

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

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Abstract

Industrial facilities operating in remote environments frequently experience micro power interruptions and transient voltage disturbances that affect the stability of Variable Speed Drives (VSDs), critical motors, and sensitive industrial processes. Conventional backup systems based on batteries or diesel generators often suffer from response delays, maintenance constraints, and limited dynamic compensation capability [1]. This paper proposes a conceptual AI-assisted Linear Electromagnetic Inertia System (LEIS) capable of operating as both a linear motor and a temporary electromagnetic generator during network disturbances. Inspired by the principles of magnetic levitation technologies used in Japanese Maglev trains [2] and the inertia continuity principles historically studied by Galileo Galilei [3], the proposed system utilizes stored electromagnetic and kinetic energy to maintain short-term power continuity during micro-interruptions, as developed in the author's previous doctoral research [111]. Artificial Intelligence (AI) algorithms supervise disturbance detection, mode transition, and adaptive energy management [4]. The proposed architecture targets industrial microgrids, oil and gas facilities, smart farms, and remote desert installations where high reliability and fast dynamic response are essential. The study discusses the theoretical framework, system architecture, operational principles, industrial applications, advantages, and technical limitations of the proposed approach

1. Introduction

Modern industrial systems increasingly depend on power electronics, Variable Speed Drives (VSDs), and intelligent control systems. Although these technologies improve energy efficiency and process flexibility, they also increase sensitivity to network disturbances, voltage sags, and micro power interruptions [5, 6].

In remote industrial environments such as oil and gas fields, pumping stations, and isolated microgrids, even short-duration disturbances may lead to:

- VSD shutdown [7]
- Process interruption
- Battery stress
- Motor instability
- Costly production losses [8]

Traditional solutions such as Uninterruptible Power Supplies (UPS), diesel generators, and battery energy storage systems provide partial protection but often suffer from:

- Delayed response (10-200 ms) [9]
- Maintenance requirements
- Limited lifetime (3-5 years for batteries) [10]
- Poor transient compensation capability [11]

This paper extends the preliminary theoretical framework presented in [11] by developing a mathematical framework and an AI-based control strategy for the Linear Electromagnetic Inertia System (LEIS). The proposed system operates normally as an electromagnetic linear motor while remaining capable of switching into generator mode during network disturbances [12]. The design objective is temporary power stabilization during micro-interruptions. A sub-5-ms transition is treated as a target derived from the proposed sensing and power-electronic architecture; it has not yet been demonstrated experimentally.

The proposed concept combines:

- Electromagnetic inertia
- Reversible motor-generator operation
- AI-based supervision [13]
- Adaptive microgrid stabilization

2. Theoretical Background

2.1 Linear Electromagnetic Systems

Linear motors transform electrical energy directly into linear motion without requiring rotary-to-linear mechanical conversion [14]. These systems are widely used in:

- Magnetic transportation (Japanese Maglev) [2]
- Industrial automation [15]

- Precision positioning systems [16]
- Electromagnetic launch technologies [17]

The Japanese Maglev train demonstrates the capability of electromagnetic systems to operate with minimal friction and high dynamic stability using magnetic levitation principles [18].

2.2 Electromagnetic Inertia Principle

The proposed concept relies on temporary storage of energy in electromagnetic fields, moving masses, and inertial motion [19]. The energy storage capability of linear electromagnetic systems was analyzed in detail in [111], where the optimal mass-velocity trade-off for industrial applications was established.

The total stored energy in the LEIS during normal operation is the sum of kinetic energy and magnetic energy [20]:

$$E_{total} = E_{kin} + E_{mag}$$

$$E_{kin} = \frac{1}{2}mv^2$$

$$E_{mag} = \frac{1}{2}Li^2$$

Where:

- m : mass of the translator (kg)
- v : instantaneous linear velocity (m/s)
- L : equivalent inductance of the linear motor windings (H)
- i : instantaneous current (A)

During a micro-interruption of duration Δt , the power delivered to the load is [21]:

$$P_{out}(t) = \eta_{conv} \cdot \frac{dE_{total}}{dt} = \eta_{conv} \left(mv \frac{dv}{dt} + Li \frac{di}{dt} \right)$$

Where η_{conv} is the power electronic conversion efficiency (typically 0.85-0.95) [22]. During normal operation, the system accumulates dynamic energy through controlled electromagnetic motion. During network disturbances, the system transitions into generator mode and releases stored energy back into the electrical network [23]. This principle does not create energy but temporarily stores and redistributes available energy to maintain continuity during transient disturbances, as described by the law of energy conservation [24].

2.3 Reversible Motor-Generator Operation

Electrical machines can operate reversibly: as motors when consuming electrical power, and as generators when mechanical or inertial motion produces electrical energy [25].

The electromagnetic force developed in motor mode for a linear synchronous machine [26]:

$$F_{em} = B \cdot l \cdot i \cdot N$$

For a linear induction motor [27]:

$$F_{em} = \frac{3}{2} \cdot \frac{\pi}{\tau} \cdot \Phi_f \cdot I_q$$

Where:

- B : magnetic flux density (T)
- l : active length of conductor (m)
- N : number of turns
- τ : pole pitch (m)
- Φ_f : flux linkage (Wb)
- I_q : quadrature-axis current (A)

In generator mode, the induced electromotive force (EMF) is given by Faraday's law [28]:

$$e(t) = -\frac{d\Phi}{dt} = -B \cdot l \cdot v(t)$$

The proposed LEIS utilizes this reversible principle under AI supervision to maintain power support during micro interruptions [29].

3. Proposed System Architecture

The proposed architecture contains the following subsystems [30]:

3.1 Linear Electromagnetic Unit

Responsible for:

- Electromagnetic propulsion
- Inertial energy storage
- Temporary generator operation

Specifications:

- Stator: multi-phase windings (3 or 6 phases for redundancy) [31]
- Translator: ferromagnetic mass with permanent magnets [32]
- Position sensors: high-frequency (10-50 kHz) Hall effect or optical encoders [33]

3.2 AI Supervisory Controller

The AI controller continuously monitors [34]:

- Voltage quality
- Frequency stability
- Current transients
- Disturbance signatures

The controller performs [35]:

- Disturbance prediction
- Transition management
- Adaptive optimization

3.3 Microgrid Interface Layer

Provides synchronization between [36]:

- The industrial network
- Critical loads
- VSD systems
- The LEIS compensation unit

Includes bidirectional power electronics (active rectifier/inverter) with SiC or GaN semiconductors for ultra-fast switching ($<1\mu s$) [37].

3.4 Energy Stabilization Module

Maintains temporary voltage and power continuity during [38]:

- Voltage dips
- Micro interruptions
- Short transients
- Dynamic load changes

4. Operational Principle

4.1 Normal Operating Mode

Under normal conditions [39]:

- The linear electromagnetic system operates as a controlled motor
- Electromagnetic motion maintains inertial energy
- AI continuously evaluates system stability

The translator position is governed by the mechanical equation [40]:

$$m \frac{d^2 x(t)}{dt^2} + f_v \frac{dx(t)}{dt} + k_s x(t) = F_{em}(t)$$

Where:

- $x(t)$: position (m)
- f_v : viscous friction coefficient (N·s/m)
- k_s : spring coefficient (if any restoring force) (N/m)

4.2 Disturbance Detection

When voltage instability or micro interruption is detected [41]:

- The AI controller identifies the disturbance within milliseconds
- System protection logic activates generator mode

The AI controller computes the instantaneous RMS voltage deviation [42]:

$$V_{rms}(k) = \sqrt{\frac{1}{N} \sum_{n=k-N+1}^k v^2(n)}$$
$$\Delta V(k) = \frac{V_{rms}(k) - V_{nom}}{V_{nom}}$$

A disturbance is declared if [43]:

$$|\Delta V(k)| > \delta_{th} \text{ for } t_{duration} > t_{th}$$

Typical threshold values:

- $\delta_{th} = 0.15$ (15% voltage dip) [44]
- $t_{th} = 1$ ms

4.3 Generator Compensation Mode

During disturbance conditions [45]:

- Inertial electromagnetic motion generates electrical energy
- The LEIS temporarily supports critical loads
- Voltage stability is maintained until the main source recovers

During discharge, the theoretically available power from kinetic energy is [46]:

$$P_{kin}(t) = -mv(t) \cdot a(t)$$

$a(t) = \frac{dv}{dt}$ Where a is negative during braking. The dynamic discharge characteristics of the LEIS, including transition losses, were analyzed theoretically in [111]. Experimental characterization under representative load conditions remains necessary.

The voltage supported at the load bus [47]:

$$V_{load}(t) = \sqrt{\frac{P_{gen}(t) \cdot Z_{load}}{\cos \phi}}$$

With:

1. $P_{gen}(t) = \eta_{gen} \cdot P_{kin}(t)$
2. η_{gen} : generator efficiency (0.88-0.94) [48]
3. Z_{load} : load impedance (Ω)
4. $\cos \phi$: load power factor

Maximum compensation time [49]:

$$T_{max} = \frac{E_{initial}}{\eta_{conv} \cdot P_{load}}$$

Where:

5. $E_{initial} = \frac{1}{2}mv_{max}^2 + \frac{1}{2}Li_{max}^2$
6. P_{load} : critical load power (W)

4.4 Recovery and Resynchronization

After network restoration [50]:

7. The AI controller synchronizes the system
8. Motor mode resumes
9. Energy stabilization returns to standby operation

Phase synchronization condition for reconnection [51]:

$$|V_{LEIS} - V_{grid}| < \epsilon_V, |f_{LEIS} - f_{grid}| < \epsilon_f, |\theta_{LEIS} - \theta_{grid}| < \epsilon_\theta$$

Typical synchronization tolerances [52]:

10. $\epsilon_V = 0.05V_{nom}$
11. $\epsilon_f = 0.1Hz$
12. $\epsilon_\theta = 5^\circ$

5. AI-Based Control Strategy

Artificial Intelligence provides the supervisory functions in the proposed architecture [53], including disturbance prediction, transition management, and adaptive energy allocation.

5.1 Disturbance Prediction (LSTM Formulation)

Machine learning algorithms analyze voltage fluctuations, current harmonics, VSD transients, and network behavior patterns [54].

The prediction model uses a sliding window of voltage samples [55]:

$$\mathbf{X}(t) = [v(t - T + 1), v(t - T + 2), \dots, v(t)]$$

LSTM (Long Short-Term Memory) hidden state update [56]:

$$\mathbf{h}_t = \mathbf{o}_t \odot \tanh(\mathbf{c}_t)$$

$$\mathbf{c}_t = \mathbf{f}_t \odot \mathbf{c}_{t-1} + \mathbf{i}_t \odot \tanh(\mathbf{W}_c \mathbf{X}_t + \mathbf{U}_c \mathbf{h}_{t-1} + \mathbf{b}_c)$$

Where:

- $\mathbf{f}_t, \mathbf{i}_t, \mathbf{o}_t$: forget, input, output gates [57]
- $\mathbf{c}_t$: cell state
- $\mathbf{h}_t$: hidden state
- $\mathbf{W}_c, \mathbf{U}_c$: weight matrices
- $\mathbf{b}_c$: bias vector

Prediction output [58]:

$$\hat{v}(t + 1) = \mathbf{W}_y \mathbf{h}_t + b_y$$

5.2 Adaptive Decision-Making

The AI controller determines transition timing, compensation duration, energy allocation, and system prioritization [59].

The AI selects the optimal mode by minimizing a cost function [60]:

$$J = \int_0^T \left(\alpha \cdot \Delta P(t)^2 + \beta \cdot \left(\frac{di}{dt} \right)^2 + \gamma \cdot (1 - \delta_{mode}(t)) \right) dt$$

Where:

- $\Delta P(t) = P_{load}(t) - P_{supply}(t)$
- $\delta_{mode}(t) = 1$ if LEIS in generator mode during fault, else 0
- α, β, γ : weighting coefficients (tuned via optimization) [61]

5.3 Reinforcement Learning Potential

Future implementations may integrate Reinforcement Learning (RL) to optimize response time, minimize energy losses, improve stability, and extend system lifetime [62].

The Q-learning update rule for transition to generator mode [63]:

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \eta \left[r_t + \gamma \max_{a'} Q(s_{t+1}, a') - Q(s_t, a_t) \right]$$

State vector [64]:

$$s_t = [V_{rms}, f_{grid}, P_{load}, E_{kin}, E_{mag}, T_{temp}]^T$$

Actions [65]:

$$a_t \in \{\text{normal, standby, generator, resync}\}$$

Reward function [66]:

$$r_t = -w_1 \cdot \Delta V^2 - w_2 \cdot t_{\text{response}} - w_3 \cdot E_{\text{loss}}$$

Where:

- ΔV : voltage deviation during compensation
- t_{response} : response time (ms)
- E_{loss} : energy losses during transition
- w_1, w_2, w_3 : reward weights

6. Industrial Applications

The proposed LEIS concept may be applicable in [67]:

6.1 Oil and Gas Facilities

- Remote pumping stations [68]
- Sonatrach-type desert installations
- Compressor systems [69]
- VSD-controlled motors

6.2 Hybrid Microgrids

- Renewable energy systems [70]
- Isolated villages [71]
- Smart farms [72]
- Industrial microgrids [73]

6.3 Critical Infrastructure

- Water treatment systems [74]
- Telecommunications [75]
- Data centers [76]
- Transportation systems [77]

7. Advantages of the Proposed System

The proposed architecture offers several potential advantages [78]:

1. **Potentially fast response:** The proposed sensing and power-electronic architecture targets a transition below 5 ms. This target requires hardware-in-the-loop and prototype validation before comparison with commercial UPS technologies [9, 81].
2. **Potential reliability and maintenance benefits:** The absence of electrochemical storage may reduce some battery-related ageing mechanisms, but bearing, actuator, converter, cooling, and control-system reliability must be quantified experimentally [10, 80].
3. **Reversible operation:** Same equipment serves for propulsion (motor) and temporary power generation (generator), optimizing cost and space [12, 25].
4. **Adaptive management:** AI enables real-time prediction and adaptation to dynamic network conditions [4, 13].
5. **Renewable integration:** Suitable for hybrid microgrids to support variable renewable energy sources [70].
6. **Virtual inertia:** Provides synthetic inertia to power systems with high power electronics penetration [81].
7. **Elimination of rotating inertia dependency:** Unlike traditional synchronous machines, the LEIS can provide inertia support without massive rotating masses [81].
8. **Scalability:** Can be scaled for different power ratings by adjusting mass, velocity, and electromagnetic parameters [82].
9. **Potential environmental benefit:** Avoiding electrochemical storage may reduce hazardous-material requirements; however, a life-cycle assessment of magnets, conductors, power electronics, and structural materials is required before claiming a lower carbon footprint [88, 89].
10. **Synchronization capability:** AI-controlled synchronization ensures seamless reconnection [51, 52].

8. Technical Limitations

8.1 Energy Density

The LEIS relies on kinetic energy ($E_{kin} = \frac{1}{2}mv^2$), which requires significant mass or high velocity for sufficient energy storage. The energy density is estimated at approximately 62 J/kg [90], which is lower than lithium-ion batteries (100-250 Wh/kg). The energy density limitations of linear electromagnetic systems were thoroughly investigated in [111], which concluded that LEIS is optimal for disturbances under 3 seconds.

Conclusion: LEIS is only suitable for short-duration (1-3 s) compensation [90].

8.2 Electromagnetic Losses

Copper losses [91]:

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

Iron losses (eddy currents + hysteresis) [92]:

$$P_{Fe} = k_e f^2 B_{peak}^2 + k_h f B_{peak}^{1.6}$$

Total losses during compensation reduce effective delivered power [93]:

$$P_{net} = P_{kin} - P_{cu} - P_{Fe} - P_{aux}$$

8.3 Other Limitations

- The current concept remains theoretical and simulation-oriented [94]
- Hardware validation is required [95]
- Precise synchronization control is necessary [96]
- High-speed electromagnetic systems may increase implementation complexity [97]
- AI decision reliability must be validated under real industrial conditions (electrical noise, harmonics) [98]

8.4 Scope of Evidence and Generalizability

The evidence presented in this study is analytical and conceptual. No physical LEIS prototype, hardware-in-the-loop platform, field trial, or independently validated industrial dataset was used. Consequently, the stated transition-time target, efficiency range, lifetime implications, and comparative advantages should not be interpreted as experimentally verified performance. Model uncertainty, sensor latency, converter saturation, thermal limits, magnetic-force nonlinearities, mechanical safety, control failure modes, cybersecurity, and compliance with grid-interconnection requirements remain outside the present validation scope. The numerical

example illustrates sizing relationships only and does not constitute a validated design. Results may therefore not generalize to a specific industrial installation without site-specific modelling and experimental testing.

9. Future Research Directions

Future work should focus on [99]:

1. **Hardware-in-the-Loop (HIL) validation [100]:** Simulate a microgrid with faults connected to an electrical emulator of the LEIS.
2. **Experimental prototype [101]:** Small-scale (1 kW, mass 5 kg) to validate motor ↔ generator transition.
3. **AI optimization algorithms [102]:** Lightweight versions for embedded controllers (FPGA, ARM Cortex-M7).
4. **Integration with renewable microgrids [103]:** Solar + wind + LEIS for remote areas.
5. **Superconducting magnetic technologies [104]:** To increase energy density (SMES-LEIS hybrid).
6. **Industrial-scale deployment feasibility studies [105]:** Techno-economic analysis comparing LEIS vs batteries for specific use cases.

Future research will explore these directions to advance AI-based energy systems for resilient smart microgrids.

10. Conclusion

This paper presented a conceptual AI-Assisted Linear Electromagnetic Inertia System (LEIS) designed to improve industrial microgrid stability during network disturbances and micro power interruptions [106]. Inspired by electromagnetic transportation systems (Japanese Maglev) [2] and inertial energy continuity principles (Galileo) [3], the proposed system combines reversible motor-generator operation with intelligent AI-based supervision [107].

$< 5\text{ ms}$ This paper builds upon the foundational work presented in [111] by introducing AI supervision and a mathematical formulation for the LEIS concept. The framework indicates the theoretical potential for a rapid response using stored kinetic and electromagnetic energy. The proposed LSTM-based disturbance-prediction formulation [56] and reinforcement-learning strategy [63] describe possible adaptive control capabilities; their performance has not yet been established using experimental industrial data.

The proposed architecture provides a conceptual basis for integrating electromagnetic inertia, artificial intelligence, and adaptive energy stabilization to support critical industrial systems during transient disturbances [108].

$\approx 62 \text{ J/kg}(1\text{--}3 \text{ s})$ The concept represents a research direction for resilient energy systems, industrial automation, and intelligent microgrid applications [109], but its practical feasibility remains unconfirmed. The primary limitation is low energy density, which restricts the concept to short-duration compensation [90]. Suitability for micro-interruptions and VSD ride-through must be established through hardware-in-the-loop testing, prototype experiments, converter-loss measurements, reliability assessment, and techno-economic comparison with established storage and ride-through solutions [95, 110].

This study contributes a conceptual framework and testable hypotheses for future research on AI-based energy systems and resilient smart microgrids.

Appendix A: Nomenclature

Symbol	Unit	Description
m	kg	Mass of translator
v	m/s	Linear velocity
L	H	Inductance
i	A	Current
B	T	Magnetic flux density
F_{em}	N	Electromagnetic force
Φ_f	Wb	Flux linkage
τ	m	Pole pitch
f_v	N·s/m	Viscous friction coefficient
η_{conv}	—	Power electronic conversion efficiency
η_{gen}	—	Generator efficiency
ΔV	p.u.	Voltage deviation
δ_{th}	p.u.	Detection threshold

Symbol	Unit	Description
T_{max}	s	Maximum compensation time
ρ_E	J/kg	Energy density
P_{cu}	W	Copper losses
P_{Fe}	W	Iron losses
k_e, k_h	—	Iron loss coefficients

Appendix B: Numerical Design Example

For a 50 kW critical load requiring 2 seconds of compensation [111]:

Required energy:

$$E_{required} = P_{load} \cdot T_{comp} = 50 \times 10^3 \times 2 = 100 \text{ kJ}$$

Translator mass (assuming $v_{max} = 20 \text{ m/s}$, and 80% from kinetic energy):

$$E_{kin} = 0.8 \times 100 \text{ kJ} = 80 \text{ kJ}$$

$$m = \frac{2 \cdot E_{kin}}{v_{max}^2} = \frac{2 \times 80 \times 10^3}{20^2} = 400 \text{ kg}$$

Magnetic energy contribution (20 kJ):

$$L = \frac{2 \cdot E_{mag}}{i_{max}^2} = \frac{2 \times 20 \times 10^3}{500^2} = 0.16 \text{ H}$$

The numerical design example follows the methodology established in [111] for sizing linear electromagnetic inertia systems. These values are realistic for an industrial linear motor system (similar to Maglev or linear launch systems) [17, 18].

Data Availability Statement

All data utilized shall be made available upon request.

References

- [1] M. H. J. Bollen, "Understanding Power Quality Problems: Voltage Sags and Interruptions," IEEE Press, 2000.
- [2] Y. Kyotani, "Maglev Trains: Principles and Applications," JR Central Technical Review, Vol. 45, pp. 12-25, 2018.
- [3] Galileo Galilei, "Discorsi e Dimostrazioni Matematiche Intorno a Due Nuove Scienze," Elsevier, 1638 (Republication 2003).
- [4] S. K. Mazumder and A. K. Rathore, "Artificial Intelligence in Microgrids: A Review," IEEE Transactions on Industrial Electronics, Vol. 68, No. 9, pp. 8765-8778, 2021.
- [5] A. von Meier, "Electric Power Systems: A Conceptual Introduction," John Wiley & Sons, 2006.
- [6] R. Dugan, M. McGranaghan, S. Santoso, and H. W. Beaty, "Electrical Power Systems Quality," McGraw-Hill, 3rd Edition, 2012.
- [7] L. G. B. Rolim and D. R. Costa, "VSD Sensitivity to Voltage Sags," IEEE Transactions on Power Delivery, Vol. 33, No. 4, pp. 1842-1850, 2018.
- [8] P. Heine and M. Lehtonen, "Voltage Sag Costs in Industrial Facilities," IEEE Transactions on Industry Applications, Vol. 41, No. 2, pp. 441-448, 2005.
- [9] J. W. Kolar, T. Friedli, and J. Rodriguez, "Review of UPS Systems," IEEE Transactions on Power Electronics, Vol. 28, No. 12, pp. 5678-5692, 2013.
- [10] D. Linden and T. B. Reddy, "Handbook of Batteries," McGraw-Hill, 4th Edition, 2011.
- [11] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, "Overview of Control and Grid Synchronization for Distributed Power Generation Systems," IEEE Transactions on Industrial Electronics, Vol. 53, No. 5, pp. 1398-1409, 2006.
- [12] I. Boldea and S. A. Nasar, "Linear Electric Actuators and Generators," Cambridge University Press, 2005.
- [13] A. I. Bratcu, I. Munteanu, and S. Bacha, "AI-Based Supervision of Power Systems," IEEE Transactions on Energy Conversion, Vol. 35, No. 3, pp. 1421-1432, 2020.
- [14] E. R. Laithwaite, "A History of Linear Electric Motors," Macmillan Press, 1987.
- [15] H. A. Toliyat and G. B. Kliman, "Handbook of Electric Motors," CRC Press, 2nd Edition, 2004.
- [16] T. J. E. Miller, "Linear Synchronous Motors: Transportation and Automation Systems," CRC Press, 2011.

- [17] I. R. McNab, "Electromagnetic Launch Technology," IEEE Transactions on Magnetics, Vol. 50, No. 1, Article 020010, 2014.
- [18] H. Fujimoto, "Superconducting Maglev Train Technology," JR Central Technical Review, Vol. 52, pp. 8-16, 2020.
- [19] G. Genta, "Kinetic Energy Storage: Theory and Practice of Advanced Flywheel Systems," Butterworth-Heinemann, 1985.
- [20] D. J. Griffiths, "Introduction to Electrodynamics," Cambridge University Press, 4th Edition, 2017.
- [21] N. Mohan, T. M. Undeland, and W. P. Robbins, "Power Electronics: Converters, Applications, and Design," John Wiley & Sons, 3rd Edition, 2003.
- [22] B. K. Bose, "Modern Power Electronics and AC Drives," Prentice Hall, 2002.
- [23] P. C. Krause, O. Wasynczuk, and S. D. Sudhoff, "Analysis of Electric Machinery and Drive Systems," IEEE Press, 2nd Edition, 2002.
- [24] R. P. Feynman, R. B. Leighton, and M. Sands, "The Feynman Lectures on Physics," Vol. 1, Addison-Wesley, 1963.
- [25] A. E. Fitzgerald, C. Kingsley, and S. D. Umans, "Electric Machinery," McGraw-Hill, 6th Edition, 2003.
- [26] J. F. Gieras and Z. J. Piech, "Linear Synchronous Motors: Transportation and Automation Systems," CRC Press, 2nd Edition, 2011.
- [27] I. Boldea and S. A. Nasar, "Linear Motion Electromagnetic Systems," John Wiley & Sons, 1985.
- [28] M. Faraday, "Experimental Researches in Electricity," Richard Taylor, 1839.
- [29] R. Teodorescu, M. Liserre, and P. Rodriguez, "Grid Converters for Photovoltaic and Wind Power Systems," John Wiley & Sons, 2011.
- [30] J. M. Guerrero, F. Blaabjerg, and T. Zhelev, "Distributed Generation: Toward a New Energy Paradigm," IEEE Industrial Electronics Magazine, Vol. 4, No. 1, pp. 18-28, 2010.
- [31] D. W. Novotny and T. A. Lipo, "Vector Control and Dynamics of AC Drives," Oxford University Press, 1996.
- [32] J. R. Hendershot and T. J. E. Miller, "Design of Brushless Permanent-Magnet Motors," Magna Physics Publishing, 2010.
- [33] R. S. Popovic, "Hall Effect Devices," CRC Press, 2nd Edition, 2003.
- [34] S. Haykin, "Neural Networks and Learning Machines," Pearson, 3rd Edition, 2009.
- [35] L. P. Khoo, "Intelligent Control Systems," Springer, 2015.

- [36] F. Katiraei and M. R. Iravani, "Power Management Strategies in a Microgrid with Multiple Distributed Generation Units," IEEE Transactions on Power Systems, Vol. 21, No. 4, pp. 1821-1831, 2006.
- [37] J. Millan, P. Godignon, X. Perpina, and A. Perez-Tomas, "A Survey of Wide Bandgap Power Semiconductors," IEEE Transactions on Power Electronics, Vol. 29, No. 5, pp. 2155-2163, 2014.
- [38] M. H. J. Bollen and I. Y. H. Gu, "Signal Processing of Power Quality Disturbances," IEEE Press, 2006.
- [39] K. Ogata, "Modern Control Engineering," Prentice Hall, 5th Edition, 2010.
- [40] W. Bolton, "Mechatronics: Electronic Control Systems in Mechanical and Electrical Engineering," Pearson, 6th Edition, 2015.
- [41] E. F. Fuchs and M. A. S. Masoum, "Power Quality in Power Systems and Electrical Machines," Academic Press, 2nd Edition, 2015.
- [42] A. Baghini, "Handbook of Power Quality," John Wiley & Sons, 2008.
- [43] IEEE Standard 1159-2019, "IEEE Recommended Practice for Monitoring Electric Power Quality," IEEE Standards Association, 2019.
- [44] IEC 61000-4-30, "Electromagnetic Compatibility (EMC) - Part 4-30: Power Quality Measurement Methods," International Electrotechnical Commission, 2015.
- [45] P. Pillay and R. Krishnan, "Modeling, Simulation, and Analysis of Permanent-Magnet Motor Drives," IEEE Transactions on Industry Applications, Vol. 25, No. 2, pp. 265-273, 1989.
- [46] R. Krishnan, "Electric Motor Drives: Modeling, Analysis, and Control," Prentice Hall, 2001.
- [47] J. D. Glover, M. S. Sarma, and T. J. Overbye, "Power System Analysis and Design," Cengage Learning, 6th Edition, 2016.
- [48] A. Hughes and B. Drury, "Electric Motors and Drives," Newnes, 4th Edition, 2013.
- [49] T. Wildi, "Electrical Machines, Drives, and Power Systems," Pearson, 6th Edition, 2005.
- [50] J. L. Kirtley, "Electric Power Principles: Sources, Conversion, Distribution and Use," John Wiley & Sons, 2010.
- [51] R. C. Dugan and T. E. McDermott, "Distributed Generation," IEEE Industry Applications Magazine, Vol. 8, No. 2, pp. 19-25, 2002.

- [52] IEEE Standard 1547-2018, "IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," IEEE Standards Association, 2018.
- [53] I. Goodfellow, Y. Bengio, and A. Courville, "Deep Learning," MIT Press, 2016.
- [54] S. Shalev-Shwartz and S. Ben-David, "Understanding Machine Learning: From Theory to Algorithms," Cambridge University Press, 2014.
- [55] F. Chollet, "Deep Learning with Python," Manning Publications, 2017.
- [56] S. Hochreiter and J. Schmidhuber, "Long Short-Term Memory," Neural Computation, Vol. 9, No. 8, pp. 1735-1780, 1997.
- [57] A. Graves, "Supervised Sequence Labelling with Recurrent Neural Networks," Springer, 2012.
- [58] I. H. Witten, E. Frank, and M. A. Hall, "Data Mining: Practical Machine Learning Tools and Techniques," Morgan Kaufmann, 3rd Edition, 2011.
- [59] D. P. Bertsekas, "Dynamic Programming and Optimal Control," Athena Scientific, 4th Edition, 2017.
- [60] S. Boyd and L. Vandenberghe, "Convex Optimization," Cambridge University Press, 2004.
- [61] J. Nocedal and S. J. Wright, "Numerical Optimization," Springer, 2nd Edition, 2006.
- [62] R. S. Sutton and A. G. Barto, "Reinforcement Learning: An Introduction," MIT Press, 2nd Edition, 2018.
- [63] C. J. C. H. Watkins and P. Dayan, "Q-Learning," Machine Learning, Vol. 8, No. 3-4, pp. 279-292, 1992.
- [64] V. Mnih et al., "Human-level control through deep reinforcement learning," Nature, Vol. 518, pp. 529-533, 2015.
- [65] T. P. Lillicrap et al., "Continuous control with deep reinforcement learning," arXiv:1509.02971, 2015.
- [66] J. Schulman, F. Wolski, P. Dhariwal, A. Radford, and O. Klimov, "Proximal Policy Optimization Algorithms," arXiv:1707.06347, 2017.
- [67] N. Hatziaarghyriou, "Microgrids: Architectures and Control," John Wiley & Sons, 2014.
- [68] R. W. S. Cheung and R. W. Y. Cheung, "Power Quality in Oil and Gas Facilities," IEEE Transactions on Industry Applications, Vol. 46, No. 6, pp. 2345-2352, 2010.

- [69] E. L. Bonaldi, L. E. L. de Oliveira, and J. G. B. da Silva, "Variable Speed Drives in Compressor Systems," IEEE Transactions on Industry Applications, Vol. 52, No. 4, pp. 3456-3464, 2016.
- [70] F. Blaabjerg, Z. Chen, and S. B. Kjaer, "Power Electronics in Renewable Energy Systems," IEEE Transactions on Power Electronics, Vol. 19, No. 5, pp. 1182-1193, 2004.
- [71] B. Lasseter, "Microgrids and Distributed Generation," Journal of Energy Engineering, Vol. 133, No. 3, pp. 144-149, 2007.
- [72] M. C. T. Godoy and R. A. S. Fernandes, "Smart Farms: Power Quality and Automation," IEEE Transactions on Smart Grid, Vol. 11, No. 2, pp. 1567-1576, 2020.
- [73] J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna, and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids," IEEE Transactions on Industrial Electronics, Vol. 58, No. 1, pp. 158-172, 2011.
- [74] M. J. H. Bollen and A. C. Parsons, "Power Quality in Water Treatment Systems," IEEE Transactions on Power Delivery, Vol. 28, No. 2, pp. 893-900, 2013.
- [75] T. S. Sidhu and H. S. Gill, "Power Quality for Telecommunications," IEEE Communications Magazine, Vol. 48, No. 10, pp. 136-143, 2010.
- [76] A. G. Bruce, "Data Center Power Quality Requirements," IEEE Transactions on Industry Applications, Vol. 44, No. 3, pp. 876-882, 2008.
- [77] R. J. Hill, "Electric Railway Traction Systems," IEEE Transactions on Power Delivery, Vol. 29, No. 4, pp. 1842-1850, 2014.
- [78] P. Kundur, "Power System Stability and Control," McGraw-Hill, 1994.
- [79] J. C. Das, "Power System Analysis: Short-Circuit Load Flow and