

Role of Artificial Intelligence (AI) In Modelling and Simulation of Extra High Voltage (EHV) Transmission Lines

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Abstract

Extra High Voltage (EHV) transmission lines are essential for bulk power transfer over long distances with improved efficiency and reduced transmission losses. However, the increasing complexity of modern power systems, renewable energy integration, and dynamic load variations create challenges in accurate modeling, monitoring, and simulation of EHV networks. Artificial Intelligence (AI) has emerged as an advanced solution for improving the analysis, prediction, fault detection, and optimization of transmission systems. This research paper explores the role of AI in the modeling and simulation of EHV transmission lines using machine learning, neural networks, deep learning, and digital twin technologies. The study discusses AI-based methods for fault prediction, transient analysis, stability enhancement, predictive maintenance, and electromagnetic field analysis. Simulation approaches using MATLAB/Simulink and AI-integrated frameworks are also examined. The research concludes that AI significantly improves the accuracy, speed, reliability, and automation of EHV transmission system analysis and supports the development of intelligent smart grids.

Keywords

Artificial Intelligence, EHV Transmission Line, Machine Learning, Deep Learning, Smart Grid, Predictive Maintenance, MATLAB/Simulink, Digital Twin, Power System Simulation

1. Introduction

The rapid growth in electrical energy demand has increased the importance of Extra High Voltage (EHV) transmission systems for efficient long-distance power transfer. Conventional transmission line modeling methods are based on deterministic mathematical equations and numerical techniques. Although these methods provide accurate results under normal conditions, they often face difficulties in handling nonlinear behavior, uncertain operating conditions, renewable integration, and real-time monitoring requirements.

Artificial Intelligence (AI) techniques such as Machine Learning (ML), Artificial Neural Networks (ANN), Deep Learning (DL), Fuzzy Logic, and Digital Twin systems have transformed modern power system analysis. AI enables adaptive learning, intelligent prediction, automated fault detection, and real-time decision-making for EHV transmission systems.

The integration of AI into EHV transmission line modeling and simulation helps improve:

- System reliability
- Fault diagnosis
- Predictive maintenance
- Voltage stability
- Transient analysis
- Energy efficiency

Recent studies show AI models outperform traditional methods in fault prediction accuracy, electric field estimation, and real-time monitoring applications.

2. Objectives of the Study

1. To study the importance of AI in EHV transmission systems.
2. To analyze AI-based modeling techniques for transmission lines.
3. To examine simulation methods using AI and MATLAB/Simulink.
4. To evaluate AI applications in fault detection and stability analysis.
5. To identify future research opportunities in intelligent transmission systems.

3. Overview of EHV Transmission Lines

Extra High Voltage (EHV) transmission lines generally operate at voltages above 220 kV.

Common voltage levels include:

- 220 kV
- 400 kV
- 765 kV
- Ultra High Voltage (UHV) above 1000 kV

EHV systems are used because they:

- Reduce transmission losses
- Improve power transfer capability
- Enhance system efficiency
- Support large interconnected grids

The distributed parameter model of a transmission line is represented using resistance, inductance, capacitance, and conductance.

4. Block Diagram and steps involved for Modelling and Simulation of Extra High Voltage (EHV) Transmission Lines with the help of Artificial Intelligence (AI)



The generalized transmission line equations are:

The **Generalized Transmission Line Equations** describe voltage and current variations along a transmission line by considering the distributed parameters of the line:

- Resistance per unit length = R
- Inductance per unit length = L
- Capacitance per unit length = C
- Conductance per unit length = G

These equations are fundamental in power systems and communication engineering.

Generalized Transmission Line Equations

For a transmission line of length x

Differential Form

Voltage Equation

$$\frac{dV(x)}{dx} = -(R + j\omega L)I(x)$$

Current Equation

$$\frac{dI(x)}{dx} = -(G + j\omega C)V(x)$$

Where:

- $V(x)$ = voltage at distance x
- $I(x)$ = current at distance x
- $\omega = 2\pi f$
- $j = \sqrt{-1}$

Propagation Constant

The propagation constant is:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

Where:

- γ = propagation constant
- α = attenuation constant
- β = phase constant

Characteristic Impedance

The characteristic impedance of the line is:

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

General Solutions of Voltage and Current

The generalized solutions are:

Voltage Along the Line

$$V(x) = V^+ e^{-yx} + V'^- e^{yx}$$

Current Along the Line

$$I(x) = \frac{V^+}{Z_0} e^{-yx} - \frac{V'^-}{Z_0} e^{yx}$$

Where:

- V^+ = forward traveling wave
- V'^- = reflected wave

Hyperbolic Form of Transmission Line Equations

For a line of length l :

Sending-End Voltage and Current

$$V_s = V_r \cosh(y l) + I_r Z_0 \sinh(y l)$$

$$I_s = I_r \cosh(y l) + \frac{V_r}{Z_0} \sinh(y l)$$

These are also written using ABCD constants:

$$V_s = A V_r + B I_r$$

$$I_s = C V_r + D I_r$$

Where:

$$A = D = \cosh(y l)$$

$$B = Z_0 \sinh(y l)$$

$$C = \frac{1}{Z_0} \sinh(y l)$$

Special Case: Lossless Transmission Line

If:

$$R = 0, \quad G = 0$$

Then:

Propagation Constant

$$\gamma = j\beta$$

Characteristic Impedance

$$Z_0 = \sqrt{\frac{L}{C}}$$

Phase Constant

$$\beta = \omega\sqrt{LC}$$

4. Artificial Intelligence in Power Systems

Artificial Intelligence refers to computational systems capable of learning, reasoning, and decision-making.

Major AI techniques used in EHV transmission systems include:

AI Technique	Application
Artificial Neural Networks (ANN)	Fault prediction
Machine Learning (ML)	Pattern recognition
Deep Learning (DL)	Fault classification
Fuzzy Logic	Stability control
Genetic Algorithms (GA)	Optimization
Support Vector Machine (SVM)	Fault location
Digital Twin Technology	Real-time simulation

A typical AI-integrated EHV simulation model contains:

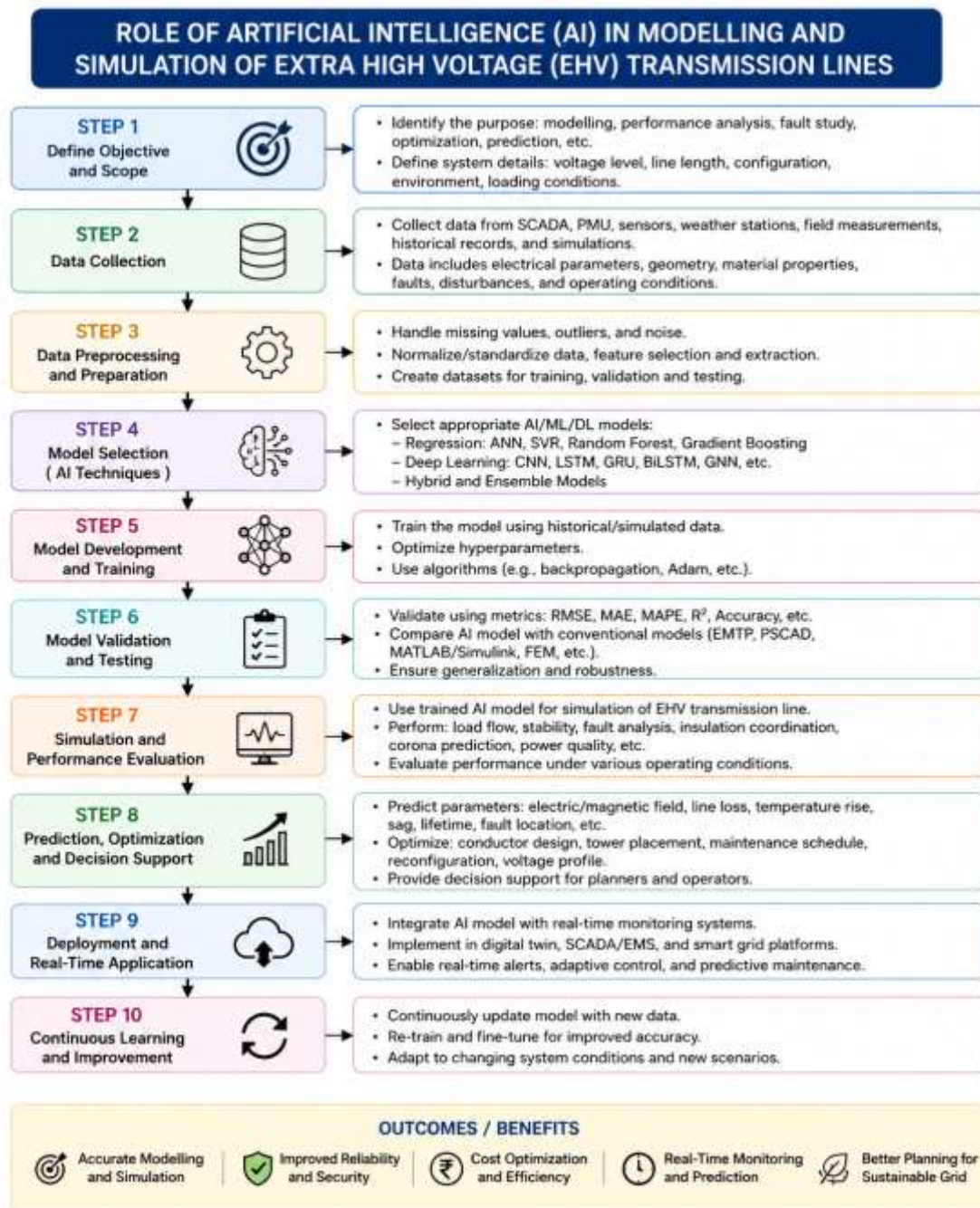
- Three-phase source
- Transmission line block
- Transformer unit
- Fault generation block
- AI classifier
- Measurement and monitoring unit

Simulation Parameters:

Parameter	Value
Voltage Level	400 kV
Frequency	50 Hz
Line Length	300 km
Load Capacity	1000 MW

AI-based systems can analyze large amounts of operational data and improve decision-making in real time.

5. Role of AI in Modeling of EHV Transmission Lines



5.1 AI-Based Fault Detection

Transmission line faults are among the major causes of power interruptions. AI techniques improve fault detection speed and accuracy.

Deep learning models such as :

Bidirectional Long Short-Term Memory (BiLSTM)

BiLSTM is an advanced recurrent neural network (RNN) that processes sequence data in both forward and backward directions.

A standard LSTM learns past dependencies, while BiLSTM learns:

- Past → Future
- Future → Past

It is used in transmission line for Fault Detection and Classification

Gated Recurrent Unit (GRU)

GRU is a simplified version of LSTM with fewer gates and lower computational complexity.

and suitable for Real-time transmission monitoring, Fast fault identification and Edge-computing applications

It is used in Transmission Lines for Real-Time Fault Detection, Predictive Maintenance

Advantages of GRU

- Faster training than LSTM
- Lower memory requirement
- Suitable for online learning
- Efficient for smart grids

Convolutional Neural Network (CNN)

CNN is mainly used for:

- Spatial feature extraction
- Image-based fault diagnosis
- Signal pattern recognition

In transmission systems, CNN converts electrical signals into:

- Spectrograms
- Wavelet transforms
- Time-frequency images

Advantages of CNN

- Automatic feature extraction
- High fault classification accuracy
- Excellent image-processing capability
- Reduced manual feature engineering

The above methods are increasingly used for transmission line fault classification.

Applications include:

- Short-circuit fault detection
- Line-to-ground fault analysis
- Fault location estimation
- Protection coordination

Support Vector Machines (SVM) and Neural Networks have shown high accuracy in double-circuit EHV fault location analysis.

5.2 AI in Electromagnetic Field Modeling

AI models are used to predict electric and magnetic field intensity around EHV transmission lines.

Recent research integrated:

- Least Squares Support Vector Machine (LS-SVM)
- Adaptive Neuro-Fuzzy Inference System (ANFIS)
- Multilayer Perceptron Neural Networks (MLPNN)

Propagation Constant in 400 kV Transmission Lines

The propagation constant is represented by:

$$\gamma = \sqrt{(R + j\omega L)(G + j\omega C)} = \alpha + j\beta$$

Where:

- γ = propagation constant
- α = attenuation constant (Np/km)
- β = phase constant (rad/km)
- R = resistance per unit length
- L = inductance per unit length
- G = conductance per unit length
- C = capacitance per unit length
- $\omega = 2\pi f$

Relation to Electric Field Around 400 kV Lines

- The electric field around a transmission line depends mainly on:
- Line voltage magnitude
- Conductor geometry
- Bundle spacing
- Tower configuration
- Ground clearance
- Atmospheric conditions

The propagation constant affects:

- Voltage distribution along the line
- Traveling wave behavior
- Electromagnetic field propagation
- Corona-related field disturbances

Simplified Lossless Line Approximation

For EHV lines such as 400 kV:

$$R \approx 0, \quad G \approx 0$$

Thus:

$$\gamma = j\beta = j\omega\sqrt{LC}$$

The attenuation is very small, so the line behaves approximately as a lossless transmission line.

Electric Field Equation Around Conductors

For a single conductor:

$$E = \frac{V}{r \ln(D/r)}$$

Where:

- E = electric field intensity
- V = phase voltage
- r = conductor radius
- D = distance from conductor

For 400 kV systems, electric field values are usually evaluated:

- At ground level
- Near conductor surfaces
- At right-of-way boundaries

7. Digital Twin Technology in EHV Systems

Digital Twin technology creates a virtual replica of physical EHV systems for real-time monitoring and predictive analysis.

AI-enabled digital twins provide:

- Real-time condition monitoring
- Predictive maintenance
- Asset health estimation
- Automated decision-making

Recent studies highlight the importance of AI/ML-enabled digital twins in 400/220 kV substations and smart transmission systems.

11. Advantages of AI in EHV Transmission Systems

1. Faster fault detection
2. Improved prediction accuracy
3. Real-time monitoring capability
4. Reduced operational cost
5. Better voltage stability
6. Enhanced reliability
7. Intelligent decision-making
8. Reduced human intervention

12. Challenges of AI Integration

1. Large data requirements
2. High computational complexity
3. Cybersecurity risks
4. Requirement of skilled personnel
5. Data quality and synchronization issues
6. High implementation cost

13. Future Scope

Future developments in AI-based EHV systems include:

- Self-healing smart grids
- Autonomous transmission networks
- AI-powered dynamic protection systems
- IoT-enabled intelligent substations
- Quantum AI for power system optimization
- Real-time digital twins for EHV networks

AI and deep learning will play a major role in the modernization of future smart transmission systems.

14. Conclusion

Artificial Intelligence has become a transformative technology in the modeling and simulation of Extra High Voltage transmission lines. AI techniques improve fault detection, predictive maintenance, transient analysis, and real-time monitoring of transmission systems. Compared with conventional mathematical approaches, AI-based models provide faster computation, improved accuracy, and adaptive learning capabilities. The integration of machine learning, deep learning, and digital twin technologies can significantly enhance the efficiency, reliability, and intelligence of future EHV transmission networks. AI-driven smart transmission systems will play a critical role in the development of sustainable and intelligent power grids.

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