

EMRAX 208 motor and drivetrain test bench

Engineering planning report

7 October 2026

1 Executive summary and scope

The proposed bench is technically feasible as a four-quadrant electric dynamometer, subject to verification of the machine envelopes, energy-management system, mechanical assembly and safety functions. It will characterize the EMRAX motor and a 4.7:1 reduction drivetrain under steady and transient loading. A driven load machine with measured shaft torque and speed forms an absorption dynamometer; a load drive capable of returning shaft power electrically makes it regenerative. When the load machine can also drive the DUT in either direction, the assembly is a four-quadrant dynamometer. Regeneration to a shared DC bus does not necessarily mean export to the grid.

The proposed 800 N·m sensor is a reasonable provisional choice at the drivetrain output for controlled steady tests and bounded peak tests. The ideal 705 N·m peak leaves 95 N·m of measurement headroom, only 11.9% of capacity. At an assumed 95% drivetrain efficiency, 669.75 N·m leaves 130.25 N·m, or 16.3% of capacity. These are static calculations, not transient design margins. Shaft inertia, torque reversal, backlash and control overshoot can consume the margin. Release for transient testing requires an established maximum transmitted torque, verified sensor dynamics and independent protection.

Moving that sensor to the motor side sacrifices useful torque resolution. Its current webpage rating for this capacity class is 6,000 rpm, with 8,000 rpm stated as a maximum [S2]. Operation at 7,000 rpm therefore requires written approval of duration, torque, bearings and balance. Prefer a separate 200 or 300 N·m motor-side transducer, independently verified for speed and dynamics, while retaining the output transducer. Simultaneous measurements are necessary to isolate drivetrain efficiency during transients.

The welding table is the common structural foundation. A separate full-length bedplate is not included. Removable motor, gearbox, sensor and load-machine modules should use local mounting plates, locating features, alignment adjustment and positively retained fasteners. The table's mass and flatness are helpful but do not establish joint stiffness, local deflection, fatigue resistance or containment strength. These require engineering checks of the actual assembly.

The datasheet is not a single rectangular operating envelope. Its page 1 maxima disagree with some page 2 and 3 curves. In particular, 80 N·m continuous torque cannot be assumed through 6,000 rpm, and 150 N·m cannot be combined with 7,000 rpm or 80 kW without qualification. Procurement should preserve capability to cover the headline envelope; commissioning should remain within the more restrictive verified motor, cooling, inverter, gearbox and sensor limits.

Status	Planning basis	Consequence
Confirmed user concept	EMRAX 208 DUT, second electric load machine, 4.7:1 reduction, heavy welding table	Design around modular mounts and controllable electrical loading
Proposed selection	800 N·m ATO output sensor	Conditional acceptance only; exact build and calibration unconfirmed
Assumption	Drivetrain efficiency 0.95	Illustrative calculations only; measure in both power-flow directions
Unresolved	Motor voltage/cooling, inverter, load set, supply and regeneration architecture	No other equipment is selected by this report

Status	Planning basis	Consequence
Within scope	Architecture, sizing basis, channels, equations, risks and staged commissioning	Supports supplier discussions and detailed design
Outside scope	Released fabrication drawings, certified containment, final wiring, protection coordination and safety validation	Qualified mechanical, electrical and machine-safety engineers must complete and approve these

Before purchase, settle the motor configuration and test duty, obtain an approved torque-speed map, choose the energy-return architecture, define uncertainty and transient bandwidth, and validate gearbox and sensor mechanical limits. A headline power or overload rating is insufficient evidence for purchase.

2 Requirements derived from the motor datasheet

Source S1 is the complete three-page attachment. Page 1 is the technical-data table; page 2 contains the HV combined-cooled torque/power plot and efficiency map; page 3 contains torque versus RMS current, free-run losses and variant notes. All three pages, including image-only graphs, were reviewed. Values below are manufacturer statements unless labeled calculated, approximate graph readings, assumptions or recommendations. SI units are used, with rpm, litres per minute and degrees Celsius retained where useful for comparison with the source.

Quantity	Manufacturer value and qualification	Bench implication
Torque	150 N·m maximum peak; 80 N·m continuous [S1 p1 table]	Independent maxima, not torque available at every speed; see curves below
Mechanical power	80 kW peak at maximum speed; a few minutes from cold, a few seconds from hot [S1 p1]	No defined temperature, exact duration or repetition cycle; obtain an approved duty map
Continuous mechanical power	AC/LC 20–32 kW; CC 25–40 kW at 3,000–5,000 rpm, speed dependent [S1 p1]	Load system must sustain the selected cooling envelope; 80 kW is not continuous
Speed	6,000 rpm maximum normal; 7,000 rpm peak for a few seconds [S1 p1]	628.32 and 733.04 rad/s calculated; no unlimited dwell above normal limit
Thermal ceiling	Winding copper and magnets each 120 °C [S1 p1]	Set lower warning/trip thresholds using sensor lag and hotspot margin; winding temperature does not prove rotor temperature
Temperature sensing	KTY 81/210 [S1 p1]	Compatible excitation, conversion and open/short diagnostics required
Physical size and mass	Diameter 208 mm, width 85 mm; AC 9.1 kg, LC 9.4 kg, CC 9.3 kg [S1 p1]	Obtain shaft/flange drawing, fasteners, centre of mass and permissible loads before mount design
Rotor inertia	256 kg·cm ² = 0.0256 kg·m ² [S1 p1; unit conversion]	Use table value provisionally; confirm because parenthetical 160 mm diameter and 4 kg do not independently define mass distribution
Bearings	6206:6206, or 6206:7206, or 6206:3206 depending on force direction; alternatives possible [S1 p1]	Exact build, axial/radial capacity and life under coupling loads remain unknown

Quantity	Manufacturer value and qualification	Bench implication
Electrical form	Star connection, sinusoidal control, 10 pole pairs [S1 p1]	Electrical fundamental is 1,000 Hz at 6,000 rpm and 1,166.7 Hz at 7,000 rpm, calculated; verify inverter frequency and position feedback
Efficiency	92–98% table claim [S1 p1]; page 2 map includes lower regions	Do not assume constant efficiency or substitute it for measured motor power

Voltage and current variants

All entries in the next table are from S1 page 1. Phase RMS current is not DC supply current. Maximum battery voltages are ceilings, not nominal bus setpoints; reserve headroom for regeneration and ripple. Current ratings apply across the cooling columns but remain subject to the stated cooling and thermal limitations.

Parameter	High voltage	Medium voltage	Low voltage
Maximum battery voltage	470 VDC	320 VDC	125 VDC
Full-load / no-load speed at that voltage	5,170 / 7,050 rpm	5,760 / 7,040 rpm	6,250 / 7,250 rpm
Maximum phase current	200 A RMS	320 A RMS	800 A RMS
Continuous phase current	100 A RMS	160 A RMS	400 A RMS
Peak current duration	2 min with cooling as described in the full manual	Same qualification	Same qualification
Torque constant	0.83 N·m/A RMS	0.54 N·m/A RMS	0.20 N·m/A RMS
Phase resistance at 25 °C	12.0 mΩ	5.7 mΩ	0.8 mΩ
Inductance Ld / Lq	125 / 130 μH	52 / 56 μH	7.2 / 7.5 μH
Line-to-line voltage constant	0.0487 V RMS/rpm	0.0319 V RMS/rpm	0.0117 V RMS/rpm
No-load speed constant	15 rpm/VDC	22 rpm/VDC	58 rpm/VDC
Loaded speed constant	11–15 rpm/VDC	18–22 rpm/VDC	50–58 rpm/VDC
Motor input wire cross-section	10.2 mm ²	15.2 mm ²	38 mm ²

The wire figures describe the motor, not approved bench cable sizes. Cable ampacity, pulse voltage, routing, thermal environment, fault current and termination temperatures need separate design. The LV variant shifts the problem toward high current, low inductance and current ripple; HV shifts it toward insulation and voltage coordination. Inverter compatibility must include rotor feedback, motor parameters, electrical frequency, current definition and field weakening.

Cooling and duty qualifications

AC means air cooling, LC liquid cooling and CC combined air plus liquid cooling [S1 p1]. AC requires 20 m/s air velocity at 25 °C ambient. LC lists 8 L/min water/glycol at 50 °C inlet and 25 °C ambient. CC lists the same liquid and ambient conditions, but does not explicitly repeat an air velocity. The CC label implies both cooling modes; obtain EMRAX's

required airflow geometry and velocity rather than silently assigning the AC value. The liquid flow is $1.333 \times 10^{-4} \text{ m}^3/\text{s}$, calculated. Glycol concentration, permitted pressure, pressure drop, coolant chemistry and maximum inlet temperature are not specified in the attachment.

Ingress protection is IP21 for AC and CC and IP65 for LC [S1 p1]. A higher motor IP rating does not protect adjacent sensors, connectors or inverters from leaks. The note that colder inlet coolant or ambient can increase continuous power is qualitative; no derating curve is supplied. Do not extrapolate ratings upward.

Page 3 says AC and LC continuous power is 20% lower than CC, with equal peak power. Its heading incorrectly calls air cooling “CC”; the page 1 definition resolves the abbreviation but does not resolve cooling details. The 2 min maximum-current qualification, cold/hot peak-power wording and few-second overspeed limit are separate constraints. Apply the shortest applicable duration and temperature limit. There is no permission for repeated peaks with arbitrary recovery time, continuous stall torque, or sustained 7,000 rpm operation. The full cooling manual referenced by page 1 is not part of this three-page attachment.

The coupled operating envelope

The following approximate readings are planning interpretations of S1 page 2, upper HV CC plot, not certified numerical data. Read dashed curves against the right torque axis and solid curves against the left power axis, as its notes specify. Reading precision is about several N·m and 1–2 kW. Do not use this table as a controller limit file. Values are rounded independently from the graph; calculate actual shaft power from measured torque and speed.

Motor speed	Continuous torque / power	Peak torque / power	Ideal output speed and torque
1,000 rpm	about 65 N·m / 7 kW	about 139 N·m / 14 kW	213 rpm; 306 / 653 N·m
3,000 rpm	about 66 N·m / 21 kW	about 137 N·m / 43 kW	638 rpm; 310 / 644 N·m
4,000 rpm	about 65 N·m / 29 kW	about 134 N·m / 55 kW	851 rpm; 306 / 630 N·m
5,000 rpm	about 60 N·m / 34 kW	about 128 N·m / 64 kW	1,064 rpm; 282 / 602 N·m
6,000 rpm	about 55 N·m / 36 kW	about 115 N·m / 68 kW	1,277 rpm; 259 / 541 N·m

The upper plot is itself imperfect: 65 N·m at 4,000 rpm gives 27.2 kW, versus about 29 kW on the solid line; 115 N·m at 6,000 rpm gives 72.3 kW, versus about 68 kW. The efficiency map below it places the dashed peak boundary around 128 N·m at 5,000 rpm and the continuous boundary around 60 N·m. Its best labeled region is 96%, approximately within 1,500–3,500 rpm and 40–80 N·m, and it includes 86–90% regions. The table's 98% must not be imposed on this map [S1 p2].

Page 3's torque-current plot is explicitly at 1,000 rpm: approximately 72 N·m at 100 A RMS and 125 N·m at 200 A RMS, reaching about 132 N·m near 230 A RMS. These are inconsistent with simply multiplying the tabulated 0.83 N·m/A by current; the graph extending past the 200 A ceiling does not authorize that current. The free-run-loss graph rises from roughly 0.1 kW at 1,000 rpm to 0.57 kW at 3,000, 1.25 kW at 5,000 and 1.68 kW at 6,000 [S1 p3]. Its electrical/mechanical measurement boundary is unspecified, so use it as a trend to investigate, not a loss correction.

Page 3 describes similar MV/LV graphs, with LV current $\times 4$ and voltage $\div 4$ and MV current $\times 1.52$ and voltage about one-third lower. Page 1 actually gives HV-to-MV maximum-current ratio 1.60 and HV-to-LV voltage ratio 3.76. These are approximate narrative scaling statements, not exact conversion laws. The LV axial flux entry of 0.095 V·s also does not follow the voltage-constant scaling; seek corrected motor parameters rather than editing the value by inference. The field-weakening entry “up to 100%” is not an operating-speed authorization [S1 pp1,3].

For procurement, use a conservative capability ceiling $T \leq 150 \text{ N}\cdot\text{m}$ and $P \leq 80 \text{ kW}$ for peaks, and $T \leq 80 \text{ N}\cdot\text{m}$ with $P \leq 40 \text{ kW}$ CC or 32 kW AC/LC for continuous capability. These intersections are planning bounds, not demonstrated motor curves. At 6,000 rpm, 150 N·m would be 94.25 kW; at 7,000 rpm it would be 109.96 kW. An 80 kW bound allows only 127.32 and 109.13 N·m respectively. Likewise 80 N·m at 6,000 rpm is 50.27 kW, exceeding either continuous power ceiling. Obtain a corrected per-variant envelope before setting test limits [calculated from S1 p1].

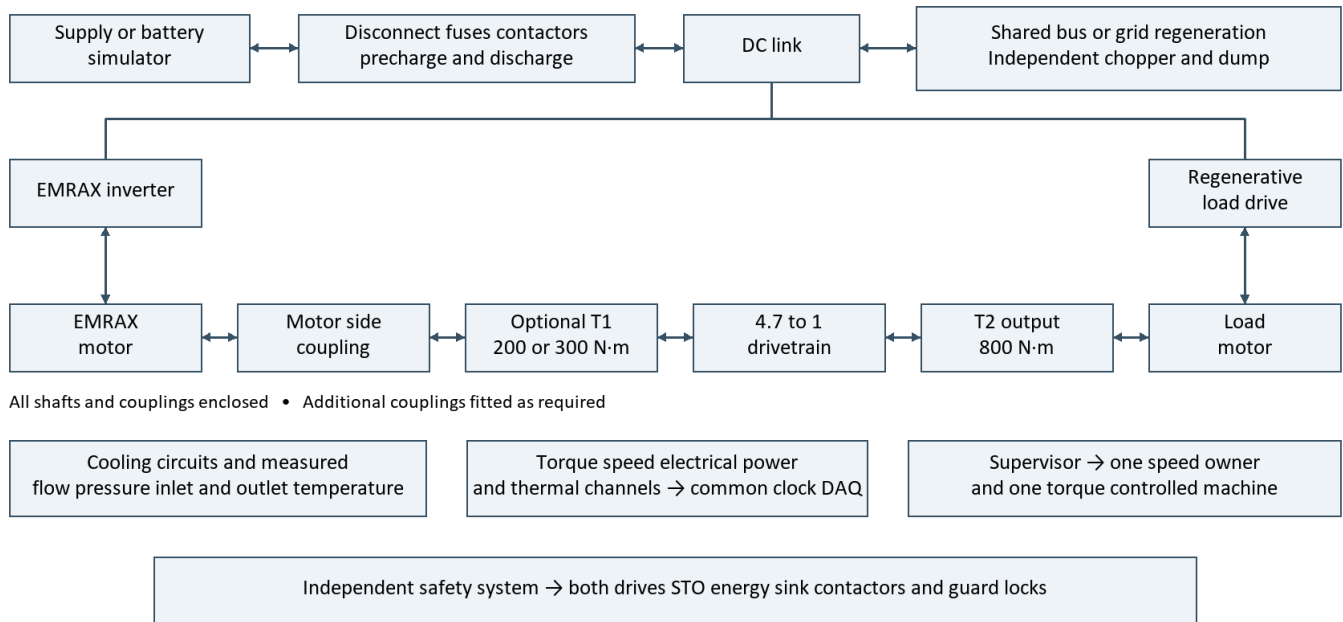
Independent drivetrain checks

Use $i = n_{\text{in}}/n_{\text{out}} = 4.7$. For forward steady power flow, $T_{\text{out}} = i \eta_g T_{\text{in}}$. The assumed $\eta_g = 0.95$ is not a measured property. Ideal torque multiplication provides a conservative static forward sizing reference, but not a dynamic torque bound or a reverse-power formula.

Check	Calculation	Result
Ideal continuous torque	80×4.7	376 N·m
Illustrative continuous torque	$80 \times 4.7 \times 0.95$	357.2 N·m
Ideal peak torque	150×4.7	705 N·m
Illustrative peak torque	$150 \times 4.7 \times 0.95$	669.75 N·m
Normal output speed	$6,000 / 4.7$	1,276.596 rpm = 133.685 rad/s
Brief peak output speed	$7,000 / 4.7$	1,489.362 rpm = 155.966 rad/s
Continuous CC / AC or LC output power	$40 \times 0.95 / 32 \times 0.95$	38 / 30.4 kW illustrative maxima
Peak output power	80×0.95	76 kW illustrative maximum

3 Proposed test bench architecture

The diagram shows physical boundaries for measurement. “T1” is the optional motor-side transducer and “T2” the proposed output transducer. Couplings are required wherever alignment, support and interface design demand them, including both sides of each transducer. Every rotating segment is contained. In reverse operation the arrows reverse; electrical measurement channels retain their defined polarity.



Choose one of three electrical arrangements. A compatible shared DC bus recirculates load-drive energy to the DUT inverter; the external source supplies net losses during steady motoring. Each drive and bus segment still handles its own circulating power. Bus voltage ranges, grounding, isolation, precharge, fault propagation, capacitor current and regeneration permissions must be compatible. A non-sinking DC supply can still overvoltage if returned energy exceeds DUT demand, particularly during shutdown.

A grid-regenerative front end or separate regenerative supply can return net energy to the electrical service. Verify service voltage, export permission, harmonic limits, protection coordination and behavior on grid loss. A braking-resistor arrangement dissipates absorbed energy as heat. It can support absorption tests, but a resistor alone cannot power the load motor to back-drive the DUT; four-quadrant testing still requires an energized bidirectional drive system. Size continuous resistor duty for the actual test envelope and pulse duty for fault stops. An independent dump may remain necessary even with shared-bus or grid regeneration.

Normally command the load machine in speed control and the EMRAX in torque/current control. This holds a mapping point while DUT torque is swept. For DUT speed-controller evaluation, explicitly transfer speed authority to the EMRAX and run the load in torque control. Never run two stiff integral speed loops against one shaft. Enforce mode ownership, bumpless transfer, matched command ramps, torque/current limits and anti-windup. Tune the outer speed loop below significant torsional modes and validate it with the assembled inertias; no control bandwidth is yet justified.

Separate acquisition, supervision and safety. The DAQ uses a common hardware timebase. The supervisor sets test points, checks data quality and schedules dwell/recovery. A safety controller or validated safety circuit acts independently of the PC, communication link and test script. Encoder feedback controls speed; a separate protective speed channel provides fault tolerance where the risk assessment requires it. Cooling flow, temperature, bus energy acceptance and locked guards must be proven before torque enable.

Use removable local modules on the welding table with machined or shimmed mounting interfaces, dowels or repeatable locators, jack screws for alignment and positive restraint against torque reaction. Preserve a documented datum and shaft-height scheme. Quick-disconnect cooling and keyed electrical connectors should prevent cross-connection and include spill control. Store modules with shaft protection and certified lifting provisions. After every reassembly, repeat alignment, fastener, protective-bonding and polarity checks. Welding on the table while test equipment is connected is prohibited by the proposed operating procedure.

4 Evaluation of the proposed torque sensor

The current product is SKU ATO-TQS-D03 with model designation ATO-TQS-DYN-200 [S2]. The following compact specification register records the current webpage. “FS” is interpreted as the selected 800 N·m capacity for the calculations below; confirm the manufacturer's definition for bipolar span.

Specification	Current webpage value [S2]
Rated / maximum speed above 500 N·m	6,000 / 8,000 rpm
Nonlinearity; hysteresis; repeatability	0.1%; 0.03%; 0.03% FS
Zero / output temperature effects	Each <0.01% FS/°C
Response; acquisition; delay	1 kHz; 550/1,200 s ⁻¹ ; 0.6 ms
Ultimate overload	200% FS
Supply; current; load resistance	24 VDC; <150 mA; ≥2 kΩ
Outputs	RS-485, ±5 V, 0–10 V, 4–20 mA; combinations available
Speed pulses	60/rev, open collector; optional 5 V TTL
Environment	IP43; –10 to 70 °C; 0–85% RH
500–800 N·m class mass	3.5 kg

S2's July 2026 answer instead gives 120 pulses/rev for a 300 N·m unit. Another answer limits internally calculated power to 25 Hz. Its deformation, stiffness and inertia entries have unclear units/exponents. Obtain build-specific corrected data; no resonance calculation can rely on them. The 10 N·m radial-load answer is not an 800 N·m rating. Its anti-rotation wording is unclear. [S2]

The older manual states 10,000 rpm rated, 15,000 rpm maximum and an upper temperature of 50 °C [S3 p3], conflicting with the webpage. Use the webpage's lower speed rating provisionally; do not use the manual to authorize higher speed. S3 pp2–3 repeats the accuracy terms and 60 pulses/rev. The upgraded manual offers several pulse builds with different speed limits: 60 pulses/rev at 10,000 rpm, 120 at 3,000 rpm and 10 at 15,000 rpm; these concern speed-output configurations, not permission to exceed rotor mechanics [S4 PDF p12]. It also gives protocol-dependent transmission rates, up to 1,000 frames/s, and filter-dependent lag [S4 PDF pp5,7–9]. A high frame rate can repeat a slower speed estimate. Confirm firmware, analog update rate, filter response, torque and RPM synchronization, pulse electrical interface, and allowable speed for the exact ordered unit.

Capacity and application verdict

Case	Arithmetic	Preliminary conclusion
Output continuous reference	$376/800 = 47.0\%$ FS ideal; $357.2/800 = 44.65\%$ illustrative	Good nominal utilization, subject to thermal and mechanical limits
Output peak ideal	$800 - 705 = 95$ N·m; 11.875% FS headroom; $95/705 = 13.48\%$ above demand	Limited room for overshoot
Output peak at $\eta_g = 0.95$	$800 - 669.75 = 130.25$ N·m; 16.281% FS; 19.45% above demand	More nominal room, but efficiency is unknown

Case	Arithmetic	Preliminary conclusion
Motor continuous / peak	80/800 = 10%; 150/800 = 18.75% FS	Oversized for precision at low motor torque
Output speed	1,489 rpm brief motor-overspeed case	Below published mechanical rating; verify pulse build and assembled critical speeds
Motor speed	6,000 rpm equals rated; 7,000 exceeds rated but is below stated maximum	No margin at normal ceiling; overspeed use needs written approval
Bidirectional operation	Torque and speed signs must be acquired separately	Verify bipolar calibration and output scaling; add directional encoder
Transients	Peak transmitted torque and bandwidth unknown	Not yet released for shock, reversals or high-frequency torque testing

Rated capacity is the calibrated measurement range. A safe overload would specify a recoverable load without permanent performance change; no adequate build-specific safe-overload or fatigue-cycle rating is established here. Ultimate overload is a survival-related limit, not calibrated range, repetitive capacity or a protective trip target. Numerically, 200% of 800 N·m is 1,600 N·m, but that calculation does not authorize any test beyond 800 N·m. Confirm combined torque/speed/load limits and post-overload recalibration requirements.

A 1,000 N·m sensor leaves 295 N·m above the 705 N·m ideal demand (29.5% of capacity; 41.84% above demand), or 330.25 N·m above 669.75 N·m (33.03% of capacity; 49.31% above demand). This is preferable when predicted transients would approach 800 N·m, provided its dimensions, inertia, speed rating and bandwidth are acceptable. It still requires a calculated dynamic envelope. At the same FS accuracy class it worsens absolute nonlinearity to 1 N·m, compared with 0.8 N·m for the proposed unit. Do not buy the larger sensor solely for its capacity.

Uncertainty and low torque

For 800 N·m FS, the listed nonlinearity corresponds to 0.8 N·m; hysteresis and repeatability each correspond to 0.24 N·m. Nonlinearity alone is 1% of an 80 N·m motor reading, 0.53% at 150 N·m, 8% at 10 N·m and 0.224% at 357.2 N·m [calculated from S2]. Display digits do not establish resolution, noise floor or traceable accuracy.

If, only for illustration, those three independent limits are rectangular error distributions, their combined standard uncertainty is $\sqrt{(0.8^2 + 0.24^2 + 0.24^2)/3} = 0.502$ N·m, and expanded uncertainty with $k = 2$ is about 1.00 N·m before drift, calibration, installation, electronics and dynamics. The simple sum of these bounds is 1.28 N·m. Neither is a guaranteed total uncertainty: statistical independence and distributions have not been established.

Each temperature coefficient corresponds to less than 0.08 N·m/°C. A 10 °C change can contribute up to 0.8 N·m for each term, or 1.6 N·m if conservatively added. Combined with the three static bounds, this gives an illustrative 2.88 N·m bound before other errors, 3.6% of 80 N·m. Confirm whether the output coefficient is truly FS-based or proportional to reading. Temperature stabilization and zero tracking are essential; never zero away real drivetrain preload.

For equivalent 0.1% FS nonlinearity, a 200 or 300 N·m motor sensor contributes 0.2 or 0.3 N·m instead of 0.8 N·m. At 80 N·m that is 0.25% or 0.375% of reading. These are comparison assumptions, not specifications of a selected second sensor. The 300 N·m option offers more transient capacity; the 200 N·m option uses more of its range. Require a separate torsional and overspeed assessment for either.

Acquisition and installation

Prefer synchronous ± 5 V torque output into isolated differential DAQ channels, plus hardware-timestamped speed pulses or a separate quadrature encoder on the same clock. Retain RS-485 for configuration, monitoring and redundant

comparison. Verify simultaneous availability of all requested outputs. An analog path is only better for timing if its update, filtering and delay are characterized; it does not bypass the sensor's internal sampling.

For a verified ± 800 N·m to ± 5 V mapping, sensitivity is 160 N·m/V. Unipolar 0–10 V and 4–20 mA outputs need a documented signed mapping, such as a midscale zero; never assume that mapping. Voltage paths favor easy synchronous capture but require careful grounding. Current loops tolerate cable voltage drop but introduce shunt, isolation and conversion errors. RS-485 requires frame decoding, signed values, scaling, CRC checks and measured sample age. PC arrival times are not shaft-event timestamps. RPM pulses measure speed magnitude unless direction encoding is explicitly provided. Torque polarity is not rotation direction, especially in regeneration.

At 60 pulses/rev, 6,000 rpm generates 6,000 Hz and 1,489.36 rpm generates 1,489.36 Hz. At 120 pulses/rev these double. Verify pulse count by hand rotation before operation. A 0.6 ms torque delay would cause 21.6° phase lag at 100 Hz, calculated as $360^\circ f \Delta t$. A claimed 1 kHz response with 550 or 1,200 samples/s cannot by itself support alias-free 1 kHz waveform capture; Nyquist limits are 275 or 600 Hz even before practical filtering. Establish an initial analysis bandwidth no higher than 100 Hz, as a recommendation pending measured transfer response. Use anti-alias filtering and at least 2 kS/s DAQ capture; this oversampling does not create missing sensor bandwidth.

Arrange two suitable flexible couplings and independent machine supports so the sensor does not carry belt tension, gearbox overhung loads or alignment forces. Quantified 800 N·m axial/radial loads, bending limits, runout and misalignment allowances remain unknown. Obtain a controlled dimensional drawing, shaft/key tolerances, engagement length, retention method, allowable hub clamping pressure, balancing convention and assembly balance grade. Check key shear, bearing pressure, shaft fatigue and combined loads with reversals. Retain keys and hubs against axial release. Do not drill an improvised retention pin through a shaft without design approval.

Secure the nonrotating housing to a manufacturer-approved support or compliant anti-rotation arrangement that restrains drag torque without preloading bearings. A cable is not an anti-rotation restraint. The welding table requires a local adjustable sensor support even without a full bedplate. Keep coolant spray and oil mist away with barriers, drip trays and drainage; IP43 is not a washdown specification. Keep signal electronics thermally separated from machines and braking resistors.

Obtain bidirectional calibration from an ISO/IEC 17025 accredited laboratory whose scope covers the intended torque range, with traceability, uncertainty, loading/unloading sequences, zero return and multiple relevant setpoints. Include the selected signal path and DAQ scaling. Static calibration does not validate dynamic bandwidth, high-speed effects or shaft installation. Verify speed independently and check zero before and after each test, after remounting, and after any overload or abnormal vibration. Set recalibration intervals from use and drift evidence.

5 Remaining equipment and selections

“Minimum” below means capability required to cover the planning envelope, not a finalized component rating. Actual hardware must also accommodate validated transients, tolerances and faults. M means mandatory; C means conditional on the architecture or measurement objective; O means optional enhancement. All numerical sizing in this section is calculated from S1 or is explicitly a design recommendation.

Load machine and drive sizing

For a directly coupled output load, conservatively preserve continuous torque capability up to 376 N·m and peak capability up to 705 N·m over the relevant low-speed region, with 1,277 rpm normal and 1,489 rpm brief speed capability plus engineered overspeed margin. Require a supplier torque-speed-duty plot for both motoring and generating, including zero/low-speed cooling. Preserve up to 40 kW continuous CC capability and 80 kW peak as input-based conservative power ceilings; forward losses reduce load absorption, but must not be relied upon as protective margin.

The procurement bounds intersect: the ideal 80 kW and 705 N·m curves meet at about 1,084 rpm output; the 40 kW and 376 N·m curves meet at about 1,016 rpm. Above those points the constant-power limits reduce available torque.

These are capability intersections, not an approved EMRAX operating schedule. Page 2's lower plotted envelope must also be supplied to vendors.

For example, a hypothetical 80 kW machine rated at 3,000 rpm has only 254.65 N·m at that point. Its power rating alone does not prove 376 N·m continuous at approximately 1,000 rpm or 705 N·m peak at lower speed. Drive current, magnetic saturation, thermal duty, base speed, field weakening and external cooling decide suitability. Select a direct low-speed high-torque machine or evaluate an additional load-side ratio, which changes inertia, loss measurements and alignment.

Reverse testing also changes torque demand. To generate 150 N·m at the EMRAX shaft through a gearbox of reverse efficiency 0.95, the load-side driving torque is $150 \times 4.7 / 0.95 = 742.11$ N·m, not 669.75 N·m. This leaves only 57.89 N·m below 800 N·m before acceleration or overshoot. At 80 N·m motor-side absorption the corresponding load-side torque is 395.79 N·m. Reverse efficiency is unmeasured and may differ from forward efficiency. Full reverse-envelope capability therefore requires additional capacity or reduced test limits. Likewise 80 kW delivered mechanically to the motor through 95% efficient gearing needs 84.21 kW from the load machine, before its own losses. The motor's permissible generator envelope itself needs confirmation.

Subsystem and function	Minimum capability and selection criteria	Status and missing information
Load motor absorbs or supplies shaft power	Cover the torque-speed-duty bounds above, reversals, independent cooling and inertia/overspeed limits	M; supplier maps, duty, regenerative motor envelope and chosen coupling ratio
Load regenerative drive	Four-quadrant current and voltage capability for selected machine; controlled torque and speed; validated stop functions	M; machine parameters, bus range, overload time, feedback and energy destination
EMRAX inverter	Per-variant continuous/peak phase current from section 2, compatible bus ceiling and margin; 10-pole-pair frequency, feedback and field weakening	M; exact variant, switching frequency, rotor sensor, software limits and EMRAX approval
DC source or battery simulator	Source and, where needed, sink the test envelope; voltage below motor and drive limits; fault-current definition	M; service, current versus voltage, isolation and charge acceptance
Battery pack alternative	Voltage/current/energy duty, BMS, fuse and contactor coordination; permitted regenerative SOC/temperature window	C; chemistry, SOC range, cooling and fault response
Shared DC bus	Each branch carries full drive power/current; coordinated precharge, bus capacitance, isolation and fault clearing	C; drive compatibility and supplier-approved bus integration
Grid regenerative front end	Absorb worst permitted net return continuously and during stops; service and export compatible	C; grid utility conditions, service capacity and loss-of-grid sequence
Brake chopper and resistor or energy sink	Pulse power and energy for worst stop; continuous power if used as primary absorber; independent bus-voltage activation	M energy strategy; chopper current, resistance limits, thermal duty and total inertia unknown
Disconnect, fuses and contactors	DC interruption rating above maximum operating voltage and prospective fault current; monitored poles and coordinated clearing	M; short-circuit study, grounding scheme, drive capacitance and cable design
Precharge and discharge	Limit charging current; verify bus convergence before main closure; discharge and prove safe state after isolation	M; total capacitance, resistance, repetition rate and contactor weld detection

Subsystem and function	Minimum capability and selection criteria	Status and missing information
Output torque and conditioning	Proposed ± 800 N·m range; conditional dynamics and speed approval; isolated supply/DAQ interface	M; exact ATO build, safe overload, bandwidth and calibration
Motor torque measurement	Proposed ± 200 or ± 300 N·m; speed and dynamic margin beyond test envelope	C for motor/gear efficiency; supplier data and uncertainty target
Speed and position	Direction-capable sensors covering 7,000 rpm motor and 1,489 rpm output plus trip margin; independent protective sensing	M; encoder interfaces, pulse count, resolution and mounting
Electrical power measurement	Bidirectional DC and PWM three-phase real power; voltage/common-mode and current pulse ranges suit chosen inverter	M for efficiency; instrument bandwidth, phase error and calibration
Temperature instrumentation	Winding interface and bearing, inverter, oil and coolant sensors; range beyond warning/trip levels	M; KTY circuit, sensor locations, rotor temperature availability
Coolant skid	EMRAX liquid flow 8 L/min where applicable at specified inlet condition; pump head from full circuit, fluid compatibility	M for LC/CC; pressure drop, glycol mix and other component flows
Heat exchanger and reservoir	Reject measured/estimated continuous losses with ambient margin; deaeration, expansion volume and filtration	M for liquid circuits; heat load, ambient, permitted pressure and utility temperature
Flow and pressure instruments	Resolve low-flow faults and circuit restrictions at actual operating range; pressure protection independent of software	M; approved flow/pressure limits and sensor uncertainty
Air cooling and ducting	Reproduce AC 20 m/s at motor, 25 °C reference condition; prove CC requirement with EMRAX	M where required; velocity distribution, obstructions, blower curve and noise
Vibration sensors	Bearing/module accelerometers with bandwidth covering shaft orders and identified resonances	M protective monitoring; expected vibration spectrum and trip thresholds
Synchronized DAQ	Isolated simultaneous analog inputs, encoder counters, anti-alias filters and common timebase	M; channel count, electrical bandwidth, uncertainty and recording duration
Real-time or supervisory controller	Enforce one speed owner, sequenced limits and deterministic abort; log commands and states	M supervisor; real-time platform C for required dynamics
Safety system	Independent validated E-stop, guard lock, overspeed, torque, cooling and thermal protections	M; risk assessment, required integrity, architecture and stop validation
Welding table and local mounts	React machine torques, weight, vibration and fault loads; stiffness/alignment checked at fastening points	M existing foundation; local plates and adjustable mounts M; full bedplate omitted
Gearbox/drivetrain	4.7 ratio; input speed up to 7,000 rpm brief, torque/power duty and reverse loads; thermal/lubrication capacity	M; type, maps, backlash, life, bearings, inertia, lubrication and mounting

Subsystem and function	Minimum capability and selection criteria	Status and missing information
Couplings and hubs	Torque fatigue and speed capability including engineered overspeed margin, balance and retention	M; bores/keys, alignment tolerances, torsional stiffness and critical-speed analysis
Shaft and coupling containment	Engineer for credible fragment energies and paths, including exposed EMRAX rotor; positively attached modules	M; rotor/shaft geometry, materials, failure scenario and verified enclosure design
Guards and cell enclosure	Interlocked access, retained during rundown, coolant/noise separation and remote controls	M; layout, visibility, access and egress risk assessment
Calibration equipment	Traceable torque reference or calibrated arm/force fixture, independent tachometer, electrical/thermal checks	M access to calibration; O ownership of full laboratory equipment

At 80 kW shaft power, even an ideal lossless source would need 170.2 A at 470 V, 250 A at 320 V or 640 A at 125 V. Actual DC source currents are higher with losses and lower voltage. These calculated examples are not inverter phase currents or final source ratings. A shared bus can reduce net mains power but not branch current ratings.

The motor rotor alone stores $0.5 \times 0.0256 \times (2\pi \times 7,000/60)^2 = 6.88$ kJ at 7,000 rpm, or 5.05 kJ at 6,000 rpm. Include gearbox, couplings, transducers and load rotor, with inertia referred through the square of the ratio. At the output, the motor inertia appears as $0.0256 \times 4.7^2 = 0.5655$ kg·m², calculated. DC capacitor energy is $0.5 C V^2$. Resistor energy must include all rotating and electrical energy plus power supplied during fault-detection and shutdown delay; its rating cannot be chosen from 6.88 kJ alone.

6 Raw data to acquire

The following ranges and accuracies are design targets, not purchased instrument specifications. E means essential to the stated measurement or protection objective; C means conditional; O means optional diagnostic information. “Per second” sampling refers to recorded engineering data unless identified as waveform capture. Protection must not depend on slow logging. Adopt a common hardware clock, trigger and calibrated delay model across torque, speed and power channels.

Channel and location	Sensor and expected range	Recommended accuracy and rate	Need
Motor torque T1 before gearbox	Rotary transducer, signed operating ± 150 N·m; propose $\pm 200/300$ N·m instrument	Target $\leq 0.1\%$ FS class with full uncertainty budget; ≥ 2 kS/s capture, initially ≤ 100 Hz analysis	C; E for isolated motor and gearbox efficiency
Output torque T2 before load	ATO proposed ± 800 N·m; planning static demand to ± 705 , reverse example 742	Verify section 4 errors; ≥ 2 kS/s capture with analog filtering	E
Motor speed and position	Quadrature encoder/resolver and independent overspeed channel; $\pm 7,000$ rpm, 0–733 rad/s magnitude	$\leq 0.05\%$ reading above low-speed floor; edge timestamps, 1 kHz speed result	E
Output speed and position	Directional encoder; $\pm 1,489$ rpm, 0–156 rad/s; independent pulses if useful	$\leq 0.05\%$ reading, timestamps; 1 kHz result with stated window	E

Channel and location	Sensor and expected range	Recommended accuracy and rate	Need
DUT branch DC voltage	Isolated calibrated analyzer channel at inverter terminals; 0–125/320/470 V nominal ceilings	Target $\leq 0.1\%$ reading; synchronous waveform capture and 1 kHz power record	E
DUT branch DC current	Bidirectional precision transducer; range based on source current and fault protection, not phase RMS	Target $\leq 0.1\%$ reading plus offset; synchronized with voltage	E
Three-phase voltage at EMRAX terminals	PWM power analyzer, suitable differential and common-mode range beyond selected bus transients	Target total power uncertainty $\leq 0.2\%$ reading at useful load; waveform sampling/bandwidth selected for PWM	E for motor/inverter split
Three-phase current and real power	Analyzer current sensors covering HV/MV/LV 200/320/800 A RMS peak-duty currents plus ripple/crest margin	Same power target; log real power at 100–1,000 s^{-1} ; retain selected raw waveform bursts	E for motor/inverter split
Load-drive electrical power	Bidirectional analyzer at load DC branch; AC measurement optional for drive/motor separation	Target $\leq 0.2\%$ reading; 100–1,000 s^{-1} , synchronized	E for energy balance; C phase split
Facility net power	Grid/source meter at defined upstream boundary including auxiliaries	Target $\leq 0.5\%$ reading; 10–100 s^{-1}	C for total facility efficiency/energy
Winding temperature	KTY 81/210, compatible isolated input; ambient to 120 °C ceiling	Target ± 1 °C system; 10 s^{-1} ; detect broken sensor	E
Magnet or rotor temperature	Approved telemetry or validated estimator; ambient to 120 °C ceiling	Target ± 2 °C if measurable; 10 s^{-1} ; document estimator uncertainty	C availability, E thermal protection strategy
Inverter temperatures	Internal telemetry plus independent critical-location probes where needed	Range to supplier limit plus margin; ± 2 °C, 10 s^{-1}	E
Gearbox oil temperature	Immersed RTD at representative oil point	Supplier range; target ± 1 °C, 10 s^{-1}	E
Motor, gearbox, sensor and load bearings	Surface/embedded RTDs or thermocouples	Supplier range; ± 2 °C including installation effects, 10 s^{-1}	E critical bearings
Coolant inlet/outlet temperatures for each circuit	Matched calibrated RTDs close to component boundaries	Target absolute ± 0.5 °C, differential uncertainty ≤ 0.1 K; 10 s^{-1}	E for cooling; matched pair E calorimetry
EMRAX coolant flow	Compatible flowmeter, initial 0–16 L/min recommendation around 8 L/min	Target $\leq 1\%$ reading near duty; 10–100 s^{-1}	E LC/CC
Other coolant circuit flows	Flowmeters sized to selected inverter/load requirements	Target $\leq 1\%$ reading; 10–100 s^{-1}	E where liquid cooled
Coolant inlet/outlet pressure	Pressure sensors and differential calculation	Range above supplier maximum with overrange margin; target $\leq 0.5\%$ FS, 100 s^{-1}	E liquid circuits

Channel and location	Sensor and expected range	Recommended accuracy and rate	Need
Ambient and inlet air temperature	Shielded RTD near intake; plan 0–60 °C instrumentation	Target ± 0.5 °C, $1\text{--}10\text{ s}^{-1}$	E
Air velocity at motor	Anemometer traverse or fixed validated airflow indicator; plan 0–30 m/s	Target $\leq 5\%$ reading at 20 m/s; 10 s^{-1}	E AC; C pending CC specification
Vibration on bearing housings and table modules	Triaxial accelerometers; range after survey with overload margin	Calibrated amplitude target $\leq 5\%$; initially 25.6 kS/s with ≤ 10 kHz band	E protection/diagnostics
Commands and limits	Both drives: torque/speed commands, measured currents, saturation, mode ownership, DC limits	Preserve native units and scaling; 1 kHz if supported, otherwise native rate	E
Fault and safety states	Timestamped digital inputs, STO, contactor feedback, guard lock, flow and thermal trips	Event timestamp target ≤ 1 ms; latched first-out cause	E
Rotation and torque signs	Directional encoder plus calibrated torque polarity and mode state	Verify all four quadrants; log with every measurement block	E
Time and synchronization	Hardware clock, trigger, sample counter and instrument sync status	Initial interchannel skew target $\leq 10\text{ }\mu\text{s}$ for ≤ 100 Hz analysis; verify full latency	E
Coolant leakage and reservoir level	Leak detector and level switches in trays/reservoirs	On/off diagnostics; $\geq 10\text{ s}^{-1}$ logging and independent interlock as needed	E where leak exposure exists

The sampling and skew values above are recommendations for initial low-bandwidth mechanical testing. They do not qualify this sensor for torque ripple at the motor's 1,000–1,166.7 Hz electrical fundamental or at PWM frequencies. If that is a requirement, choose a faster calibrated torque chain and increase acquisition bandwidth after a resonance assessment.

Ordinary multimeters or RMS current clamps do not provide accurate inverter-output real power. Use a PWM-capable analyzer with simultaneous voltage/current sampling, characterized phase error, sensor deskew, common-mode rejection, adequate voltage transient rating and suitable integration windows. Measure total real power, including relevant harmonics, not only fundamental RMS values. A proper three-wire two-wattmeter or three-channel configuration may be used according to the instrument's wiring method. Yokogawa specifically emphasizes synchronized DC/AC measurement and the distinction between PWM fundamental voltage and total waveform quantities [S5].

At the DC bus, instantaneous ripple can correlate voltage and current. Average $v(t)i(t)$, not merely the product of separately averaged voltage and current. In a shared bus, place DUT branch current measurement after the branch split; measuring only the external supply would measure net recirculation losses, not DUT input power. Record instrument configuration, ranges, filter settings, serial numbers and calibration dates with each run.

7 Quantities that can be calculated

Define forward rotation consistently at both measurement planes after accounting for gearing direction. Define signed transmitted torque so T_w is positive for power flowing from the DUT toward the load at each plane. DC current is positive into the DUT inverter; three-phase real power is positive into the DUT motor. A reverse-rotating motoring

point can have both T and ω negative and still have positive power. Opposite signs mean reverse energy flow. Load-drive branch power uses its own sign definition, positive from bus into load drive.

The efficiencies below are positive ratios of useful output to supplied input for the chosen direction. Forward equations apply only to forward motoring. For regeneration, invert the boundary roles and use magnitudes; do not report a negative efficiency or blindly use a forward ratio greater than one. Avoid efficiency calculation near zero power, during sign crossing or where uncertainty overwhelms the result.

Quantity and equation	Raw channels and unit	Availability and main uncertainty
Angular speed $\omega = 2\pi n/60$	Signed speed n ; rad/s	One sensor plus directional speed; pulse timing, count/window and direction
Motor shaft power $P_1 = T_1\omega_1$	Synchronous T_1 , n_1 ; W	Needs T_1 at motor boundary; torque calibration, speed, time skew and local inertia
Drivetrain output power $P_2 = T_2\omega_2$	Synchronous T_2 , n_2 ; W	Proposed output sensor plus speed sufficient; torque offset, speed and alignment
DC input $P_{DC} = \text{mean}(v_{DC} i_{DC})$	DUT branch voltage/current waveforms; W	Requires electrical instruments; ripple, offsets, common timebase and bandwidth
Three-phase power $P_3 = \text{mean}(\sum v_k i_k)$	Correctly referenced phase or equivalent three-wire analyzer channels; W	Requires PWM analyzer; phase error, common mode, bandwidth and integration
Motor efficiency $\eta_m = P_1/P_3$	T_1 , n_1 and P_3 ; dimensionless or %	Needs motor sensor plus analyzer; mechanical and electrical boundary errors
Inverter efficiency $\eta_{inv} = P_3/P_{DC}$	Synchronized electrical powers; dimensionless	No torque sensor required; power-channel errors and integration mismatch
Gear efficiency $\eta_g = P_2/P_1$	T_1 , n_1 , T_2 , n_2 ; dimensionless	Two simultaneous sensors preferred/required for transients; ratio uncertainty and stored energy
Overall DUT efficiency $\eta_{sys} = P_2/P_{DC}$	T_2 , n_2 , DUT branch P_{DC} ; dimensionless	Output sensor sufficient with electrical measurement; excludes auxiliaries unless added explicitly
Regenerated power $P_{reg} = \max(0, -P_{DC})$	DUT branch DC power; W	Electrical instrumentation; define exported grid power separately at mains
Consumed / regenerated energy	Integrals of $\max(P_{DC}, 0)$ and $\max(-P_{DC}, 0)$; J	Electrical data plus time; offsets, gaps and clock accuracy
Component loss $P_{loss} = P_{in} - P_{out}$	Power at both boundaries; W	Gear/motor need T_1 ; inverter does not; small difference magnifies uncertainty
Torque multiplication $M_T = \text{abs}(T_2/T_1)$	Both torques, steady flow; dimensionless	Two sensors; offset, torsional preload and reverse direction
Speed reduction $i = \text{abs}(n_1/n_2)$	Both speeds; dimensionless	No second torque sensor needed; count/clock error; invalid at standstill
Coolant heat $\dot{Q} = \rho q c_p \Delta\theta$	Flow q , fluid density/heat capacity, inlet/outlet temperatures; W	Additional thermal instruments; small $\Delta\theta$, mixture, sensor mismatch and heat leakage

Quantity and equation	Raw channels and unit	Availability and main uncertainty
Approximate thermal resistance $R\theta = (\theta_{hot} - \theta_{ref})/P_{loss}$	Steady hotspot/reference temperatures and relevant loss; K/W	Needs identified loss boundary; distributed cooling makes this an effective value
Thermal time constant τ	Temperature transient after known loss step; s	Fit first-order model only if data supports it; sensor lag, changing loss and multiple thermal nodes
No-load/parasitic loss	P3 or PDC at defined unloaded state; alternatively motored torque $\times$ speed; W	Output sensor alone cannot isolate motor/gear losses; no-load definition, drag and low-torque offset
Torque-speed and power-speed maps	Stable T, n, temperatures, voltage and mode	Single sensor gives only its measurement plane; repeatability and insufficient dwell
Efficiency maps	Appropriate power ratios at each steady point	Overall map possible with T2 and electrical input; separate maps need T1/PWM measurement
Power and efficiency uncertainty	Channel standard uncertainties, covariances and sensitivities	All chains need budget; section 8 gives propagation equations

One output torque sensor can measure output mechanical performance and overall inverter–motor–gearbox efficiency with electrical instrumentation. It cannot independently separate motor shaft power, motor efficiency and gearbox efficiency. Inverter efficiency remains electrically measurable. Moving the same sensor between positions permits sequential steady-state comparisons, but the temperatures, mounting losses, zero drift and operating point must be reproducible; it is not simultaneous drivetrain measurement and cannot capture transient efficiency accurately.

With both sensors, locate T1 immediately upstream and T2 immediately downstream of the drivetrain boundary. Account for intervening couplings and bearings. In acceleration, $P_1 - P_2$ includes change in rotational kinetic energy, elastic torsional energy and thermal storage; it is not all gearbox dissipation. Use quasi-steady points for efficiency maps, or subtract identified storage terms with an uncertainty allowance. An inverter's commanded torque or current-based estimate is useful for control and fault plausibility but is not a substitute for calibrated T1.

No-load motor testing should disconnect the gearbox or explicitly retain its drag in the reported boundary. When the load machine back-drives an unenergized motor, losses may differ from energized no-load operation because flux, electrical termination and field weakening differ. A coast-down estimate $P \approx -J_{eq} \omega d\omega/dt$ needs known inertia and a defined loss boundary. Do not use the page 3 free-run graph to subtract “known” losses from a bench measurement.

8 Consolidated equations and uncertainty

Use SI units in calculations: torque T in N·m, angular velocity ω in rad/s, power P in W, time t in s, energy E in J, voltage V in V, current I in A, inertia J in kg·m², mass flow $\dot{m}$ in kg/s, density ρ in kg/m³, volumetric flow q in m³/s, heat capacity cp in J/(kg·K), and temperature differences in K. Speed n may be entered in rpm only where the conversion is explicit. Subscripts 1 and 2 denote motor and output measurement planes; g denotes gearbox; “in” and “out” refer to the selected component and energy direction.

$$\omega = 2\pi n/60$$

$$P_{mech} = T\omega; P_{mech} [kW] = T [N \cdot m] n [rpm] / 9549.2966 \approx Tn/9550$$

$$n_{out} = n_{in}/i; T_{out} = T_{in} i \eta_g \text{ (forward steady flow)}$$

$$\eta_g = P_2/P_1 \text{ (forward)}; \eta_{g,rev} = |P_1|/|P_2| \text{ (reverse)}$$

$$|T_2| = i |T_1|/\eta_{g,rev} \text{ (reverse steady drive from output)}$$

$$\begin{aligned}
PDC(t) &= v_{DC}(t)i_{DC}(t); PDC, avg = (1/\Delta t) \int v_{DC}(t)i_{DC}(t) dt \\
P3\phi &= \sqrt{3} V_{LL} I_L PF \text{ (balanced sinusoidal steady state only)} \\
P3\phi &= (1/\Delta t) \int [v_{aia} + v_{bib} + v_{cic}] dt \text{ (proper phase reference)} \\
\eta_{motor} &= P1/P3\phi; \eta_{inverter} = P3\phi/PDC; \eta_{overall} = P2/PDC \\
\eta_{motor, gen} &= |P3\phi|/|P1|; \eta_{inverter, reg} = |PDC|/|P3\phi| \\
\eta_{overall, reg} &= |PDC|/|P2|; P_{loss} = P_{in} - P_{out} \\
E &= \int P dt; E_{cons} = \int \max(PDC, 0) dt; E_{reg} = \int \max(-PDC, 0) dt \\
Qdot &= \dot{m} c_p (\theta_{out} - \theta_{in}) = \rho q c_p \Delta\theta \\
R\theta &\approx (\theta_{hot} - \theta_{ref})/P_{loss} \\
\theta(t) &= \theta_{\infty} + [\theta(0) - \theta_{\infty}] \exp(-t/\tau) \\
E_{rot} &= \frac{1}{2} J \omega^2; E_{bus} = \frac{1}{2} C V^2; T_{acc} = J \dot{\omega} / \omega \\
P_{diss} &= P_{in} - P_{out} - dE_{stored}/dt
\end{aligned}$$

The 9550 denominator is a rounded unit-conversion constant, not an efficiency factor. The balanced-sinusoidal equation is not generally adequate for PWM inverter output: voltage/current harmonics, phase reference and waveform timing matter. Use the analyzer's valid instantaneous-power method and wiring configuration [S5]. At steady DC, the average power reduces to VI. For losses, Pin and Pout are positive magnitudes in the actual energy-flow direction. If using signed forward powers during regeneration, change the boundary expression accordingly so dissipation remains positive.

First order uncertainty propagation

Let $u(x)$ be a standard uncertainty and $cov(x,y)$ a covariance. For independent terms, root-sum-square propagation applies; common calibration, shared clocks and correlated filters can require covariance terms. Expanded uncertainty $U = k u$ is meaningful only with a documented coverage basis. The following equations are first-order approximations, not valid relative-error formulas at zero torque or zero power.

$$\begin{aligned}
u^2(y) &= \Sigma (\partial y / \partial x_j)^2 u^2(x_j) + 2 \Sigma_j < k (\partial y / \partial x_j)(\partial y / \partial x_k) cov(x_j, x_k) \\
u^2(P) &= \omega^2 u^2(T) + T^2 u^2(\omega) + 2T\omega cov(T, \omega) \\
[u(P)/P]^2 &= [u(T)/T]^2 + [u(n)/n]^2 \text{ (independent, nonzero)} \\
[u(\eta_g)/\eta_g]^2 &= [u(P2)/P2]^2 + [u(P1)/P1]^2 - 2cov(P2, P1)/(P2P1) \\
[u(\eta_g)/\eta_g]^2 &= [u(T2)/T2]^2 + [u(n2)/n2]^2 + [u(T1)/T1]^2 + [u(n1)/n1]^2 \\
[u(\eta_{overall})/\eta_{overall}]^2 &= [u(P2)/P2]^2 + [u(PDC)/PDC]^2 - 2cov(P2, PDC)/(P2PDC) \\
u^2(P_{loss}) &= u^2(P_{in}) + u^2(P_{out}) - 2cov(P_{in}, P_{out}) \\
[u(Qdot)/Qdot]^2 &\approx [u(\dot{m})/\dot{m}]^2 + [u(c_p)/c_p]^2 + [u(\Delta\theta)/\Delta\theta]^2
\end{aligned}$$

The expanded gearbox equation assumes all four channels independent. If the speeds are calculated from one encoder and a fixed ratio, they are correlated and cannot be counted as independent checks. For time misalignment, a first-order power error is approximately $\omega(dT/dt)\Delta t_T + T(d\omega/dt)\Delta t_\omega$. Include alignment, temperature, zero drift, filtering and dynamic transfer errors; calibration certificates alone do not cover the installed system.

As an uncertainty illustration, assume $u(T2) = 0.5 \text{ N}\cdot\text{m}$ at $357.2 \text{ N}\cdot\text{m}$, $u(n)/n = 0.05\%$ and $u(PDC)/PDC = 0.2\%$. Then output mechanical-power standard uncertainty is about 0.149% and overall-efficiency standard relative uncertainty about 0.249%, or about 0.50% expanded at $k = 2$. These chosen inputs are assumptions, not an achieved specification. Add $u(T1) = 0.2 \text{ N}\cdot\text{m}$ at $80 \text{ N}\cdot\text{m}$ and a second independent 0.05% speed term: drivetrain-efficiency relative standard uncertainty is about 0.295%, or 0.590% expanded. At $\eta_g = 0.95$, this is approximately ± 0.0056 absolute efficiency at $k =$

2. Gearbox loss uncertainty is much larger relative to the small loss than efficiency uncertainty is relative to transmitted power.

9 Potential complications and failure modes

The following mitigations are preliminary design recommendations. Trips need validated sensor integrity and measured response time. The allowable operating region must be the intersection of every component's torque, speed, current, thermal, duty and load limits.

Failure mode	Consequence	Practical mitigation and evidence needed
Torque spikes and sudden reversal	Sensor/coupling overload despite nominal 705 N·m calculation	Model acceleration and fault torque; rate-limit commands; independent overtorque monitor; verify stopping overshoot and dynamic headroom
Gear backlash	Impact loading and oscillation near torque sign changes	Measure backlash; cross zero gradually with validated control; prohibit shock reversals until qualification
Torsional resonance	Amplified local shaft torque not visible in average load	Model both rotors, shaft/coupling/sensor stiffness and gearbox; identify modes at low energy; tune bandwidth away from modes and validate damping
Critical speed or local sensor mode	Rotor whirl, bearing damage or rupture	Obtain rotor/bearing and assembled critical-speed data; balance complete hubs and keys; do not treat catalog natural frequency as assembly proof
Misalignment and table/module movement	Bearing heating, fatigue and biased torque	Laser/dial alignment cold and hot; verify mount stiffness and fastener slip; repeat after moving modules
Axial/radial sensor loading	Cross-talk, bearing failure and permanent offset	Independently support adjacent equipment; flexible couplings; quantify permitted loads; avoid belt/chain force through sensor
Keyway stress and hub imbalance	Fretting, shaft cracks and ejected keys	Check fatigue/shear/contact stress; approved engagement and retention; matched balancing convention and inspection
Competing controllers or saturation	Runaway acceleration or torsional hunting	One speed owner, anti-windup, current limits, watchdogs and validated mode transitions
Regenerative DC overvoltage	Drive damage and loss of controlled torque	Independent bus clamp/dump; branch monitoring; validated sink acceptance and trip logic
Loss of grid or full battery	Returned energy has no destination	Detect sink unavailability; transfer to rated dump or validated coast; prevent restart until energy destination proven
Undersized emergency resistor	Fire or overvoltage during stop	Size pulse energy, peak power and repetition; monitor temperature; include continuing source input and all inertias
PWM power measurement error	False efficiency or apparent negative losses	PWM analyzer, calibrated sensors, deskew, appropriate ranges and simultaneous integration

Failure mode	Consequence	Practical mitigation and evidence needed
EMI and ground loops	Corrupt torque, false trips or missed faults	Segregate power/signal wiring, differential isolated channels, deliberate shielding and bonding; test immunity under PWM
Unsynchronized torque/speed	False transient power spikes	Common clock and edge capture; measure signal latency and filter phase; timestamp data quality
Aliasing or insufficient sensor rate	Hidden oscillation and misleading spectra	Analog anti-alias filters; bandwidth qualification; oversample only as appropriate; upgrade sensor for faster objectives
Temperature or calibration drift	Incorrect torque zero and efficiency bias	Warm-up, matched thermal conditions, pre/post zero, bidirectional checks and scheduled recalibration
Cooling differs from datasheet	Claimed continuous rating cannot be reproduced	Measure inlet conditions/air velocity at motor; record ambient and temperatures; derate until thermal equilibrium demonstrated
Rotor hotspot not sensed	Magnet damage below apparent winding limit	Obtain thermal estimator/telemetry and hotspot margins; conservative duty until validated
Gearbox oil or bearing limits	Scuffing, seizure, viscosity loss or leakage	Supplier lubrication schedule and orientation; oil level/temperature monitoring; forced lubrication if specified
Overspeed after torque loss	Motor, coupling or load rotor rupture	Independent speed trip for both ends; account for shaft separation and detection latency; contain all rotating parts
Shaft/coupling separation	Projectiles and disconnected rotor acceleration	Engineered fragment containment anchored to structure; independent speed feedback; remote operation
High voltage and arc energy	Shock, burns and fire	Enclosed electrical cabinet, protective bonding, coordinated DC interruption, lockout and proven discharge; qualified electrical review
Coolant leaks	Short circuit, slip hazard and sensor failure	Separate plumbing from HV, drip trays, leak detection, compatible hoses and restrained quick disconnects
Incorrect torque/rotation signs	Wrong control feedback or erroneous efficiency	Verify physical direction and torque polarity at low energy in all quadrants; freeze conventions in channel metadata
Peak rating used continuously	Thermal damage while below headline maximum	Time-at-limit counters, temperature-based derating and recovery criteria; enforce current, power and speed duty separately
Module reassembly error	Wrong shaft height, missing retention or miswired sensors	Configuration-specific inspection checklist, keyed connectors, locating fixtures and commissioning reset

The heavy table can couple structural vibration between modules. Check local plate bending, clamp/bolt preload, thread engagement, overturning, table support stability and torque-reaction paths. A sensor support should not

become a structural bridge that forces misaligned machine shafts into line. Containment and table attachments must remain effective in every approved modular configuration.

10 Preliminary safety architecture

This concept addresses an approximately 80 kW peak DUT, up to 470 VDC depending on winding and up to 7,000 rpm briefly [S1 p1]. It is a planning basis, not an authorization to energize. Qualified mechanical, electrical and machine-safety engineers must determine applicable requirements, safety integrity, fault tolerance, containment design and test acceptance. ABB's functional-safety guidance describes drive safety functions and risk-based integrity assessment [S6]; this report does not assign a performance level or claim compliance.

Safety function	Preliminary implementation	Release criterion
Enclosure and access	Contain all shafts, couplings, motor rotors and gearbox interfaces; locked interlocked doors	Mechanical review of credible fragments, fixings and access paths; no unguarded test state
Overspeed	Independent speed monitoring, including each machine if shaft separation is credible	Trip below lowest allowed component limit by detection/actuation/acceleration margin
Overtorque	Dedicated fast threshold path with sensor-fault detection, plus drive current/torque limits	Trip plus worst overshoot and uncertainty stays below approved transmitted torque; ATO display alone is insufficient
Vibration	Independent protective monitoring at critical bearings/modules	Baseline survey, validated thresholds and response; trips distinguish sensor failure
Temperature	Winding, critical bearings, inverter, oil and rotor strategy	Limits below approved ceilings with sensor lag/hotspot allowance; fail safely on open/short
Cooling	Flow proven before enable; temperature and pressure supervision	Loss of flow triggers validated stop; retain cooling after torque removal where needed
Bus overvoltage	Hardware chopper or equivalent independent sink and trip	Absorbs credible stop energy with mains absent; thermal capacity and diagnostic coverage verified
Emergency stop	Accessible hardwired/safety-rated inputs independent of test PC	Selected controlled stop then STO, or immediate STO/coast as risk assessment requires; tested under load
Isolation and contactors	Monitored main contactors, disconnect and precharge; welded-contact detection	Validated opening sequence and DC interrupt capability; independent lockable isolation
Stored energy	Discharge resistors and monitored bus voltage	Verify safe residual voltage using qualified procedure; DC source isolation alone is insufficient
Standstill and guard release	Speed/energy proof, manual reset, no automatic restart	Door remains locked until all accessible motion/energy is safe
Fault recording	Latched first-out cause, pre/post-trigger data, drive states and stop outcome	Logs survive PC/network loss where needed; reset requires cause review

During an ordinary stop, ramp torque/speed with the accepted energy sink online, verify decreasing speed, disable torque and isolate/discharge in the supplier-approved sequence. During a fault, the safe state depends on whether controlled braking remains trustworthy. If it does, execute the validated stop before torque removal. If not, remove

torque and maintain containment during coast-down, with the bus protected against continued permanent-magnet generation. A mechanically separated rotor may coast independently.

STO inhibits commanded motor torque; it is not electrical isolation, a holding brake or guaranteed removal of generated voltage. Opening the main supply contactor does not instantly remove rotating energy or DC charge. A spinning permanent-magnet machine can feed a drive's diode path, depending on topology. Do not casually open motor-phase contactors under load; any such function must be explicitly approved for the inverter and fault case. A mechanical brake, if added, needs its own speed, torque and energy rating and must not create destructive shaft torque.

The emergency energy path must remain available when grid regeneration, the source or a control computer fails. For a resistor branch, $P = V^2/R$ and $I = V/R$ set electrical demand, while $E = \int P dt$ and the duty cycle set thermal demand. Bus clamp thresholds must remain below the lowest approved voltage limit including tolerances. No resistor value, contactor size or trip setpoint is finalized until capacitance, all inertias, source fault current and stop time are known.

Operate remotely with an exclusion zone. Before each test inspect mounts, keys, couplings, guards, hoses, bonding, lubrication, sensor zeros and active limits; confirm the configured module arrangement matches the approved file. Electrical maintenance requires isolation, lockout, discharge verification and appropriate qualified-person procedures. The table's protective bond must be intentional; mechanical contact alone is not a reliable bond. Do not use the torque sensor as a protective-earth path.

11 Staged commissioning and testing

Each stage requires documented approval of the previous stage and an approved configuration-specific limit file. “Common aborts” means unexpected noise/vibration, torque or speed beyond the stage limit, cooling failure, temperature approaching its approved threshold, bus overvoltage, signal loss, guard fault, controller instability or sensor saturation. All aborts latch the cause and invoke the validated stop; do not reset and continue without review. The numeric early-stage limits below are recommended starting points, not manufacturer ratings.

Stage	Prerequisites and limits	Data and acceptance or abort
1 Mechanical and instrumentation checks	De-energized inspection; approved mount/containment design; align shafts, verify runout, fasteners, lubrication and bonds	Record alignment, torque fastener checks and sensor calibration; reject any exceeded drawing tolerance or incomplete guard
2 Safety and energy-path checks	Rotors stationary; validate E-stop, guard lock, contactor feedback, precharge/discharge and sink loss logic with low energy	Record response times, bus voltage and first-out faults; abort for welded contacts, missing diagnostics or failed discharge
3 Zero and polarity verification	Thermally stable unloaded sensor; no arbitrary automatic zero; apply known small positive/negative reference torque	Record zero, reference readings and encoder direction; reject wrong sign, unstable zero or calibration deviation
4 Low-speed unloaded rotation	Guards locked; torque limited; recommend ≤ 100 motor rpm initially with gearbox/load drag explicitly identified	Record torque, both speeds, vibration, current and temperatures; abort on binding, pulse mismatch or rising vibration
5 Low-torque loading	Verified speed control owner; recommend ≤ 500 motor rpm and ≤ 10 N·m DUT torque initially	Record command/response, bus power and T2; reject hunting, unexpected torque amplification or current limiting
6 Incremental speed and torque	Approved envelope; increase one variable at a time with review, suggested steps $\leq 10\%$ of approved range	Record synchronized channels and peak overshoot; stop expansion if margin or stability is unproven

Stage	Prerequisites and limits	Data and acceptance or abort
7 No-load loss tests	Define isolated motor or complete-train boundary; stable temperatures; verified low-torque uncertainty	Record DC/phase power, speed, drag torque and temperatures; reject unexplained negative losses or excessive zero drift
8 Steady torque-speed map	Validated operating region and cooling; one speed owner; dwell until speed/torque/power stable	Log mean, variation, uncertainty and all thermal states per point; omit points with saturation, drift or inadequate dwell
9 Continuous thermal tests	Selected cooling conditions reproduced; approved continuous current/power curve; no peak-duty values	Log until thermal equilibrium or approved duration; suggested equilibrium criterion <1 K change over 10 min, subject to review; abort on persistent rise or temperature margin loss
10 Short peak tests	Manufacturer-defined cold/hot conditions, peak duration and recovery approved; dump and thermal margin proven	Record high-rate torque/current, temperatures, elapsed peak time and post-test zero; abort on any shorter applicable duty limit or excessive overshoot
11 Regenerative tests	Four-quadrant machine maps approved; source/sink ready; begin low speed/torque; validate sign in both directions	Record all branch powers, DC voltage, SOC if battery, torque/direction and energy; abort on sink loss or bus rise
12 Drivetrain efficiency	Both torque sensors calibrated and synchronized; stable oil/coolant; defined boundaries	Measure both powers simultaneously and repeat directions; reject ratios outside physical bounds after uncertainty/storage assessment
13 Transient tests	Torsional modes and delay characterized; protection response proven; maximum transient torque predicted below limits	Start slow ramps/small steps, then expand bandwidth deliberately; record raw signals and spectra; abort on resonant growth, aliasing, saturation or unexpected phase lag
14 Reassembly and repeatability	Any module moved, sensor relocated or coupling changed	Return to alignment, safety, zero and low-energy checks; compare reference points before accepting new data

For steady mapping, choose speed points spanning base-speed and field-weakening regions and torque points spanning low, middle and permitted high load. Randomize or repeat selected points to expose thermal drift. Report actual bus voltage, cooling conditions, direction, uncertainty and dwell for each point. Settle a numerical repeatability criterion from the required accuracy rather than declaring a visually smooth curve sufficient.

Peak testing must not begin merely because the current timer allows 2 min. Hot-start power and overspeed may permit only seconds, and a peak-torque duration is not independently supplied. A 7,000 rpm test requires separate authorization for every rotating component and must not extend the page 2 curve beyond its data. No high-energy fault injection is proposed; simulate faults at low energy first and use a qualified validation plan for remaining cases.

12 Open questions and next decisions

Resolve the following in priority order. “Manufacturer confirmation” and “engineering approval” identify release dependencies, not assumed answers.

Priority	Decision or missing information	Required result
1	Exact EMRAX winding, cooling and serial/configuration	HV/MV/LV and AC/LC/CC order definition; shaft, feedback, bearing and mounting drawings

Priority	Decision or missing information	Required result
1	Conflicting EMRAX tables and graphs	Manufacturer-approved torque-speed-current-power maps in motoring/generating, per cooling and bus voltage; resolve power/torque and flux inconsistencies
1	Test duration and thermal duty	Cold/hot definitions, peak duration/recovery, continuous stall allowance, overspeed duration and rotor temperature strategy
1	Energy architecture and utilities	Shared bus versus separate regeneration versus resistor; available service, export constraints, fault current and cooling utilities
1	Gearbox definition	Type, actual ratio/direction, continuous/peak torque, input speed, both-direction efficiency, backlash, inertia, lubrication and thermal limits
1	Safety and structure	Qualified review of table, local mounts, containment, stop energy, electrical protection and functional safety; approved limits
2	EMRAX inverter	Approved motor compatibility, feedback, phase-current duty, bus range, field weakening, switching and stop behavior
2	Load motor and drive	Joint four-quadrant torque-speed-duty map, low-speed cooling, peak duration, inertia and energy-return compatibility
2	ATO exact 800 N·m build	Signed capacity/FS definition, rated versus maximum-speed duty, pulse count/interface, pinout, safe overload, fatigue and allowable axial/radial loads
2	ATO dynamics and mechanics	Analog transfer function, update/latency, timestamp semantics, corrected stiffness/inertia, bearing life, balancing and anti-rotation drawing
2	Accuracy and bandwidth	Required uncertainty at low/nominal torque; fastest transient; whether PWM torque ripple is in scope; synchronized instrument specification
2	One or two transducers	Two recommended for component efficiency; select 200/300 N·m motor sensor or justify restricted sequential testing
3	Cooling design	Glycol concentration, pressure drop/limits, CC airflow, heat rejection, reservoir and facility capacity
3	Budget and automation	Capital limit, duty hours, staffing, data storage, remote control, calibration access and planned expansion

The immediate engineering disposition is to retain the modular welding-table concept, pursue a supplier-approved four-quadrant load system and provision for two torque sensors. The 800 N·m output sensor remains conditionally suitable for steady mapping and controlled peaks within a verified limit. It is not yet accepted for unrestricted transients, full reverse peak testing or motor-side operation above its rated speed. Confirm the unresolved manufacturer specifications and obtain engineering approval before purchase commitments tied to those capabilities.

References

S1. EMRAX, EMRAX 208 Technical Data Table and graphs, supplied file [emrax_208_technical_data_4.5.pdf](#), three pages. Page 1 technical table and notes; page 2 HV CC torque/power graph and efficiency map; page 3 HV CC torque-current

graph, free-run losses and variant notes. Attachment filename identifies version 4.5; no publication date is shown on these pages. All EMRAX source ratings in this report refer to this attachment, not a substituted current motor revision.

S2. ATO, Digital Rotary Torque Sensor, SKU ATO-TQS-D03, model ATO-TQS-DYN-200, current Specification, Installation and manufacturer Q&A sections, accessed 7 October 2026. <https://www.ato.com/rotary-torque-sensor-10000-nm>

S3. ATO, Digital Rotary Torque Sensor User Manual, seven-page PDF linked from S2; pp2–3 specifications and pp5–7 configuration/protocol. <https://www.ato.com/Content/doc/Digital-rotary-torque-sensor-user-manual-ATO-TQS-DYN-200.pdf>

S4. ATO, Digital Rotary Torque Sensor Instructions, upgrade version, 24-page PDF linked from S2. References in this report use PDF page numbers, including cover and contents, rather than its offset printed numbering. <https://www.ato.com/Content/doc/digital-rotary-torque-sensor-user-manual-upgrade-version.pdf>

S5. Yokogawa Test and Measurement, Measurement of Inverter Efficiency, manufacturer application note, accessed 7 October 2026. <https://tmi.yokogawa.com/library/resources/application-notes/measurement-of-inverter-efficiency/>

S6. ABB, Drive Based Functional Safety Solutions, manufacturer guidance, accessed 7 October 2026. <https://www.abb.com/global/en/areas/motion/drives/connectivity/functional-safety>

All unreferenced calculated values derive from the cited input ratings, the user-specified ratio, the explicitly stated efficiency assumptions or the equations in section 8. All acquisition targets, mounting concepts and commissioning practices are preliminary engineering recommendations. Missing component limits remain release dependencies and must not be replaced by these planning targets.