grid power panel and positive power in Battery and Propulsion motor power panel).
19. Change the torque reference values to other and we can observe that the Propulsion motor will get loaded more and the regeneration power from the Induction motor is also more (You can load up to 3KW, 60A as the propulsion motor is rated for 3KW,9Nm at 3000RPM).
20. Enter negative Torque reference (T_ref= -2).
21. We can observe that the Propulsion motor will go to regeneration and the Induction machine (loading machine) will go to motoring mode and the power is taken by the grid to drive the Induction machine (observe the positive power in grid power panel and negative power in Battery and Propulsion motor power panel).
22. Change the torque reference values to other and we can observe that the Propulsion motor will generate more power and the power taken from the grid is also more to drive the Induction machine (You can load up to 3KW as the Induction Machine is rated for 3KW,9Nm at 3000RPM).
23. Change the speed for constant Torque, Torque for constant speed and observe the dynamic behaviour of the propulsion motor for these operations.
24. Disable M2_en and M1_en.
25. Enter negative speed for the reverse motoring and breaking operation. We can Observe that the motor will run in opposite direction.
26. Repeat the steps from 17 to 23 to operate the set up for reverse motoring and breaking.
27. Disable M2_En and enter torque select to 2(torqueselect=2) to load the different torque profile. Enter torque step time (in terms of sec).

28. Go to itable section load the csv file which we have created for different torque profiles and enable M2_en. We can observe that the actual torque will track the profile torque and accordingly the propulsion motor will get loaded for mooting and regeneration and the power flow can be observed by using grid and battery power panels.
29. Repeat the above 2 steps for reverse direction and observe the power flow.
30. To turn off the setup disable M2_en -> GSC_en -> PLL_en -> M1_en -> Bidir_en -> gPwmEn.
31. Turn off grid MCB, Battery MCB and Torque sensor conditioner supply.
32. Below are the hardware results of setup.

Results:

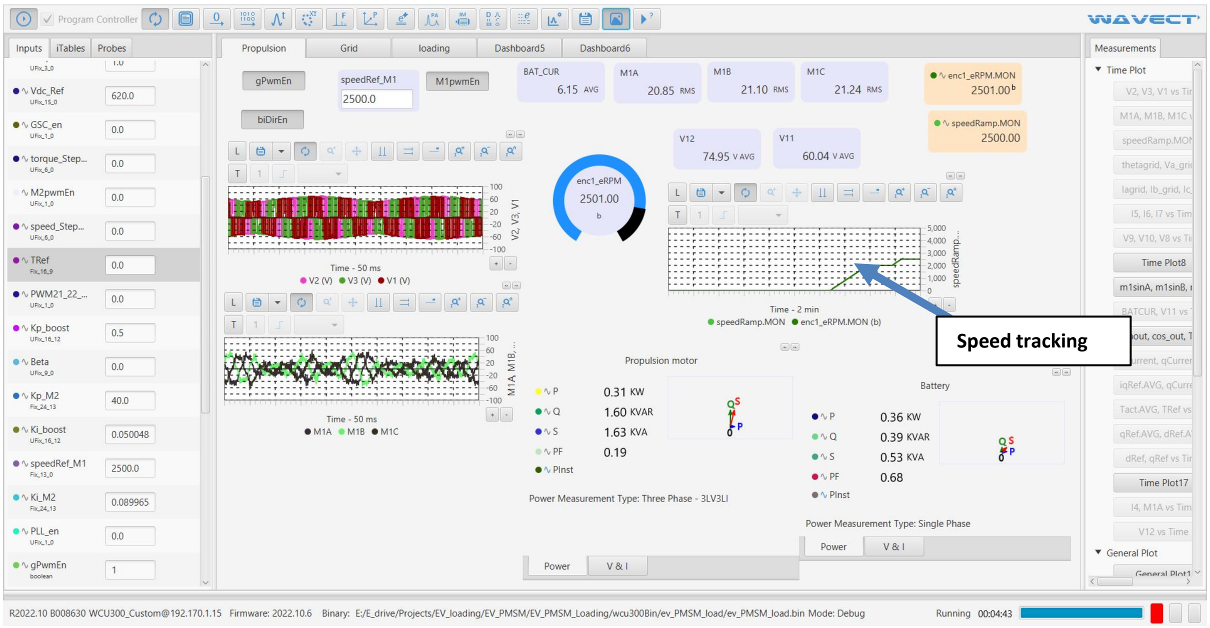


Fig.44 various characteristics with speed tracking

Speed reference given manually, we can observe the soft starting and the speed is maintaining as per the reference.

Fig.45   various characteristics and DC voltage profile

We can observe grid voltages and currents in the above image. When we turned on the PLL, grid theta is matching with Phase a of grid voltage. Also, we can observe the Vdc voltage is maintaining as per the reference.

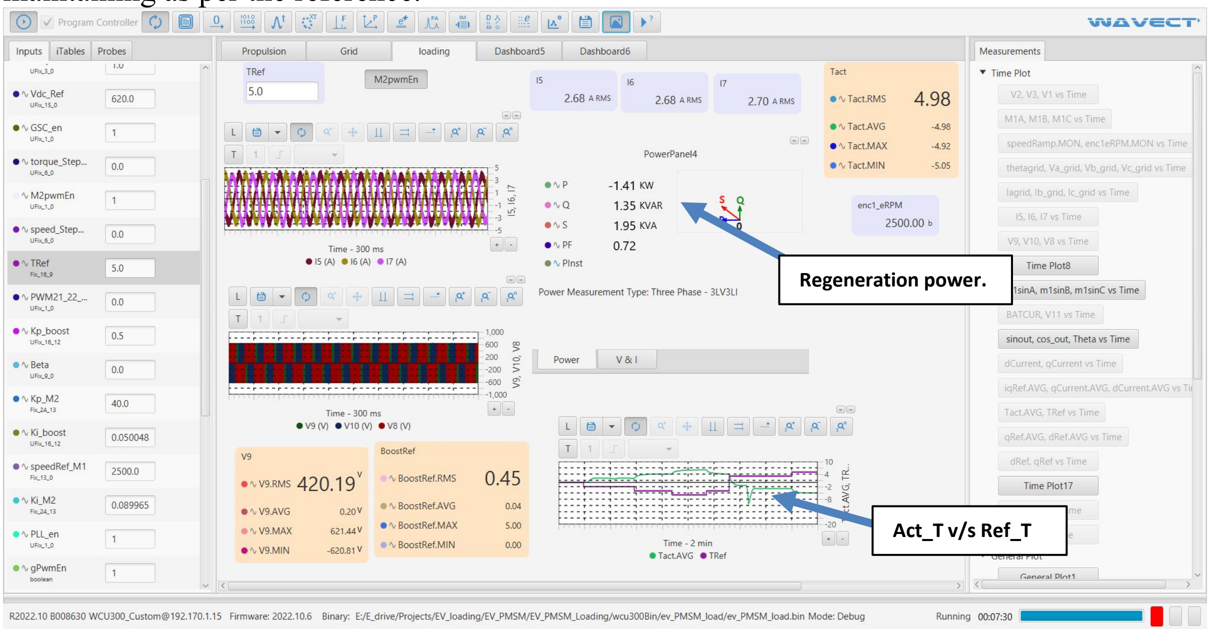


Fig.46 various characteristics and regenerative power action

We can observe that the reference torque and actual torques were opposite because the motor torque and the load torque will be opposite.

The actual torque is tracking as per the reference accordingly, propulsion motor will get loaded and regeneration power sent to the grid.

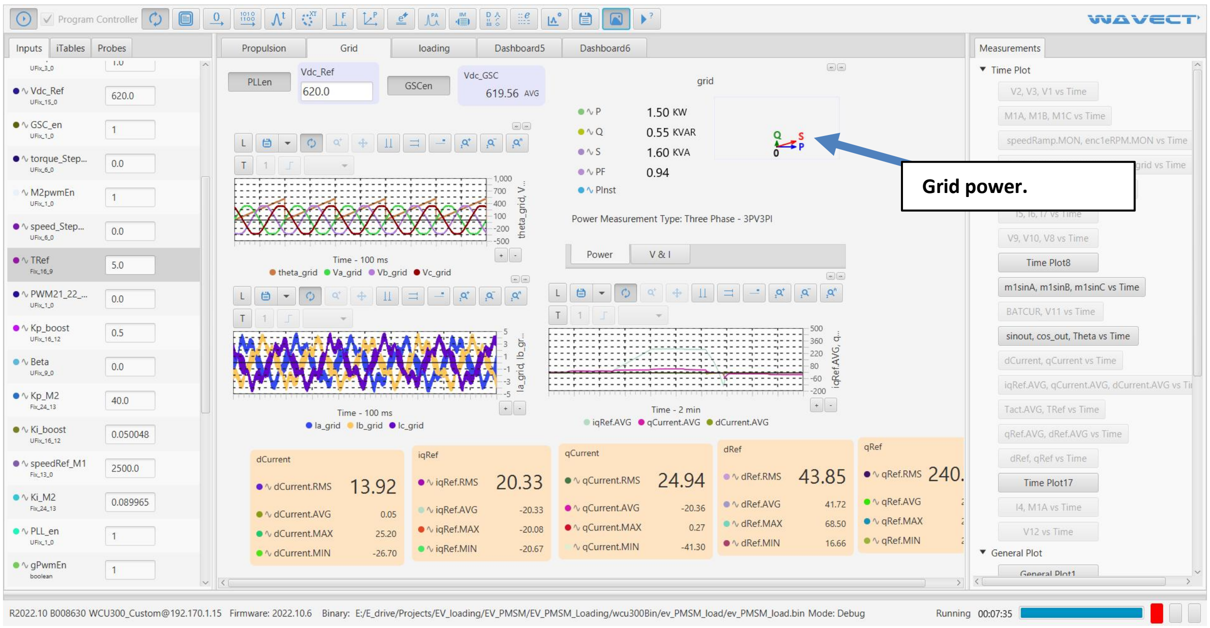


Fig.47 regenerative grid power

During the regeneration mode of propulsion motor the power taken from the grid to drive the Induction machine (Motoring). From the above image we can observe the power from the grid.

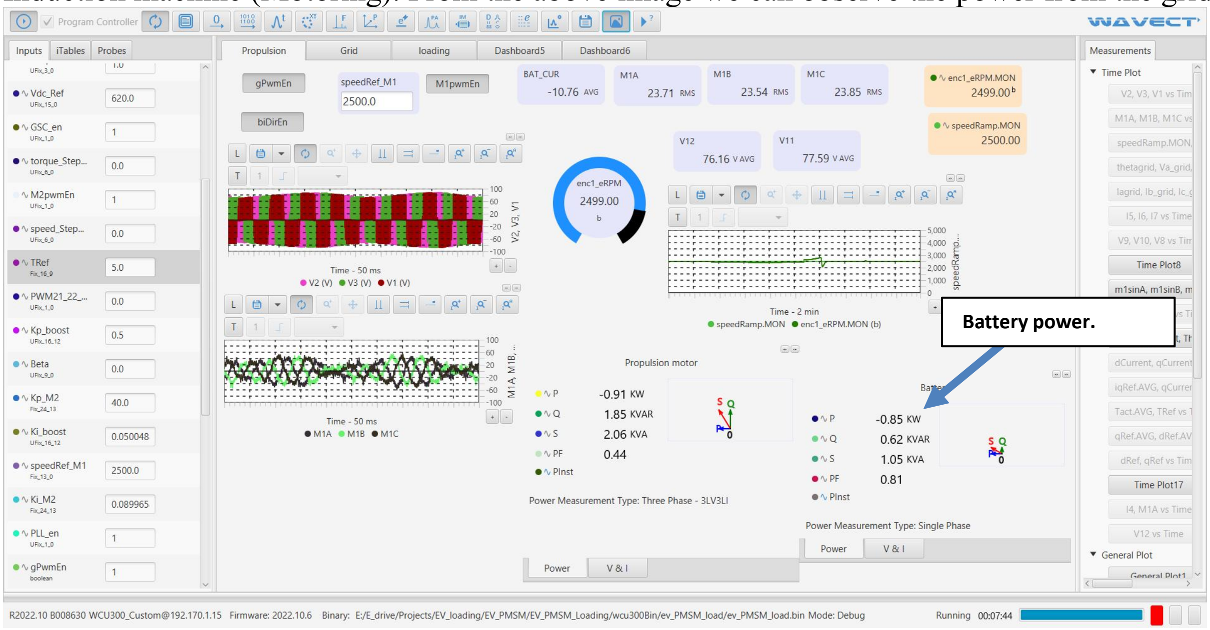


Fig.48 battery power waveform

In the above image we can see that the regeneration power from the propulsion machine the power is sent to the battery (charging using regeneration power).

Experiment No. 9

Aim: Study of grid side converter operation and analyse the active power flow and reactive power compensation

Apparatus Required: Hardware and software set up

Procedure:

Same as in experiment no.8

Results:

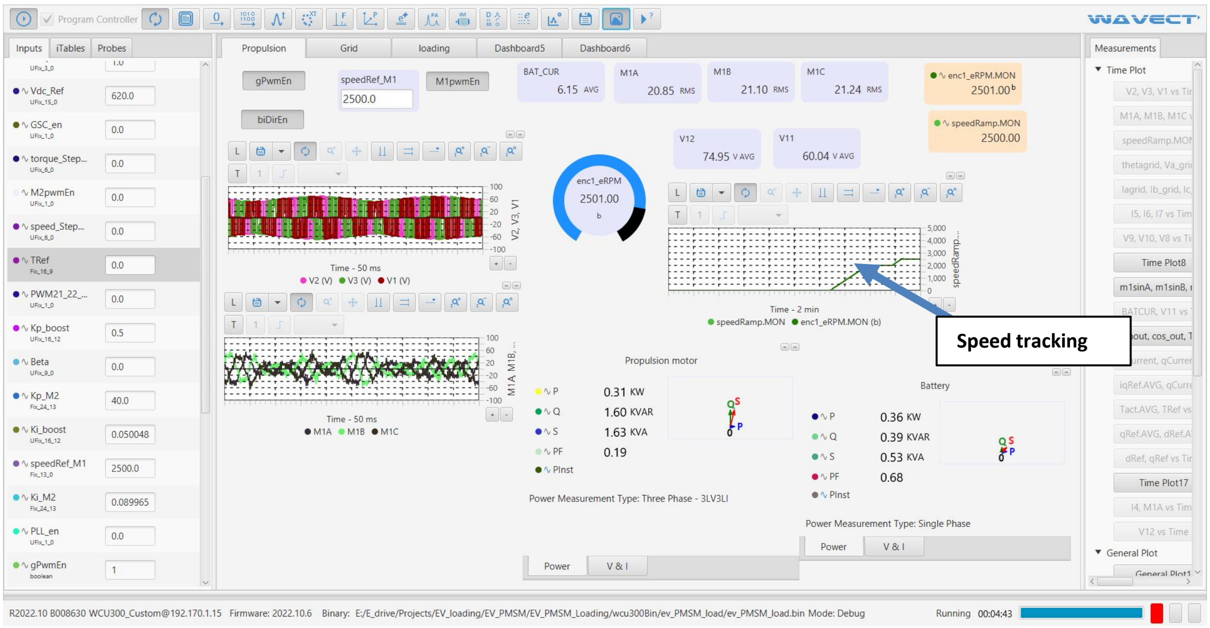


Fig.49 speed tracking waveform

Speed reference given manually, we can observe the soft starting and the speed is maintaining as per the reference.

Fig.50 DC link voltage waveform

We can observe grid voltages and currents in the above image. When we turned on the PLL, grid theta is matching with Phase a of grid voltage. Also, we can observe the Vdc voltage is maintaining as per the reference.