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Hybrid AI Models for Enhanced Harmonic Source Localization in Renewable-Dominated Microgrids

Harshwardhan Sachin Pande[1], Rupalee S. Ambekar[2], Rajesh M. Holmukhe[3]

[1,2,3]Department of Electrical Engineering, Bharati Vidyapeeth (Deemed to be University) College of Engineering
Pune, Maharashtra, India

[1]harshwardhanpande2001@gmail.com, [2]rsambekar@bvucoep.edu.in, [3]rmholmukhe@bvucoep.edu.in

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Abstract

This paper proposes a hybrid artificial intelligence framework that combines Graph Neural Networks (GNNs) and Transformer architectures for harmonic source localization in renewable-dominated microgrids. The proposed method utilizes spatial information derived from network topology along with temporal harmonic measurements to improve detection accuracy. Simulation scenarios based on a modified IEEE 34-bus microgrid demonstrate the effectiveness of the proposed approach under different operating conditions including grid-connected and islanded modes.

Keywords: Graph Neural Networks; Transformer Architecture; Harmonic Source Localization; Renewable-Dominated Microgrids; Power Quality Analysis; Artificial Intelligence.

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Introduction

For The rapid integration of renewable energy technologies such as solar photovoltaic systems, wind turbines, and battery energy storage systems has significantly transformed modern power systems.

Microgrids provide an effective solution for integrating distributed energy resources while enhancing system resilience and reliability.

However, renewable energy systems are typically interfaced through power electronic converters, which introduce nonlinear characteristics into the electrical network. These nonlinearities generate harmonic distortions, which propagate through the system and degrade power quality. High harmonic levels can result in overheating of electrical equipment, interference with protection devices, increased power losses, and voltage waveform distortion.

Traditional harmonic analysis techniques rely on impedance-based calculations and signal processing approaches. While effective for small systems, these techniques become less reliable in complex microgrids with high renewable penetration and varying operating conditions.

Recent developments in artificial intelligence (AI) have provided powerful tools for analysing complex electrical networks. In particular, deep learning techniques such as Graph Neural Networks (GNNs) and Transformer models can effectively capture spatial and temporal dependencies in power system data.

Problem Formulation

First In renewable-dominated microgrids, harmonic voltages and currents may originate from multiple inverter-based sources such as photovoltaic inverters, wind turbine converters, and battery storage systems. These harmonics propagate through the network, making it difficult to determine the original source location.

Let the harmonic voltage magnitude at bus i for harmonic order h be denoted as $V_{i,h}$.

The Total Harmonic Distortion (THD) at a bus is defined as:

$$THD = \frac{\sqrt{\sum_{h=2}^{H} V_h^2}}{V_1}$$

where:
V_1= fundamental voltage magnitude
V_h= voltage magnitude of the hth harmonic component
H= highest harmonic order considered

Accurate harmonic source localization requires the analysis of both:

- Network topology
- Time-varying harmonic measurements

This motivates the development of a hybrid AI-based framework capable of learning both spatial and temporal relationships in microgrid data.

Proposed Hybrid AI Framework

The proposed approach integrates spatial learning using Graph Neural Networks with temporal sequence modelling using Transformer architectures.

Graph-Based Spatial Feature Extraction

The microgrid network is represented as a graph structure where:

- Nodes represent buses in the microgrid
- Edges represent electrical connections
- Node features include harmonic voltage and current measurements

Graph Neural Networks learn spatial dependencies between buses and capture harmonic propagation patterns across the network.

Transformer-Based Temporal Modelling

Harmonic signals exhibit significant temporal variation due to changes in load demand and renewable generation.

Transformer models employ self-attention mechanisms to capture long-range dependencies in sequential data. By processing time-series harmonic measurements, the Transformer module extracts temporal features associated with harmonic behaviour.

Hybrid Model Integration

The outputs of the GNN and Transformer modules are combined to perform harmonic source localization.

The overall process includes:

1. Graph representation of microgrid topology
2. Extraction of harmonic voltage and current features
3. Spatial feature learning using Graph Neural Networks
4. Temporal modelling using Transformer networks
5. Final harmonic source localization

Model Architecture

The hybrid architecture is designed to support scalable and practical deployment in microgrid monitoring systems.

Key features include:

- Integration of spatial and temporal learning modules
- Capability to detect multiple harmonic sources
- Robust operation under grid-connected and islanded modes
- Adaptability to varying renewable penetration levels

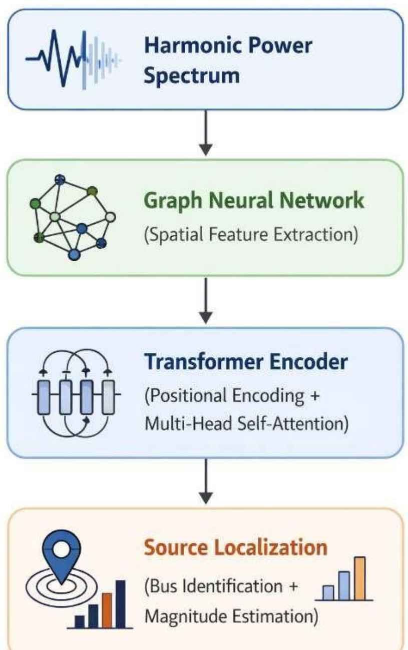

Fig. 1 *Illustrates the proposed hybrid GNN–Transformer architecture for harmonic source localization.*

Simulation Setup

Indicate The proposed framework is validated using a modified IEEE 34-bus microgrid test system.

Simulation studies are conducted to evaluate the performance of the model under different operating conditions.

Table 1. *Parameters Used for Simulation Studies*

Parameter	Description
Test System	Modified IEEE 34-bus microgrid
Operating Modes	Grid-connected and islanded
Renewable Penetration	Up to 40%

Harmonic Orders	3rd to 25th
Harmonic Sources	Multiple inverter-based sources
Simulation Tools	ETAP and MATLAB

These scenarios evaluate the ability of the model to accurately identify harmonic source locations under varying load and renewable generation conditions.

Results and Discussion

The proposed hybrid framework improves harmonic source localization by combining spatial and temporal analysis.

The Graph Neural Network module captures network topology and harmonic propagation paths, while the Transformer module effectively models temporal variations in harmonic signals.

Compared with conventional machine learning methods, the hybrid model demonstrates:

- Improved localization accuracy
- Better adaptability to varying operating conditions
- Scalability for larger microgrid systems

These results highlight the potential of hybrid AI techniques for advanced power quality monitoring in renewable-dominated power systems.

Conclusion

All This paper presented a hybrid artificial intelligence framework combining Graph Neural Networks and Transformer architectures for harmonic source localization in renewable-dominated microgrids.

By integrating spatial network topology with temporal harmonic signal analysis, the proposed method significantly improves the accuracy and reliability of harmonic source detection.

Simulation studies based on a modified IEEE 34-bus microgrid demonstrate the effectiveness of the proposed framework under different operating conditions. Future work will focus on real-time implementation and integration with harmonic mitigation techniques such as active power filtering and adaptive inverter control.

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