Chapter 6

Independent Control of Two Motors Fed by Dual-Output Multilevel Converter

6.1 Background

The primary limitation of reduced-switch-count dual-output converters in [20, 21, 22, 23, 24, 25, 26, 27, 79] is the restriction in the operating boundary region. It is caused by the unavailability of certain switching states, which impact the modulation technique, DC-link voltage, and output voltage. However, the TLDO-ANPC converter overcomes this drawback by offering a full region of operation. This chapter proposes the independent control of two different motors—an induction motor and a PMSM using the TLDO-ANPC converter as a single inversion stage, replacing parallel voltage-source inverter systems. The configuration functions as a mono-inverter dual-parallel (MIDP) system, sharing a common DC-link voltage without compromising motor control. This approach is particularly suitable for applications in electric transportation systems, EVs, 4WD vehicles, fans, pumps, and more. Two primary requirements for these applications are that both motors operate at the same and different speeds, regardless of load conditions. The TLDO-ANPC has been experimentally validated for its effectiveness with two different motors.

TABLE 6.1: Switching States, Corresponding Output Voltage and Capacitor Charging State of the TLDO-ANPC

S.No.	Switching Signals	Output Voltages (V_{dc})		Capacitor state ($i_{x1} > 0$, $i_{x2} > 0$)		Count
	S_{x1} S_{x2} S_{x3} S_{x4} S_{x5} S_{x6} S_{x7} S_{x8}	v_{x1}	v_{x2}	C_1	C_2	
1	0 1 0 1 1 0 1 0	0	0	NA	NA	6
	0 1 1 0 1 0 1 0	0	0	NA	NA	
	0 1 1 0 1 0 0 1	0	0	NA	NA	
	0 1 1 0 0 1 0 1	0	0	NA	NA	
	1 0 1 0 0 1 0 1	0	0	NA	NA	
	0 1 1 0 0 1 1 0	0	0	NA	NA	
2	1 0 1 0 0 1 1 0	0	0.5	↓	NA	1
3	0 1 0 1 1 0 0 1	0	-0.5	NA	↑	1
4	1 0 1 0 1 0 0 1	0.5	0	↓	NA	1
5	1 0 1 0 1 0 1 0	0.5	0.5	↓	NA	2
	1 0 0 1 1 0 1 0	0.5	0.5	NA	NA	
6	1 0 0 1 1 0 0 1	0.5	-0.5	↓	↑	1
7	0 1 0 1 0 1 1 0	-0.5	0	NA	↑	1
8	1 0 0 1 0 1 1 0	-0.5	0.5	↓	↑	1
9	0 1 0 1 0 1 0 1	-0.5	-0.5	NA	↑	2
	1 0 0 1 0 1 0 1	-0.5	-0.5	NA	↑	
Total						16

↑ is for charging, ↓ is for discharging state and NA = Not affected

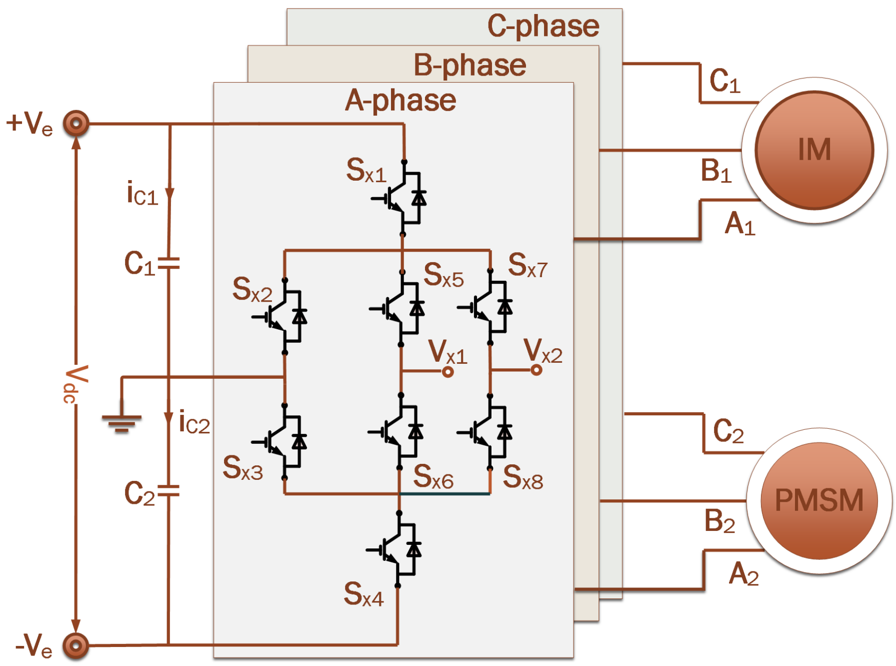


FIGURE 6.1: TLDO-ANPC fed two motors.

6.2 Three-Level Dual Output Active Neutral Point Clamped (TLDO-ANPC) Converter for EVs

The TLDO-ANPC converter-fed induction motor (IM) and permanent magnet synchronous motor (PMSM) is shown in Fig. 6.1. TLDO-ANPC produces two sets of output voltages and offers complete independent control of its output terminals. The single phase TLDO-ANPC converter consists of eight switches (S_{x1} to S_{x8}) and two DC-link capacitors (C_1, C_2). Out of these eight switches, S_{x1}, S_{x2}, S_{x3} and S_{x4} are inner switches and S_{x5}, S_{x6}, S_{x7}, and S_{x8} are outer switches per leg. Where "x" mentioned in the following part is all x $\in$ {A, B, and C}. The DC-link neutral point is connected to the midpoint of switches S_{x2} and S_{x3}. The output voltages v_{x1} and v_{x2} are the two distinct phase voltages obtained from the combination of inner and outer switches with respect to the neutral point. The two output load currents are the i_{x1} and i_{x2}. For driving a six-phase machine or two three-phase loads, conventional three-level ANPC requires 36 switches, while TLDO-ANPC requires only 24 switches. A typical in-phase PWM-based modulation technique used for the TLDO-ANPC converter is illustrated in Fig. 6.2, where the inverter is shown. In this figure, the blue lines indicate the current flow paths. The output voltages at the two terminals of TLDO-ANPC are positive (P), zero (O), and negative (N). In the 'P' state, leg voltage is equal to V_{c1}, i.e., $+V_dc/2$. In the 'N' state, leg voltage is V_{c2}, i.e.,

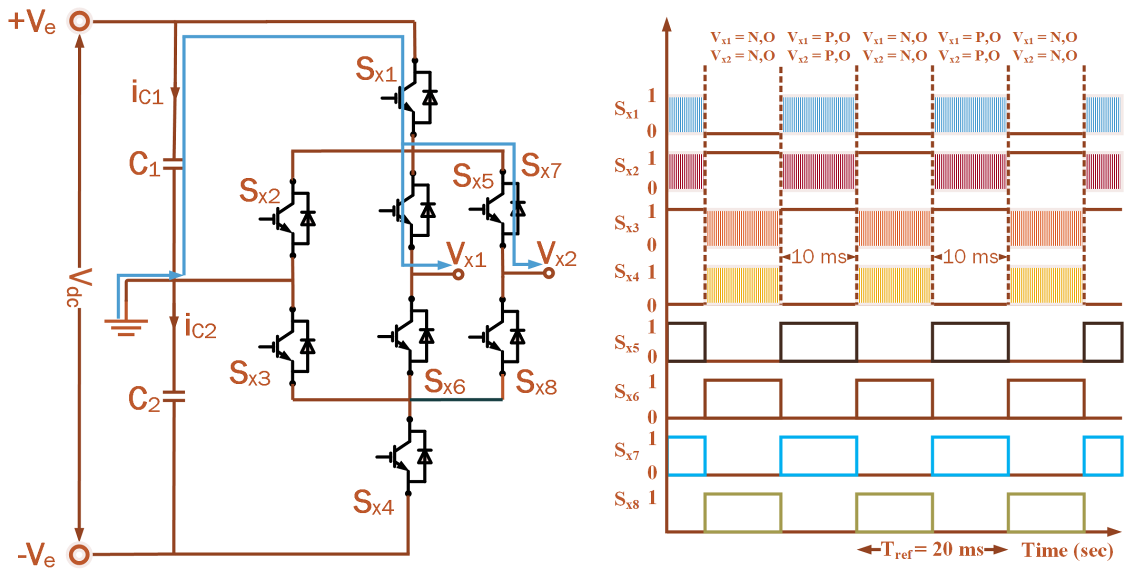


FIGURE 6.2: Commutation method and switching states of the TLDO-ANPC converter using IPD-PWM modulation.

$V_{dc}/2$. In the 'O' state, the output terminal is connected to the neutral point of the DC-link. All possible switching combinations of the single-phase TLDO-ANPC converter are shown in Table 6.1. Among sixteen valid states per phase of the converter, seven are redundant. These redundant switching states reduce the average device switching frequency and dynamic power loss while balancing the DC-link capacitor.

6.3 Control Methodology

The Field Oriented Control (FOC) control methodology is employed for induction motor (IM) and permanent magnet synchronous motor (PMSM). FOC uses three-phase to two-phase transformation to facilitate independent control over the torque-producing (q-axis) and flux-producing (d-axis) current components. Consequently, the control algorithm ensures optimal motor performance during both steady-state and transient operations. Some key advantages of FOC include:

- The ability to regulate the torque and flux independently by controlling the stator current components.
- Enhanced torque response and efficiency due to precise vector control.
- The capability to achieve high dynamic performance in various operating conditions.

By aligning the rotor flux along the d-axis (Ψ_R), a direct relationship between torque and q-axis current (i_q) is established, allowing precise torque regulation.

6.3.1 Mathematical Model of IM

The mathematical model governing the dynamics of an induction motor in the d-q reference frame can be expressed as:

$$v_{dqs} = R_s i_{dqs} + \frac{d\Psi_{dqs}}{dt} + j\omega_s \Psi_{dqs} \tag{6.1}$$

$$0 = R_r i_{dqr} + \frac{d\Psi_{dqr}}{dt} + j(\omega_s - \omega_m)\Psi_{dqr} \tag{6.2}$$

$$\Psi_{dqs} = L_s i_{dqs} + L_m i_{dqr} \tag{6.3}$$

$$\Psi_{dqr} = L_r i_{dqr} + L_m i_{dqs} \tag{6.4}$$

$$T_{em} = \frac{3}{2} p(\Psi_{ds} i_{qs} - \Psi_{qs} i_{ds}) \tag{6.5}$$

where:

- ω_m represents the rotor mechanical speed.
- ω_s is the stator flux speed.
- $\omega_{slip} = \omega_s - \omega_m$ denotes the slip speed.
- R_s and R_r are the stator and rotor resistances, respectively.
- L_s and L_r denote the stator and rotor inductances, respectively.
- L_m represents the mutual inductance.
- p is the number of pole pairs.
- v_{dqs}, i_{dqs}, and Ψ_{dqs} are the d-q axis stator voltage, current, and flux linkage, respectively.
- i_{dqr} and Ψ_{dqr} represent the rotor current and flux linkage in the d-q reference frame.

Assuming that the rotor flux aligns with the direct axis ($\Psi_{qr} = 0$), the electromagnetic torque simplifies to:

$$T_{em} = \frac{3}{2} p \frac{L_m}{L_r} \Psi_{dr} i_{qs} \tag{6.6}$$

6.3.2 Mathematical Model of PMSM

In most PMSM control strategies, the motor equations depend on the rotor position. However, expressing these equations in the rotor reference frame eliminates this dependency, simplifying control implementation. The transformation from the three-phase system to the d-q frame results in the following mathematical model:

$$v_d = Ri_d + \frac{d\Psi_d}{dt} - \omega_s \Psi_q \tag{6.7}$$

$$v_q = Ri_q + \frac{d\Psi_q}{dt} + \omega_s \Psi_d \tag{6.8}$$

$$P_o = \frac{3}{2}\left(-\omega_s \Psi_q i_d + \omega_s \Psi_d i_q\right) \tag{6.9}$$

$$T_e = \frac{3}{2}p\left[\Psi_m i_q + (L_d - L_q) i_q i_d\right] \tag{6.10}$$

For a surface-mounted PMSM where $L_d = L_q$ or when i_d is controlled to zero, the torque equation reduces to:

$$T_e = \frac{3}{2}p\Psi_m i_q \tag{6.11}$$

where:

- L_d and L_q are the d- and q-axis inductances, respectively.
- v_d and v_q are the d- and q-axis stator voltages.
- i_d and i_q are the d- and q-axis stator currents.
- ω_s is the rotor's angular velocity.
- R is the stator resistance per phase.
- Ψ_d and Ψ_q represent the d- and q-axis flux linkages.
- Ψ_m denotes the permanent magnet flux linkage.

From the electromagnetic torque equation, it is evident that the torque can be regulated solely through the q-axis current component, as the permanent magnet flux linkage remains constant. This characteristic enables precise and decoupled control in the FOC scheme.

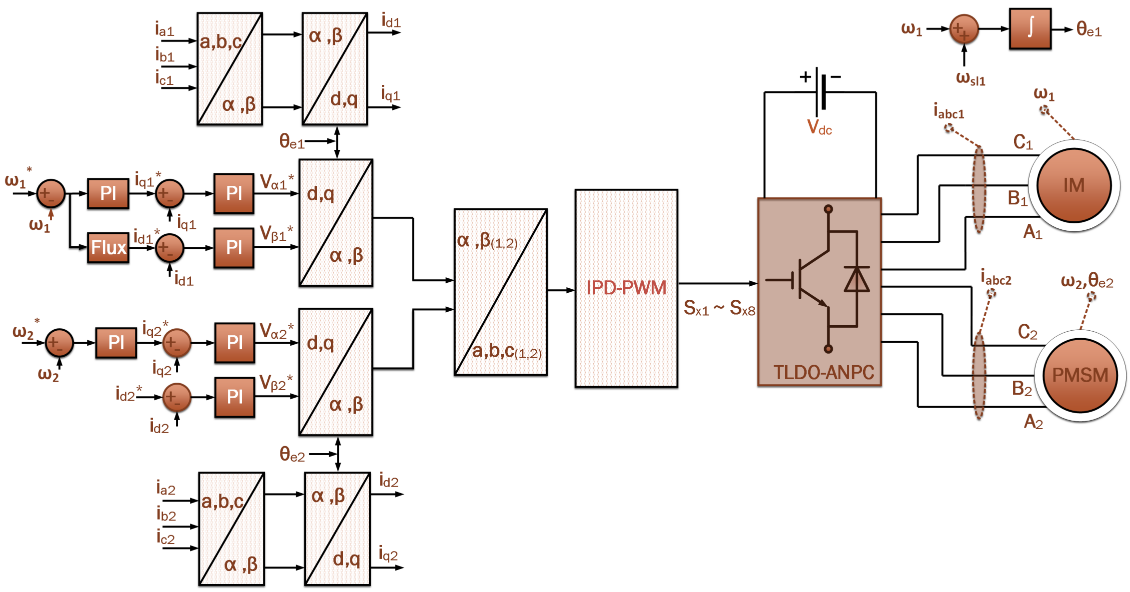


FIGURE 6.3: Schematic diagram of the field-oriented control for two different motors powered by the TLDO-ANPC converter.

6.4 Independent Control of Two Different Motors Fed by TLDO-ANPC

The independent speed and torque control of two different motors, an induction motor (IM) and a permanent magnet synchronous motor (PMSM) is a crucial requirement in many industrial and transportation applications. Fig. 6.3 presents the schematic diagram of field-oriented control for two different motors driven by the TLDO-ANPC converter. Fig. 6.4 shows the flow chart of independent control two different motors. The TLDO-ANPC converter enables this functionality by generating two distinct sets of three-phase voltages, allowing each motor to operate under different electrical and mechanical conditions without interference. By employing field-oriented control (FOC) for both motors, precise decoupled control of speed and torque is achieved, improving overall system efficiency and dynamic performance. For the both the motors direct FOC (DFOC) is utilized where rotor position feedback allows for direct torque control, ensuring fast dynamic response and high efficiency. The torque-producing component of the current (iq) is regulated separately from the flux-producing component (id) to maintain desired torque and speed. The PMSM typically operates with id = 0 to maximize torque per ampere, whereas the IM requires proper slip regulation to achieve optimal efficiency. The TLDO-ANPC converter enables fully independent operation of both motors, even when running at different speeds and load conditions. For example, the IM can operate at 50 Hz while the PMSM runs

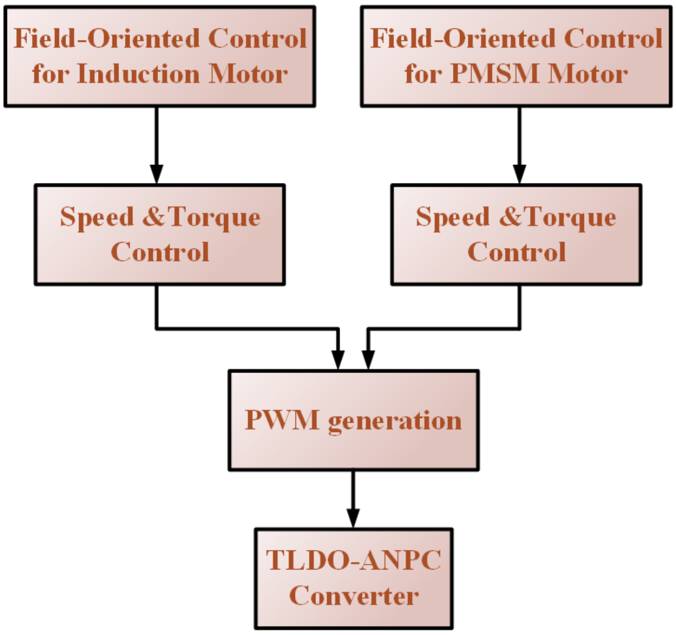


FIGURE 6.4: Independent control of two different motors.

at 100 Hz, allowing the system to drive applications such as multi-motor electric vehicles, industrial robots, conveyor belts, and variable-speed compressors. This independent frequency operation is facilitated by the different frequency (DF) Mode of the converter, where separate control loops regulate voltage, frequency, and phase for each motor. Another significant advantage of this system is independent control of two motors, ensuring that variations in one motor's load do not affect the performance of the other. Traditional dual-motor drive systems with shared power inverters often suffer from mutual coupling effects, leading to speed fluctuations, master-slave operation, and instability. However, the TLDO-ANPC converter eliminates this issue by ensuring that each motor receives a dedicated and stable power supply, controlled by independent FOC loops. This results in improved transient response and steady state response. Moreover, the use of in-phase disposition pulse width modulation (IPD-PWM) helps maintain DC-link voltage balancing, eliminating the need for additional control complexity. The converter's high efficiency and low switching losses further enhance its suitability for high-performance drive applications where compactness, cost-effectiveness, and reliability are critical. Fig. 6.5(a) illustrates the projection of reference signals onto the boundary region for IM and PMSM operating at the same speed of 400 rpm. In contrast, Fig. 6.5(b) depicts the projection of reference signals onto the boundary region for different operating speeds: 400 rpm for IM and 900 rpm for PMSM.

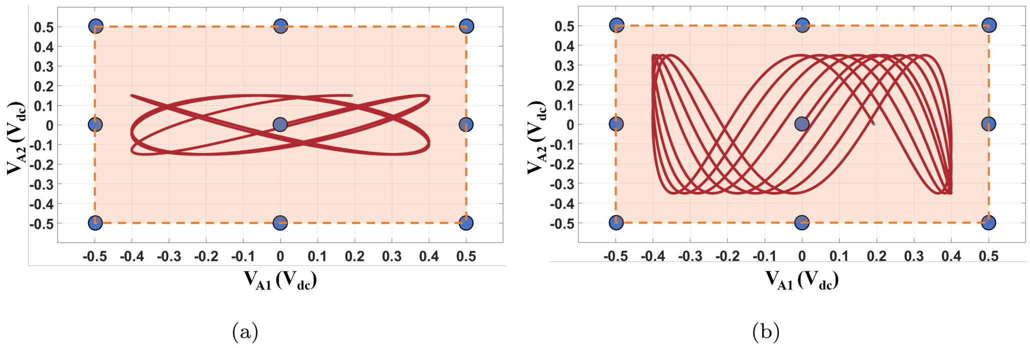


FIGURE 6.5: Projections of reference signals onto the 5LDO-ANPC converter's boundary region (a) same speed of operation and (b) different speed of operation.

6.5 Simulation Result

Simulation is performed using MATLAB/Simulink to evaluate the performance of a TLDO-ANPC-fed Induction Motor (IM) and Permanent Magnet Synchronous Motor (PMSM). Table 6.2 lists the parameters of the TLDO-ANPC and both motors. The TLDO-ANPC parameters are derived from the laboratory test bench and are consistently applied to both simulation and experimental setups to ensure uniformity.

TABLE 6.2: Main Parameters of TLDO-ANPC and Motors.

TLDO-ANPC		
Parameter	**Value**	
DC-link voltage (V_{dc})	200 V	
DC-Link capacitor ($C_1 = C_2$)	2200 μ F	
Switching frequency (fs)	2 kHZ	
Motor		
Parameter	**IM**	**PMSM**
Rated speed (N)	960 rpm	6500 rpm
Rated current (I)	5.2 A	16.96 A
Moment of inertia (J)	0.0404 kgm^2	0.003 kgm^2
Number of poles (p)	6	8
Stator resistance (Rs)	9.075 Ω	0.35 Ω
Rotor resistance (Rr)	10.72 Ω	-
Stator Inductance (Ls)	0.0511 H	0.00135 H
Rotor Inductance (Lr)	0.0511 H	-
Mutual inductance (Lm)	0..6687 H	-

Two dynamic scenarios are considered for performance analysis. Fig. 6.6 (a) and (b) illustrate the simulation results for the IM and PMSM, respectively. The following signals are monitored: line voltages (V_{AB1}, V_{BC1} for IM; V_{AB2}, V_{BC2} for PMSM), phase currents

(I_{ABC1} for IM, I_{ABC2} for PMSM), d-q axis currents (I_{dq1} for IM, I_{dq2} for PMSM), motor speeds (N_1 for IM, N_2 for PMSM), and electromagnetic torques (T_{e1} for IM, T_{e2} for PMSM).

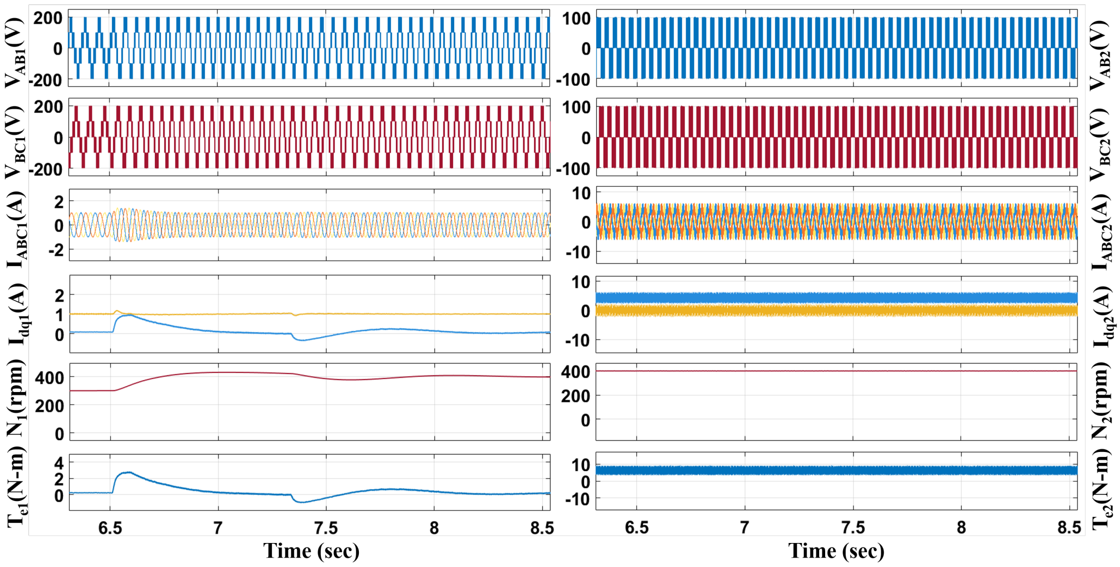
Scenario 1: In the first scenario (Fig. 6.6(a)), both motors initially operate at the different speed: $N_1 = 300$ rpm $N_2 = 400$ rpm, with load torques of $T_1 = 0.2$ N·m (IM) and $T_2 = 6$ N·m (PMSM). At 6.5 seconds, the speed of the IM is increased from 300 rpm to 400 rpm, while the PMSM speed remains constant. This setup demonstrates equal-speed operation under different load torques. The d-axis currents are 1 A (IM) and 0 A (PMSM), and the q-axis currents are 0.3 A (IM) and 4.12 A (PMSM).

Scenario 2: In the second scenario (Fig. 6.6(b)), the motors begin at different speeds: $N_1 = 400$ rpm (IM) and $N_2 = 700$ rpm (PMSM), with the same load torques as in Scenario 1. This configuration demonstrates independent speed control under different load torques. At 5.1 seconds, the PMSM speed is increased from 700 rpm to 900 rpm, while the IM speed remains unchanged. The d-axis currents are at 1 A (IM) and 0 A (PMSM), and the q-axis currents are at 0.3 A (IM) and 4.12 A (PMSM). The DC-link capacitor voltage remains balanced in both scenarios, as illustrated in Fig. 6.7.

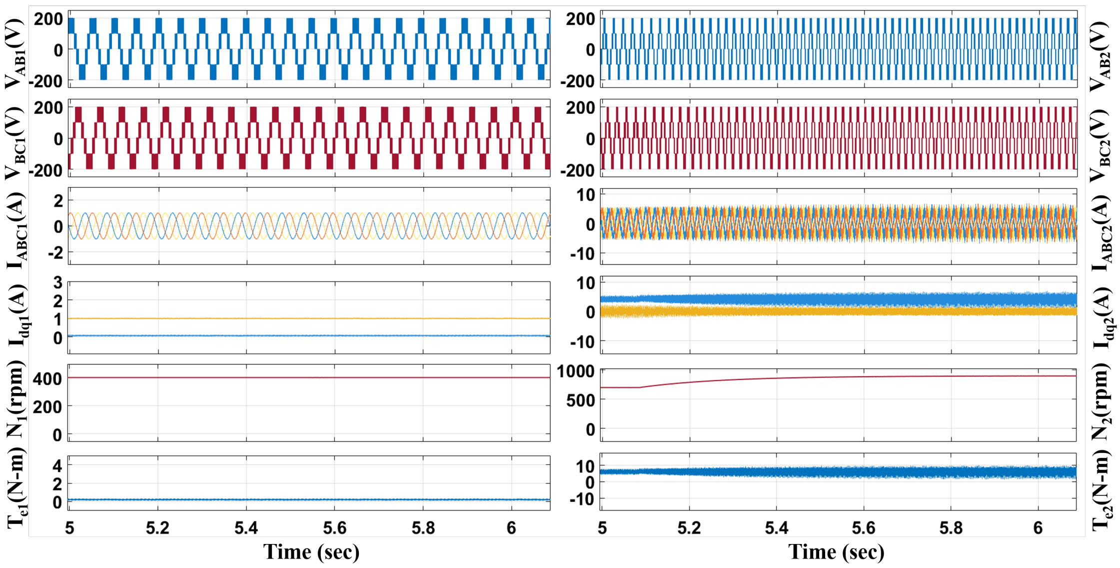
6.6 Experimental Verification

6.6.1 Experimental Setup

Experiments are conducted to validate the performance of the TLDO-ANPC converter driving two different motors using the field-oriented control method. Fig. 6.8 illustrates the experimental setup, which includes the TLDO-ANPC converter operating with both IM and PMSM motors. The test bench comprises a dSPACE 1202 controller, two motors, a DC power supply, the necessary current sensors, and the TLDO-ANPC converter. Two DC motors connected to rheostats serve as distinct loads for the induction motor (IM) and permanent magnet synchronous motor (PMSM). The parameters of the IM and PMSM are provided in Table 6.2. Incremental encoders are used to determine the rotor's angular position. The DC-link voltage is set to 200 V, and the switching frequency used in the experiment is 2 kHz. In all test scenarios, the PI controller parameters are carefully tuned to achieve optimal control performance.



(a)



(b)

FIGURE 6.6: Dynamic performance of IM and PMSM under (a) speed variation of the IM and (b) speed variation of the PMSM

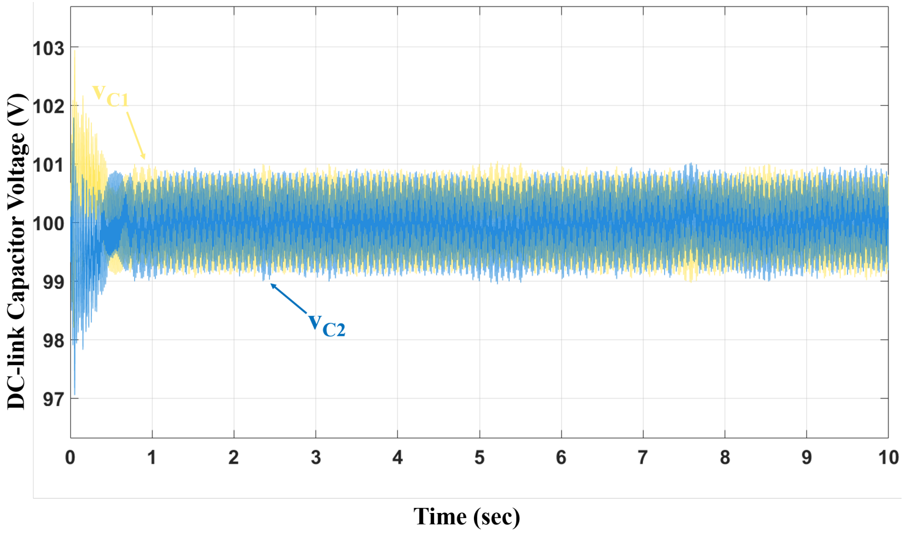


FIGURE 6.7: DC-link Capacitor voltage balancing.

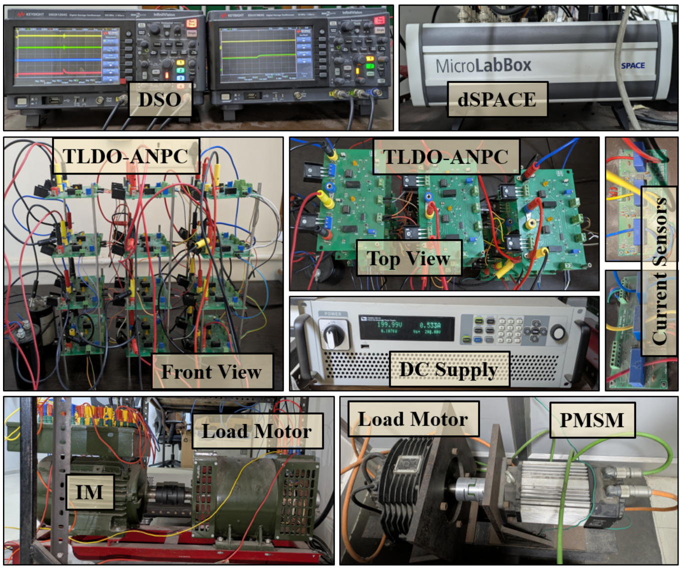
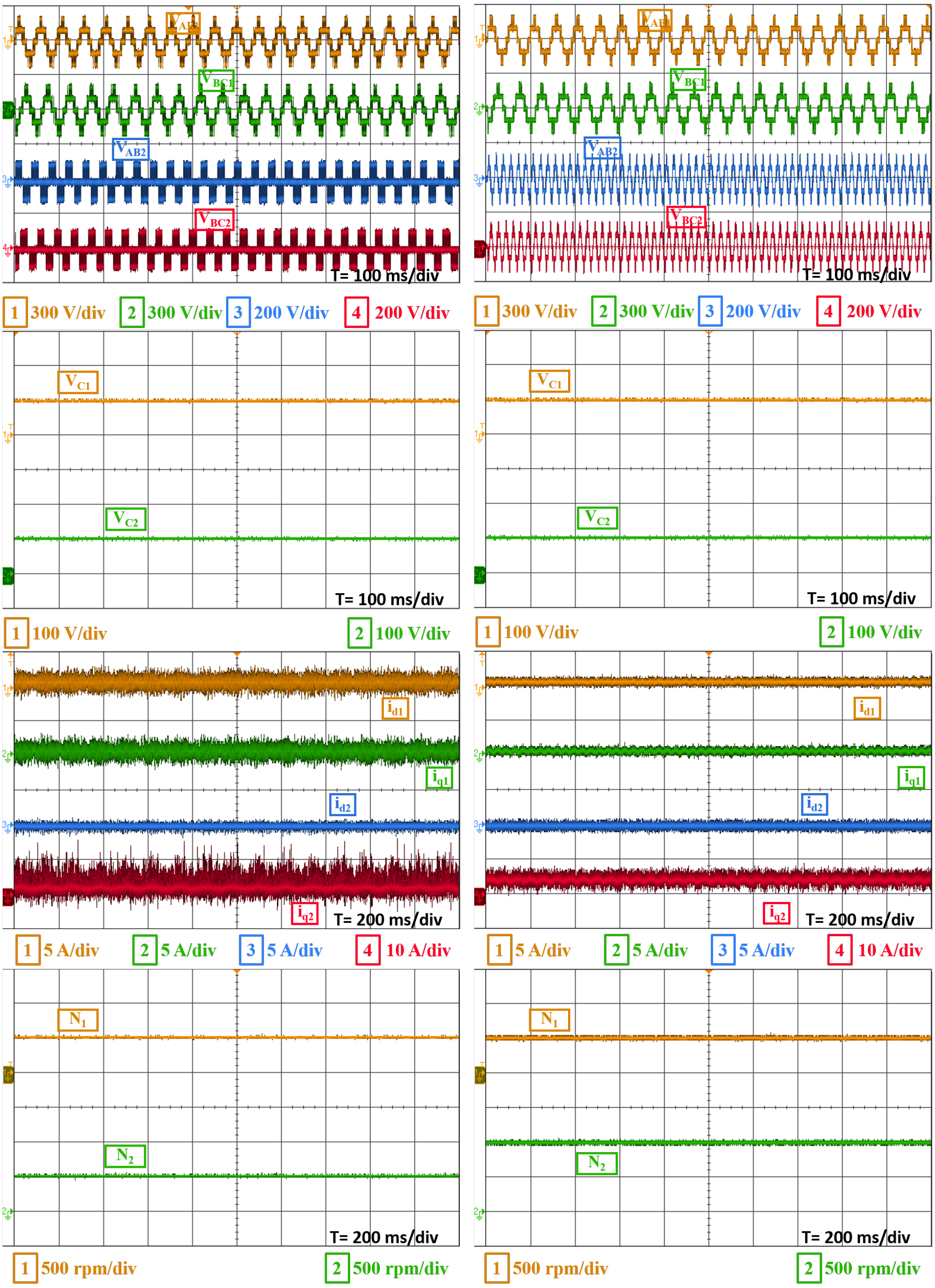


FIGURE 6.8: Test platform.

6.6.2 Steady-State Performance

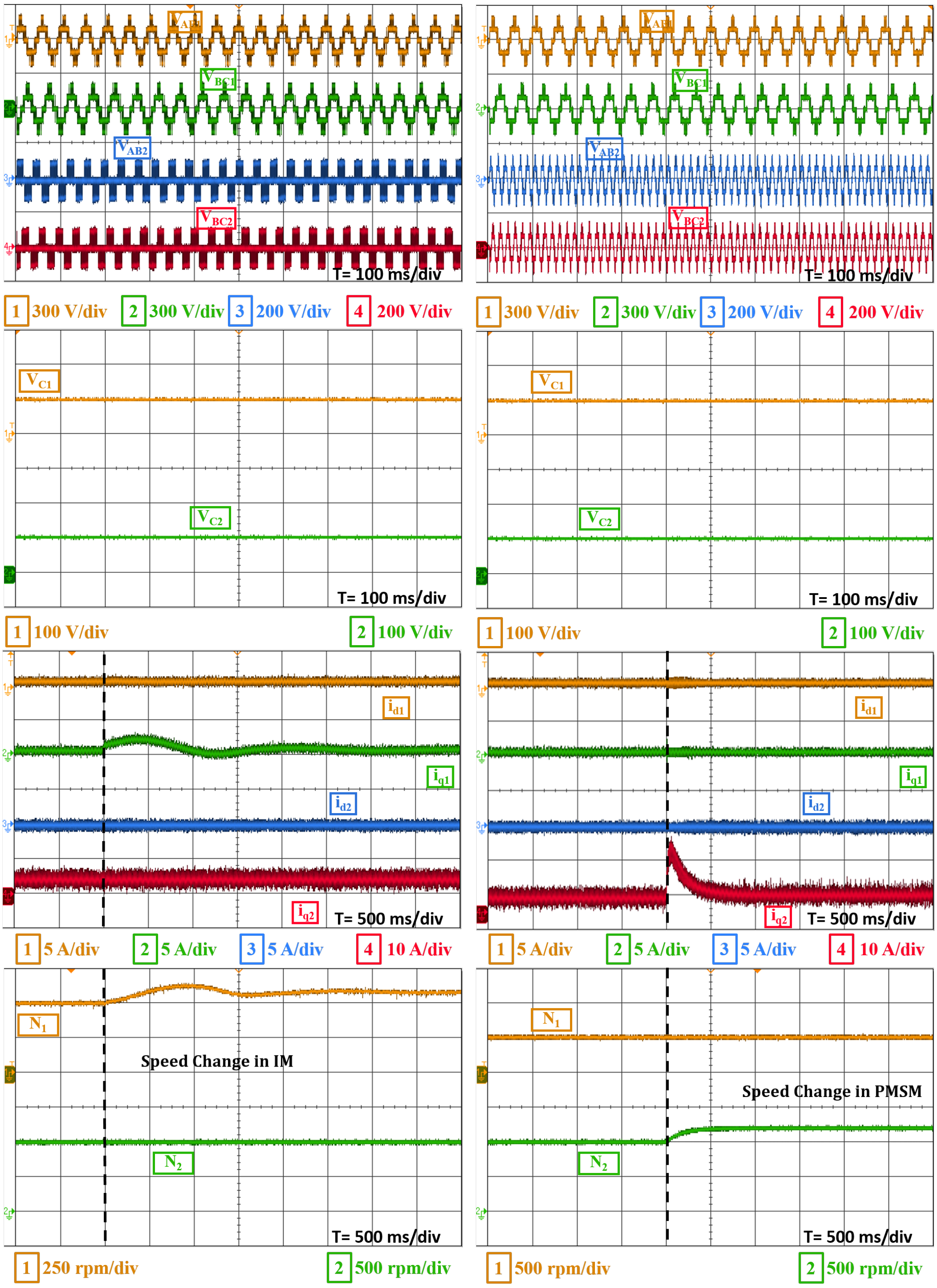
Figs. 6.9(a) and (b) presents the steady-state experimental results for two scenarios:

- **Fig. 6.9(a): Same Speed Operation**
  Both motors, IM and PMSM, are operated at $N_1 = N_2 = 500$ RPM under different load torques. The d-axis currents are 0.96 A for the IM and 0 A for the PMSM, while the q-axis currents are 0.39 A for the IM and 2.537 A for the PMSM. This setup demonstrates synchronized speed operation of two different motors. Additionally,



(a) (b)

FIGURE 6.9: Experimental Result of line voltages (v_{AB1}, v_{BC1}, v_{AB2}, v_{BC2}), dc-link capacitor voltage (V_{C1}, V_{C2}), direct and quadrature axis currents (i_{d1}, i_{d2}, i_{q1}, i_{q2}) and speed (N_1, N_2) for IM and PMSM under (a) Same speed of operation, (b) different speed of operation.



(a) (b)

FIGURE 6.10: Experimental Result of line voltages (v_{AB1}, v_{BC1}, v_{AB2}, v_{BC2}), dc-link capacitor voltage (V_{C1}, V_{C2}), direct and quadrature axis currents (i_{d1}, i_{d2}, i_{q1}, i_{q2}) and speed (N_1, N_2) for IM and PMSM under (a) speed variation of the IM, and (b) speed variation of the PMSM.

the figure displays the line voltages v_{AB1}, v_{BC1}, v_{AB2}, and v_{BC2}, along with the balanced capacitor voltages V_{C1} and V_{C2}.

- **Fig. 6.9(b): Different Speed Operation**
  The IM operates at $N_1 = 500$ RPM, while the PMSM runs at $N_2 = 1000$ RPM, each under different load torques. The d-axis currents (i_{d1} and i_{d2}) are 0.96 A for the IM and 0 A for the PMSM, while the q-axis currents (i_{q1} and i_{q2}) are 0.39 A for the IM and 4 A for the PMSM. This scenario highlights independent speed control of two different motors under varied load conditions. The figure also displays the line voltages v_{AB1}, v_{BC1}, v_{AB2}, and v_{BC2}, as well as the balanced capacitor voltages V_{C1} and V_{C2}.

6.6.3 Dynamic Performance

Figs. 6.10(a) and (b) present the dynamic performance of the two motors fed by TLDO-ANPC for two scenarios:

- **Fig. 6.10(a): Speed Change in IM**
  Initially, the IM operates at $N_1 = 500$ RPM, and the PMSM at $N_2 = 1000$ RPM under different load torques. At a specific moment, the IM speed changes from 500 RPM to 580 RPM, while the PMSM maintains its speed at 1000 RPM. The d-axis currents, $i_{d1} = 0.96$ A (IM) and $i_{d2} = 0$ (PMSM), while the q-axis currents, $i_{q1} = 0.39$ A (IM) and $i_{q2} = 4$ A (PMSM). The figure also shows the line voltages v_{AB1}, v_{BC1}, v_{AB2}, and v_{BC2}, along with the balanced capacitor voltages V_{C1} and V_{C2}.

- **Fig. 6.10(b): Speed Change in PMSM**
  Initially, the IM operates at $N_1 = 500$ RPM, and the PMSM at $N_2 = 1000$ RPM under different load torques. At a specific point, the PMSM speed changes from 1000 RPM to 1200 RPM, while the IM maintains its speed at 500 RPM. The d-axis currents are $i_{d1} = 0.96$ A (IM) and $i_{d2} = 0$ (PMSM), while the q-axis currents remain at $i_{q1} = 0.39$ A (IM) and $i_{q2} = 4$ A (PMSM). This figure also presents the line voltages v_{AB1}, v_{BC1}, v_{AB2}, and v_{BC2}, and the balanced capacitor voltages V_{C1} and V_{C2}.

In both steady-state and dynamic conditions, the TLDO-ANPC configuration demonstrates independent control of two distinct motors while balancing the DC-link capacitor voltages. This design eliminates the master-slave requirement in a conventional mono-inverter dual-parallel (MIDP) system operating two motor drives.

Unlike reduced switch count topologies such as Five-leg inverters (FLI), nine-switch inverters (NSI), and six-switch converters (SSC), three-level dual ouput voltage (TLDOV) converter etc, this configuration offers unrestricted operation of two motors. It avoids the inherent limitations of these reduced-switch configurations while providing flexible, independent control over both motors.