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AI-Assisted Linear Electromagnetic Inertia System for Industrial Microgrid Stability During Network Disturbances

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Abstract. Short voltage interruptions and deep voltage sags can trip variable-speed drives before conventional standby generation becomes effective. This paper develops a loss-aware conceptual design for a linear electromagnetic inertia system (LEIS) intended only for sub-second-to-few-second ride-through of selected industrial loads. The selected actuator is a permanent-magnet linear synchronous machine (PMLSM) with a guided translator, a bidirectional converter, and a constrained kinetic-energy reserve. The term *electromagnetic inertia* is used as a system name and not as an assertion that magnetic-field energy, mechanical inertia, and power-system inertia are physically interchangeable. A unified electromechanical model includes copper, core, eddy-current, guide-friction, converter, and auxiliary losses, together with translator travel and current limits.

The distinguishing contribution is the coordinated combination of a travel-limited linear kinetic store, one reversible PMLSM/converter path, a safety-gated disturbance predictor, and explicit ride-through energy and stopping-distance constraints for industrial microgrids. Artificial intelligence is restricted to anticipatory supervision; deterministic protection retains authority and initiates support if the predictor is late, unavailable, or uncertain. A 50 kW, 2 s analytical sizing example shows that losses and reserve margins materially increase the required kinetic energy and translator speed. No experimental performance or prediction-accuracy claim is made. The paper specifies the data, metrics, latency budget, edge cases, and hardware-in-the-loop tests required before industrial deployment.

Keywords. Industrial microgrid; Voltage sag; Ride-through; Permanent-magnet linear synchronous machine; Kinetic energy storage; Variable-speed drive; LSTM; Safety-gated control

INTRODUCTION

Industrial microgrids increasingly supply variable-speed drives (VSDs), process controllers, and converter-interfaced loads that can be sensitive to voltage sags and short interruptions (Bollen, 2000; IEEE, 2019; Fuchs and Masoum, 2015).

A disturbance lasting only a few cycles may cause undervoltage protection to operate, interrupt a pumping or compression process, and require a time-consuming restart. Batteries and uninterruptible power supplies can provide ride-through, while engine-generator sets provide longer-duration backup, but these technologies serve different time scales and impose different maintenance, lifetime, and power-density constraints (Bollen, 2000; Linden and Reddy, 2011).

This paper investigates a deliberately narrow question: can a reversible linear electrical machine maintain a precharged kinetic-energy reserve and return part of that reserve through a bidirectional converter during a short grid disturbance? Linear motor-generator reversibility and kinetic-energy storage are established technologies (Boldea and Nasar, 2005; Gieras et al., 2012; Genta, 1985; Bolund et al., 2007).

Therefore, neither principle is claimed as new. The proposed contribution is the following system-level integration for industrial VSD ride-through:

- A **travel-limited, guided translator** operated as the kinetic store rather than a rotary flywheel;
- One explicitly selected topologya **permanent-magnet linear synchronous machine (PMLSM)**—used in both motoring and generating modes;
- A **loss- and constraint-aware energy manager** that respects current, speed, temperature, and stopping-distance limits;
- A **safety-gated predictor** that may pre-arm the converter but cannot replace deterministic undervoltage and overcurrent protection; and
- An explicit **verification framework** linking prediction errors and inference latency to the physical ride-through requirement.

The resulting LEIS is not presented as a replacement for batteries or conventional flywheels. It is a conceptual short-duration buffer for critical loads where rapid bidirectional conversion, a nonchemical storage medium, and linear mechanical integration may be useful.

The paper provides a consistent topology, dynamic model, analytical sizing example, AI verification protocol, limitations, and required experimental work. Claims are limited to analytical feasibility; prototype and hardware-in-the-loop validation remain necessary.

POSITIONING AND TERMINOLOGY

Relation to established technologies

Linear machines have long been operated as actuators and generators (Boldea and Nasar, 2005; Gieras et al., 2012), while flywheels use mechanical inertia and a motor-generator to exchange kinetic and electrical energy (Genta, 1985; Bolund et al., 2007).

Power-electronic converters already provide rapid bidirectional control and grid synchronization (Mohan et al., 2003; Teodorescu et al., 2011).

The proposed LEIS combines these established elements but changes the mechanical geometry, operating constraints, and supervisory coordination.

The practical value of the concept must ultimately be judged against mature alternatives by efficiency, cost, footprint, safety, maintenance, and demonstrated reliability. The architecture alone does not establish superiority.

Table 1 . Comparative assessment of rotary flywheel ride-through, conventional linear motor/generator systems, and the proposed LEIS concept.

Aspect	Rotary flywheel ride-through	Conventional linear motor/generator	Proposed LEIS concept
Stored energy	Rotational kinetic energy	Normally not maintained as a grid reserve	Translational kinetic reserve within a finite guide length
Mechanical constraint	Rotor stress, bearings, containment	Stroke and end-stop constraints	Stroke, braking distance, end-stop avoidance, guide friction
Electrical path	Rotary machine plus converter	Application-specific drive or generator	One PMLSM and bidirectional converter for charge, hold, and discharge
Triggering	Protection/control dependent	Application dependent	Deterministic protection with optional predictive pre-arming
Energy management	Speed and state-of-charge limits	Usually motion/force objectives	Energy, current, temperature, speed, and remaining-travel constraints
Intended claim	Mature storage technology	Established machine technology	A system architecture and verification framework for short VSD ride-through

Three distinct meanings of inertia

Three physical concepts must not be conflated:

- **Mechanical inertia** is the resistance of a mass to acceleration. In the LEIS, usable stored energy is predominantly translator kinetic energy, $E_k = 1/2\,mv^2$.
- **Magnetic-field energy** is $E_m = 1/2\,Li^2$ for a lumped linear inductance. It is important during current commutation and converter transients, but it is not treated here as the main sustained energy source.
- **Power-system inertia** describes the frequency response historically supplied by synchronously rotating masses. Converter-controlled fast power injection may emulate part of that response, but it does not create synchronous inertia (Kundur, 1994).

Accordingly, *Linear Electromagnetic Inertia System* is retained as the architecture name. In all energy and sizing equations, mechanical kinetic energy, magnetic-field energy, and converter-controlled grid support are separately identified.

SELECTED MACHINE AND SYSTEM ARCHITECTURE

Permanent-magnet linear synchronous machine

The proposed topology is a three-phase PMLSM with permanent magnets on the translator, a stationary multiphase winding, position and velocity sensing, and low-friction guided motion. A six-phase winding may later be evaluated for fault tolerance, but it is not part of the baseline model. The PMLSM is selected because its flux linkage can be represented consistently in motoring and generating modes and because field-oriented control is well established (Gieras et al., 2012; Pillay and Krishnan, 1989). No linear induction-machine equation is used in the proposed model.

For a sinusoidal surface-magnet PMLSM with negligible saliency, the longitudinal electromagnetic force is

$F_e = \frac{3\pi}{2\tau_p} \psi_f i_q$ (1)

Where τ_p is pole pitch, ψ_f is permanent-magnet flux linkage, and i_q is the force-producing current. The speed-induced quadrature-axis voltage is approximated by

$e_q = \frac{\pi}{\tau_p} \psi_f v$ (2)

The same electromechanical coupling therefore produces thrust in motor operation and electrical power during controlled regenerative braking.

Power and control path

The baseline architecture contains:

1. The PMLSM and guided translator;
2. Position, velocity, winding-temperature, and guide-condition sensors;
3. An active rectifier/inverter connected to the protected DC or AC bus;
4. A precharge and isolation stage;
5. Deterministic protection implemented in the converter controller; and
6. An optional predictor that issues only *normal*, *pre-arm*, or *confidence-low* supervisory signals.

During normal service the converter accelerates the translator to a permitted reserve speed and maintains it within the usable travel envelope. When deterministic voltage protection operates, the converter commands regenerative force while controlling the protected bus. If an accepted predictor signal arrives earlier, the controller may pre-arm gates, reserve current headroom, and modify the translator trajectory; it may not connect an unsafe source or suppress a protection trip.

LOSS-AWARE DYNAMIC MODEL

Mechanical dynamics and travel constraint

The translator dynamics are

$m\dot{v} = F_e - F_d - bv - F_c \mathrm{sgn}(v)$ (3)

$\dot{x} = v$ (4)

Where m is translator mass, F_d is the externally imposed longitudinal force, b is the viscous-friction coefficient, and F_c represents Coulomb and guide friction. Position must satisfy

$x_{\min} + x_{safe} \leq x(t) \leq x_{\max} - x_{safe}$ (4)

where x_{safe} is an engineering margin that includes sensing uncertainty and emergency stopping distance. A ride-through command is feasible only if the remaining travel permits the requested electrical energy extraction and a controlled stop.

Electrical and conversion losses

The principal loss terms are modeled as

$P_{cu} = 3R_s I_{rms}^2$ (5)

$P_{core} = k_h f_e B_p^{\alpha} + k_e f_e^2 B_p^2$ (6)

$P_{guide} = bv^2 + F_c|v|$ (7)

$P_{conv} = P_{sw} + P_{cond}$ (8)

Where R_s is phase resistance, f_e is electrical frequency, B_p is peak flux density, and k_h, k_e, α are identified core-loss coefficients. Additional magnet/structure eddy-current loss

$P_{eddy,stray}(v, i_q)$ and auxiliary consumption P_{aux} must be obtained from finite-element analysis or tests for a particular machine.

During regenerative support, the net bus power is

$$P_{bus} = \eta_{conv}\left[-F_e v - P_{cu} - P_{core} - P_{eddy,stray}\right] - P_{aux} \quad (9)$$

with the sign convention $F_e v < 0$ during braking. The kinetic-energy balance is

$$\frac{dE_k}{dt} = mv\dot{v} = F_e v - P_{guide} - F_d v \quad (10)$$

Magnetic-field energy $E_m = 1/2\, L_d i_d^2 + 1/2\, L_q i_q^2$ is retained in the transient electrical balance but is not counted as a long-duration energy reserve. This prevents the term $Li\, di/dt$ from being interpreted as freely available sustained output.

Deliverable energy and compensation time

Between initial and minimum permitted speeds, the upper bound on delivered energy is

$$E_{del} = \frac{1}{2}m(v_0^2 - v_{min}^2) - \int_0^T \left(P_{guide} + P_{cu} + P_{core} + P_{eddy,stray} + P_{conv} + P_{aux}\right) dt \quad (11)$$

For a demanded load profile $P_L(t)$, ride-through is feasible only when

$$\int_0^{T_c} P_L(t)dt \le E_{del} \quad (12)$$

and the force, current, thermal, speed, and travel constraints remain satisfied. Thus $T_c = E/P$ is only an ideal first estimate, not a complete dynamic model.

DISTURBANCE DETECTION AND SAFETY-GATED AI

Deterministic protection baseline

The mandatory protection path calculates positive-sequence RMS voltage and DC-bus voltage and applies independently validated thresholds based on power-quality practice (Bollen, 2000; IEEE, 2019). A disturbance request is asserted when an undervoltage, loss-of-mains, excessive rate of voltage change, or DC-bus collapse criterion is satisfied. This path has priority and does not depend on a trained model.

The total support delay is

$$t_{support} = t_{sense} + t_{decision} + t_{gate} + t_{current} \quad (13)$$

Where sensing, decision, gate-enabling, and current-control delays must be measured on the target controller. The earlier claim of a demonstrated response below 5 ms is withdrawn. A sub-5-ms design target is plausible for modern converters but remains an acceptance test, not a result of this conceptual study.

Predictor inputs and output

The optional sequence predictor uses synchronized, per-unit features rather than voltage samples alone:

$$\mathbf{z}_t = \left[V_1, V_2, f, \dot{f}, \mathrm{THD}_V, I_d, I_q, V_{dc}, P_L, Q_L, v, x, T_w, c_g\right]^T \quad (14)$$

where V_1 and V_2 are positive- and negative-sequence voltage, f and $\dot{f}$ are frequency and rate of change of frequency, V_{dc} is converter DC-bus voltage, P_L, Q_L are load powers, T_w is winding temperature, and c_g is a guide-condition indicator. Harmonics, missing samples, sensor quality flags, and switching-state context are included because industrial VSD waveforms are not ideally sinusoidal.

An LSTM processes a window $\mathbf{Z}_t = [\mathbf{z}_{t-N+1}, \dots, \mathbf{z}_t]$ and estimates the probability that a ride-through-triggering event will occur within a defined horizon H:

$$\hat{p}_t = \sigma\left(\mathbf{W}_y \mathbf{h}_t + b_y\right) \quad (15)$$

The predictor may issue a *pre-arm* request only when $\hat{p}_t \geq p_{arm}$, input-quality tests pass, and the prediction is physically consistent with translator energy and travel. Otherwise, control remains deterministic.

Training data and leakage control

No trained model or industrial dataset is claimed in this paper. Validation requires an event-level dataset assembled from three traceable sources:

- Time-synchronized field recordings from power-quality monitors at VSD buses;
- Electromagnetic-transient simulations covering sag depth, phase angle, duration, fault type, source impedance, load, harmonics, and sensor noise;
- Hardware-in-the-loop records including converter saturation, communication delay, missing samples, and protection actions.

Events must be labeled by disturbance type, onset, depth, duration, and whether ride-through support was required. Training, validation, and test partitions must be separated by complete event and, preferably, by site or operating campaign. Randomly splitting adjacent samples from the same event would leak waveform information and overstate generalization.

Required metrics and acceptance criteria

Prediction performance must be reported with the confusion matrix, precision, recall, F1 score, false-positive rate (FPR), false-negative rate (FNR), area under the precision-recall curve, calibration error, and the distribution of warning lead time. Definitions include

$$\text{Recall} = \frac{TP}{TP+FN} \quad (16)$$

$$\text{FPR} = \frac{FP}{FP+TN} \quad (17)$$

$$\text{FNR} = \frac{FN}{TP+FN} \quad (18)$$

Because a missed disturbance can trip the load, FNR is safety-critical. Because frequent false pre-arms waste stored energy and increase cycling, FPR is operationally important. Before deployment, project-specific acceptance limits should be fixedfor example, FNR below 1%, FPR below 2%, 99.9th-percentile inference time below 0.5 ms, and sufficient warning lead time to reduce measured support delay. These are proposed acceptance criteria, not achieved results.

Real-time implementation and failure modes

The inference task should run on an isolated real-time core, FPGA fabric, or an industrial controller with bounded scheduling. Model size, arithmetic precision, memory, worst-case execution time, and electromagnetic compatibility must be verified. The deterministic loop must continue if the AI task overruns or restarts.

Edge case or failure	**Required response**
Missing, frozen, or implausible sensor data	Reject AI output; use deterministic protection; raise diagnostics
Unseen waveform or low confidence	Do not pre-arm from AI; preserve reserve energy
False positive	Cancel pre-arm without bus injection; log event and energy cost
False negative or late prediction	Deterministic undervoltage trigger initiates support
Converter current saturation	Limit current, prioritize protected load, and coordinate load shedding
Insufficient kinetic energy or travel	Block unsupported command and request

	alternate source/load shedding
Position-sensor disagreement	Controlled braking and isolation; no AI override
Thermal limit exceeded	Derate or block recharge/discharge
Communication or processor failure	Local protection and safe-state operation remain available

Control Sequence

Charge and reserve mode
The controller accelerates the translator subject to current and travel limits. A receding-horizon trajectory can maintain a target kinetic reserve while leaving braking distance at both guide ends. Reserve state is estimated from measured speed, identified mass, and a conservative loss model rather than from current alone.

Ride-through mode
When protection asserts support, the converter changes the force reference from reserve control to protected-bus regulation. A constrained controller minimizes
$J = \sum_{k=0}^{N_p} \left[w_v \left(V_{bus,k} - V^* \right)^2 + w_i i_{q,k}^2 + w_x \phi(x_k) + w_T \phi\left(T_{w,k}\right) \right]$ (19)
Where barrier functions $\phi(x)$ and $\phi(T_w)$ penalize approach to travel and thermal limits. The implementation may use model-predictive control or a validated cascaded bus-voltage/current controller. AI does not directly generate switching commands.

Recovery and resynchronization
After the grid satisfies voltage, frequency, phase-angle, and dwell-time criteria, the converter transfers the protected bus without abrupt torque or current. The translator is then recharged only when the grid and process load have adequate margin. Repeated disturbances invoke an energy-aware lockout or derating rule to prevent an attempted discharge from an insufficient reserve.

ANALYTICAL SIZING EXAMPLE
Consider a 50 kW critical load requiring 2 s of support. The load-energy demand is
$E_L = P_L T_c = 50 \times 10^3 \times 2 = 100$ kJ (20)
Assume, for preliminary sizing only, that aggregate electrical, mechanical, and auxiliary losses consume 12% of the initial-to-final kinetic-energy change and that a 10% design reserve is retained. The required kinetic-energy change is then
$\Delta E_k \geq \frac{1.10 E_L}{1-0.12} = 125$ kJ (21)
With a 400 kg translator and a permitted final speed of 5 m/s,
$v_0 \geq \sqrt{v_{min}^2 + \frac{2\Delta E_k}{m}} = \sqrt{5^2 + \frac{2(125000)}{400}} = 25.5 \text{ m/s}$ (22)
This result is more demanding than an ideal lossless calculation. It also exposes a central engineering difficulty: a linear store needs adequate travel. If constant effective deceleration were limited to 10 m/s², the approximate braking distance from 25.5 to 5 m/s would be
$s_b = \frac{v_0^2 - v_{min}^2}{2a} = 31.3$ m (23)
Higher controlled deceleration reduces travel but increases force, current, structural loading, and loss. The example therefore demonstrates analytical feasibility of the energy balance but also shows why footprint and guide length may dominate an industrial design. It does not prove economic advantage over a flywheel, supercapacitor, or battery.

VERIFICATION PLAN

A credible validation program should proceed in four stages:

- **Parameter identification:** measure phase resistance, flux linkage, thrust constant, friction, core/eddy loss, converter loss, and thermal parameters over the operating envelope.
- **Electromagnetic-transient simulation:** test single-, two-, and three-phase sags, interruptions, phase jumps, harmonics, VSD regeneration, source recovery, and repeated events.
- **Controller and AI hardware-in-the-loop:** measure worst-case sensing-to-current delay, prediction metrics, processor overruns, quantization effects, current limiting, and safe fallback.
- **Guarded prototype:** validate energy, travel, containment, emergency braking, thermal behavior, acoustic/vibration limits, and protected-load ride-through before any industrial trial.

Reported results must distinguish simulated, HIL, and physical measurements. At minimum, bus-voltage deviation, unserved energy, support time, converter current, translator position/speed, total efficiency, temperature, FPR, FNR, warning lead time, and worst-case latency should be disclosed with test conditions.

LIMITATIONS AND APPLICABILITY

The present work is conceptual and analytical. It has no prototype, field dataset, trained predictor, finite-element loss map, reliability demonstration, or cost assessment. Linear kinetic storage has inherently finite travel and may require a long guide or high force. End-stop and containment safety, magnet heating, eddy currents, bearing/guide wear, acoustic noise, and failure during grid reconnection require detailed engineering.

The system is intended for short ride-through, not sustained backup. Battery, supercapacitor, dynamic voltage restorer, rotary flywheel, or hybrid solutions may be smaller, more mature, or more economical. The proposed architecture is potentially relevant only where the critical-load duration, available linear footprint, maintenance strategy, and process value justify it. Its environmental impact cannot be claimed lower without a life-cycle assessment.

CONCLUSION

This paper reformulated LEIS as a constrained linear kinetic-energy ride-through system based on one reversible PMLSM topology. Mechanical kinetic energy, magnetic-field energy, and converter-mediated power-system support were separated physically and mathematically. The complete energy balance includes copper, core, eddy-current, guide-friction, converter, and auxiliary losses, while travel, current, speed, and temperature bound the deliverable energy.

The novelty claim is limited to the coordinated architecture: a travel-limited linear kinetic reserve, a shared PMLSM/converter path, constraint-aware energy management, and safety-gated predictive supervision for industrial VSD ride-through. AI is optional and subordinate to deterministic protection. The analytical example indicates that losses, reserve margin, and stopping distance materially affect feasibility. Experimental and HIL evidence is required before claims about response time, accuracy, reliability, efficiency, cost, or industrial superiority can be made.

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