

BLACKOUT IN THE ELECTRICAL GRID CAUSED BY FLUCTUATIONS OF RENEWABLE ENERGY –CASE STUDY

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Abstract

The rapid integration of renewable energy sources into modern electrical power systems has created new operational challenges for transmission system operators worldwide. Renewable energy sources such as solar and wind power are inherently intermittent and weather-dependent, causing fluctuations in power generation that can significantly affect grid stability. In weak or developing transmission systems, sudden variations in renewable energy production may lead to voltage instability, frequency deviations, power oscillations, and ultimately large-scale blackout events. This paper investigates the impact of renewable energy fluctuations on the electrical grid of North Macedonia, with a particular focus on the role of the transmission system operator, MEPSO. The study analyzes the operational challenges faced by MEPSO during periods of high renewable energy penetration and examines the partial blackout event that occurred on 18 May 2025. The research evaluates the relationship between high photovoltaic generation, low system demand, overvoltage conditions, and transmission instability within the Macedonian power network. According to investigations conducted by ENTSO-E, unusually high voltages in the transmission system contributed to the separation of the 400 kV and 110 kV networks, resulting in the loss of approximately 79% of the country's electrical load. The paper further discusses the technical limitations of traditional transmission infrastructure when integrating large quantities of variable renewable energy sources. Particular attention is given to insufficient reactive power compensation, lack of energy storage systems, reduced system inertia, and inadequate flexibility mechanisms. The study also reviews preventive measures adopted by MEPSO, including temporary disconnection of photovoltaic plants during periods of low demand and excessive solar generation.

Key words: [Keywords]infrastructure.

Introduction

The global transition toward clean and sustainable energy systems has significantly increased the integration of renewable energy sources into national electrical grids. Countries worldwide are investing heavily in solar photovoltaic (PV) systems, wind farms, and other renewable technologies to reduce greenhouse gas emissions and dependence on fossil fuels. However, unlike conventional thermal or hydroelectric power plants, renewable energy sources are characterized by intermittent and variable generation patterns that depend on weather conditions and environmental factors.

This variability introduces serious technical challenges for electrical grid operators responsible for maintaining stable voltage levels, frequency balance, and continuous electricity supply. Rapid fluctuations in renewable energy generation can disturb the equilibrium between production and consumption, causing overloads, instability, and cascading failures across interconnected transmission systems.

North Macedonia has experienced rapid growth in renewable energy investments in recent years, particularly in photovoltaic power plants connected to the transmission and distribution networks. MEPSO, as the national transmission system operator, plays a crucial role in maintaining the stability and reliability of the country's electrical grid. According to MEPSO, more than 80 applications for renewable energy connections totalling approximately 9,000 MW have been submitted, representing a major transformation of the national power system. Despite the environmental and economic benefits of renewable energy, the increased penetration of variable generation has exposed weaknesses in the existing transmission infrastructure. The partial blackout event of May 2025 demonstrated how excessive voltage

levels and insufficient grid flexibility can threaten system stability under conditions of low demand and high renewable generation.

This paper investigates the causes and consequences of blackout events associated with renewable energy fluctuations in North Macedonia and evaluates possible technical and operational solutions for improving grid resilience.

Renewable Energy and Grid Stability

and hydroelectric plants provide rotational inertia that stabilizes grid frequency during disturbances. In contrast, solar PV systems are connected through power electronic converters that contribute little or no natural inertia to the system.

The increasing penetration of renewable energy can therefore create several technical problems:

- Voltage fluctuations

- Frequency instability

- Reduced system inertia

- Reverse power flows

- Transmission congestion

- Reactive power imbalance

- Difficulty in maintaining reserve margins

In North Macedonia, periods of low electricity demand combined with high solar generation create conditions where excess electricity cannot be adequately absorbed by the grid. These situations are especially critical during spring and holiday periods when consumption decreases but solar production remains high.

Modern transmission systems require advanced balancing mechanisms to maintain operational security under these changing conditions.

Overview of the Macedonian Transmission System

The transmission system of North Macedonia forms part of the Continental European interconnected electrical network. The system is operated by MEPSO and consists primarily of:

- 400 kV transmission lines

- 110 kV regional transmission network

- Interconnection lines with neighbouring countries

- High-voltage substations and transformers

- National dispatch and control centre's

The 400 kV network serves as the backbone of the transmission system and provides interconnection with neighbouring Balkan countries. The 110 kV network distributes electricity to regional substations and end consumers throughout the country.

Historically, the system was designed around centralized thermal and hydroelectric generation. However, increasing renewable energy penetration has significantly altered power flow patterns and voltage regulation requirements.

Renewable energy technologies differ fundamentally from conventional synchronous generators. Traditional thermal

The system has recently experienced periods of elevated voltage caused by low electricity demand combined with high reactive power generation from transmission lines and renewable energy sources. According to the ENTSO-E investigation, similar overvoltage conditions had been observed repeatedly before the blackout event

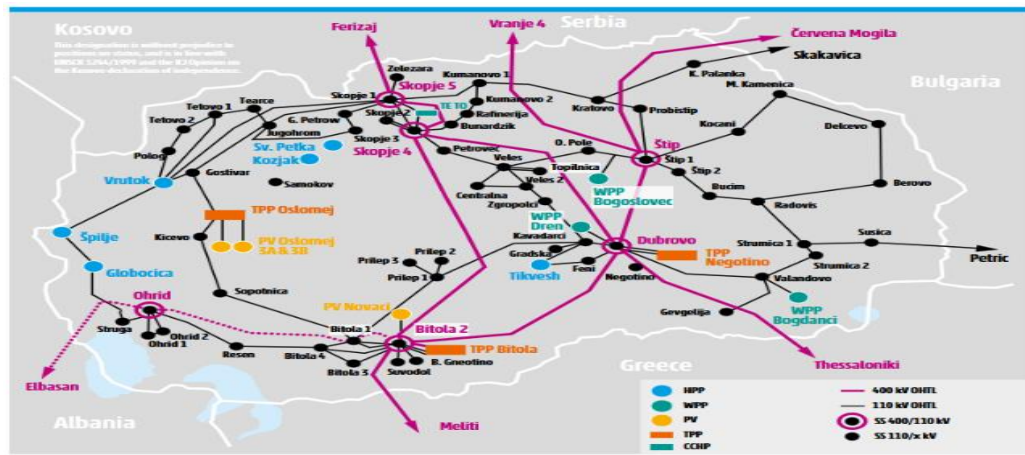


Figure 1 Topology of the transmission system of North Macedonia

Historically, the system was designed around centralized thermal generation and predictable demand patterns. However, the rapid growth of distributed renewable energy generation has introduced operational conditions that were not fully considered in the original network design. According to MEPSO reports, maintaining voltage stability has become increasingly challenging due to variable renewable production and changing electricity flow patterns.

Case Study: The 18 May 2025 Blackout

On 18 May 2025, North Macedonia experienced a significant disturbance in its electrical transmission system that resulted in a large-scale blackout affecting most consumers connected to the 110 kV network.

According to the investigation conducted by ENTSO-E, unusually high voltages were observed in the Macedonian transmission network before the event occurred. The overvoltage condition eventually caused the separation of the 400 kV and 110 kV transmission levels.

The blackout caused:

- Loss of approximately 79% of national electricity load

- Collapse of the entire 110 kV transmission network

- Interruption of industrial and residential electricity supply

- Regional operational instability

- Emergency restoration procedures by MEPSO

The restoration process lasted less than three hours, during which MEPSO operators gradually re-energized substations and restored synchronization with the European interconnected system.

The incident highlighted several important vulnerabilities:

- Excessive voltage caused by low demand and high renewable generation

- Limited reactive power compensation capabilities

- Insufficient flexibility resources

- Lack of large-scale battery storage systems

- Aging transmission infrastructure

- Reduced system inertia due to inverter-based generation

Chronology of the Blackout Event

5.1 System Conditions before the Blackout: During the early morning hours of 18 May 2025, the electrical system was operating under low-load conditions typical for spring weekends. Electricity demand was significantly reduced, while reactive power generation in the transmission network remained high.

The ENTSO-E investigation identified persistent overvoltage conditions in the 400 kV network prior to the disturbance. Voltages exceeded acceptable operational limits and approached dangerous levels above 420 kV.

The transmission system was already operating close to stability limits due to:

Low electricity consumption

Excess reactive power

Weak voltage control capability

Limited transformer regulation margins

High voltage conditions across multiple substations

5.2 Initial Transformer Trips: According to the ENTSO-E factual report, several 400/110 kV transformers experienced automatic disconnection due to activation of overvoltage protection systems. Transformer trips occurred at major substations including:

Bitola 2

Skopje 5

Initial transformer disconnections occurred around 02:26 CEST and were followed by repeated unsuccessful reconnection attempts. Additional transformer trips occurred at 02:59 and 03:34 as overvoltage conditions persisted.

These transformer outages weakened the connection between the 400 kV and 110 kV systems and reduced the capability of the network to maintain stable voltage conditions.

5.3 Network Separation and Collapse: At approximately 04:59 CEST, the electrical system experienced complete separation between the 400 kV transmission network and the 110 kV network. This separation caused immediate instability within the 110 kV system and resulted in widespread loss of supply.

The blackout affected nearly the entire 110 kV network, leading to:

Loss of approximately 79% of national load

Interruption of electricity supply to consumers

Shutdown of industrial facilities

Temporary loss of regional power system stability

Despite the collapse of the 110 kV network, the 400 kV transmission backbone remained operational throughout the incident.

Technical Causes of the Blackout

6.1 Overvoltage in the 400 kV System: The primary technical cause of the blackout was excessive voltage within the 400 kV transmission network. According to the ENTSO-E final report, the system operated above the defined voltage limit of 420 kV.

Overvoltage conditions were intensified by:

Low active power demand

High reactive power generation from transmission lines

Insufficient reactive power compensation

Limited voltage control resources

Reduced loading of transmission corridors

Long high-voltage transmission lines naturally generate reactive power under light-load conditions. When system demand is low, this reactive power cannot be sufficiently absorbed, causing voltage to rise throughout the network.

6.2 Reactive Power Imbalance: Reactive power management is essential for maintaining stable voltage profiles in transmission systems. In the North Macedonian network, reactive power absorption capability was insufficient during the event.

Factors contributing to reactive power imbalance included:

- Lack of sufficient shunt reactors

- Limited transformer tap adjustment capability

- Insufficient dynamic voltage control devices

- Increased contribution from inverter-based generation

The inability to absorb excess reactive power allowed voltage levels to increase continuously until protective systems activated.

6.3 Reduced System Inertia: Modern renewable energy sources connected through power electronic converters provide significantly less mechanical inertia compared to conventional synchronous generators.

Reduced inertia decreases the system's capability to resist rapid disturbances and maintain stable operation during abnormal conditions.

The blackout highlighted how modern power systems with increasing renewable penetration become more sensitive to:

- Voltage oscillations

- Frequency deviations

- Dynamic instability

- Cascading protection operations

6.4 Protection System Operation Restoration Process: The overvoltage protection systems installed on 400/110 kV transformers operated correctly according to their design parameters. However, repeated transformer disconnections progressively weakened the connection between transmission voltage levels.

Once all major transformers disconnected simultaneously, the 110 kV system lost stability and collapsed.

Immediately after the blackout, operators from MEPSO initiated emergency restoration procedures.

The restoration strategy included:

- Stabilization of the 400 kV network

- Gradual re-energisation of substations

- Controlled synchronization of transmission corridors

- Sequential restoration of consumer load

- Coordination with neighboring transmission operators

According to ENTSO-E, the restoration process was completed by 07:47 CEST, less than three hours after the blackout occurred.

The rapid restoration demonstrated effective emergency response procedures and coordination capabilities within MEPSO's control centres.

Impact of the Blackout

The blackout produced significant technical and economic consequences throughout North Macedonia.

which includes among others

Collapse of the entire 110 kV network

Loss of approximately 485 MW of load

Interruption of generation units

Temporary suspension of balancing markets

Increased operational risk in neighboring systems

Industrial production interruptions

Commercial activity disruption

Financial losses for businesses

Emergency operational costs

Increased balancing energy expenses

Although the rest of the Continental European power system remained stable, neighboring countries experienced elevated voltage conditions and increased operational alert levels during the event.

7.1. Lessons Learned

The blackout revealed several important weaknesses in the North Macedonian transmission system.

Modern transmission systems require advanced reactive power compensation devices such as:

Shunt reactors

STATCOM systems

SVC compensators

Dynamic voltage regulators

Regarding Renewable energy integration they must be accompanied by:

Grid modernization

Energy storage deployment

Synthetic inertia capability

Grid-forming inverter technology

Improved coordination between Southeast European transmission system operators is necessary to manage regional voltage stability under changing operating conditions.

Aging infrastructure must be upgraded to support modern operational requirements and renewable energy integration.

Recommendations

To reduce the probability of future blackout events, the following measures are recommended:

Installation of additional reactive power compensation equipment

Deployment of large-scale battery energy storage systems

Improvement of voltage monitoring and forecasting systems

Strengthening of transformer protection coordination

Expansion of regional operational cooperation

Implementation of smart grid technologies

Increased operational flexibility during low-load periods

Improved renewable generation forecasting

The ENTSO-E final report also recommended establishment of a coordinated action plan for the Southeast European region to mitigate high-voltage operating conditions.

Conclusion

The blackout that occurred in the North Macedonian power system on 18 May 2025 represents a significant example of the operational challenges facing modern electrical grids during the energy transition process.

The event was primarily caused by uncontrolled overvoltage in the 400 kV transmission network under low-load operating conditions. The resulting transformer protection operations caused separation of the 400 kV and 110 kV systems and led to collapse of the national 110 kV network.

The incident demonstrated that modern power systems require substantial modernization to ensure stable operation under conditions of increasing renewable energy penetration and reduced conventional generation.

Although the blackout exposed vulnerabilities in voltage control and system flexibility, the rapid restoration carried out by MEPSO demonstrated effective emergency response capability and operational professionalism.

Future prevention of similar incidents will require coordinated investments in smart grid technologies, reactive power compensation systems, energy storage, and advanced voltage management strategies across the Southeast European region.

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