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Design of a gravity energy storage device; for storing electrical energy from renewable power generation systems

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Abstract. This article presents the design of a gravitational potential energy storage system for storing electrical energy from renewable power generation systems. The system incorporates a balanced double-arm ‘A’-frame tower crane along with a layered weight array to enhance energy density. It utilizes a permanent magnet stepper motor (NEMA23) as the main hoist motor. The design calculation is based on an energy storage capacity of 1 Wh, utilizing a total mass of approximately 46.8 kg per layer over seven layers (total 327.6 kg) with automated control. The novelty lies in the compact, modular design, offering geographic flexibility compared to pumped hydro systems. This design aims to improve the stability of electrical energy from renewable power generation systems, reduce excess energy losses, and enhance the potential for future practical applications.

1 Introduction

At present, the demand for electricity in Thailand tends to increase continuously [1]. If producing electricity with renewable energy is necessary to replace fossil fuels in electricity production, as outlined in the Alternative Energy Development Plan of Thailand 2018–2037 (Alternative Energy Development Plan: AEDP 2018) [2], system designers must take into account the limitations of electricity generation systems that rely on renewable energy. The power generation is unpredictable and contingent on the prevailing environmental conditions. Thus, calculating the capacity for renewable energy power generation requires scaling up the system to ensure that sufficient power is delivered to meet demand. Therefore, electrical energy can exceed demand. Without appropriate energy storage, this excess energy becomes wasted. Storing excess electricity also enables renewable energy power generation systems to meet demand during periods when energy cannot be sufficient due to unfavorable environmental conditions. Such storage reduces electricity consumption from diesel-powered power generation systems, thereby reducing Thailand's long-term electricity production costs. This article will focus on the design of a

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gravitational potential energy storage system for storing electrical energy from renewable power generation systems. The primary objective of this research is to develop a gravitational potential energy storage system that can be used to efficiently store excess energy from renewable energy power generation, especially excess electricity from solar power generation systems. Since the amount of solar radiation the Earth receives per year is more than 7,500 times the average annual global energy consumption [3], solar energy is a tangible avenue for Thailand and the world to continue developing and progressing.

Currently, pumped hydroelectric energy storage (PHES) is the most widely used form of energy storage worldwide. Over the years, various traditional and alternative PHES schemes have been studied. Pumped hydroelectric energy storage accounts for more than 99% of the world's large-scale energy storage, making it the most prevalent method. Typically, this system consists of two dams or reservoirs, with one reservoir positioned at a higher elevation than the other. This design enables the system to store potential energy from the water in the higher reservoir. When water is released from the higher reservoir through a turbine to the lower reservoir, this potential energy is converted into electricity. This system offers numerous benefits, including substantial storage capacity, high efficiency ranging from 65% to 87%, and scalability. However, there are some disadvantages. For instance, the energy density of the system is low, as water has a low mass per volume. Consequently, the system requires either a large reservoir capacity or a greater elevation difference between the reservoirs. Additionally, specific geographical requirements limit the installation area for this system [4].

The development of pumped hydroelectric energy storage systems (PHES) has been widely researched. This includes systems that store energy using pistons with weights at the piston rod to increase the mass density per volume of water, which helps reduce the size of the system. Additionally, research has explored the addition of air compression to the cylinder to lower the height while maintaining the same energy capacity [5]. However, air compression causes the temperature to rise rapidly, resulting in energy loss in the cooling system.

Due to the limitations of water's mass density per volume, water-free energy storage systems have been widely developed. In 2021, a gravity-assisted energy storage system was designed in conjunction with solar power generation and focused on household applications, using a single-mass hoisting system via a pulley system to store energy and release it by moving the mass from the highest point of the weight to a lower level. That system achieved an overall efficiency of 62% [6]. The basic principles of that system are quite similar to the ones that this research will present. The form presented is different in that energy storage is done by arranging the weights in many layers, not a single one, which allows for the calculation of the capacity and the electrical power released independently. The new type of gravity-based energy storage system, which uses the solid mass, is gaining traction, and efforts are underway to achieve the same cost and power reliability as pumped hydro, but without any of the limitations, enabling a future shift to 100% renewable energy.

2 Design of a gravity energy storage device

The system has a capacity of 1 watt-hour, as it is constructed on a lab scale to facilitate testing of its controllability and evaluate its feasibility for potential future applications. Understanding the relationship between energy storage and output efficiency is crucial for optimizing the design. This foundational research will guide improvements that could lead to larger-scale implementations in gravity energy storage systems. The calculation of capacity can be derived from the potential energy equation.

$$E = mgh \tag{1}$$

However, the system has a continuous arrangement of masses, so the h value, or height of the mass, has a specific value for each weight. The conversion of gravitational potential energy into electrical energy will incur losses in the system, which necessitates a variable energy conversion efficiency η_T. It is also used in calculations in equations. Therefore, it can be calculated according to the following equation.

$$E_{Electrical} = \eta_T \sum_{i=1}^{n} m \cdot g \cdot h_i \tag{2}$$

In this context, $E_{Electrical}$ represents the total electrical energy stored in the system, measured in watt-seconds. η_T is the efficiency of the system in converting potential energy into electrical energy. *m* is the weight of the mass in layer i, *g* is the acceleration due to the Earth's gravity, which has a value of approximately 9.8 m/s², *h* is the height of the mass layer i, and *n* is the total number of mass layers. The proposed system employs a complex program design to fully automate the entire system. The system consists of a crane, an automatic control device, a main power motor/generator, a wheel motor, a crane boom motor, a gripper system, and a weight. Fig. 1 displays the detailed component diagram.

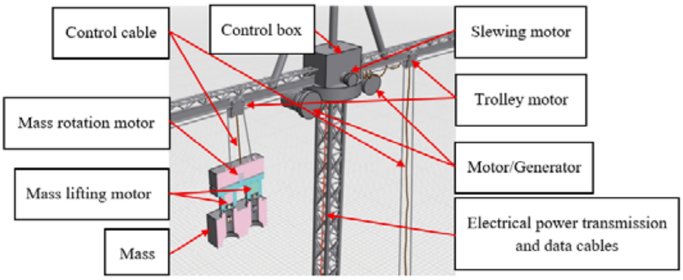


Fig. 1. Components of the crane used in the research.

2.1 Tower crane design

Tower cranes can be classified into three types based on their structural features. The first type is a horizontal trolley with an 'A' frame. There are two types of balancing models: single-arm and double-arm. It is a large-capacity crane. It can be fitted while the tower is within the structure. However, there must be space for installation and removal. The crane is a semipermanent structure. The boom radius cannot be adjusted. The second type, Horizontal Trolley Flat Top Type, has a crane with a directly welded top structure, making it less flexible than the 'A'-frame type. However, the crane's height is lower than the original design, which may be an issue near airports or in places with a large number of tall cranes [8]. The last type is the luffing jib. It is a tower crane with an adjustable crane arm angle that allows for varied lifting positions at different radii. The capacity is smaller than the other crane, but the tower height is significantly lower.

2.2 Lifting equipment design

Taking into account the speed, stability, and ease of lifting masses in areas with small gaps between them, the lifting device uses a cylindrical internal clamp and is designed to allow the lifting set to be rotated to precisely adjust the angle of the weight placement.

2.3 Design of weight buoys and their arrangement

From equation (2), when substituting g = 9.8 m/s^2 And the arrangement of the weight that has 7 levels in total, assume the energy conversion efficiency of the system is 0.8 as shown in (3).

$$\boldsymbol{E_T = 0.8\sum_{i=1}^{7} m \cdot 9.8 \cdot (1 + 0.1i)} \text{ Ws} \tag{3}$$

$$\boldsymbol{E_T} = 1 \text{ Wh, } 1 \text{ Wh} = 3600 \text{ Ws} \tag{4}$$

Thus, the weight of the mass is 46.8 kg per layer.

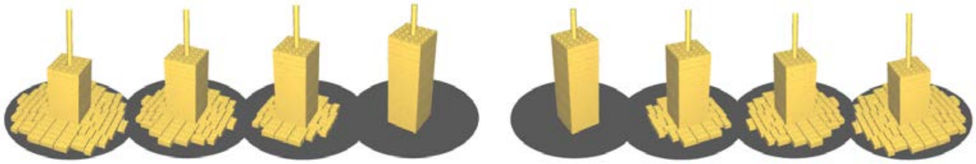
The arrangement is in a square shape around the crane base , with internal locks between each weight to prevent slippage and to facilitate transport and automatic operation design. There will be a total of 12 weights per layer.

2.4 Select the type of main power motor

These are the top four types of electric generators. Direct current electric motors are first. Direct current electric motors have been popular since ancient times, but they can control flux and torque separately. The structure of direct current electric motors includes carbon brushes, which cause maintenance issues. Direct current electric motors lost popularity after the alternating current motor was invented. Induction motors with squirrel cages are the second type. Due to its reliability, durability, low maintenance, and ability to operate in harsh environments, it is the best option. AC motors with the most technological applications are induction motors. Torque and current can be separated by speed. Reducing flux in the constant power range increases speed but decreases torque. This motor has lower efficiency and higher losses at high speeds. A drawback of induction motors is their lower efficiency than permanent magnet motors [9]. The third motor is a permanent magnet synchronous motor. This motor has many benefits, including higher power density. These motors improve environmental heat dissipation and efficiency. Although these motors have a narrow constant power range, their speed range can be extended to three to four times the fundamental speed. Heat can destroy the magnetic state of these motors, so proper motor temperature control is needed. Gravitational potential energy storage systems benefit from these motors if the system is large [9]. The fourth type of motor, the permanent magnet stepper motor, has a cylindrical rotor made of permanent magnets and a stator section with several coils wound around it. The stator coils repel the rotor under DC power. Without power, the rotor stops, producing more torque than other motors. The motor operates silently and maintains precise rotation control [10].

2.5 Design of energy accumulation and release

Energy accumulation and release is the lifting and dropping of the mass; the arrangement from the initial energy accumulation to the full capacity charge is shown in Fig. 2(a), where the grey area is the extent of the crane boom arm and the energy release is carried out in reverse as shown in Fig. 2(b).



(a) (b)

Fig. 2. Working principle of the system; (a) energy accumulation, (b) energy release.

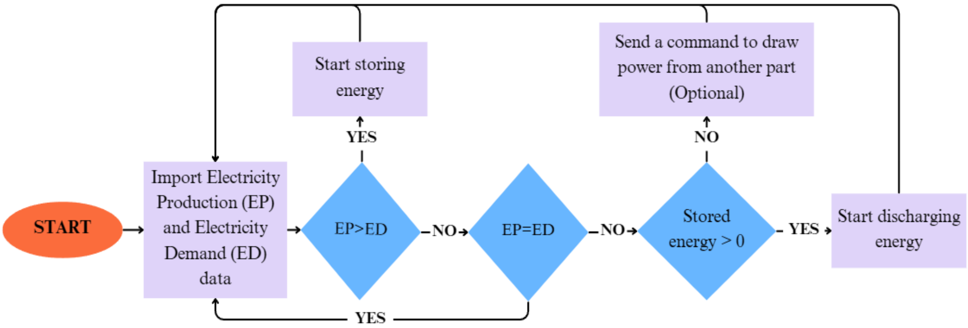


Fig. 3. System operation diagram.

The system operation diagram can be drawn as shown in Fig. 3. The system uses data on the electrical power generation capacity from the renewable energy power generation system, along with current electrical power consumption demand, to control its energy accumulation and release operations.

3 Design result

3.1 Results of the selection and design of cranes used in the research

This research has developed a design for an A-frame double-arm balanced tower crane. The structural design has overall dimensions of 5x5x2.5 meters, with each crane arm measuring 2.5 meters in length. The crane will consist of 49 component sets, including one set for the tower crane base (as shown in Fig. 4(a)), twelve sets for the core structure (as shown in Fig. 4(b)), one set for the swing waist gear installation point (as shown in Fig. 4(c)), two sets for the crane arm ends (as shown in Fig. 4(d)), one set for the crane top (as shown in Fig. 4(e)), two sets for the trolley pulleys (as shown in Fig. 4(f)), and thirty sets for the arm crane (as shown in Fig. 4(g)).

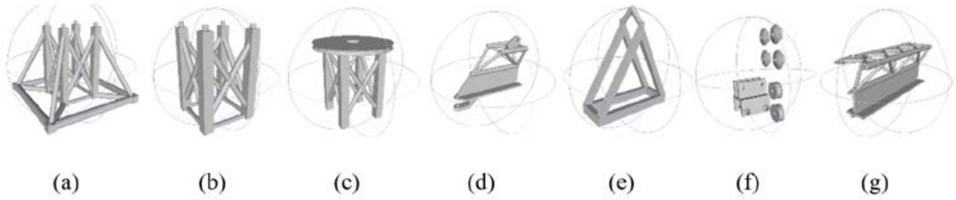


Fig. 4. Components of the A-frame double-arm balanced tower crane: (a) tower crane base, (b) core structure, (c) swing waist gear installation point, (d) crane arm ends, (e) crane top, (f) trolley pulleys, (g) arm crane.

3.2 Lifting equipment design results

The lifting equipment shown in Fig. 5 will comprise eight component sets: three sets of pivot shaft handles with gears, two sets of sun gears, two sets of motor bodies, and one set of main bodies for the lifting equipment.

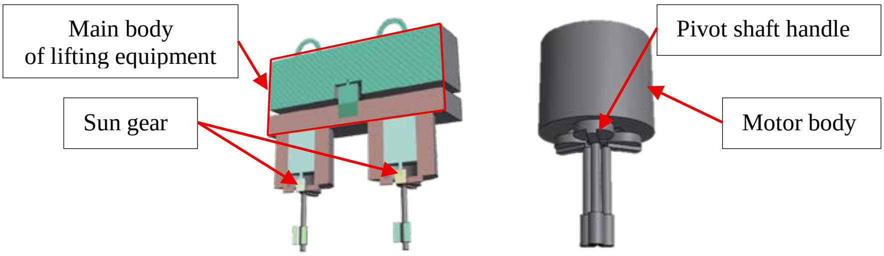


Fig. 5. Structure of the designed lifting equipment.

3.3 Weight design results and arrangement methods

The weight block, equipped with two wedges, improves the adhesion between masses. According to the calculations from equation (2), the design, which includes 12 blocks in each layer, yields a mass of 3.9 kg per block. The weight block incorporates a wedge with a hemispherical bump on the top and a concave bottom of the same dimensions to facilitate assembly with the subsequent block, effectively locking movement along the horizontal axis. A hole with a diameter of 3 centimeters is drilled from top to bottom at the center of the bump on both sides, as illustrated in Fig. 6(a).

The design of the arrangement method involves alternately arranging 12 weights to securely lock them in place between each other and between the layers, ensuring stability and preventing slipping. There will be two types of arrangements with alternating layers, as shown in Fig. 6(b) and Fig. 6(c).

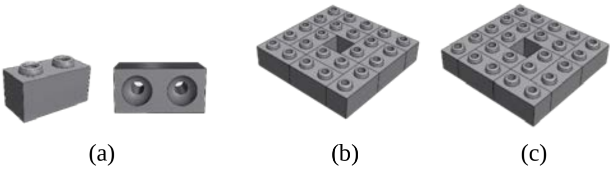

(a) (b) (c)

Fig. 6. Weight block (a), Weight arrangement pattern; Type 1 (b), Type 2 (c).

3.4 Motor type selection results

This paper selects a permanent magnet stepping motor due to its exceptional precision in rotation control and its efficiency in generating electric power at low rotational speeds [10]. The permanent magnet stepping motor is considered appropriate for designing compact gravity energy storage systems. The design calculation indicates that each layer of the weight buoys has a total weight of 46.8 kg, consisting of 12 blocks per layer, resulting in an individual block weight of 3.9 kg. The motor in question should possess a torque exceeding 7.8 kg·cm. The shaft of the crane hoist has a radius of 2 cm, and due to the limited size of available permanent magnet stepping motors, general stores don’t have many specifications to choose from; the NEMA23 motor was selected. This choice is based on its affordability and classification within the permanent magnet stepping motor category, and its power is 120 watts, which includes investigations into its potential as a power generation device. Despite this, its torque surpasses the required value by a factor of 25. It is 200 kg·cm. The outcome is viewed as advantageous for increasing mass size in the future.

3.5 Design results, energy accumulation and release

A physical activity that represents the accumulation and release of energy is lifting and dropping weights. The energy accumulation process is the weight being lifted until there is no longer any cable length to prevent swinging, as shown in Fig. 7. This task is accomplished by accumulating energy at the same time. When the first weight is released into the placement region, another weight is hoisted. This process is done by sending the electrical power that is created by the first weight's release to the motor that lifts the weight on the opposite side of the crane. This procedure is done to compensate for the energy that is lost during the lifting process above the placement level. The energy release process is a weight being released from the top of the layer and descending, which generates kinetic energy that is then transformed back into electrical energy by a generator. Those processes all not only enhance the efficiency of the crane's operation but also minimize energy waste.

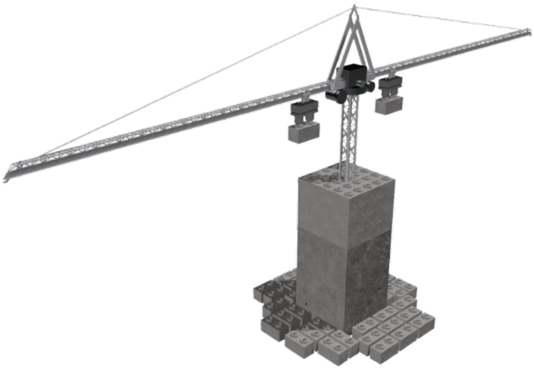


Fig. 7. Complete design of a gravity energy storage device.

4 Summary of design results

This research proposes a gravity energy storage system for storing energy from renewable power generation systems that use a double-armed, balanced A-frame-type tower crane. Because of its enormous capacity, it takes less time and energy to move the total load, and it can work in a wide range of settings [8]. It measures 5x5x2.5 meters in total, with the crane arm reaching 2.5 meters on each side, and is made up of 7 components divided into 49 sets. The weightlifting set is designed to be assembled using equipment, which includes four components and six sets of weightlifting equipment. The proposed design and arrangement, which are based on calculations for a 1 Wh system, will result in a mass of 46.8 kg per layer. Arranging 12 weights in each layer in two alternate configurations yields a mass of 3.9 kg per block. The weight has a half-sphere wedge at the top and a concave of the same size at the bottom, which will be assembled with the next block. It helps to lock the movement totally in the horizontal axis. On both sides, a 3-centimeter-diameter hole is drilled through the middle of the convex button from top to bottom to grip and lift the weight. This article chooses to use a 120 W NEMA23 motor. The motor has a torque of 200 kg/cm. It is a permanent magnet stepping motor because of its precise rotation control and excellent efficiency in producing electric power at low speeds [10]. The design of the gravitational potential energy storage system in this study illustrates the viability of building such a system to improve the energy security of solar power generation systems. The designed prototype system, which can store and recover energy, will be developed and tested in the following steps. The use with solar power generation systems will be examined, and the effectiveness of the energy storage will be determined as having potential for future practical applications.

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