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GLOBAL IMPACT OF ELECTRICAL GRID CODES: CASE STUDY OF IMPLEMENTATION AND RESULTS IN DIFFERENT COUNTRIES

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Abstract: At the National Technological Institute of Mexico, Veracruz Campus, in the Electrical Engineering program, the subject "Introduction to the Grid Code" is taught in the 9th semester. This course provides electrical engineers with the ability to apply the knowledge acquired throughout their studies on electrical power systems, legislation, industrial installations, and electrical distribution networks to solve technical and economic problems in the electrical industry. See Figure 1 Likewise, the general objective of this course is to understand and analyze the regulations associated with the Grid Code in order to diagnose and solve problems of non-compliance with it. Based on the above, this study, entitled "Global impact of electrical grid codes: Case study of implementation and results in different countries," has been conducted as a contribution to this subject. Grid (electricity) codes have been established as essential regulatory frameworks to ensure the stability, reliability, and efficiency of electricity systems worldwide. From Mexico and other Latin American countries, as well as the major European and Asian powers, these codes have evolved to respond to the challenges of energy transition, the integration of renewable energies, and the digitization of grids. This article analyzes the implementation of grid codes in different regions, their impact on energy efficiency and sustainability, the challenges of international harmonization, examples of penalties imposed on companies for non-compliance, and the future prospects for regulation.

Keywords — Network Code, Energy regulation, Renewable energies, ENTSO-E, CRE, FERC, Network integration, Sanctions.

Introduction

Modern electrical systems face rapid growth in energy demand and the integration of non-conventional energy sources, which has made it necessary to create technical regulatory frameworks known as Grid Codes. These documents specify the guidelines for connection, operation, and safety that ensure a reliable and stable electricity supply, avoiding power failures and all the problems that they entail [1], [2].

In Mexico, the Grid Code published by the Energy Regulatory Commission (CRE) in 2016 was a watershed moment in the technical regulation of the national electricity system [1]. In the European Union, the Network Codes developed by ENTSO-E have sought regulatory harmonization to promote cross-border operation [3]. In recent years, cybersecurity provisions have even been incorporated to protect critical infrastructure [4], [5].

Nombre de la asignatura:	**Introducción al Código de Red**
Clave de la Asignatura:	**AIS – 2006**
SATCA[1]:	**5 – 0 – 5**
Carrera:	**Ingeniería Eléctrica**

Figure 1.- Heading of the subject Introduction to the Grid Code

In recent decades, sustained growth in electricity demand, diversification of generation sources—especially renewables—and the need to improve the reliability of electricity systems have driven the development and implementation of network codes globally. These technical regulatory frameworks establish the minimum requirements that participants in the electricity sector—generators, transmitters, distributors, and large consumers—must meet to ensure the efficient, safe, and coordinated operation of the electricity system. Far from being simple technical regulations, grid codes are now a key tool for energy transformation, contributing both to the modernization of infrastructure and the sustainability of electricity systems.

Interest in thoroughly understanding these instruments has grown not only in industry but also in academia. In this context, the course "Introduction to the Grid Code," taught in the 9th semester of the Engineering program at TecNM Campus Veracruz, plays an essential role in the training of future electrical engineers. This course provides students with a comprehensive overview of the structure, objectives, and requirements of the Mexican Grid Code, while familiarizing them with the technical and regulatory challenges associated with its implementation. Through the analysis of real cases, simulations, and current regulations, the professional profile of graduates is strengthened so that they can actively participate in the development and operation of modern, resilient electrical systems that are aligned with international standards.

This article aims to analyze the global impact of grid codes, considering implementation experiences in different countries, their compliance mechanisms, effects on the efficiency and sustainability of electrical systems, and emerging challenges in the face of grid digitization. Through case studies, it seeks to identify best practices, lessons learned, and opportunities for im-

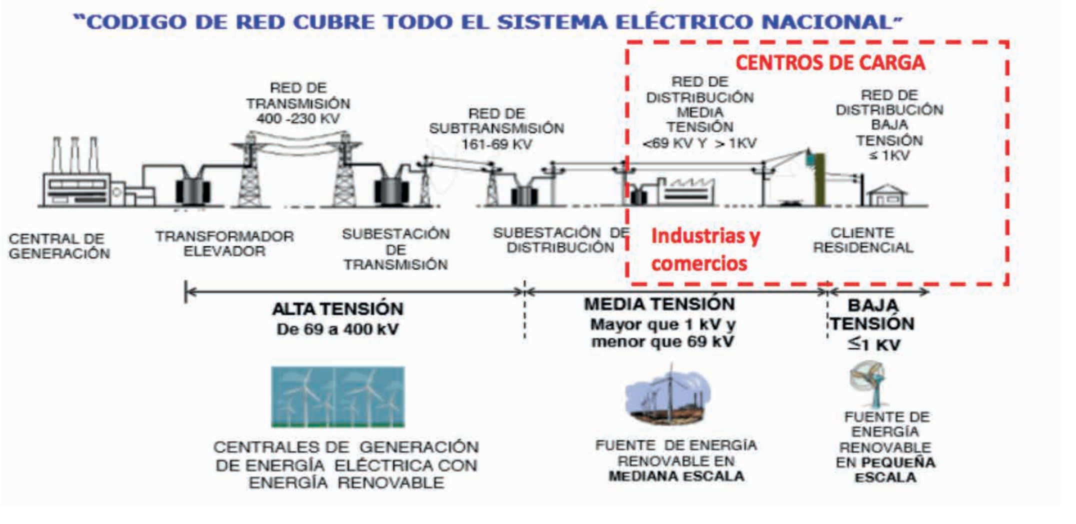

Figure 2.- Global Implementation of Grid Codes

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provement that can enrich both the technical debate and academic training in this key area for the future of energy.

Global Implementation of Grid Codes

The first generation of Grid Codes emerged with the aim of standardizing the technical requirements for interconnection in generation, transmission, and distribution [3]. In countries such as Germany, these codes require renewable plants to provide ancillary services such as frequency control and reactive power [6]. In the United States, the Federal Energy Regulatory Commission (FERC) has issued orders such as 841 and 2222 to integrate energy storage and distributed resources [7].

In China, the State Grid Corporation (SGCC) has developed guidelines that prioritize digitization and ultra-high voltage (UHV) transmission as the backbone for the massive integration of renewables [8].

Technological Adaptations and Renewables

The documents have been updated to incorporate requirements related to:

- Voltage and frequency control.
- Fault Ride-Through capability.
- Reactive power ancillary services.

These measures enable the efficient integration of intermittent sources such as solar and wind power [6], [7].

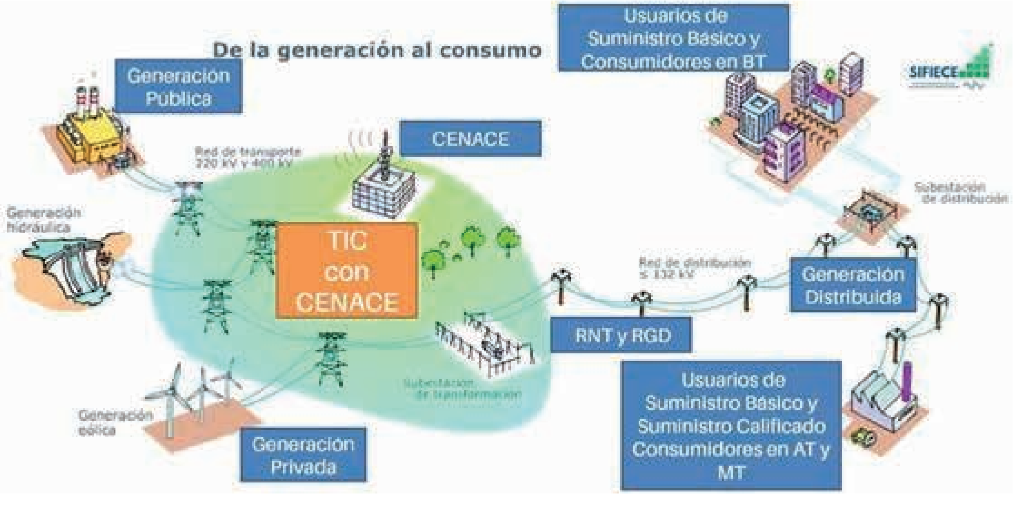

Figure 3.- The grid code and safety standards, their impact on the national electricity system

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Challenges in International Harmonization

The standardization of codes faces technical obstacles (heterogeneous infrastructures, differences in frequency and voltage levels), economic obstacles (unequal investment capacity), and geopolitical obstacles (energy sovereignty) [9]. A notable case occurred in 2021, when a failure in the interconnection between Kosovo and Serbia caused a frequency deviation in the European grid, affecting digital clocks in 25 countries and highlighting the need for greater coordination [11].

Sanctions and Compliance Regime

The application of sanctions has been a determining factor in ensuring compliance with network codes. In Mexico, in 2019, the CRE imposed fines of up to 2.4 million pesos on companies for failing to comply with the established technical criteria [1], [2]. In Spain, Red Eléctrica de España (REE) and the CNMC have sanctioned generators for failing to provide frequency control services, with fines reaching €5 million in 2018 [13]. In the United States, FERC fined Constellation Energy $135 million in 2012 for failing to comply with rules related to the operation of the electricity market [7]. These cases show that sanctions are not only intended to punish, but also to foster a culture of technical and regulatory compliance.

Case Studies

Mexico: Network Code 2.0 (2021) reinforced SEN efficiency and stability requirements [2].

European Union: The Network Code on Requirements for Generators (RfG) and the new Cybersecurity Grid Code (2024) seek to standardize criteria [3], [4].

China: Investments in UHV transmission and digitization through the SGCC [8].

United States: FERC regulations on DER and storage [7].

India: The CEA introduced codes requiring voltage and frequency control to meet renewable integration targets [10].

Impacts on Efficiency and Sustainability

Grid codes have helped reduce electricity losses by incorporating efficiency standards, promoting sustainability, and driving more integrated electricity markets [6], [7], [9]. According to the World Bank, countries that have adopted grid codes have managed to reduce technical and non-technical losses by an average of 3% to 5% over the last decade [12]. In India, for example, transmission and distribution losses were reduced from 26.4% in 2001 to 19.05% in 2019 following the implementation of regulatory and technical improvements [10]. In Latin America, average electricity losses fell from 17% in 1990 to 12% in 2020, supported by regulatory reforms and code enforcement [12]. These data show that grid codes not only strengthen stability but also generate direct economic benefits.

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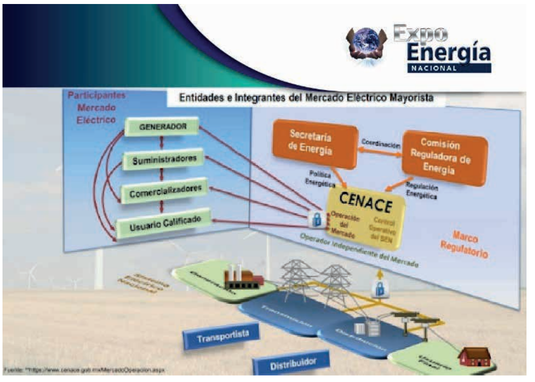

Figure 4.- Impacts on Efficiency and Sustainability

https://expoenergia.com.mx/blog/energia/calidad-de-la-energia-y-el-codigo-de-red-en-mexico--claves-para-el-cumplimiento-y-la-eficiencia/

Future Challenges and Digitization

Future updates will focus on:

- International harmonization of standards.
- Digitization with IoT, artificial intelligence, and blockchain [9].
- Cybersecurity in critical energy systems [4], [5].

Figure 5.- Future Challenges and Digitization

https://www.ift.org.mx/transformacion-digital?page=7

Conclusions

Electricity network codes have become established as fundamental instruments for ensuring the security, stability, and efficiency of the electricity system in different countries. Their implementation allows technical operation to be harmonized with regulatory and energy policy objectives.

Although the technical principles of grid codes tend to be similar internationally, their effective implementation depends on local factors such as the structure of the electricity system, the degree of penetration of renewable energies, and the institutional maturity of each country. The cases studied show that there is no single model for application, but there are good practices that can be adapted between regions.

Among the main challenges faced by countries are resistance to change on the part of industry players, the need for investment in infrastructure, and the difficulty of supervision and enforcement. This suggests the need to accompany network codes with training policies, incentives, and clear regulatory frameworks.

In countries where robust implementation has been achieved, network codes have contributed to improved service quality, reduced losses, more efficient integration of renewable sources, and greater competitiveness in electricity markets. This demonstrates their potential as a tool for energy transformation.

The progressive convergence of technical standards and the exchange of experiences between countries can accelerate the global energy transition. It is recommended to strengthen regional collaboration spaces (such as forums for network operators or regulators) and promote minimum international standards that guarantee interoperability and best practices.

Finally, network codes are a key element in the global energy transition. Their evolution has made it possible to integrate high percentages of renewable energy, improve reliability, and prepare electricity systems for the challenges of digitalization and cybersecurity. The future points toward their global harmonization, driven by multilateral initiatives such as those of ENTSO--E and IRENA.

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