International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Construction and Analysis of Varying Length Constant Current Inductance and Magneto-Mechanical Energy Storage

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Abstract: ***We have prescribed a method of storage of energy. We have converted the chemical/electrical energy stored in a dc cell into magnetic and mechanical energy of a conducting spring-inductor. Current is allowed to flow through the spring-inductor connected in series with a resistor and a dc cell. Because of mutual force of attraction between the large area and large current carrying large number of spring loops the spring compresses continuously. As a result, flux through the spring-inductor varies without varying the current through the loop. Energy analysis establishes our assumption. We determined the effective resistance of this spring-inductance and the constant current flowing through the LR circuit. Since the variation of flux with current is not a constant here but depends upon device length (time) so this device may also be termed as quantum inductor. The spring-inductance stores a combination of magnetic as well as mechanical energy that may be reused.***

Keywords: spring-inductance; constant current; magnetic energy; mechanical energy; energy flow

Alternative sources of energy or useful conversion of energy from one source to another is of great importance in modern era, a lot of research is going on storage of energy. One example of storing electrical energy is in the form of capacitor, depending upon the shape and insulation material of the capacitor. Kirk *et.al.* [1] prepared a mechanical capacitor using a spoke-less magnetically levitated composite ring rotor. In a different work Michaelis *et.al.* [2] designed and analysed a 10 *kW-hr*, 15 *kW* mechanical capacitor system. It was determined that magnetically supported wheels constructed of advanced composites have the potential for high energy density and high power density. They analysed the structural concepts those yield the highest energy density of any structural design. Kirk in a different literature [3] discussed about the basic concepts of the energy storage possibilities of fly-wheels.

In this note we address a typical such conversion of chemical/electrical energy to usable magneto-mechanical energy (i.e. a combination of magnetic as well as mechanical energy). Energy could change and transform from one kind to another. Electricity may of course be stored as spring potential energy (mechanical energy), however, one cannot imagine the volume of equivalent spring that will supply energy equal to a typical electrical cell. The volume of the corresponding cell may be quite small in comparison. Difference will be clear once we think about the clockwork spring. If we compress the spring up to maximum it would drive the clock only a few days, by contrast, two piece of small 1.5 V batteries would drive it for years. So clearly no chance of volume comparison in this case.

On the contrary if we look into the cost effectiveness, definitely the spring will win the game, whatever may be the number of spring combination required to generate the same power as battery, does not matter. Though we know that springs are characterized by relatively low energy density (about 0.1*Wh/ kg* for steel) being therefore a relatively poor choice for large scale application in energy storage devices. Nevertheless, they typically possess high power density (around 10K*W/kg* for steel) what results in capacity to generate high forces from relatively small compression or expansion displacements. This favours its application as power storage devices. A typical application is at electrically controlled door opening systems, where they are used to accumulate power that is released to open the door. Storage of spring energy also requires continuous application of force to keep spring in compressed form. In a recent work (2015) Rossi *et.al.* [4] discussed about the benefits and challenges of using mechanical spring like systems if they are used as energy storage device. In his/her work [4] he/she mentioned the importance of storing energy in elastic format and clearly indicates the advantage of this format in comparison to the electrical, electrochemical, chemical, and thermal energy storages because of its ability to discharge quickly, enabling high power densities. He/she pointed out that this available amount of stored energy may be delivered not only to mechanical loads, but also to systems those convert it to drive an electrical load. He/she studied the energy storage systems with conventional torsional springs and presented a data showing the relative energy densities of different spring materials. In another patented work by Cripps [5] a self-sustaining electrical power generating system that includes a spring system with stored energy was discussed and invented. The spring system used, have an input and an output for recharging and releasing the stored energy respectively.

With a view of such background idea we plan to design an inductor and quite reasonably that may also be used as a spring. While designing the inductor we plan to vary the flux linked through it without varying the current passing through it. We let the length of the inductor vary in course of time keeping the current constant. So that flux linked with the device should also vary with time. We connect the spring-shaped inductor of initial length L to a resistance R and a dc cell of electromotive force E in series. We design the spring-inductor with large number of turns N and large loop area A.

Also we are looking for large constant current I to pass through it. When a current is passed through the spring-inductor its each turn will carry the same current in the same direction, forming parallel current elements. Hence all these turns will attract each other and clearly the resultant pull on each loop is towards the centre of the spring-inductor. Also due to the choice of large N, A, I these pulling force is sufficiently strong and the spring starts compressing. We can write the expression of this internal pull on the entire spring following Bio-Savart law

$$F = \frac{\mu_0 I^2}{4\pi}\sum_{i=1}^{N}\sum_{j=1}^{N-1}\oint_{L_1}\overrightarrow{dl_l} \times \oint_{L_2}\frac{\overrightarrow{dl_2} \times \overrightarrow{a}_{R_{21}}}{R_{21}^{\;2}}. \tag{1}$$

Let at any instant of time t the spring compresses by a length x and hence the flux linked through it

$$\varphi = \frac{\mu_0 NAI}{L-x}. \tag{2}$$

Magnetic Induction $\vec{B}$ and inductance L_I also varies with the spring compression. Application of Faraday's law and KVL in the series LR circuit (with the assumption of constant current) described earlier one obtains

$$E - \frac{\mu_0 NAI}{(L-x)^2}\frac{dx}{dt} = RI. \tag{3}$$

The constant current assumption demands

$$\frac{\mu_0 NA}{(L-x)^2}\frac{dx}{dt} = E_b, \tag{4}$$

where E_b being the constant back electromotive force generated by spring-inductor (if at all exists). We will come back to this point once we establish our assumption.

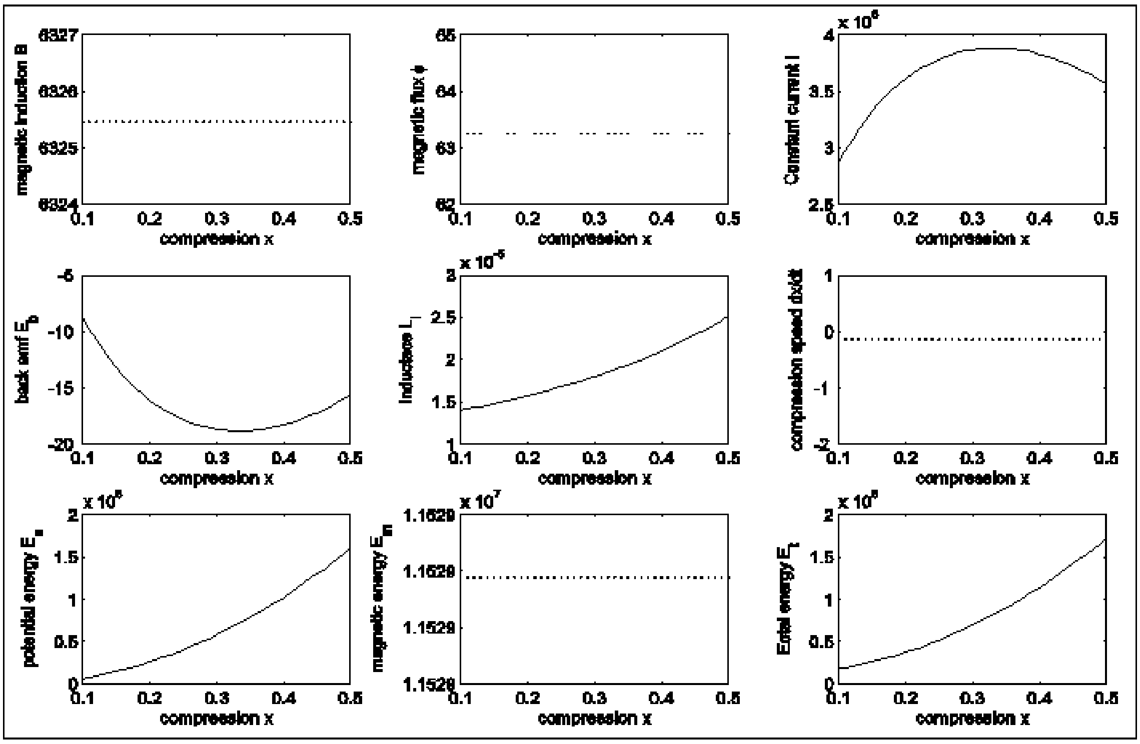

Figure 1: Variation of all the parameters of the system with spring compression x. Parameter names are mentioned in the figure label

Paper ID: SR25418214402 DOI: https://dx.doi.org/10.21275/SR25418214402

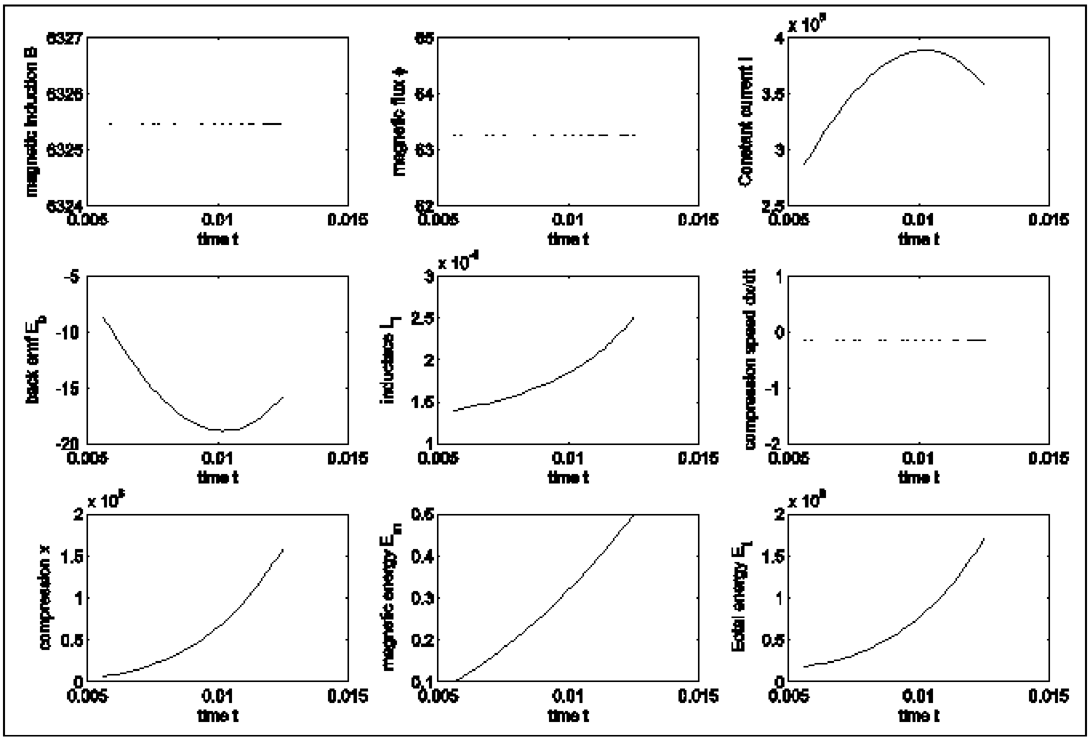

Figure 2: *Variation of all the parameters of the system with time t. Parameter names are mentioned in the figure label*

We now look into the energy analysis of this system. The only source of energy of this dynamical system is the dc battery (chemical energy) or storage cell (electrical energy) with constant current which is supplying continuous energy to the system under concern. One part of which is dissipated in the resistor and the remaining part is stored as the elastic potential energy of the spring and the electromagnetic energy of the inductance. The kinetic energy of the spring is neglected assuming light spring assumption. Knowing the expression of electromagnetic energy stored per unit volume of the inductance one may write the energy flow equation of the LR circuit at any given time t (spring constant $K = YA/L$, Y Elastic Modulus of the material)

$$\int_0^t EIdt = \frac{\mu_0 N^2 A I^2}{2(L-x)} + \frac{Kx^2}{2} + \int_0^t I^2 R dt. \tag{5}$$

Constant current demand leads to

$$EIt = \frac{\mu_0 N^2 A I^2}{2(L-x)} + \frac{Kx^2}{2} + I^2 Rt. \tag{6}$$

This equation with constant current I is right not valid for $t = 0$, as at $t = 0$, $x = 0$ and I has to be zero (from the previous equation). After some initial compression of the spring the current should become constant. We shall take into consideration this fact while choosing suitable numerical values of the system parameters. Time derivative of (6) yields

$$\frac{dx}{dt} = \frac{2\left(EI - I^2 R\right)(L-x)^2}{2\frac{YA}{L}x(L-x)^2 - \mu_0 N^2 A I^2}. \tag{7}$$

If we take copper wire to construct the spring, then $Y \sim 10^{11} Nmt^{\;2}$ and $\mu_0 \sim 10^{\;6} Hmt^{\;1}$ (SI), so even for moderate large values of N, A and I the second term in the denominator of (7) may be neglected in compared to the first term. In other words

$$\frac{dx}{dt} = \frac{IL(E - IR)}{YAx}. \tag{8}$$

Using (8) in (3) and a few algebraic steps yield

$$I = \frac{\sqrt{x}(L-x)}{\sqrt{NL}}\sqrt{\frac{Y}{\mu_0}}. \tag{9}$$

To verify whether or not one may achieve a constant current using these special inductor we choose a typical set of parameter with $L = 1mt$, $N = 10^3$ and the basic or minimum length of the spring $L_{min} = L/2$. Clearly the basic or minimum length of the spring is equal to the total number of turns of the spring multiplied by the constant thickness of spring wire. Consequently the maximum compression of the spring will be $x_{max} = L - L_{min} = L/2$. Numerical computation shows that for a range of values of x in between $0.1mt$ to $0.5mt$ (we start with some initial compression $0.1mt$ because of the reason explained earlier) the variable part of (9) remains almost constant ($\sqrt{x}(L-x) \approx 0.37$, see **Fig.3**)

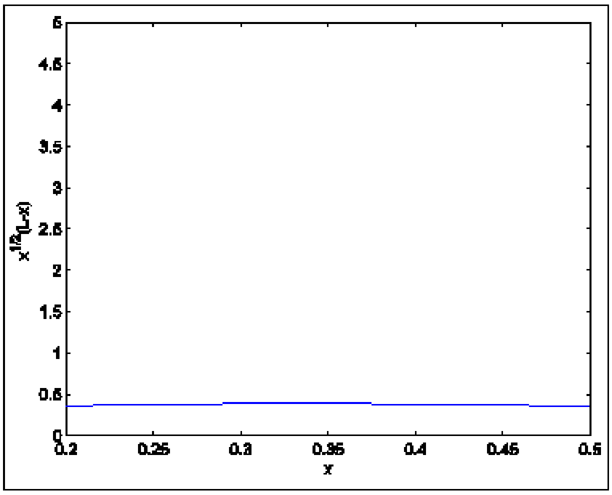

Figure 3: *Variation of* $\sqrt{x}(L-x)$ *with* x *for* $L=1$ *mt.*

which gives a very large constant current of the order of $10^6 A$ flowing through the circuit. So, we must take R very very small. A typical choice of $R = 10^5$ *ohm* computes a back e.m.f. of order 10 *volt*. A dc battery with $E = 20V$ will do the job here.

$$E_b = E - \frac{\sqrt{x}(L-x)R}{\sqrt{NL}}\sqrt{\frac{Y}{\mu_0}}. \tag{10}$$

(10) gives the expression of back electromotive force generated due to the spring-inductance. The device will operate for a time T as long as the spring does not reach to its maximum compression which may be determined from (6)

$$T = \frac{\dfrac{\mu_0 N^2 A I^2}{2L_{min}} + \dfrac{K(L-L_{min})^2}{2}}{I(E-IR)}. \tag{11}$$

Substitution of constant current I from (9) in (6) and (11) the dynamical equation of the system and the maximum compression time will become (with our preferred choice $L_{min} = L/2$ for large N)

$$t = \frac{\mu_0^{1/2} A Y^{1/2} N^{3/2}}{2L^{1/2}(E-IR)} x^{1/2} \tag{12}$$

and

$$T = \frac{\mu_0^{1/2} A Y^{1/2} N^{3/2}}{2^{3/2}(E-IR)}. \tag{13}$$

(12) indicates a parabolic dynamics of the spring compression. We choose $A = 0.01 mt^2$ and obtain $T = 0.0125S$. Once after the spring reached its maximum compressed state, automatically dx/dt vanishes and the flux will become stable, consequently the back electromotive force vanishes and hence the current through the device will increase. But because of the presence of magnetic field, the attractive force between the spring loops is still present so the spring remains in it compressed state. New current will be simply E/R. For our choice of parameter it will be $2x\ 10^6$ A. The compressed spring-inductor now stores a combination of magnetic and mechanical energy and may be used as an energy source. However, there are certain limitations of our model. We mention them below:

- The proposed model in this manuscript is a pure theoretical model and lacking any experimental verification, however we have included simulations using MATLAB (**Fig.1** and **Fig.2**) as far as practicable.
- As this is a theoretical modelling hence the practical constraints like material fatigue of the spring(s), energy losses due to resistance heating (Joule Heating), mechanical damping, electromagnetic losses due to leakage etc. are omitted here which may impact on the performance of the device under real situations.
- Theoretical nature of our modelling also restricts us from comparison of our work with real-world existing energy storage technological applications like those used in industries, biomedical sectors etc. in terms of efficiency and feasibility.
- The assumption of constant current in the *LR* circuit model may not hold in real-world conditions due to variations in resistance, inductance, and external factors.
- We have used a set of model numerical data here, which may not match with the real situations.

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