1 Computer Simulation and Analysis

Following the topology selection, a high-fidelity simulation model was developed using MATLAB/Simulink (Simscape Electrical). The objective was to validate the design requirements ($f_{ripple} > 1$ kHz), verify thermal limits (inrush currents), and predict the system response under realistic dynamic loading.

Unlike simplified average-value models, this simulation incorporates discrete switching devices, non-linear friction dynamics, and a physically coupled Motor-Generator (MG) set to replicate the laboratory test bench.

1.1 System Modeling Implementation

The simulation architecture is divided into three distinct subsystems: the Power Stage, the Control Logic, and the Electro-Mechanical Plant. Figure 1 illustrates the complete block diagram.

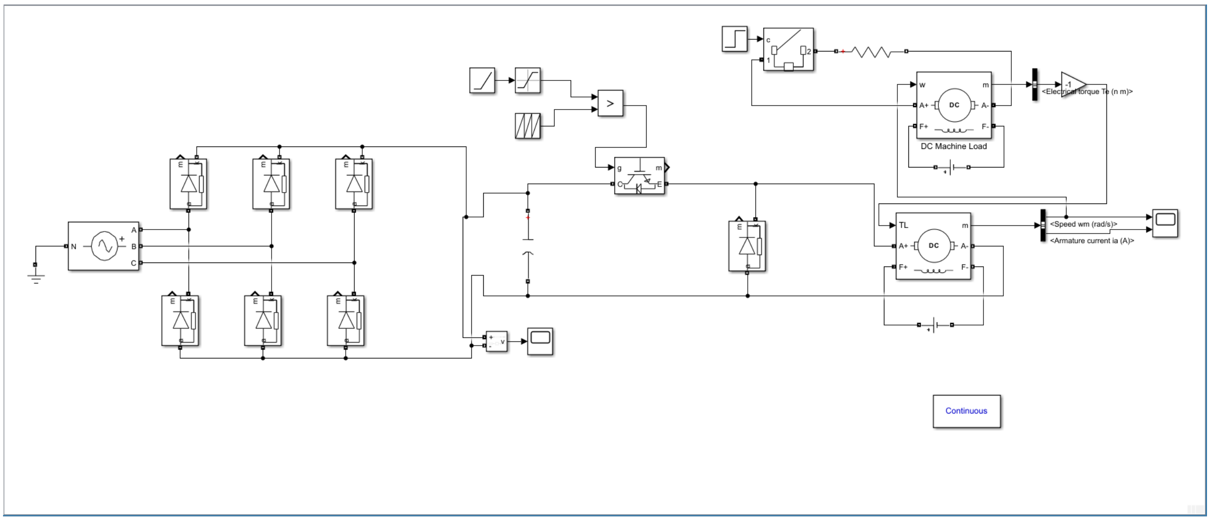

Figure 1: Overview of the Simulink model showing the Discrete Rectifier, Buck Converter, and Coupled Motor-Generator Set.

1.1.1 Discrete Power Stage

To accurately model component stresses, standard library blocks were avoided in favor of discrete component construction:

- **AC-DC Rectifier:** Constructed using six discrete power diode models in a three-phase bridge configuration. This enables the observation of individual diode conduction angles. The input is a programmable source (150 V_{rms} L-L), and the output is filtered by a 1000 μF capacitor, yielding a DC link voltage of approx. 205 V.

- **DC-DC Buck Converter:** Implemented with a discrete IGBT and Freewheeling Diode. This allows for the verification of the 10 kHz switching frequency and the observation of Discontinuous Conduction Mode (DCM) at light loads.

1.1.2 Control Logic (Open-Loop Soft Start)

Direct-on-line starting was found to generate dangerous inrush currents exceeding 140 A. To mitigate this, a custom Soft Start logic was implemented. A ramp generator increases the duty cycle reference linearly from 0 to 0.85 over 2.0 seconds.

$$D(t) = \mathrm{sat}\left(0.425 \times t\right) \quad \text{for } 0 \leq D(t) \leq 0.85 \tag{1}$$

This reference is compared against a 10 kHz sawtooth carrier to generate the PWM pulses, clamping the inrush current to safe levels.

1.1.3 Coupled Motor-Generator Plant

To simulate the load accurately, a second DC machine (Generator) was mechanically coupled to the drive motor via signal feedback:

- **Coupling:** The speed output (ω) of the drive motor is fed to the generator. The electromagnetic torque (T_e) produced by the generator is fed back as a load torque (T_L) to the drive motor.
- **Inertia:** The total system inertia ($J = 0.06\ \mathrm{kg}\cdot\mathrm{m}^2$) was distributed equally ($0.03\ \mathrm{kg}\cdot\mathrm{m}^2$ each) between the two blocks.
- **Load Step:** The generator armature is connected to a $12\,\Omega$ resistor via a controlled breaker. The simulation closes this breaker at $t = 2.5$ s, creating a realistic Step Load event.

1.2 Simulation Results

1.2.1 Transient Response and Load Rejection

The simulation was executed for 4.0 seconds to observe startup and load impact. The results are presented in Figure 2.

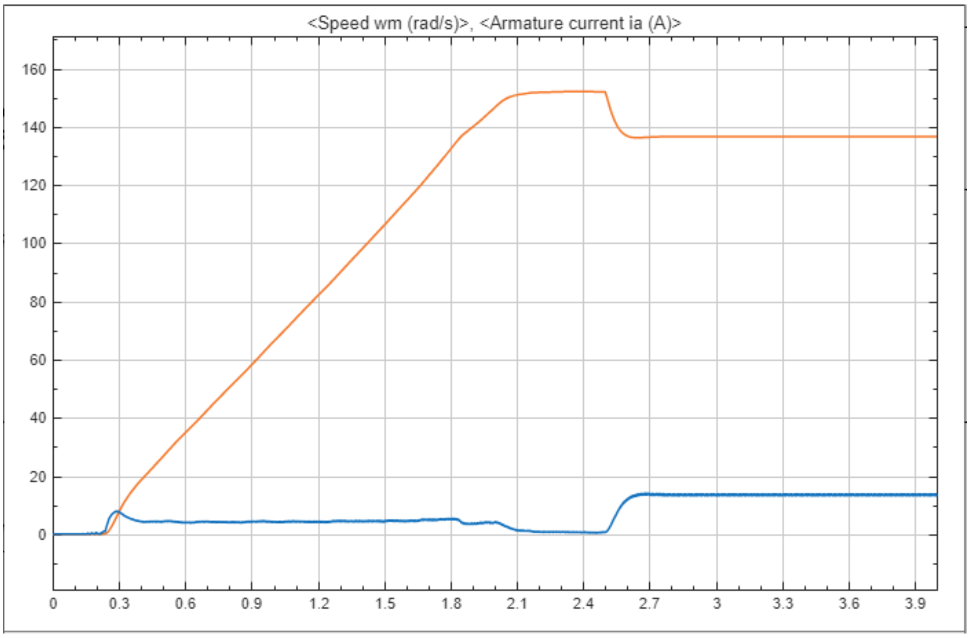

Figure 2: System Transient Response. Top: Motor Speed (rad/s). Bottom: Armature Current (A). The distinct phases of Dead Time, Acceleration, and Load Impact are visible.

Phase 1: Friction Dead-Band ($0-0.22$ s): A realistic delay is observed at startup. The motor remains stationary until $t = 0.22$ s, as the soft-start duty cycle is initially too low to generate current exceeding the Coulomb friction torque ($T_f = 0.3$ Nm).

Phase 2: Acceleration ($0.22-2.5$ s): Once breakaway occurs, the motor accelerates smoothly to ≈ 165 rad/s. The Soft Start logic successfully limits the inrush current to a peak of 25 A, well within the safety margins of the intended hardware.

Phase 3: Load Impact ($t = 2.5$ s): The generator breaker closes, applying the resistive load. The motor speed momentarily dips as the generator produces braking torque. The drive automatically draws increased current (rising to the rated 21 A) to stabilize the speed at a new equilibrium of 130 rad/s.

1.2.2 Current Ripple Verification

Steady-state current analysis (Figure 3) confirms the switching frequency of 10 kHz. The waveform exhibits a triangular ripple period of $100\,\mu$s.

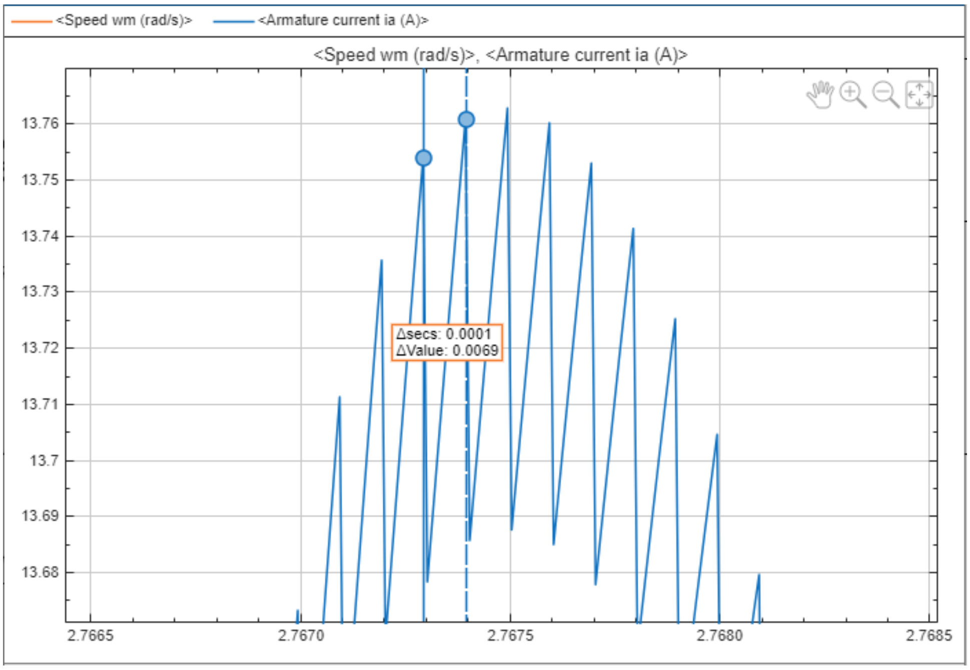

Figure 3: High-Resolution Armature Current Analysis. The triangular switching ripple ($f_{sw} = 10$ kHz) confirms compliance with project requirements.

Furthermore, a lower frequency modulation (300 Hz) is observed on the current peaks. This confirms that the simulated DC link correctly reflects the characteristics of a three-phase rectified source rather than an ideal battery.