Modeling and simulation of a 25 kV AC railway traction system with regenerative braking energy recovery

Birane Diaw

Portfolio: https://bdiaw.lovable.app/

Abstract— This report presents a system-level 25 kV AC railway traction model applied to two African railway scenarios: the ONCF Avelia Horizon high-speed case and the Dakar TER Coradia Polyvalent regional case. The project couples a physically feasible mission profile, Davis train dynamics, an average-value converter-motor chain, catenary voltage calculation, and a Newton-Raphson power-flow solver. The simulations show voltage compliance over the considered EN 50163 range, 100 % network convergence, and a higher regenerative braking energy ratio for Dakar TER because of its frequent stop-and-brake cycles.

Keywords—railway traction, 25 kV AC, regenerative braking, Simulink, Newton-Raphson, EN 50163.

I. Introduction

The project compares two electrified railway systems under a common 25 kV AC supply assumption: an ONCF high-speed mission and a Dakar TER regional mission. The model is not a hardware certification file; it is a reproducible academic simulation bench used to quantify consumption, energy recovery, and pantograph voltage behavior.

II. Architecture and model

The modeled chain includes the mission profile, speed controller, average-value FOC converter, train dynamics, catenary model, Newton-Raphson power flow, and recovered-energy management. The converter accounts for the total number of motors so that electrical power represents the complete trainset.

The main relations are: $F_{Davis} = A + Bv + Cv^2$, $T_{em} = 1.5\ np\ psi_r\ iq$, $P_{elec} = n_{motors}\ T_{em}\ omega_e / np$ with traction or recovery efficiency, and $tau_{RBE} = E_{rec} / E_{conso}$. Pantograph voltage is evaluated through an equivalent catenary impedance and checked against the 19 kV - 27.5 kV range.

III. Simulink implementation

Two modular Simulink models are generated: traction_oncf.slx and traction_ter.slx. The speed feedback between train dynamics and converter is intentionally discretized by a Unit Delay block to remove the algebraic loop and make the diagrams executable. The sps_traction_ter.slx model represents an average-value Simscape Electrical / Specialized Power Systems traction chain for the TER case.

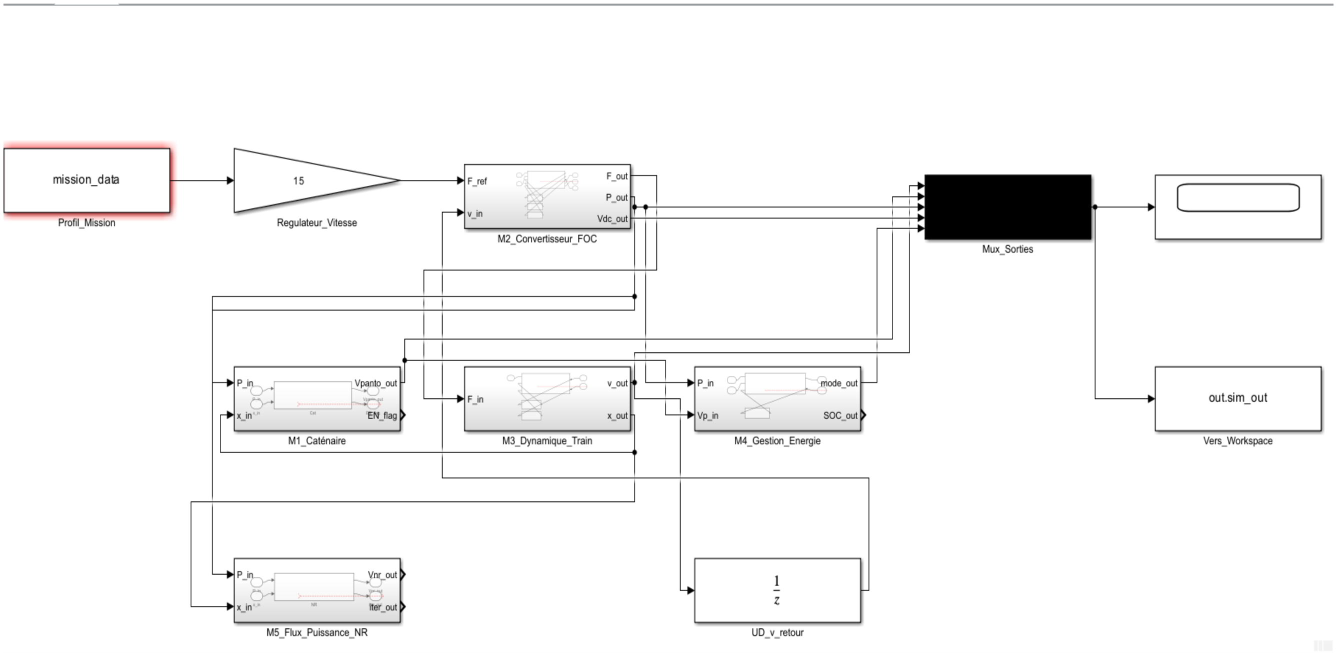

Fig. 1. Real Simulink screenshot of traction_ter.slx.

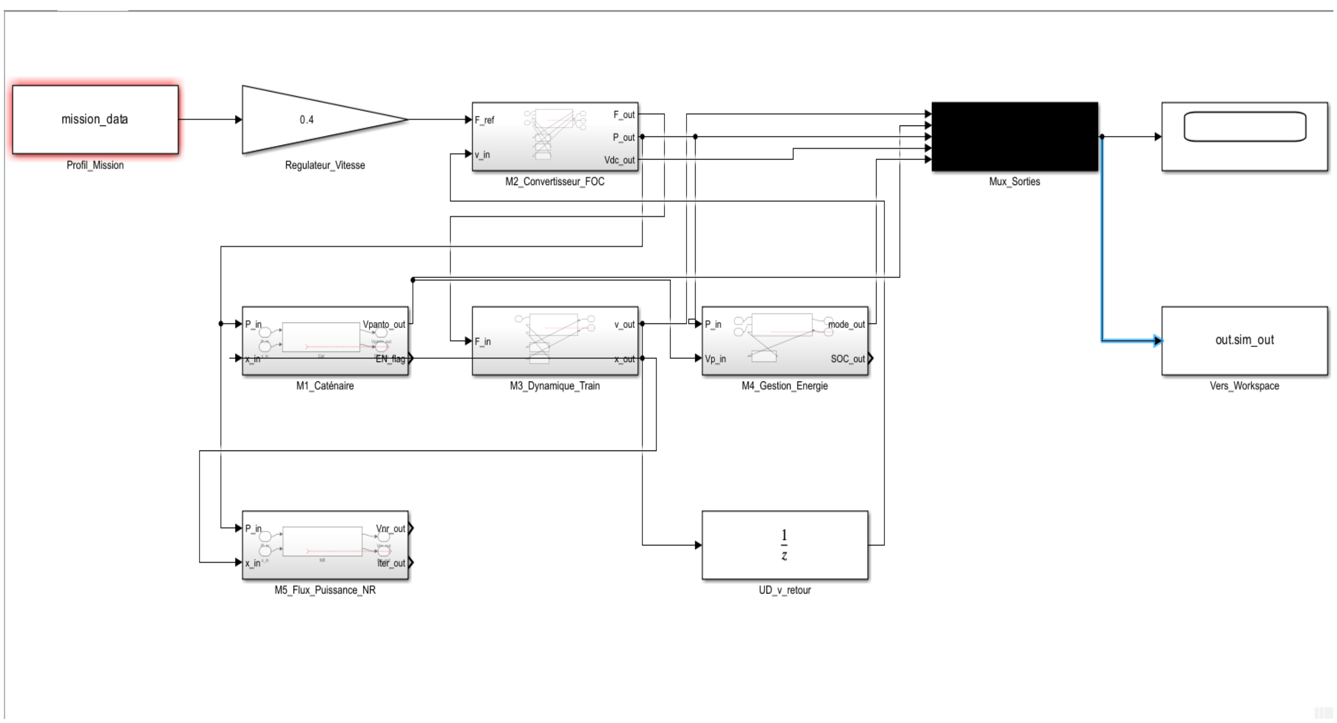

Fig. 2. Real Simulink screenshot of traction_oncf.slx.

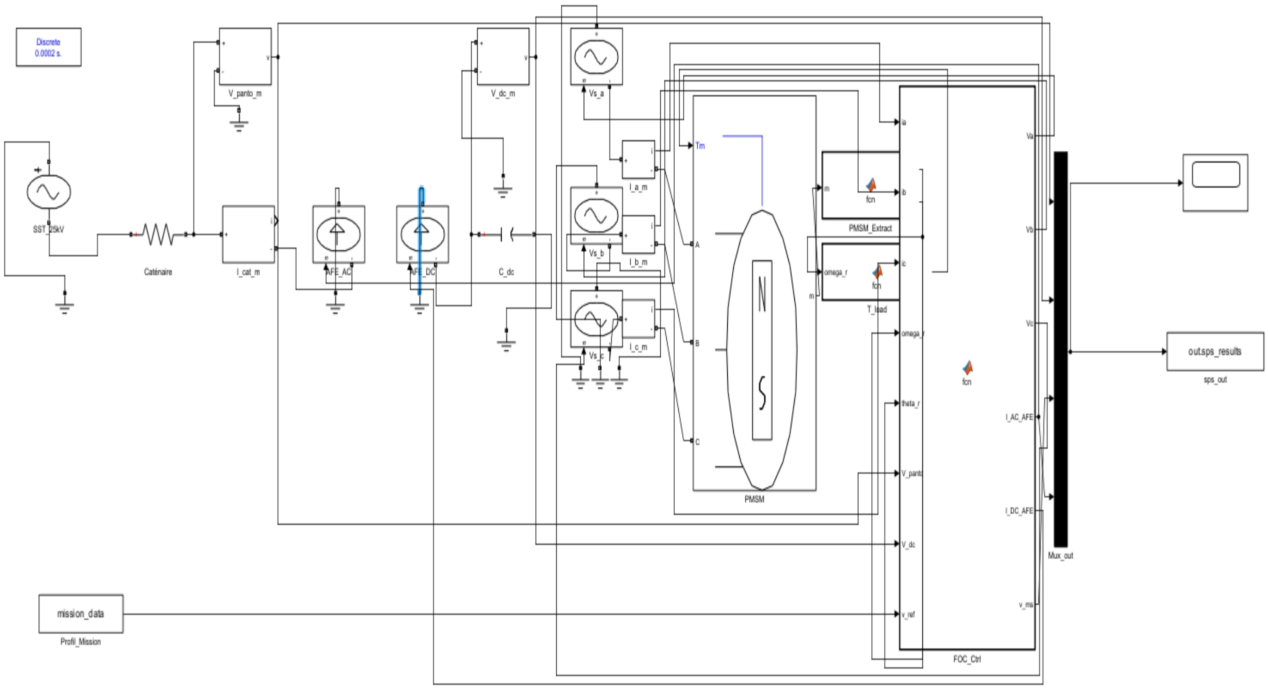

Fig. 3. Real Simscape Electrical / SPS screenshot of sps_traction_ter.slx.

IV. Simulation results

The results show that the ONCF high-speed case consumes more energy in absolute value, while Dakar TER recovers a much larger energy fraction because of repeated acceleration and braking cycles. Both scenarios reach their target distance and remain within the simulated voltage range.

Table I. Summary results

Case	Time	Distance	Vmax	E cons.	E rec.	Net E	RBE	NR	EN 50163
ONCF	83.8 min	430.0 km	320.4 km/h	1601.8 kWh	402.7 kWh	1199.1 kWh	25.1 %	100 %	100 %
TER	39.1 min	57.0 km	160.5 km/h	720.2 kWh	499.5 kWh	220.7 kWh	69.4 %	100 %	100 %

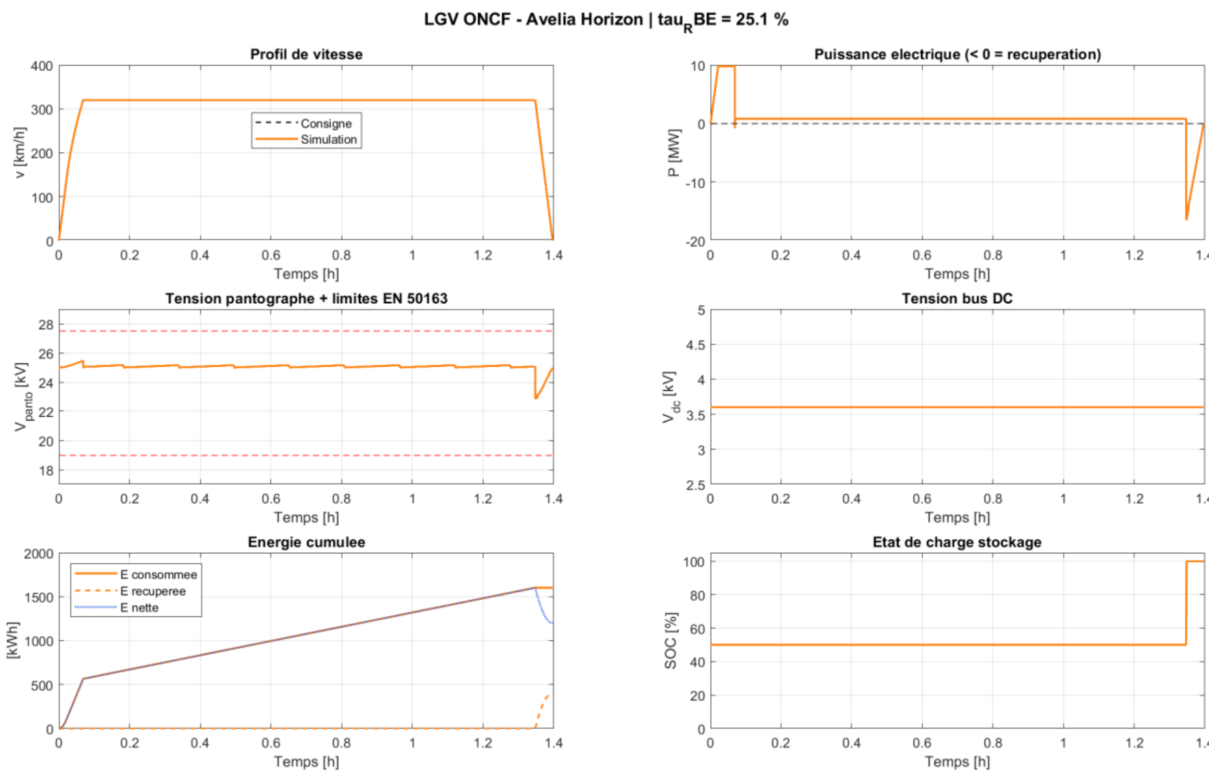

Fig. 4. ONCF profiles: speed, power, pantograph voltage, DC bus, energy, and SOC.

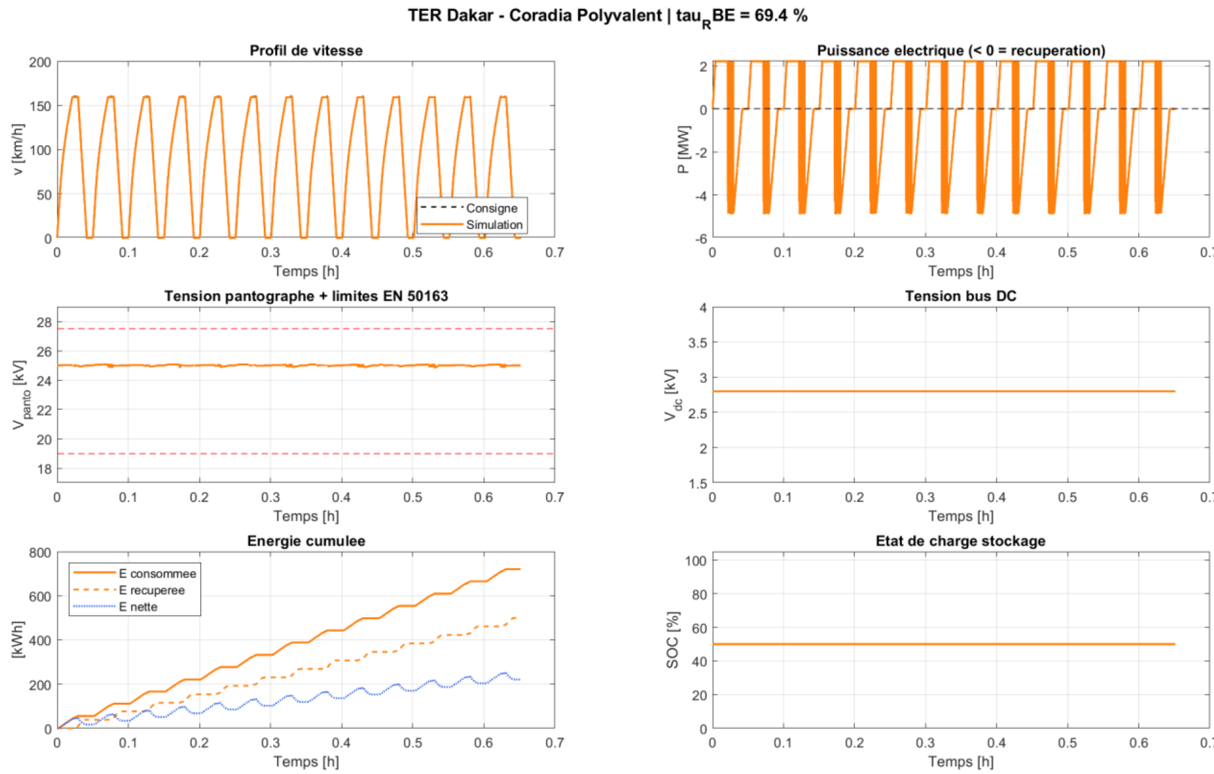

Fig. 5. Dakar TER profiles: speed, power, pantograph voltage, DC bus, energy, and SOC.

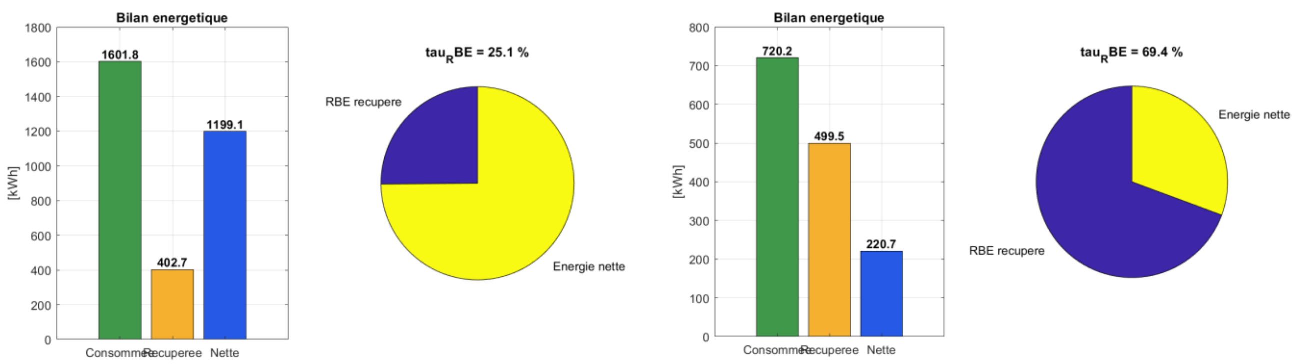

Fig. 6. Automatically generated energy balances for ONCF(left) and Dakar TER(right).

The distribution of Newton-Raphson load-flow iterations per simulation step (Fig. 7) confirms the numerical robustness of the solver: Dakar TER converges in a single corrective iteration for almost the entire mission, while ONCF, subject to higher power demands during its 320 km/h acceleration phases, occasionally requires a third iteration. In both cases convergence stays below 3 iterations for nearly the whole profile, validating the single-bus formulation for a fixed-step simulation loop.

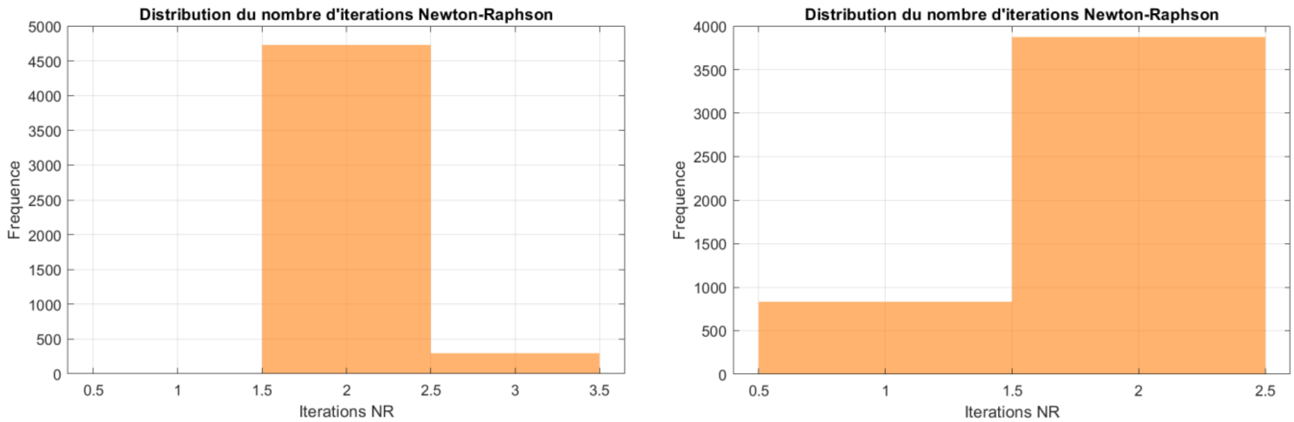

Fig. 7. Newton-Raphson iteration count distribution for ONCF(left) and Dakar TER(right).

V. Validation, standards and limits

Automatic validation checks signals, distance, speed, energy, network convergence, voltage range, and SOC. However, the project is not a full IEC/ISO compliance demonstration: IEC 61287, IEC 61377, IEC 60349, IEC 62236, IEC 61373, EN 50126/50128/50129, and ISO 22163 require tests, safety analyses, EMC, thermal, quality, and industrial documentation beyond this system-level model.

Table II. Automatic validation checks

Check	**Criterion**	**Result**
Signals	Finite values over all logs	OK
Mission	Final distance >= 99 %	OK
Speed	Reached speed >= 95 %	OK
Energy	Consumed energy > recovered energy >= 0	OK
Network	Newton-Raphson convergence >= 99 %	OK
Voltage	EN 50163 / 19-27.5 kV range >= 99 %	OK
Storage	SOC between 0 and 1	OK

VI. Conclusion

The project delivers a reproducible environment for analyzing railway regenerative energy recovery on two case studies. It is suitable for an academic or portfolio report, with explicit limitations and coherent system-level results.

References

[1] IEC 60850 / EN 50163, Railway applications - supply voltages of traction systems. [2] IEC 61287-1, Railway applications - power converters installed on board rolling stock. [3] IEC 61377, Railway applications - rolling stock combined testing. [4] IEC 62236 / EN 50121, Railway applications - electromagnetic compatibility. [5] ISO/TS 22163, Railway quality management system.