

# Theoretical investigation and improvements in contemporary man-powered electronic lighting system

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**Abstract.** With the growing emphasis on energy conservation and environmental protection, the Faraday flashlight, which converts mechanical energy into electrical energy through the principle of electromagnetic induction, has garnered significant attention in recent years for its application in emergency lighting in power-free environments. This article investigates the theoretical working principle of an existing model of a Faraday flashlight. The foundation lies in Faraday's and Lenz's law of induction, which is explained briefly using established theorems. A typical shake-type Faraday flashlight's circuitry is used for simplicity in theoretical analysis. A detailed process of the conversion of energy is provided and explained. Comparisons are made between two ways of using the flashlight: its switch is either closed or open. For each way, a method that uses resonant frequency for better efficiency is proposed and justified theoretically. Based on existing works, summarizations of some applications of the Faraday flashlight are made. Generalized and extensive applications of the flashlight's power system are introduced. Overall challenges of the Faraday flashlight are explained, concerning Faraday flashlight's practicality and usefulness. General improvements to the system and its usefulness are proposed and explained.

**Keywords:** Faraday flashlight; theoretical electromagnetism; Faraday's law; efficiency improvements; resonant frequency.

## 1. Introduction

By converting mechanical energy into electrical energy through magnetic induction, the Faraday flashlight is a man-powered device that emits light. It is particularly useful in situations where access to electricity is limited, such as camping or emergencies. Unlike conventional flashlights, Faraday flashlights can potentially work indefinitely, making them especially suit for emergencies [1].

This paper delves into the theoretical principles behind the Faraday flashlight, focusing on electromagnetic induction and circuitry. It examines the conversion of mechanical to electrical energy, compares the efficiencies of various methods, and suggests improvements using resonant frequency and complex impedance. The article also discusses practical applications, challenges, and potential enhancements, emphasizing its suitability for emergencies while recognizing its limitations compared to traditional flashlights. The investigation is primarily theoretical, with recommendations for future empirical studies.

## 2. Fundamental Theories and Analyses

### 2.1. Faraday's Law of Magnetic Induction

Theoretically, the mathematical relationship between total magnetic flux  $\phi_B$  and magnetic field strength  $B$  going through an arbitrary surface  $\Sigma$  enclosed by a wire is defined as:

$$\phi_B = \iint_{\Sigma} \vec{B} \cdot d\vec{s} \quad (1)$$

In Formula 1,  $\vec{B} \cdot d\vec{s}$  gives the perpendicular component of magnetic flux through a tiny surface on  $\Sigma$ , where  $\vec{B}$  is magnetic flux density as a vector and  $d\vec{s}$  the unit vector perpendicular to

that tiny surface on  $\sum$ . Its surface integral sums up the magnetic flux through all tiny surfaces, yielding total flux [2].

Faraday’s law states that if  $\phi_B$  changes over time, an emf  $\varepsilon$  (abbreviation for electromotive force, can be seen as voltage in wire) is induced in the wire. Lenz’s law states that the  $\varepsilon$  induced opposes the motion that causes the change in  $\phi_B$ , which could be explained by Newton’s third law. These comprise Faraday’s law of induction, stated as:

$$\varepsilon = -\frac{d\phi_B}{dt} \tag{2}$$

Formula 2 shows  $\varepsilon$  induced around one coil of wire. If Multiple layers of identical wire coils all experience the same  $\frac{d\phi_B}{dt}$ , since  $\sum$  is the same for each, the magnitude of total  $\varepsilon$  induced must be  $N\frac{d\phi_B}{dt}$ , where  $N$  is the number of layers [2]. This helps Faraday’s law apply on coils, shown in formula 3.

$$\varepsilon = -N\frac{d\phi_B}{dt} \tag{3}$$

## 2.2. Operation Principle of Faraday Flashlight

Although there are many types of Faraday flashlight in the market, Fig.1 shows a shake-type’s circuitry, which is used for simplicity in analysis [3]. A permanent magnet is positioned inside a coil, which consists of a single wire. The coil’s two ends are connected to a bridge rectifier. The rectifier’s two ends connect to a capacitor. The capacitor connects to a Light emitting diode (LED) with a switch.

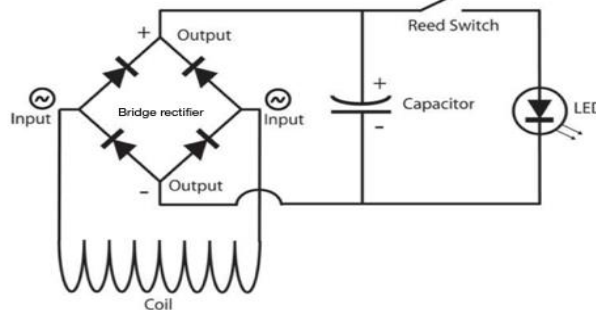


Fig. 1 Circuitry of a shake-type Faraday flashlight

### 2.2.1 Generation of $\varepsilon$

This part happens in the coil component of Fig. 1. Initially, when the flashlight is shaken, a permanent magnet moves through the coil. This motion is shown in Fig. 2.

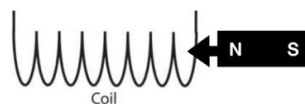
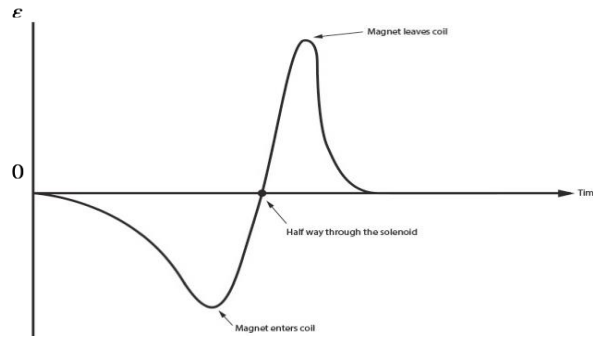


Fig. 2 A permanent magnet travels through the coil

As the magnetic flux through the coil’s surfaces changes, an  $\varepsilon$  is induced around the coil according to Faraday’s law of induction. Fig. 3 below shows the  $\varepsilon$  induced during a complete travel when a magnet falls through the coil due to gravity [4].



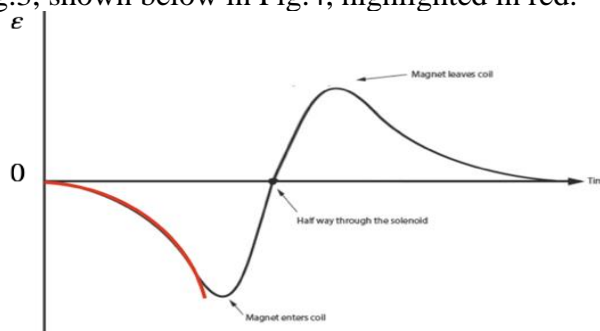
**Fig. 3** Model of  $\epsilon$  as a function of time

Fig. 3’s graph can be verified. According to online researches, there exists an inverse-cubed proportionality between the magnetic field,  $B$ , and the distance,  $r$ , of the magnetic from the test surface, assuming that the test surface is parallel to the magnet’s surface. The magnet and the coil should be close but not too close, to have the magnetic field not too weak and not affected by the edge effect. However, it is also assumed that after the magnet starts traveling with an initial velocity, there is no external force other than the initial energy input that makes the magnet move shown in Fig. 2. This means that there is no gravity’s influence, implying that the flashlight is shook horizontally. Formula 4 below shows  $\epsilon$  induced when the magnet is approaching the coil.

$$\begin{aligned}
 \text{Step(1): } B &= \frac{k}{r^3} \\
 \text{Step(2): } \phi &= BA \cos \theta \\
 \text{Step(3): } \frac{d\phi}{dt} &= \frac{d(BA \cos \theta)}{dt} \\
 \text{Step(4): } -N \frac{d\phi}{dt} &= -NA \cos \theta \frac{dB}{dt} = N Ak \cos \theta \frac{dr}{dt} \frac{1}{3r^4} \\
 \text{Step(5): } \epsilon(t) &= -\frac{NAkv(t) \cos \theta}{3(r(t))^4}
 \end{aligned}
 \tag{4}$$

Step (1) utilizes the inverse-cubed proportionality stated above. Step (2) shows the definition of magnetic flux. Step (3) differentiates both sides of (2). Step (4) multiplies all sides by the number of loops the coil from Fig.2 has and substitutes (1) into  $B$ . The LHS of step (4) is the definition of Faraday’s law of induction, which is replaced with  $\epsilon$  as a function of time,  $\epsilon(t)$ , in step (5). Step 5 replaces  $\frac{dr}{dt}$  with velocity as a function of time,  $v(t)$ , and makes  $r$  as a function of time,  $r(t)$ .

This yields formula 4, which relates  $\epsilon(t)$  with both  $v(t)$  and  $r(t)$ . When the magnet approaches the coil, the distance decreases due to velocity, while the velocity also decreases due to an opposing magnetic force according to Lenz’s law. However, the  $\epsilon$ ’s magnitude actually increases due to the fourth power in the denominator, as  $r$  is initially small, as mentioned above. Formula 4 actually models the first part of Fig.3, shown below in Fig.4, highlighted in red.



**Fig. 4** Modified model of  $\epsilon(t)$

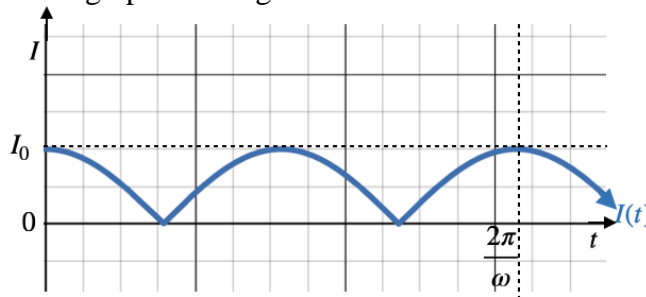
The unmarked part of Fig. 4 represents the time when the magnet falls into the coil. During this period, the edge effect of the magnet complicates the analysis and will not be discussed. Compared to Fig.3, Fig.4 has a larger timespan and a lower  $\varepsilon$  peak when exiting the coil, as explained by formula 4. Intuitively, since the velocity decreases during this travel, the magnet takes longer to exit than to enter. The lower peak results from a smaller change in  $B$  overtime due to this reduced velocity. In addition, since Fig.3 essentially models a magnet accelerated by gravity, its velocity is much larger than when no external force applies, which is Fig.4's situation.

**2.2.2 Induced Current**

Due to the generation of  $\varepsilon$ , a current is induced in the coil. This signifies the conversion of mechanical energy into electrical energy. If one keeps shaking back and forth, an alternating current (AC) is induced in the coil. Such AC goes through the bridge rectifier, which turns AC into direct current (DC), although its magnitude still oscillates due to oscillating  $\varepsilon$  shown in Fig.4. Ideally, if one shakes the flashlight consistently and the velocity of the magnet does not change (which is possible using gravity), after going through the bridge rectifier, the current is modeled by formula 5.

$$I(t) = |I_0 \cos(\omega t)| \tag{5}$$

In Formula 5,  $I(t)$  is a function of AC related to time;  $I_0$  is the maximum current in such alternation;  $\omega$  is the frequency at which the magnet travels through the coil, regardless of the direction; its absolute value suggests that current may only flow in one direction, while the oscillating magnitude still applies. This is graphed in Fig.5.



**Fig. 5** the relation between current and time.

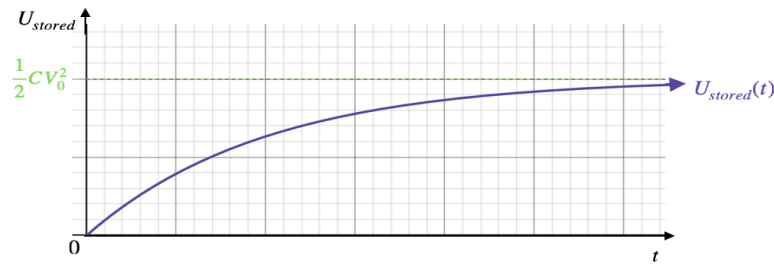
Fig. 5 shows that with each shake, a sinusoidal cycle of  $I(t)$  will be induced; each cycle's duration lasts  $\frac{2\pi}{\omega}$  seconds.

**2.2.3 Charging of Capacitor**

For analytical simplicity, assume that the DC from formula 5 stops oscillating and takes an average for this current. This DC continuously charges the capacitor by moving charges from one plate to another, creating a potential difference. The capacitor remains charged as the charged particles experience an electric force between the plates, storing electrical energy and maintaining the potential difference. Ideally, this can be modeled by formula 6 [5].

$$U_{stored}(t) = \frac{1}{2} C(V(t))^2 = \frac{1}{2} CV_0^2 (1 - e^{-\frac{t}{RC}})^2 \tag{6}$$

In this formula,  $U_{stored}$  is the electrical potential energy stored in the capacitor;  $C$  is the capacitor's capacitance;  $V$  is the maximum potential difference across the capacitor;  $R$  is the resistance throughout the circuitry, except the loop of LED. As  $t$  (time) approaches infinity,  $U_{stored}(t)$  approaches the capacitor's maximum storage,  $\frac{1}{2} CV_0^2$ . This is shown in Fig.6 below.



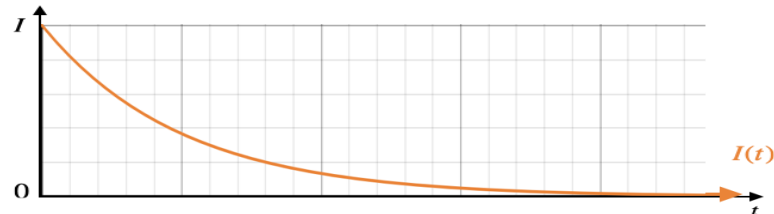
**Fig. 6** Electrical potential energy stored in the capacitor as a function of time

In addition, when the voltage across the capacitor increases, the potential difference between this voltage and the  $\epsilon$  induced decreases. This means that the current flow decreases over time. More precisely, the graph of figure 5 should show that the amplitude of the sinusoidal current decreases over time. Storing of electrical potential energy thus decreases in its efficiency over time, even though it requires the same biological energy for each shake of flashlight.

When the capacitor is fully charged and shaking stops, closing the switch creates a circuit with just the capacitor and the LED. The capacitor discharges, allowing current to flow solely through the LED, as it cannot pass through the bridge rectifier. The electrical potential energy radiates from the LED as useful light energy. However, as the capacitor discharges and the potential difference between its plates decreases, the current also decreases over time. This is modeled by formula 7 below [5].

$$\begin{aligned} \text{Step(1): } V_c(t) &= V_0 e^{-\frac{t}{R_{LED}C}} \\ \text{Step(2): } I(t) &= \frac{V_0}{R_{LED}} e^{-\frac{t}{R_{LED}C}} \end{aligned} \tag{7}$$

Step (1) signifies the voltage across the capacitor time’s function when the capacitor discharges. Step (2) divides both sides by LED’s resistance; following Ohm’s law, it expresses  $I(t)$ , which is formula 7. When  $t$  approaches infinity,  $I(t)$  approaches 0.  $I(t)$  is modeled in Fig.7 below.

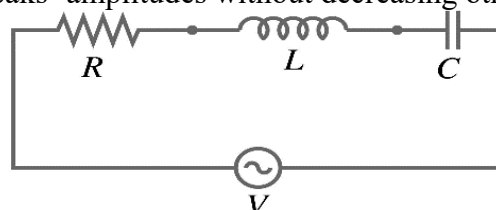


**Fig. 7** Exponentially decreasing current as a function of time

This means that the intensity of lighting decreases over time. Combining the conclusions from formulas 6 and 7, it can be inferred that fully charging the flashlight before use is highly inefficient; energy is lost during the charging process, and light intensity diminishes during use.

### 2.3. Improvement of Working Efficiency

In a series RLC circuit, as shown in Figure 8, using a resonant frequency can enhance the flashlight's efficiency and conserve the user's energy during emergencies. Intuitively, the resonant frequency increases current peaks' amplitudes without decreasing other parts' oscillating "waves."



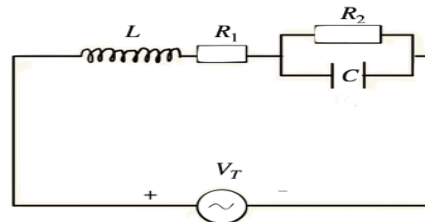
**Fig. 8** Series RLC circuit

$L$  represents coil(coil) from Fig.1;  $R$  represents resistance throughout the wire and of the rectifier from Fig.1;  $C$  represents capacitor in Fig.1;  $V$  represents DC with alternating magnitude. According to research in Georgia State University, Fig.8's resonant frequency is formulated by formula 8 [6].

$$\omega_0 = \frac{1}{\sqrt{LC}} \tag{8}$$

In formula 8,  $\omega_0$  is the resonant frequency;  $L$  is the inductance of the coil;  $C$  is the capacitance of the capacitor. Going back to Fig.1, if the switch is left open, and a continuous ideal shake happens so that  $\omega$  in formula 5 is constant, Fig.1's circuitry is viewed as that of Fig.8. When the flashlight is shaken in such a way that  $\omega_0$  is equal to  $\omega$  in formula 5, the impedance  $Z$  of the circuit reduces to the circuit's resistance  $R$ , which makes the current reach its maximum. The flashlight thus reaches its maximum efficiency in charging the capacitor. However, as said before, charging the capacitor to its fullest will have inefficiencies.

On the other hand, it would be more efficient if the switch is left closed, as proven in section 2.2. Also, in an emergency where light is needed for a prolonged time, the switch is left closed; Fig.1's circuitry can be viewed as Fig. 9 below.



**Fig. 9** RLC circuit from fig.1 with its switch closed

$R_1$  same as  $R$  from Fig.8;  $R_2$  represents the LED light from Fig.1;  $L, C, V_T$  same from Fig.8. To maximize its efficiency, its resonant frequency differs from formula 8, and is modified in formula 9 as below.

$$\begin{aligned} \text{Step(1): } & V_T(t) = Z_T I(t) \\ \text{Step(2): } & Z_T = Z_L + Z_{R_1} + Z_{C+R_2} \\ \text{Step(3): } & \frac{1}{Z_{C+R_2}} = \frac{1}{Z_C} + \frac{1}{Z_{R_2}} \\ \text{Step(4): } & \frac{1}{Z_{C+R_2}} = \frac{1}{\omega C} + \frac{1}{R_2} \\ \text{Step(5): } & Z_{C+R_2} = \frac{R_2 - i\omega R_2 C}{1 + \omega^2 R_2^2 C^2} \\ \text{Step(6): } & Z_T = i\omega L + R_1 + \frac{R_2 - i\omega R_2 C}{1 + \omega^2 R_2^2 C^2} \\ \text{Step(7): } & \text{Im}(Z_T) = 0 \\ \text{Step(8): } & \omega L + \frac{\omega R_2 C}{1 + \omega^2 R_2^2 C^2} = 0 \\ \text{Step(9): } & \omega_0 = \sqrt{\frac{1}{R_2^2 C^2} + \frac{1}{R_2 C L}} \end{aligned} \tag{9}$$

Step (1) shows the proportionality between  $V_T(t)$  and  $I(t)$ , with the coefficient  $Z_T$  being the impedance of Fig.7's circuitry. Step (2) to (7) calculates  $Z_T$  using complex numbers. Step (8) to (9) indicate that  $Z_T$  is minimum when its imaginary part is 0, which maximizes  $I(t)$  from step (1).

As mentioned, there are various types of Faraday flashlights on the market, each with different circuitries and working principles. Utilizing complex impedance can help determine their resonant frequency, maximizing the current flow that converts into electrical energy. Furthermore, this concept is not limited to Faraday flashlights; any circuitry setup resembling Fig. 1's design for generating electrical energy can use the concept of complex impedance and resonant frequency.

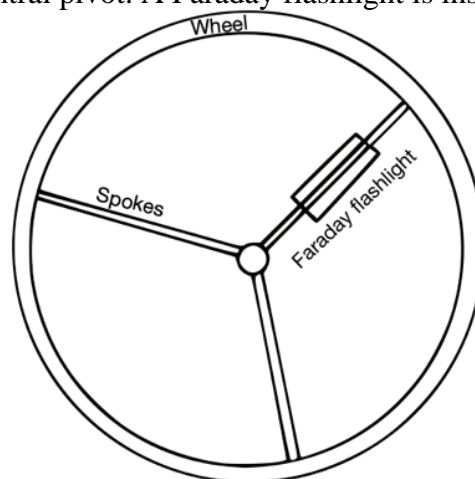
### 3. Applications, improvements, and challenges based on existing works

#### 3.1. Applications

The demand for man-powered systems arises from three key factors: 1. remoteness from electrical power sources, 2. sustainability requirements, and 3. the need to harvest wasted energy.

Remoteness is evident in mining environments, wilderness nights, natural disasters disrupting power supply, and military operations, where access to electricity is greatly limited. Sustainability is highlighted by the reusability of these systems, which are often more cost-effective than battery-operated devices in the long run. Additionally, man-powered systems convert kinetic energy into usable electrical energy for various applications, such as lighting and charging electronic devices. Daily uses might creatively include installing flashlights on bikes, shoes, etc. [7, 8].

Gasper and Omsberg have proposed and tested the feasibility of installing the shake-type Faraday flashlight, discussed in section 2, on a bike's spokes. Fig.10 shows their setup. A bicycle wheel has many spokes attached to its central pivot. A Faraday flashlight is installed on one of the spokes.



**Fig.10** Gasper and Omsberg's setup of the flashlight on a bike's wheel

As deduced from Fig. 10, when riding a bike, the spinning wheels cause the permanent magnet within the flashlight to move back and forth through the coil. This enables the energy harvesting process described in section 2, converting human biological energy into electrical energy. Furthermore, this gadget is not limited to Faraday flashlights; it can also be used to charge electronic devices by connecting a USB while riding.

Another idea is to install the gadget in the shoe's sole [8]. Hypothetically, a circular coil is installed in the shoes' sole. When one walks, the induction happens due to the magnet moving, similar to the process above. This concept could apply to kids' LED shoes currently on the market, which are mostly battery powered. Theoretically, this reusability would allow such products to function indefinitely.

In conclusion, the use of the Faraday flashlight system is extensive. By identifying locations where spare kinetic energy can move the magnet, electrical energy can be generated. This electrical energy can power not only LEDs but also any other electronic devices that could be connected to the system.

#### 3.2. Challenges

Practical challenges accompany the extensive usefulness of Faraday flashlights. As noted by Gasper and Omsberg, the system installed on the bike does not generate the expected voltage because

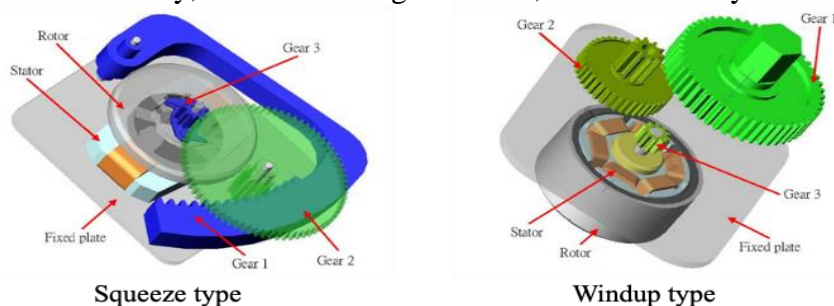
the bike's ferromagnetic spokes disturb the magnet's motion. Additionally, connecting a phone while riding is impractical. The system may also struggle with radical movements and unconditioned environments, and further testing is needed. The same applies to shoes equipped with this system, which remain largely theoretical. Thus, while there are various possibilities for using Faraday flashlight systems, real-life practicality requires validation.

More generally, the system has limitations. As shown in Fig. 2, the conversion rate from human energy to electrical energy is quite low; the energy required to move the magnet far exceeds the electrical energy generated. While charging the flashlight fully may be inefficient, as concluded in section 2, it can be necessary before emergencies. However, the capacitor can only store a limited amount of electrical potential energy, as indicated by Fig. 6. In contrast, carrying extra batteries and a conventional flashlight may be more practical. Additionally, the quality of light from the Faraday flashlight is inconsistent, as suggested by Figs. 5 and 7. When the switch is closed, the alternating current causes flickering, and when fully charged, the flashlight emits diminishing light. Thus, it can be concluded that a conventional flashlight outperforms the Faraday flashlight in both convenience and performance; the latter may only be necessary in genuine emergencies rather than as a novelty.

### 3.3. Improvements

Williams and Yates proposed improvements to enhance the inherent efficiency of the system [9]. Three viable methods for generating electrical energy in microelectromechanical systems (MEMS) are piezoelectric, electromagnetic, and electrostatic. Thus, in addition to utilizing resonant frequency, combining these methods may yield greater efficiency. For example, a piezoelectric plate could be attached to both sides of the coil in the Faraday flashlight, allowing more mechanical energy to be converted into electrical energy rather than lost as sound or heat. However, this approach has limitations: the circuitry may become complicated and costly, the flashlight's physical structure may not withstand frequent impacts, and unintentional damage could reduce the circuitry's lifespan. This combined strategy requires further practical validation. Additionally, Williams and Yates suggested several general design methods for improved efficiency, such as maximizing the space for the magnet's movement and minimizing the damping factor.

Considering the usefulness compared to a normal flashlight as explained in the previous section, there are few possibilities, yet with limitations. The number of loops in the coil may be increased to increase the conversion rate of electrical energy from human energy. The capacitor's capacitance can be increased to store more energy. More types of flashlights can be used to solve the problem of inconsistent light and efficiency, as shown in Fig.11 below, summarized by Yan and Wang [10].



**Fig.11** Dissection of components of magnetic induction

The two different types of Faraday flashlight shown in Fig.11 are more efficient in general than a shake-type flashlight. The permanent magnet is fixed in position, and magnetic induction happens due to its rotation by gears; less human energy is wasted in making the magnet move. The rotation method also induces a more stable current than that of a shake-type, thanks to the different component setups. However, all these increase production costs; upgraded materials have less economy than those of a shake-type flashlight. This creates a trade-off between efficiency and cost. Nonetheless, the Faraday flashlight's unique ability to be used indefinitely makes it suitable for many applications.

## 4. Conclusion

This article explains the theoretical working principle of Faraday flashlight's system based on a shake-type flashlight. An alternating emf and current are induced when shook consistently, and they are modeled with trigonometric functions to show their repeating phases. The influence of this AC on charging the capacitor is explained and simplified to being similar to that of DC, when they charge a capacitor. The two types of resonant frequency of either leaving the switch closed or open are proved to be different, and therefore cannot be used generally for all types of Faraday flashlights. Yet, this provides insights into more efficient ways of utilizing this tool, by suggesting the use of complex impedance in finding different resonant frequencies for different circuits.

Possible applications of the Faraday flashlight and its power system demonstrate broad usefulness but also specific limitations: while it can be used in diverse settings, real-life challenges in its configuration persist. In contrast, conventional flashlights generally offer greater utility, as batteries provide a steadier current and power supply. To address these issues, potential solutions include substituting components with better alternatives and exploring different types of Faraday flashlights. Although this introduces economic trade-offs between efficiency and cost, the Faraday flashlight's capability for long-term use makes it valuable in various situations.

The main purpose of this investigation is to use theoretical electromagnetism and circuitry to explain the Faraday flashlight system, propose potential efficiency improvements, and summarize existing ideas to outline a general application of this theoretical knowledge. It contributes detailed insights into the Faraday flashlight system, benefiting researchers in seeking in-depth understanding.

The main limitation of this investigation is its reliance solely on existing physical theories, without empirical validation. The author strongly recommends that future research include experiments to test these theories, thereby reinforcing their relevance and usefulness.

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