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DESIGN AND EXPERIMENTAL EVALUATION OF A FLYWHEEL GENERATOR

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Abstract
This study aims to design and fabricate a low-cost flywheel-assisted generator prototype to supply electrical power for basic loads in locations where access to electricity is unavailable. A series of experimental tests was carried out to validate its functionality. The prototype was constructed using an 8 kg solid-steel flywheel attached to a 12 V DC automotive alternator. The other parts of the prototype include a sewing machine motor and belt drive, as well as other electrical components, i.e., a 12 V, 60 A battery and a 600 W DC-to-AC inverter. A 27 cm diameter flywheel was operated at approximately 2,100 rpm for operation. The results show that a DC voltage of 8.9-9.0 V and 60 A, corresponding to an electrical power of 534-540 W, at the alternator/ battery side. The prototype was reported to supply a 39 W fan, a 40 W lamp, and a 90 W motor, resulting in a simultaneous connected load of 179 W. The findings show a correlation between the prototype's mechanical feasibility and its ability to supply basic AC loads. However, these findings do not indicate net energy gain or continuous self-sustaining operation because the battery, motor input, conversion losses, and discharge duration were not measured as part of a complete energy balance. Therefore, this study contributes a practical small-scale prototype and identifies the measurements required for a more comprehensive future performance evaluation.
Keywords: Flywheel Energy Storage, Flywheel Generator, Mechanical Energy Storage, Alternator, Prototype, Small-Scale Power Generation

INTRODUCTION

Reliable electricity is important for lighting, communication and the operation of basic appliances. Energy-storage technologies can support power availability where supply is intermittent, while also helping systems respond rapidly to changes in electrical demand. Flywheel energy storage systems (FESS) store energy mechanically as the kinetic energy of a rotating mass and can provide rapid charge and discharge, high power density and long cycle life (Olabi, et al, 2021)(Xu, et al, 2023). Their characteristics have led to applications in power-system support, transportation, renewable-energy integration and other short-duration applications (Bamisile et al., 2023)(Eltaweel & Herfatmanesh, 2024).

The fundamental stored-energy relationship is given by $E = 1/2\ I\omega^2$, where E is the kinetic energy, I, is the moment of inertia, and ω is the angular velocity. Thus, rotational speed strongly influences the energy stored in a flywheel. At the same time, rotor geometry, material strength, bearings, containment and rotational losses constrain safe operating conditions (Choudhury, 2021)(Li & A. Palazzolo, 2022)(Saha, et al., 2008). Experimental studies have also shown that passive discharge is influenced by bearing friction, electrical machine losses, and aerodynamic drag (Skinner & Mertiny, 2021). Consequently, a practical prototype must be assessed not only by whether an electrical load can be switched on, but also by its energy balance, losses, operating stability and safety.

Recent reviews have largely focused on advanced FESS using high-speed rotors, composite materials, magnetic bearings, power electronic converters, and grid or transportation applications (Olabi, et al, 2021)(Li & Palazzolo, 2022)(Xu, et al, 2024)(Nkomo & Alugongo, 2024)(Ji, et al, 2024). These systems demonstrate the technical potential of flywheel storage but are substantially more sophisticated than a low-cost, locally fabricated prototype. There is therefore a practical gap between advanced FESS research and small-scale educational or community-oriented prototypes that use readily available components such as steel flywheels, automotive alternators, batteries and belt drives. Pullen likewise notes that flywheels are particularly well-suited to fast-response, high-cycle applications, while cost and duration remain important considerations.

The present work addresses this gap by documenting and experimentally evaluating a low-cost flywheel-assisted generator developed from commonly available mechanical and electrical components. The objectives of the study are (1) designing a flywheel generator, (2) developing the generator, and (3) testing the generator. The study shows a description of the prototype configuration. It also measured operating performance and provided a critical interpretation of the reported electrical measurements. Specifically, the study differentiates between the electrical output observed during testing and provides proof of sustainable energy generation. It also requires a complete input-storage-output energy balance.

LITERATURE REVIEW

Flywheel Energy Storage System

A flywheel is an energy storage technology that utilizes the kinetic energy of a rotating mass. The basic principle is that mechanical energy is stored by increasing the rotational speed of the flywheel and can subsequently be converted back into electrical energy through a generator system. Olabi et al. (2021) explain that flywheel energy storage systems (FESS) have been developed for various energy requirements, including transportation, electrical power systems, and energy storage applications.

Theoretically, the kinetic energy stored in a flywheel can be expressed by the equation: $\mathbf{E = \frac{1}{2} I \omega^2}$, where *E* represents kinetic energy, *I* is the moment of inertia, and *ω* is the angular velocity. This equation indicates that energy storage capacity is influenced by the mass characteristics and mass distribution of the flywheel, as well as its rotational speed. Therefore, the design of a flywheel generator must consider the balance among rotor size, mass, material, rotational speed, and safety factors.

Design and Components of a Flywheel Generator

The design of a flywheel generator is a multidisciplinary system that integrates the rotor, motor-generator, bearings, mechanical systems, and power electronic components. Li and Palazzolo (2022) emphasize that the selection of subsystem designs affects the performance, cost, and applications of flywheel energy storage systems. Thus, the success of a flywheel generator is not determined solely by the rotor, but also by the compatibility of each component that constitutes the overall system.

In experimental design, several important parameters that need to be considered include the diameter and mass of the flywheel, rotor material, shaft type, bearing system, generator type, and transmission mechanism between the flywheel and generator. The design must produce stable rotation with minimal mechanical energy losses. In addition, symmetrical mass distribution is essential for reducing vibration while the rotor operates at high rotational speeds.

Efficiency and Performance Evaluation of a Flywheel Generator

Performance evaluation is an important part of flywheel generator development because it enables comparison between the theoretical design and the actual performance of the system. Xu et al. (2023) explain that FESS offers several advantages, including a long operating life, high efficiency, high power density, and relatively low environmental impact. These characteristics make flywheel technology an attractive alternative for energy storage applications.

In experimental evaluation, generator performance can be analyzed based on several parameters, such as rotational speed, output voltage, current, electrical power, operating time, and energy conversion efficiency. Testing at various rotational speeds can be used to determine the relationship between the available mechanical energy and the electrical energy produced. The measurement results can then be compared with theoretical calculations to determine the effectiveness of the flywheel generator design. Through this approach, experimental evaluation not only demonstrates the system's ability to generate electricity but also provides a basis for identifying energy losses and opportunities for design improvements.

METHOD

Research Design

An experimental prototype-development approach was used. The process comprised project selection, background study, concept generation and selection, material and component selection, CAD modelling, fabrication, assembly and functional testing. The original report states that Autodesk Inventor was used for design and assembly. Three design concepts were considered, and the third was selected as the final configuration through the project team's design selection process.

The prototype, as shown in Figure 1, was designed as a portable steel-frame unit. The reported frame dimensions were approximately 2 ft in length, 2.5 ft in width and 2 ft in height. Four 3-inch rollers were included to facilitate movement. A mesh casing was also included as a safety enclosure around the rotating assembly.

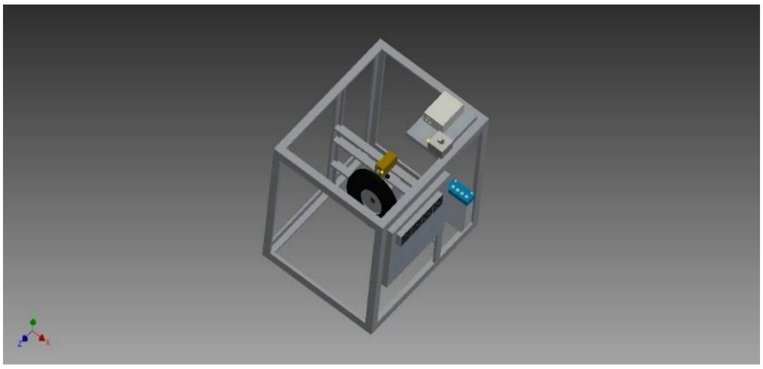

Figure 1. CAD Representation Of The Selected Flywheel-Generator Enclosure And Component Arrangement.

System Configuration

The principal components reported in the original study were an 8 kg solid-steel flywheel with a diameter of 27 cm; a 12 V DC automotive alternator rated at a maximum of 720 W; a sewing-machine motor rated at 90 W and 220–240 V AC with a reported rotational speed of 2,100 rpm; a 12 V, 60 A battery; a 600 W inverter; a belt drive; electrical wiring; a steel frame; rollers; fasteners; an extension cord; and mesh casing. The reported component cost was RM912.80. The components used are shown in Table 1.

Table 1. Principal prototype components and reported specifications.

Component	Reported specification	Quantity
Flywheel	Solid steel; 8 kg; 27 cm diameter	1
DC alternator	12 V; maximum 720 W	1
Motor	220–240 V AC; maximum 90 W; 2,100 rpm	1
Battery	12 V; 60 A; maximum 720 W (as reported)	1
Inverter	600 W; 12 V DC to 240 V AC	1
Belt drive	Sewing-machine belt	1
Frame	2 ft × 2.5 ft × 2 ft	1
Rollers	3 in diameter; 1-1/4 in tread width	4

Mechanical Assembly and Fabrication

Steel frame members were measured and cut using a cutter machine. The frame was assembled using screws and nuts rather than relying solely on welded joints. The flywheel, motor, and alternator were mounted on the frame, and the motor was coupled to the alternator via a belt drive, with the flywheel incorporated into the rotating system. The final assembly, as shown in Figure 2, was checked for mechanical stability before functional testing.

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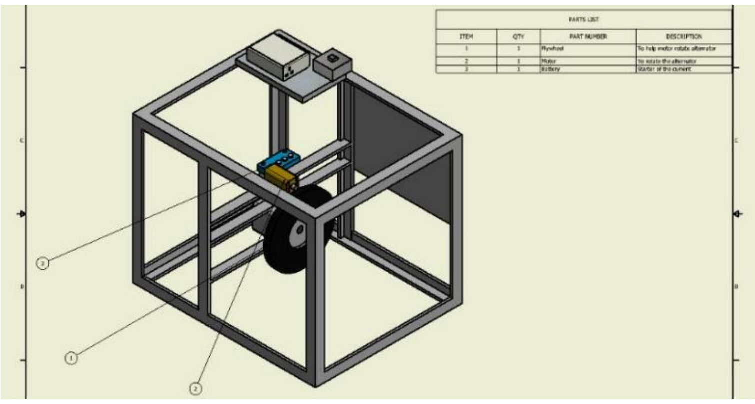

Figure 2. CAD Assembly of the Prototype

Operating Principle

The battery first supplied power to the motor, following the operating sequence. The motor rotated the flywheel and alternator using a belt-drive system. It was reported that when the alternator rotated, producing electrical power, which was then converted to DC by a rectifier. And subsequently supplied back to the battery for charging. When connected to an inverter, the battery also converts the 12 V DC supply into a nominal 240 V AC output for connected appliances.

Based on the operating system, the system involves two forms of energy storage. Energy was stored in electrochemical form, while the rotational flywheel was stored as rotational kinetic energy. It was found that the system was not a closed-loop energy source because the battery and motor supplied energy to the system from the outset. Therefore, the operating system did not continuously produce energy without an external energy input. For an initial estimation, the flywheel is assumed to be a uniform solid disc with a mass of 8 kg and a diameter of 27 cm. The moment of inertia of the flywheel can be calculated using the formula:

$$E = 1/2\ I\omega^2 \quad (1)$$

$$I = 1/2\ mr^2 \quad (2)$$

Using $m = 8$ kg, $r = 0.135$ m and $\omega = 2\pi(2{,}100)/60$ rad s^{-1} gives $I \approx 0.0729$ kg m^2 and $E \approx 1.76$ kJ. The calculated value represents the theoretical amount of rotational energy stored in the flywheel at 2,100 rpm. It should not be taken as the actual usable energy of the system because several losses are not included in this calculation. These losses may occur in the flywheel, belt drive, bearings and alternator, as well as during the electrical conversion process. Therefore, the actual energy available from the system would be expected to be lower than the theoretical value obtained above.

Experimental Measurements

Testing was conducted by operating the prototype and observing the behaviour of the rotating assembly and electrical output. A multimeter was used to measure DC voltage and current at the alternator/battery side. The reported measurements were 8.9–9.0 V and 60 A. The connected AC loads were a 39 W fan, a 40 W lamp, a 10 W lamp and a 90 W motor. The total connected load was therefore 179 W.

The original report also describes open interview questions involving people in villages in western Sabah. However, it does not provide the number of respondents, the sampling method, the interview questions, the dates, the response data, or the analysis procedure. Accordingly, the interview activity is treated as preliminary needs identification rather than as a quantified research dataset.

Data Analysis

Electrical power was calculated from P = VI. It was reported that an 8.9-9.0 V and a 60 A corresponded to 534-540 W. The total of the stated appliance ratings equalled the connected load power. No direct measurement of motor input power, battery state of charge, alternator efficiency, flywheel speed decay, test duration, torque, or energy delivered over time was reported. These omissions make it difficult to fully assess the round-trip efficiency and accurately determine the net energy.

RESEARCH RESULTS AND DISCUSSION

Research Results

Mechanical Performance

Figure 3 shows that the prototype was tested at a flywheel speed ranging from 1,800 to 2,100 rpm. The intended operating speed of the flywheel, 2,100 rpm, was computed during the operation. The belt driver was used to integrate with the alternator, with a 27 cm flywheel and a weight of 8 kg. The result showed vibration of the steel frame at high rotational speeds, but also indicated that the frame remained stable. This observation is important as the rotating steel masses retain kinetic energy and therefore require adequate balancing, bearing support and containment. Contemporary FESS research places substantial emphasis on rotor integrity, bearing technology, containment and loss reduction, particularly as speed increases (Olabi, et al, 2021)(Li, etal, 2022)(Saha, et al, 2008).

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Figure 3. Fabricated Flywheel And Alternator Assembly Used In The Prototype

The measured rotational speed, which normally relies on the high-strength composite rotor, was well below that of advanced high-speed FESS. It specialises in bearings and controlled environments (Olabi, et al, 2021)(Li, etal, 2022)(Xu, et al, 2023). The lower-speed steel configuration is nevertheless suitable for a low-cost prototype because it uses comparatively simple components. Its main limitation is the relatively small amount of kinetic energy that can be stored in the reported rotor at 2,100 rpm.

DC Electrical Output

Table 2 presents the measured DC-side electrical data, including the relevant parameters and their corresponding reported values.

Table 2. Measured DC-side electrical data.

Parameter	Reported value
DC voltage	8.9–9.0 V
DC current	60 A
Calculated DC power	534–540 W

A consistency in the arithmetic of the recorded voltage and current, as shown in Figure 4, i.e., a DC power of 534-540 W. A 720 W and a 600 W rating were reported below the alternator and inverters, respectively.

However, the result should not be interpreted as 534–540 W of net power produced by the flywheel because measuring power at the battery/alternator interface alone does not determine the actual energy source. The system contains a 12 V battery and a 90 W motor; a comprehensive assessment requires simultaneous measurement of alternator output, motor input power, battery current in both charge and discharge directions, and load power over time.

Figure 4. Multimeter Measurement Reported For The DC Side Of The Prototype

This observation is consistent with the broader FESS literature, which treats flywheels as energy storage devices rather than as primary energy sources. The stored energy is released through an electromechanical conversion chain, and losses occur in the motor-generator, bearings, power electronics and aerodynamic environment (Li & Palazzolo, 2022)(Skinner & Mertiny, 2021).

Therefore, the principal scientific finding from the present measurement is that the prototype achieved a measurable DC electrical output under the reported operating condition; the data do not demonstrate a net energy surplus.

AC Load Performance

The prototype was reported to operate four basic loads simultaneously, with a combined rated load of 179 W. This demonstrates the inverter's ability to deliver AC power to the loads. The result is below the 600 W inverter rating and therefore within the inverter's nominal load capacity. Nevertheless, the appliance ratings represent nominal load values rather than a direct measurement of instantaneous real power. In addition, the duration for which all loads were sustained was not recorded. Consequently, the test demonstrates load operation but cannot determine the system's duration or energy capacity. Table 3 summarises the AC loads connected during prototype testing and their corresponding reported power ratings.

Table 3. Connected AC loads reported during prototype testing.

Connected appliance	Rated load
Fan	39 W
Lamp 1	40 W
Lamp 2	10 W
Motor	90 W
Total	**179 W**

Figure 5. Functional Testing Of The Prototype With Connected Electrical Loads

The ability of flywheel systems to deliver high power rapidly is generally recognised, whereas their suitability for long-duration energy supply depends strongly on rotor capacity and system losses (Olabi, et al, 2021)(Bamisile, et al, 2023)(Nkomo & Alugongo, 2024). As shown in Figure 5, the fan rotates when connected to the generator, providing a visual indication that electrical power is generated by the flywheel's rotational motion. The present prototype is consistent with this principle: its calculated flywheel energy of approximately 0.49 Wh is small compared with the 179 W connected load. Even under ideal conversion, that amount of stored kinetic energy would correspond to only about 9.8 s of operation at 179 W if the flywheel alone supplied the load from 2,100 rpm to

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zero. The actual duration would be shorter or otherwise different depending on the allowable minimum speed and system losses. The battery, therefore, represents a major energy reservoir in the tested configuration.

Cost and Portability

An estimated cost of RM912,80 was calculated, including the cost of all components of the prototype. Rollers and a steel enclosure were incorporated in the design. This indicated the intention to improve the portability relative to the flywheel system. The total cost of labour, instrumentation, machining time, maintenance, and safety certification was excluded. Portability is a useful design consideration for small-scale applications, but it must be balanced against the safety requirements of a rotating 8 kg steel mass. Modern flywheel research emphasises containment and mechanical integrity because rotor failure at speed can release substantial kinetic energy (Olabi, et ala, 2021)(Xu, et al, 2023)(Saha, et al, 2008). The mesh casing described in the project is therefore a positive safety feature, but the available data does not demonstrate that the enclosure has been designed or tested to contain rotor bursts.

Comparison with Previous Research and Research Contribution

Previous studies reported that to improve energy density. Efficiency, controllability, and safety of FES could be achieved through rotor geometry optimisation. Other optimisation methods include advanced materials, magnetic bearings and power electronic control (Olabi, et al, 2021)(Li & Palazzolo, 2022)(Xu, et al, 2023)(Saha, et al, 2008). Saha et al. showed that flywheel geometry can materially affect specific-energy performance and mechanical loading (Saha, et al, 2008). Skinner and Mertiny experimentally demonstrated that passive losses can arise from bearing friction, electrical machine losses, and aerodynamic drag (Skinner & Mertiny, 2021). Thormann et al. highlighted that FESS can be attractive for high-power applications, while standby losses remain an important consideration (Thormann, et al, 2021). More recent reviews continue to identify rapid response and high-cycle capability as major strengths, while limited energy duration, system complexity, and cost remain important constraints (Bamisile, et al, 2023)(Eltaweel & Herfatmanesh, 2024)(Khodadoost, et al, 2017)(Pullen, 2019).

The study did not present a high-energy-density FESS innovation, but it served practical and educational purposes. This study presents a fabrication method and a low-cost electrochemical prototype. The cost is low and user-friendly in terms of operating performance. The study also exposes an important methodological issue common to small prototype reports, namely that a load operating at the output did not establish energy sustainability.

The prototype's reported electrical output also illustrates why future testing should move beyond single-point voltage and current readings. A time-resolved test should simultaneously record motor input power, alternator output power, battery charge/discharge power, flywheel speed, and AC load power. Such measurements would enable calculation of conversion efficiency, stored-energy utilisation, discharge characteristics and the actual contribution of the flywheel to load support.

CONCLUSION

A low-cost flywheel-assisted generator was developed as a prototype through a series of experimental tests. The components of the prototype include an 8 kg steel flywheel measuring 27 cm in diameter, together with a 12 V automotive alternator, a sewing-machine motor, a 12 V battery, and a 600 W inverter. A rotational speed of approximately 2,100 rpm was achieved in the experiment. The output of DC was recorded as 8.9-9.0 V with a current of 60 A. The result showed 534-540 W, as the electrical output when the measured voltage and current were used. The prototype was further tested with several electrical appliances connected simultaneously. These included a 39 W fan, two lamps rated at 40 W and 10 W, respectively, and a 90 W motor. The total power demand from all the connected devices was 179 W.

The study objectives were achieved with the design and fabrication of the prototype. The selection of commonly available components also makes the proposed system inexpensive and relatively simple to construct. However, the reported results alone are not sufficient to demonstrate that the system can operate continuously without an external energy source. In particular, the flywheel should be considered an energy-storage component rather than an energy-generating source. Using the reported flywheel dimensions, mass, and rotational speed, the theoretical kinetic energy is estimated at about 1.76 kJ (0.49 Wh) when the flywheel is treated as a uniform solid disc. Compared with the 179 W connected load, this stored energy is relatively limited. This suggests that the 12 V battery played an important role in supplying energy to the system during the experiment.

There are also several areas of experimental work that need further clarification. Operating duration, motor power consumption, battery state of charge, flywheel speed reduction rate, operating torque, and inverter and alternator efficiency were not within the scope of the study. The study's drawbacks include a lack of repeated measures, making it difficult to assess the reliability and consistency of the reported results. To monitor the electrical and mechanical parameters during each test, further experiments are recommended. Measurements of input and output power, rotational speed, torque and battery condition would allow a more complete energy balance to be established. Further investigation could also focus on the system's behaviour under different load conditions and flywheel speeds. These tests may provide more reliable information on efficiency, operating time and the practical limitations of the system. An appropriate containment system should also be considered for any future design involving higher flywheel speeds, mechanical stress analysis, and rotor balancing to reduce the risk associated with high-speed rotation.

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