SMART MATERIALS IN ELECTRICAL ENGINEERING. MATHEMATICAL MODELS, SIMULATIONS AND APPLICATIONS

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Abstract: This paper presents a detailed analysis of smart materials used in electrical engineering, with an emphasis on theoretical foundations, mathematical models, finite element method (FEM) numerical simulations, and industrial applications. Piezoelectric, magnetostrictive materials, and shape memory alloys are analyzed, and their advantages and limitations are discussed in comparison with conventional electromechanical systems. The results demonstrate the high potential of smart materials in modern conversion, control, and automation systems.

Keywords: smart materials, piezoelectric materials, magnetostrictive materials, FEM, electrical engineering

1. INTRODUCTION

Smart materials [1] represent a class of functional materials capable of modifying their properties in response to external stimuli such as electric and magnetic fields, temperature variations, or mechanical loads. Smart materials are also referred to as intelligent functional materials.

In electrical engineering [11], these materials enable the development of adaptive systems with high energy density, superior precision, and advanced functional integration. Compared to classical solutions, smart materials allow miniaturization and direct control of energy conversion processes.

Smart materials—also referred to as sensory, adaptive, metamorphic, multifunctional, or intelligent materials—are the result of collaboration between specialists in materials science, mechanical engineering, and civil engineering [2], [12], [18]. They can combine actuator and sensor functions within the same structure. One of the most effective methods for obtaining smart materials is particle assemblage, achieved either by attachment or by integration of active elements into a unified structure [25].

The simplest smart material structure consists of a sensor, an actuator, and a feedback amplifier. A mechanical coupling between the sensor and actuator may or may

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not exist; however, the coupled configuration is more effective because sensing and actuation occur at the same location [13], [21], [27].

The concept of smart materials originates from intelligent forms found in natural systems, namely living organisms. Consequently, smart materials are designed to perform natural functions such as sensing, actuation, control, and intelligence. Smart or intelligent materials have the ability to self-adapt to external stimuli, and their functions respond intelligently to changes in the surrounding environment [15], [20], [26].

2. CLASSIFICATION OF SMART MATERIALS

Smart materials [3] can be classified according to the type of stimulus they respond to and the type of physical response generated. The most commonly used smart materials in electrical engineering are piezoelectric materials, magnetostrictive materials, shape memory alloys, and electroactive polymers [5] [14], [24].

2.1. Piezoelectric Materials

Piezoelectric materials (such as quartz, lead zirconate titanate, ceramic materials, and piezoelectric polymers) [3] [4] generate an electric voltage when subjected to mechanical stress and, conversely, deform when exposed to an electric field.

Their main applications in electrical engineering include pressure, force, acceleration, and vibration sensors, signal generators, micro- and nano-positioning actuators, and vibration-based energy harvesting systems [16].

2.2. Electrostrictive and Magnetostrictive Materials

Electrostrictive materials exhibit deformation proportional to the square of the applied electric field and are used in applications requiring precise and stable displacement. Magnetostrictive materials exhibit spontaneous polarization and allow switching through the application of an external electric field [17], [23].

These materials are used in variable-capacitance capacitors, non-volatile memory devices, and high-precision actuators.

2.3. Shape Memory Alloys (SMA)

Shape memory materials rely on martensite–austenite phase transformations induced thermally or electrically. Applying an electric current, heats the material, causing it to return to its memorized shape. They are mainly nickel–titanium (Nitinol) or copper–zinc–aluminium alloys and are used in thermal relays, intelligent switches, and actuation elements in automated systems [19].

2.4. Smart Semiconductor Materials

Modern semiconductors can be considered smart materials due to their ability to respond to electrical, optical, or thermal stimuli.

Their main applications include temperature and light sensors, power devices (IGBT, MOSFET), control and protection circuits, and smart electrical grids.

2.5. Electrochromic Materials

Electrochromic materials change their color or transparency when subjected to an electric field.

They are used in smart displays, electrochromic windows, and status indicators in electrical equipment.

3. THEORETICAL FOUNDATIONS AND MATHEMATICAL MODELS

The behaviour of smart materials is described by coupled constitutive equations that correlate electrical, mechanical, magnetic, and thermal fields. For piezoelectric materials, linear relationships are widely used during the design phase, whereas for SMAs and magnetostrictive materials, nonlinear temperature-dependent models are required [6], [8], [22].

The mathematical models presented are generally linear or quasi-linear. In real applications, nonlinearities, hysteresis effects, and temperature- and frequency-dependent behaviour are present. Advanced modelling therefore requires numerical methods such as the finite element method (FEM) and multiphysics simulations.

3.1. Mathematical Modelling of Piezoelectric Materials

Piezoelectric constitutive equations enable bidirectional mechanical–electrical energy conversion and are essential in the design of precision transducers and actuators.

The linear behaviour of piezoelectric materials is described by the constitutive equations:

$$\begin{cases} S = s^e T + dE \\ D = dT + \varepsilon E \end{cases} \tag{1}$$

where:

S – mechanical strain vector

T – mechanical stress tensor

E – electric field intensity

D – electric displacement

s^e – elastic compliance matrix

d – piezoelectric coefficient

ε – dielectric permittivity

3.2. Modeling of Magnetostrictive Materials

Magnetostrictive strain is described by:

$$\lambda = \frac{\Delta L}{L} = k \cdot M^2 \quad (2)$$

where:

ε – relative strain

M – magnetization

k – magnetostrictive constant

The magnetic field and mechanical force are coupled through Maxwell's equations and mechanical equilibrium relationships.

3.3. Shape Memory Alloys (SMA) – Thermomechanical Model

The phase transformation is described by the martensite fraction ξ:

$$\varepsilon = \varepsilon_0 + \xi \cdot \varepsilon_L \quad (4)$$

The constitutive behaviour can be expressed in simplified form as:

$$\varepsilon = \varepsilon_0 + \xi \cdot \varepsilon_L \quad (4)$$

where:

ε_L – maximum recoverable strain

T – temperature

σ – m

echanical stress

3.4. Smart Semiconductor Materials in Electrical Engineering

The electrical conductivity of semiconductors depends on temperature and electric field:

$$\sigma(T) = q(n\mu_n + p\mu_p) \quad (5)$$

where:

q – elementary charge

n – concentration of free electrons

p – concentration of holes

μ_n – electron mobility

μ_p – hole mobility

4. FEM NUMERICAL SIMULATIONS

The finite element method (FEM) [10] is the primary numerical analysis tool for smart materials due to its ability to handle multiphysics problems. FEM simulations allow evaluation of electric, magnetic, and mechanical field distributions, as well as optimization of geometry and control parameters.

For piezoelectric actuators, simulations include electrostatic equations and mechanical equilibrium relations, while for SMAs, heat transfer equations are also incorporated. These simulations are essential for predicting dynamic behaviour and durability.

Figure 1 presents the result of a numerical simulation for a piezoelectric actuator, highlighting the near-linear relationship between applied voltage and mechanical displacement.

Figure 2 illustrates the behaviour of an actuator made from a shape memory alloy (NiTi), where deformation depends on temperature due to the martensite–austenite phase transformation.

Observations: These simulations are representative of the preliminary design phase. In real applications, models are extended using multiphysics FEM methods that include nonlinearities, hysteresis, and thermal effects.

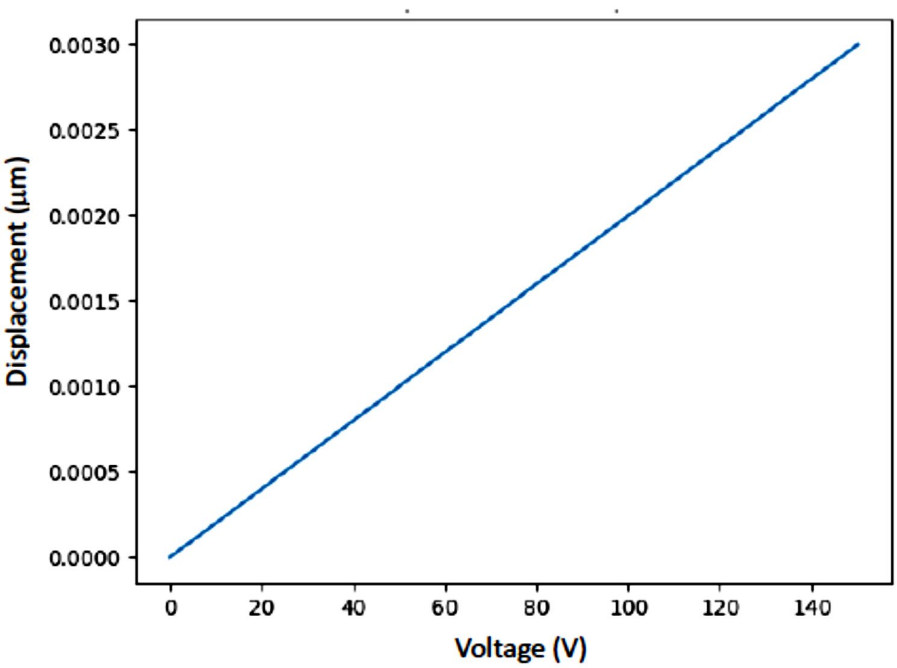

Fig.1. Piezoelectric actuator simulation – displacement versus applied voltage

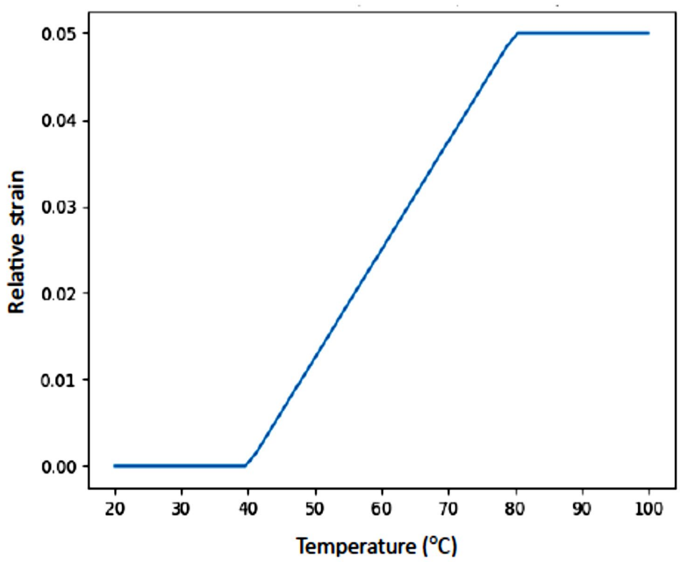

Fig.2. SMA actuator simulation – relative strain versus temperature (martensite–austenite transformation)

5. EXAMPLES OF INDUSTRIAL APPLICATIONS

Shape memory alloys are frequently used to build compact actuators and intelligent relays, demonstrating good reliability for applications with moderate duty cycles. [7]

5.1 Piezoelectric Micro-Positioning Actuators

A relevant industrial example is the use of piezoelectric actuators in micro-positioning systems for the semiconductor industry, where nanometric resolutions are achieved [9].

The miniaturization of positioning systems in semiconductor manufacturing and optics has driven the adoption of piezoelectric actuators. Linear mathematical models provide quick displacement estimates, while FEM simulations are mandatory for nonlinear analysis at high frequencies or complex electromechanical effects.

Piezoelectric actuators powered at 100–150 V provide micrometer-scale displacements with sub-1 μm accuracy in open-loop control, outperforming classical micrometric screw systems due to higher energy density and faster response.

5.2 Magnetostrictive Actuators for Vibration Control

Linear actuators based on the magnetostrictive material Terfenol-D are used in active vibration control systems for electrical turbines and generators. Although their mechanical performance is inferior to conventional hydraulic actuators, this is compensated by rapid response and direct integration with electrical systems.

Despite higher costs, their fast response and electrical integration justify their use.

6. CONCLUSIONS

This paper highlights the strategic role of smart materials in modern electrical engineering. Through mathematical modeling and FEM simulations, these materials can be effectively integrated into advanced industrial applications, contributing to the development of high-performance and energy-efficient systems.

The integration of smart materials in electrical engineering opens significant perspectives for efficient and adaptive systems. Future research focuses on multifunctional materials and advanced simulation methods.

Compared to conventional electromechanical systems, smart materials offer significant advantages such as miniaturization, high response speed, and direct integration with electrical control systems. These features are critical in applications where space and precision are essential.

However, limitations include high material costs, nonlinear behavior, temperature dependence, and the need for advanced control algorithms. In high-power applications, conventional solutions often remain more robust and cost-effective.

Current research directions focus on multifunctional materials, integration of smart materials with artificial intelligence systems, and the extension of FEM simulations toward fully multiphysics and multiscale models.

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