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Enhancing PV Stations for Charging Electric Vehicles by Utilizing Shape Memory Alloy to Track the Sun and Decrease Fatigue

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Abstract: Integrating PV systems in large commercial areas for electric vehicle charging offers a comprehensive and strategic approach to sustainable business practices. This integration aligns economic, environmental, and social benefits, potentially reducing operational costs and boosting the overall brand image. In the pursuit of improving these types of structures, the use of shape memory alloy (SMA) emerges can be an ideal smart material. These materials can strengthen the structure as a damper and improve energy collection in PV system as mechanical tracker. This study is focused on developing a new smart actuator design that can be used as a sun tracker and mechanical damper in photovoltaic stations for commercial buildings. The proposed SMA actuator can significantly move in response to solar irradiation and can reduce fatigue by stabilizing mechanical stress during bad weather. In order to integrate the proposed actuator with the PV station in response to temperature and stress variation, a mathematical model has been developed. The study seeks to capture the thermo-mechanical behavior, including both superelasticity and the shape memory effect. The findings indicate that incorporating the SMA actuator in the PV station improves energy production efficiency by 19%, decreases vibrations by 85%, and contributes to the station's longevity. These technologies collectively offer environmental, economic, and operational benefits, making it a valuable component in the optimization of solar energy systems.

Keywords: Shape memory alloys, SMA actuator, Sun tracker SMA damper, Fatigue, PV station, commercial building.

1. Introduction

The synergy of technological advances and the need for sustainable and renewable energy sources conducted to a significant increase in the incorporation of Photovoltaic (PV) systems into various public, commercial, and industrial infrastructures. In this era, PV stations have evolved into versatile powerhouses, fundamentally reshaping the energy landscape and leaving an enduring impact on residential living, industrial practices, water management, and urban infrastructure. In agriculture, PV stations became main key in providing the energy for the essential functions such as irradiation and water pumping in remote or isolated areas [1]. Beyond agriculture, their applications span diverse sectors, including the fast evolving field of electric vehicle (EV) charging infrastructure [2]. The integration of PV stations in commercial areas yields manifold benefits, not only reducing energy consumption costs for businesses but also enhancing their appeal to a growing clientele that favors eco-friendly transportation. This shift towards sustainable structures not only boosts EV infrastructure demand but also increases environmental consciousness by improving competitiveness. Recently, Deeum et al. [3] utilized a genetic algorithm to optimize the placement of electric vehicle charging stations in a distribution grid, aiming to establish the most efficient locations within an active grid integrated with photovoltaic and battery energy storage systems. Lee et al. [4] investigated agrivoltaic systems (AVS) for sustainable energy solutions and emphasized a well-rounded AVS design, considering agronomic factors and safety. Therefore, safety standards have been analyzed, revealing trade-offs between shading ratio, power generation, and structural elements. Valle et al. [5] show that combine food crops with mobile PV panels, the entire productivity of a farm can be increased. Beside conducted a comparison between fixed and dynamic photovoltaic (PV) stations in Agrivoltaic systems and show that use of solar trackers permits to balance or promote food/energy production. Consequently, to enhance energy production in a PV station, the utilization of sun trackers is a viable solution. However, a noteworthy challenge arises due to the considerable weight of these PV with sun trackers [6], posing potential risks such as vibration fatigue and susceptibility to adverse weather conditions. As technology progresses and materials evolve, there is a promising outlook for future iterations of solar tracking systems to become more efficient and lightweight, effectively addressing the existing challenges [7]. In the pursuit of safeguarding these type of structures from environmental challenges and fatigue, the use of materials that are adaptable is an adequate strategy such as shape memory alloys (SMAs) [8, 9]. Because of their remarkable performance and ability to adapt to their environment, SMAs are preferred because they guarantee higher levels of safety, longer lifespans, and higher energy output for the PV system [10-14]. Many researchers employed SMA to adapt in different environments and different areas as medicine, mechatronic, robotic and construction due to their particular characteristics as Super-Elasticity and the Shape Memory Effect (SME) [15, 16]. Actually, the unique properties of SMAs depend on the martensitic transformation, a solid-solid phase change process which can react to alterations in both mechanical stress and temperature. Therefore, by using SMA actuators, it is simple to switch between two forms, which are the austenite phase at mainly high temperatures and the martensite phase at relatively low temperatures. The superelastic effect (SE) in SMA material is a significant strain that produced in the austenite phase under mechanical load that forces the material to a transition to the martensite phase. After the load is released, the material returns to its original state [17]. Furthermore, energy loss (damping) is observed in both effects during load–unloading processes. This the reason why the SMA actuator can be used to attenuate the vibration of a structure by dissipating the energy that causes it to oscillate [18]. Consequently, SMA actuators are widely utilized in structures because of their thermo-mechanical coupling, which reacts to mechanical stress by repelling variations in mechanical activity. As a result, several research studies have been published that offer practical fixes and tactics to overcome these shortcomings, including cycle duration and low force [19-21]. Lately, Song et al. [19] displayed the importance of utilizing SMA material for passive, active structures of civil structures that proved in practical way an improvement for construction system in performance of design and experimental results. Yuse et al. [22] developed a SMA actuator for protection in order to limit the strain even the shear stress in SMA wires is created by recovery force achieved a maximum value. Lately, Ju et al. [23] proposed a model that covers multiple disciplines and disciplines to explain a wide range of phenomena, for instance thermo-mechanical coupling and fatigue in Ni-Ti. Petrini et al. [24] suggested a thermo-mechanical investigation using finite element simulations for evaluating cyclic stress in SMA devices. According to the analysis, the design of the SMA affects the residual deformation of the thermomechanical actuator, which reduces fatigue while it is integrated into the mechanical structure. Definitely, SMA actuators offer solutions to challenges such as mechanical vibration, fatigue, tracking, and alignment issues in PV stations. They achieve this by adapting to temperature and stress changes through superelasticity and enabling controlled movements using the shape memory effect.

Consequently, the integration of SMA actuators in a photovoltaic station as a mechanical sun tracker and damper can certainly offers several benefits such as optimized solar tracking, increased energy harvesting, reduced fatigue, improved reliability, durability, and adaptability to environmental conditions for commercial solar energy systems. This research focuses on creating an adaptive smart actuator adjusted to different PV stations, including electric vehicle charging stations. The proposed SMA actuators have been designed in order to serve as a tracker and damper for commercial building photovoltaic stations. We aimed to incorporate the SMA springs in order to work daily as a sun tracker, by converting thermal energy from the sun into mechanical energy, and as a mechanical damper by dissipating energy during oscillation of the spring in load-unloading processes. A thermomechanical model has been developed to adjust the SMA actuator in response to fluctuating temperatures and stresses, capturing both superelasticity and the shape memory effect. The finding shows that the thermomechanical system functions easily integrate in the PV station which improved energy production and a mechanical dissipation.

2. Proposed Systems

All buildings are intended to last an infinite amount of time, since safety and resistance to various conditions being considered a top priority. Nevertheless, physical-chemical attacks and fatigue due to climatic variations are unavoidable constraints and losses [25]. This is the reason why adding intelligent and adaptive structures is advantageous and favorable. This research focuses on creating a modern smart actuator adapted to different PV stations, including electric vehicle charging stations. Therefore, our focus is on developing a simple PV station that explains the technique for incorporating the shape memory alloy actuator into the structure (Figure 1).

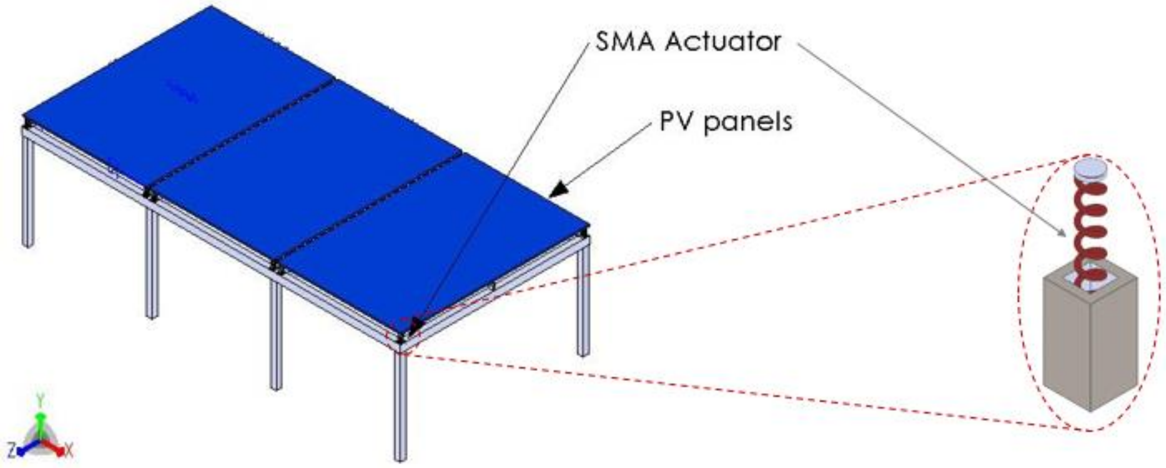


Figure 1. *The proposed SMA actuator incorporated in PV station structure.*

The integration of smart actuator in commercial building and electric vehicle charging photovoltaic stations can protect the structure and improve electric energy production. In order to achieve the intended goal, the Smart actuator is designed to easily combine SMA springs with the PV station structure in various positions (Figure 1).

The SMA spring is the most effective damper for absorbing mechanical energy, leading to a repelling of physical attacks and fatigue, which enhances safety and the lifespan of the structure. Besides, the combining of numerous SMA springs, the system of PV can work as a sun tracker and react to sun irradiation. Accordingly, the SMA spring facing the sun will compress and align the PV system with the solar irradiation.

The Martensite transformation due to temperature variation can provide a significant amount of load, which the SMA material can transform thermal energy into mechanical energy. Consequently, the loading-unloading cycle in the SMA spring can be presented in Figure 2:

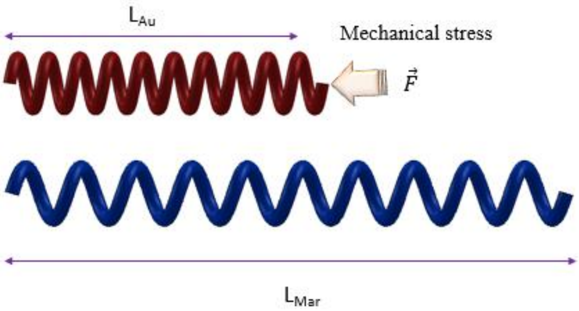


Figure 2. *SMA Spring with and without mechanical stress.*

The thermomechanical actuator features a nitinol-based mechanical spring capable of changing positions. These mechanical component is a crucial component of the entire PV structure system that contributes to its functional concept as sun tracker and a mechanical damper. By using the suitable design for the PV station, the proposed actuator can perform dual functions, which are mechanical damper in response of mechanical stress and sun tracker in response to sun radiation heating (Figure 3). In the first state the SMA can alternate between two state austenite phase at high temperature and martensitic state as relatively low temperature. At ambient temperature, the SMA's martensitic phase is normally expanded, resulting a significant deformation to any applied stress. On the other hand, the sun's rays caused a temperature increase that led to the martensitic transformation, which allowed the SMA to revert to its original compressed state. Consequently, the PV system tilted towards the sun as a result of the SMA springs being forced to compress by the heat produced by solar radiation [26].

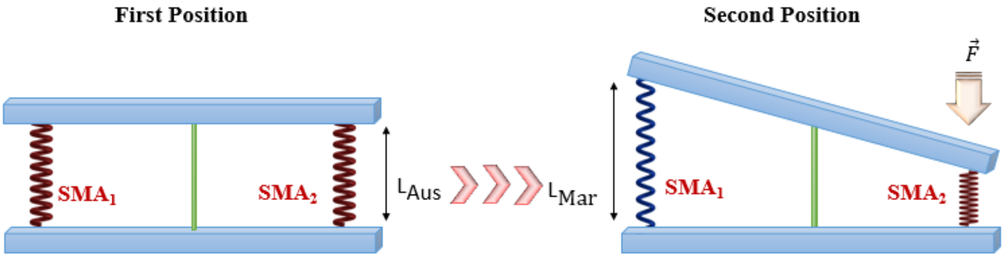


Figure 3. *The mechanical and functional concepts of the proposed system.*

3. Thermomechanical Modelling

In order to integrate the SMA material into the photovoltaic station, we propose a constitutive model that can adjust its thermomechanical behavior to the temperature and stress variations. The purpose of the proposed model is to describe the relationship between stress and temperature when adjusting to environmental conditions related to a PV station. The modeling process involves understanding the mechanical properties of the materials, specifically leveraging the exceptional behaviors such as shape memory effects and superelasticity in the designed system [27]. To interpret the characteristics of shape memory behavior, we employ the concept of partial strains as a means to express the total strain, denoted as ε^T. This parameter serves to define the comprehensive deformation exhibited by the material. This involves a conventional assumption of additive strain decomposition, wherein the total strain ϵ is divided into elastic strain ε^{inl} and inelastic strain ε^{el}:

$$\varepsilon^{T} = \varepsilon^{inl} + \varepsilon^{el} \tag{1}$$

$$\varepsilon^{T} = \sigma/\mathrm{Y} + \beta.\Delta T + \textstyle\sum_{n=1}^{24} \alpha^{n} \nu^{n} + \sum_{n=1}^{24} \gamma^{n} \nu^{n} \tag{2}$$

In the given context, σ denotes the stress, T denotes temperature, Y is the Young modulus, and β is the expansion coefficient. α denotes the martensitic fraction, while γ indicates the slippage of the friction slip system.

The relationship between the total deformation and the martensitic fraction, which is separated into thermal martensitic fraction f_T and stress-induced martensitic fraction f_S, may be explained by the equation below. The SMA actuator responds to temperature change and stress application [17].

$$\alpha = \alpha_{T} + \alpha_{\sigma} \tag{3}$$

The martensitic transformation has an effect on the orientation tensor R, and μ represents the amount of shear strain caused by the thermo-mechanical transformation.

$$\nu_{ij}^{n} = \frac{1}{2} \mu \left(n_{i}^{n} m_{j}^{n} + n_{j}^{n} m_{i}^{n} \right) \tag{4}$$

The concluding equation characterizes the thermo-mechanical model, encapsulating the description through the expression of free energy:

$$\Psi(T,\ \varepsilon^{el},\ \varepsilon^{tr},\ \varepsilon^{p}, \alpha,) = \frac{1}{2\rho}\ \varepsilon^{el}\!: Y\!:\ \varepsilon^{el} + C_{v}[\ (T - T_{0}) - T\ ln\frac{T}{T_{0}})\ ] + \beta.(T - T_{0})\alpha + \int_{0}^{t} \textstyle\sum_{n=1}^{24} Y^{p} \dot{\alpha}^{n}\, dt + \int_{0}^{t} \sum_{n=1}^{12} \nu^{n} |(1 - \alpha)\dot{\gamma}^{n}|\, dt \tag{5}$$

Where C_v is the heat capacity, T_0 is the equilibrium temperature.

The constitutive equation relates the variables of strain ε, volume fraction of stress induced martensite, and temperature T is:

$$\sigma - \sigma_{0} = \mathrm{Y}(\varepsilon - \varepsilon_{0}) + \Omega(\alpha - \alpha_{0}) + \beta\,(\mathrm{T} - \mathrm{T}_{0}) \tag{6}$$

3.1 SMA spring actuator

Three-dimensional springs, which may switch between compressed and uncompressed shapes in the austenite and martensite phases, are the basis of the suggested actuator. The initial structure position is controlled by the actuator. As a result, the actuator is able to store energy when it is crushed by heat; but, when the environment cools down, the actuator is expanded.

The energy stored in the SMA spring in the superelastic state can be describes in the next equation:

$$\psi = \frac{1}{2}\ \delta\ \sigma/S \tag{7}$$

The equation (7) can be rewritten as:

$$\psi = \frac{1}{2}\ \mathscr{k}\ \delta^{2} \tag{8}$$

The deflection of the spring (δ) in both states martensitic and austenite can be calculated as:

$$\delta = \frac{8PD^{3}n}{Gd^{4}} \tag{9}$$

The different parameter of spring is related to coils number (n) that can be described as:

$$\mathrm{n} = \frac{\mathrm{Sd}}{\pi\Delta\gamma\mathrm{D}^{2}} \tag{10}$$

On the other hand, the stiffness ($\mathscr{k}$) is related to the elastic deformation as:

$$\mathscr{k} = \frac{\mathrm{Gd}^{4}}{8\mathrm{D}^{3}\mathrm{n}} \tag{11}$$

The stroke that can be ranged by the spring (S_{max}) is:

$$\mathrm{S}_{\max} = \mathrm{P} = \frac{8\mathrm{PD}^{3}\mathrm{n}}{\mathrm{d}^{4}} [\frac{1}{\mathrm{G_l}} - \frac{1}{\mathrm{G_h}}] \tag{12}$$

The SMAA driving load (F_{sm}) and restoring load (F_l) are combined to create the total applied force on the spring during heating, F_h:

$$F_S = F_L - F_H \tag{13}$$

The restoring force can be described by:

$$\mathrm{F_L} = \frac{Gd\delta}{\pi\, D^2 n} \tag{14}$$

Finally the applied load that submit the spring actuator can be calculated by:

$$F_L = \frac{\left(\frac{d^4 S_{max}}{8D^3} G_l\right)\left(\frac{1}{n}\right) + F_{sm}\left(\frac{G_l}{G_h}\right)}{(G_l - G_h)} \tag{15}$$

Consequently, the model describe the force applied on the structure in order to generate the equilibrium in the full system of the construction. As known the normal stress can be written as shown in the equation (16):

$$\sigma_{nor} = \frac{F}{S} = \frac{4F}{\pi d^2} \tag{16}$$

And the variation of the different parameter can generate a variable stress that characterizes by a mean stress described in the below equation:

$$\sigma_a = \frac{1}{2}(\sigma_{max} - \sigma_{min}) \tag{17}$$

δ_{max} and δ_{min} are, respectively, the highest positive and lowest negative stress for each loading cycle.

4. Results and Discussion

In order to confirm the reliability of SMA actuators in a PV system for charging electric cars, a numerical study studied the aptitude of the SMA in responding to diverse conditions as to stress and temperature has been conducted [6]. In this regard, numerical simulations were tested against experimental data to demonstrate the success of the proposed model in fitting with the PV station structure (Figure 4). Moreover, The materials properties and key parameters that have been used in the simulation model are based on the article [28].

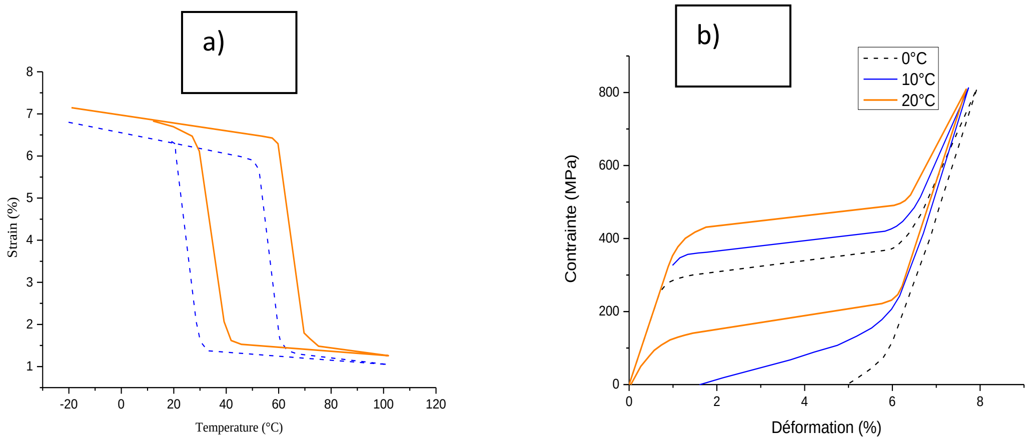


Figure 4. *evolution of the shape memory alloy in response to the stress against the temperature (a) and deformation (b)*

From the numerical results, the suggested model successes to anticipate the thermomechanical behavior of the SMA material at different thermo-mechanical condition. Furthermore, it can be observed that the variation of temperature activates the martensitic transformation from the austenite phase to the self-accommodate martensite and vice-versa.

4.1 Volume fraction as function of time

The fraction rate as a function of time depends on the kinetics of the martensitic transformation, which is influenced by several factors, including the temperature, stress, and composition of the alloy. In general, the transformation is faster at higher temperatures and under higher stresses. The volume fraction as a function of time is shown in Figure 5.

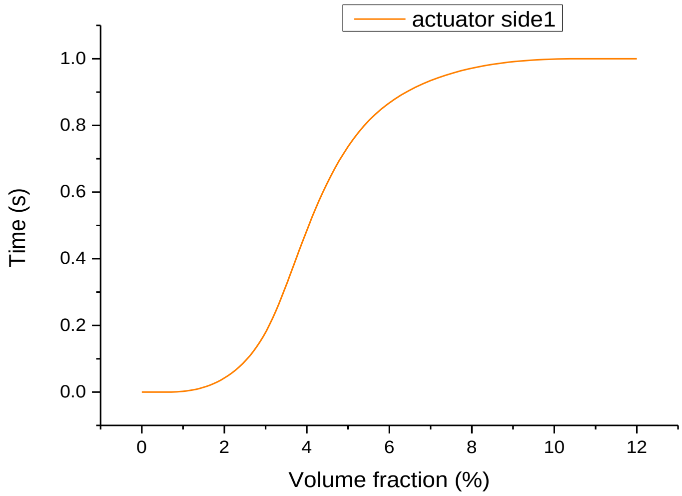


Figure 5. *the volume fraction as a function of time.*

The actuator undergoes a transition from austenite to martensite in response to temperature or stress stimuli, resulting in an increased volume fraction of martensite (Figure 6). The results show that the SMA responds quickly to the variation of the surrounding. This responsiveness makes them suitable for applications where quick and precise control of mechanical properties is required.

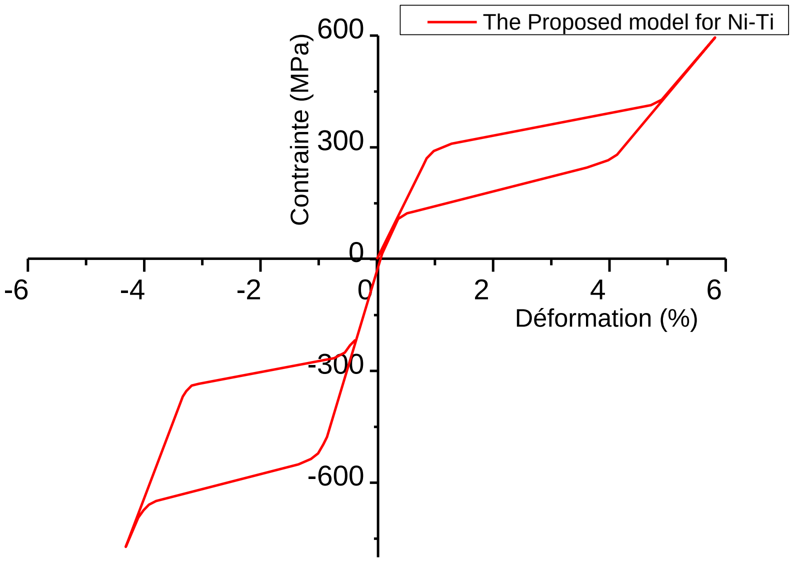


Figure 6. *The strain's response to stress for both tensile and compression loads.*

The numerical analysis showed that the SMA material was capable of handling a diverse range of stresses, resulting in a significant tensile strain. However, as can be shown in Figure 7 below, the SMA also produces a compression strain that responds to a negative stress value.

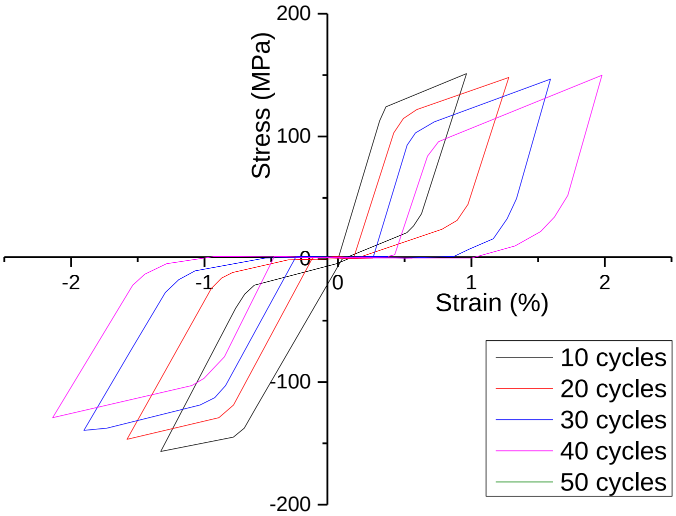


Figure 7. *The variation of strain in relation to stress for both tensile and compression loads.*

Figure 7 illustrates the material's distinctive stress-strain curves during both tensile and compression tests. The tension analysis is compared to the compression, which shows a larger change commencing for compressed stress and a lower transformation strain of roughly 3% to 4%, as opposed to the tensile tests, which yielded a strain of about 6%. The results show that the SMA is adaptable during compression and tension cycles, which makes it suitable for our proposed system that ensures alternating between two positions in response to temperature and stress variations.

4.2 Cyclic study for SMA actuator:

Variable stress over time, influenced by climatic changes and physical attacks, may initiate small cracks lead to degradation the resilience of whole structure which impacts the safety of the PV station. The study assesses the SMA material's ability to mitigate fatigue in the overall structure through cyclic loading in tensile and compression stress, as illustrated in Figure 8:

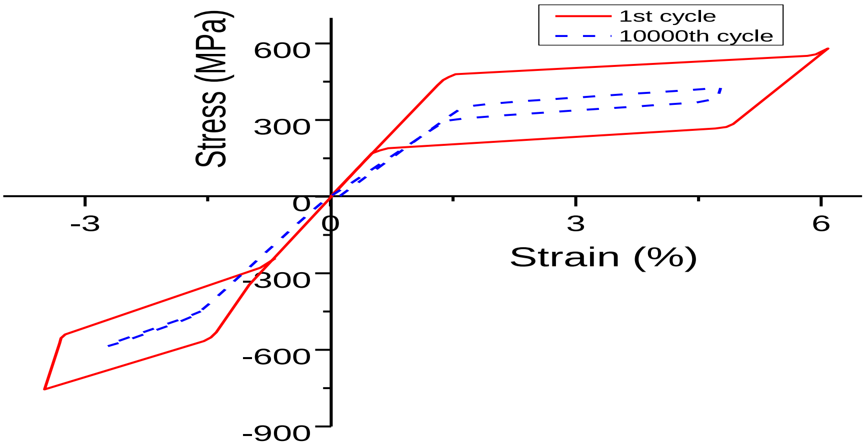


Figure 8. *The strain evolution under cyclic loadings for shape memory alloy.*

In Figure 8, the material's response during tensile-compression tests is illustrated, revealing an asymmetrical stress-strain curve. The results demonstrate the effectiveness of the proposed SMA model in capturing the shape memory effect and superelasticity when integrated into the PV station structure, as intended. Consequently, the SMA actuator ensures safety in the PV station by effectively reflecting and absorbing various stresses over time. Additionally, the

SMA eliminates deformation in both the actuator and the structure as the environmental temperature rises, thanks to the martensitic transformation that transitions the material to the austenite phase. The elimination of residual deformation occurs through the conversion of applied mechanical energy to thermal energy during the phase change and oscillation of SMA spring actuators, particularly noticeable under low cyclic stress conditions [29, 30].

In order to test the SMA actuator's capabilities and ensure it utilities effectively as a sun tracker, we intend to enhance the study by increasing the loading and unloading cycles. This extended testing will also reveal the impact of fatigue on the actuator, as illustrated in Figure 9 [31].

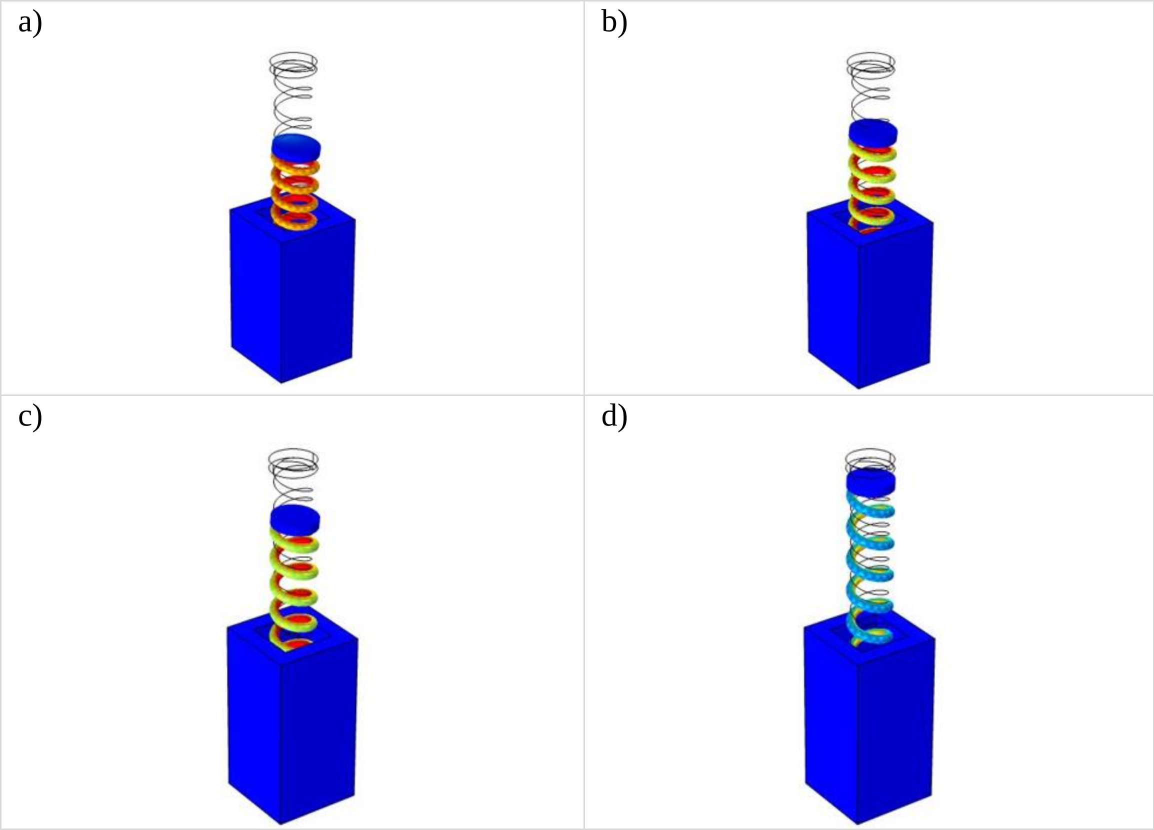
The simulation outcomes successfully predict the cyclic behavior in the SMA actuator, elucidating the thermo-mechanical effects associated with superelasticity behavior in accordance with the literature (Figure 9) [32]. As anticipated, the SMA material has the ability to absorb and reflect external cyclic stresses which ensure the safety of the structure. Moreover, the actuator functions as an efficient sun tracker, responding to stress and thermal variations over time, alternating between two positions at high temperature and low temperature (Figure 5). Indeed, after multiple cycles, the SMA material obviously exhibits residual deformation. The consecutive cycles of loading induce changes in the material, giving rise to the formation of defects, such as dislocations and twins. However, it demonstrates resilience against fatigue phenomena by operating within a constrained range of deformation and temperature, thereby enhancing the lifespan of both the PV structure and actuator.

Analyzing the strain change in response of applied stress is made feasible by the numerical investigation. The COMSOL program, which has a library of many materials, including shape memory alloys, is used to conduct the research. The software has the capability to automatically evaluate the mesh of the suggested actuator. Raising the amount of elements in this study that can accomplish around 13210 elements can thereby improve the accuracy.

As shown in the Figure 9, the study is describing the thermomechanical behavior of shape memory alloys in response to stress for both tensile and compression loads. The SMA actuator react to variation of applied stress and heat that make it compressed during martensite transformation. Then, removing stress and heat impact enables the SMA to return to its normal state. Synchronously, The SMA in the opposite position extends and exhibits a memory effect when under stress from the PV panels. As the sun faces the SMA actuator, it effectively returning to its initial state once the stress is removed. This involved the interaction highlights the adaptability and functionality of the SMA actuator in the PV station structure. Indeed, the strength of the proposed actuator lies in its effective utilization of the design and arrangement of actuators within the PV system. The study indicates that the tracker adeptly responds to radiation heat by compressing the springs and aligning the PV with the sun when facing it. In contrast, the other actuators in the opposite position are hidden by the PV panel, preventing them from undergoing a phase change. Accordingly, employing a Ni-Ti actuator as a sun tracker can address many problems by providing flexibility against weight and design constraints. This system also enhances resistance to physical and chemical attacks, in addition to minimizing energy consumption compared to traditional sun trackers.

In conclusion, the study findings support the use of SMA actuators in commercial solar energy systems, showcasing potential economic and reputational benefits. These include increased energy efficiency, reduced maintenance costs, extended lifespan of solar components, and adaptability to environmental conditions. These advantages can contribute to cost savings, improved system performance, and a positive brand image, positioning companies as leaders in the renewable energy sector.

Compression (SMA_1)



Tension (SMA_2)

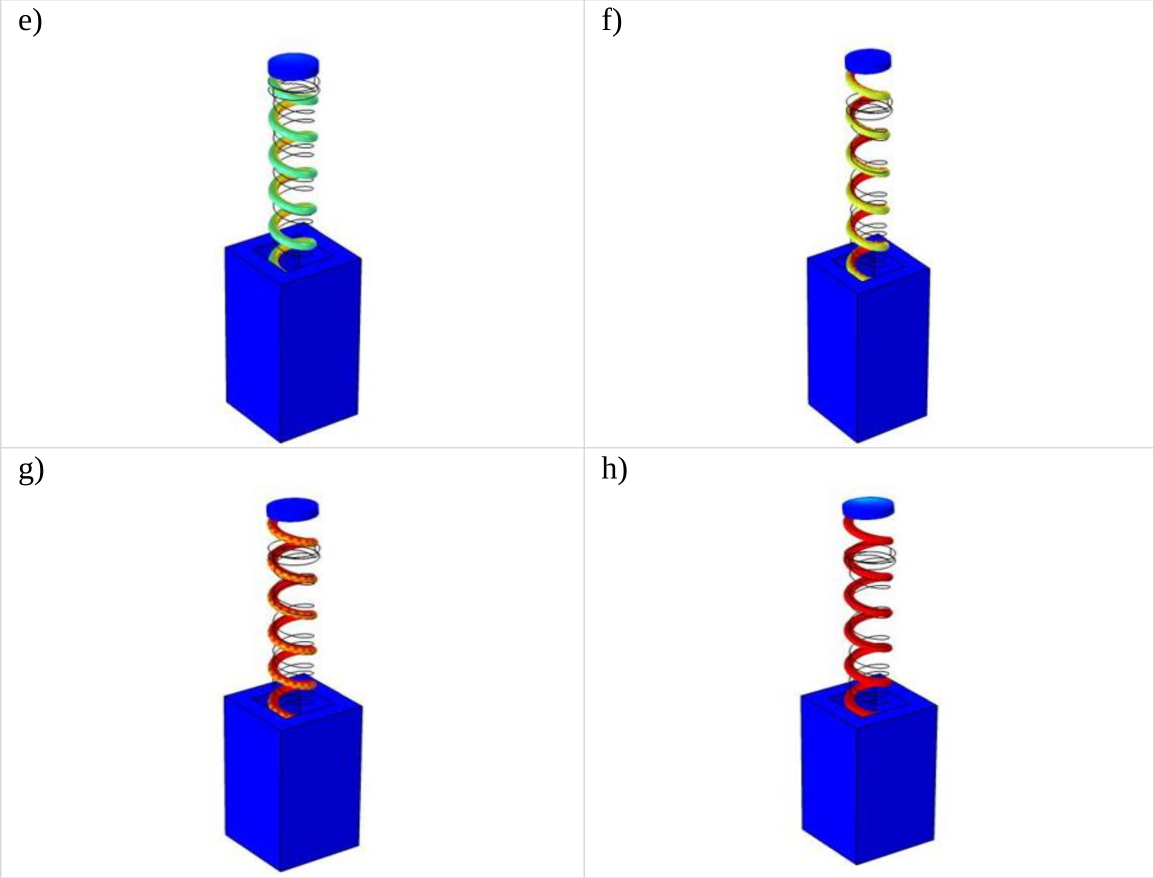


Figure 9. *The SMAA's heat transfers in response to stress for both tensile and compression loads.*

5. Conclusion

In order to improve the lifespan and the production in PV stations for electric vehicles, a numerical study that integrates an adaptive thermomechanical actuator has been proposed. This study is focused on developing a new smart actuator design that can be used as a sun tracker and mechanical damper in photovoltaic stations for commercial buildings. The proposed SMA actuator can significantly move in response to solar irradiation and can reduce fatigue by stabilizing mechanical stress during bad weather. A thermomechanical model has been developed to adjust the SMA actuator in response to fluctuating temperatures and stresses, capturing both superelasticity and the shape memory effect. Hence, a numerical study has been conducted to demonstrate the different proprieties of the model and describing the thermomechanical behavior of the proposed system in response of the different thermomechnical loading over temperature and time. The main finding of the current work is the improvement of PV station based on the Ni-Ti actuator that can achieve deformation reaction accordingly the load/unloading cycling up to 7,6 % strain. Furthermore, the response of the actuator time has been improved in order to absorb the shocks that can be decreased and delayed to avoid the plastic deformation of the structure. These technologies collectively offer environmental, economic, and operational benefits, making it a valuable component in the optimization of solar energy systems. The study takes into account real-world situations, specifically examining temperature and stress fluctuations, as well as fatigue based on existing literature. To advance this research, efforts should concentrate on optimizing temperature ranges, developing advanced alloys with improved properties, improving durability and fatigue resistance, enhancing resistance to environmental factors, optimizing scalability and cost-effectiveness and ensuring adaptability to diverse structural Configuration validation.

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