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Design and Simulation of Four-Wheel Engagement of Regenerative Brake System

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ABSTRACT

The project employed Simulink MATLAB package to design and simulate a regenerative brake that utilizes four electric motors to engage the vehicle's wheel. The engagement of the electric motors is telescopic in nature, such that one electric motor engages the wheel per time depending on the degree to which brake pedal is depressed, with emphasis on the drive axle, and then the dead axle. The results from the simulation showed that vehicles torque decreased from 294.47Nm to 12.27Nm, while the regenerative brake torque increased from 0Nm to 147.61Nm, showing that the regenerative braking significantly decelerated the vehicle's speed by about 96%. This is reflected in the voltage as the terminal of the electric motor starts at its peak at 3.08V and thereafter drops to 0.03V, while the current harvested from the vehicle peaked from 614.15A and progressively decreased to 421.04A as long as the vehicle is in motion. However, the study showed that about 48.67% of the energy that the regenerative brake system would have saved was lost when the friction brake was activated alongside the regenerative brakes.

Keywords: Regenerative Brake System, Friction Brakes, Telescopic.

1 Introduction

From ancient times various means of transportation have employed, from trekking, to rudimentary slides from trunks of trees, to wheels used in carts, animal usage (cows, camels, horse) with carted wheels, steam engine, rails and rails tracks, and vehicles. Continual improvements have been going on to date. Regenerative brake system is one such improvement that meets such eminent need in this time were premium is on safety of the users and the environment. This promises to restore energy that would have been lost to the environment back to the system while drastically reducing the wastes deployed into the environment. [1] research looked into the wear rate of brake pads on LRV Series 1100 bogies, namely the McA and McB bogies and the results reveal that the thickness of the brake pads decreases with braking force and friction, with regenerative and pneumatic braking playing important roles in reducing wear rate. The RBS Investigations on an inertia dynamometer replicate regenerative braking system and show a fantastic approach to minimize vehicle waste and environmental effect. Such an advantage is demonstrated

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by [3] whose research on an inertia dynamometer imitate regenerative braking systems utilizing speed-controlled test cycles. The study also investigates a control approach that combines RBS action with traditional friction brakes, to dramatically reduce brake wear emissions. The Regenerative Brake System (RBS) is a potent device that reduces fuel consumption by turning mechanical energy into electrical energy when braking, according to research by [12]. This technology is essential to electrical and hybrid cars, and the energy it recovers can be utilized in research projects in the future. This technology is essential for addressing restricted vehicle range and enhancing the range of electric vehicles, according to [6]. The calculations, which were conducted using AMESim and Matlab/Simulink, show that at various braking intensities of 30 km/h, the power battery's SOC, or state of charge, increases dramatically. This leads to an increase in battery energy of 6.5wh and an energy recovery of up to 20.5%. Instead of turning kinetic energy into thermal energy, they increase fuel economy by converting kinetic energy into electric energy and using the alternator concept to charge the battery was the conclusion of [12]. A noteworthy advancement was showcased by [13]. The authors suggest a technique that conserves kinetic energy by applying the maximum braking force in accordance with the speed of the vehicle. To do this, they suggest utilizing train information control systems and make-believe trains. A research by [11] created a regenerative braking system for electric scooters with an emphasis on environmental preservation and energy efficiency. By attaching an ionistor in parallel to the battery, which charges more quickly than the battery itself, the approach works. The fact that drivers can employ brake pads in emergency situations indicates that more study is necessary to completely eliminate the need of brake pads. [8], improved regenerative braking control in intelligent transportation systems by utilizing Model Predictive Control (MPC). The research takes into account several braking techniques, including conservative, forceful, and moderate. According to the simulation's results, an aggressive approach performs well while a cautious one is more efficient and comfortable. [2] investigated the frequency of the braking period while employing pulse width module (PWM) control for regenerative braking. The study finds that 10 Hz PWM control provides a pleasant and effective regenerative braking with a 54.3 percent efficiency when comparing pulse signal with full period signal. The control strategy of autonomous cars, which is based on the control algorithm developed by [5], is critical for improving driving comfort. The suggested comfort regenerative braking system (CRBS) adjusts the control algorithm depending on acceleration and deceleration restrictions using artificial neural networks. The efficacy of the approach was validated using Car Sim and MATLAB/Simulink simulations, resulting in better driving comfort for passengers. [7] examined the innovative front-to-rear axle brake force distribution approach for regenerative braking management in a high-speed electric vehicle. In order to facilitate energy recovery and improve braking performance, the method modifies brake proportioning. When the concept is implemented in Simcenter Amesim, front-wheel drive electric cars' energy recuperation is greatly improved, and the control design is also practical for high-speed drives. The link between shifting braking force distributions and noise in electric vehicles is examined in the study by [4]. It uses a closed-loop coupling disk brake model to determine the relationship between contact coupling stiffness and braking force. The investigation shows that the second braking strategy reduces brake noise more than the first, proving the effectiveness and reliability of the recommended technique.

From these studies, there is indeed rapid work going into improving RBS. This project aims to eradicate the need of convention friction brakes by improving the braking force capacity of regenerative brake system, with a four-wheel electric motor in-place design as shown in Fig. 1.

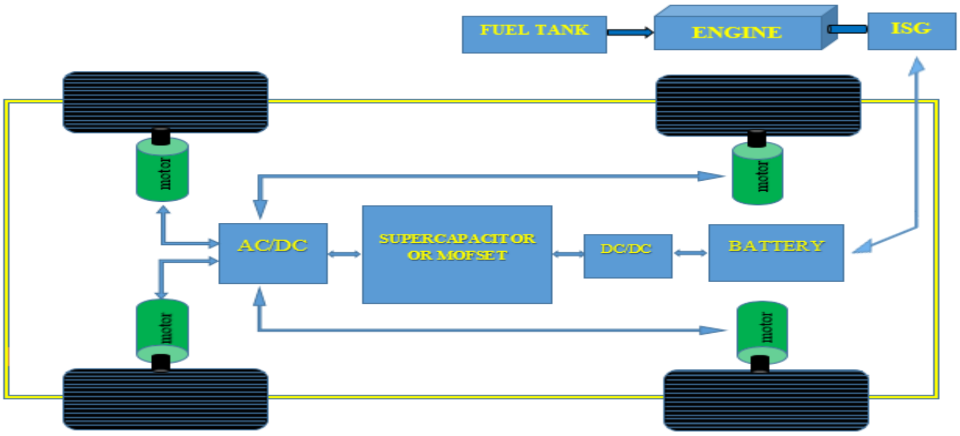

Fig.1: Vehicle schematics

1.1 Research Methodology

The regenerative brake system proposed system is carried out on the Simulink framework in MATLAB. The software is used to analyse the functionality of the system by touching how it would work, the system's nature, the efficiency of the system, and the expected outcomes/results.

Regenerative Brake System Configuration

Below in Fig. 2 is the Simulink configuration of the proposed regenerative brake system below.

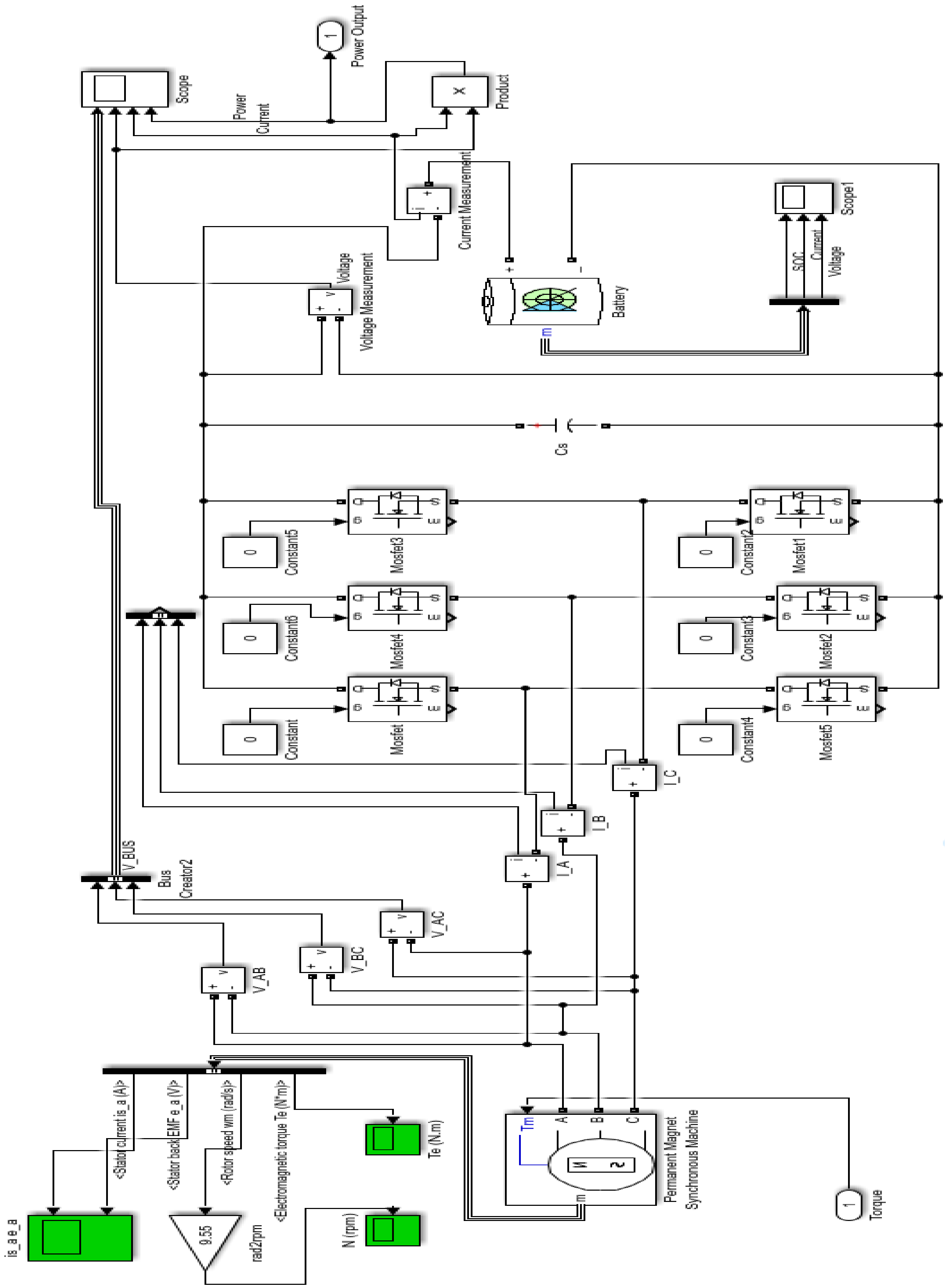

Fig. 2: RBS pedal control diagram part.

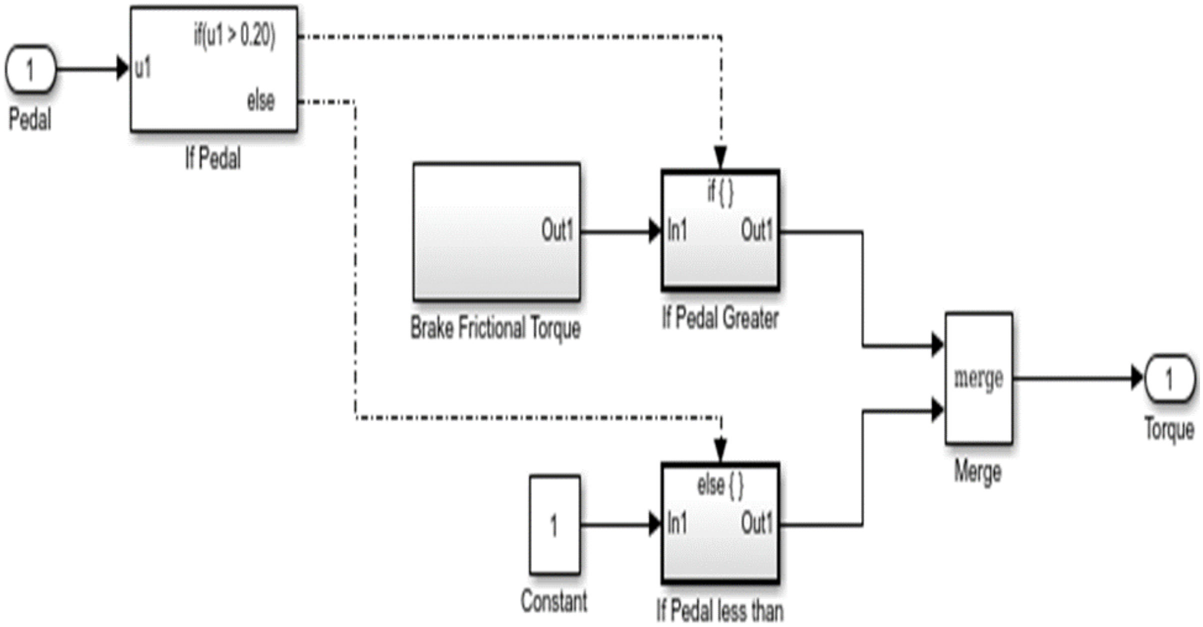

Fig. 3: Friction pedal control diagram part.

The diagram contains the necessary components needed for the functionality of the RBS. The diagram contains commands that allow the proposed system behaviour in relation to the brake pedal. The first block contains a programmed behaviour that tells the RBS to activate if there is any increase in pedal angle other than zero.

The second block diagram is the part of the frictional brake. It gives the command to the system that the friction brake should activate when the pedal angle is greater than 20^0. At this point, it means that the RBS braking torque delivered to stop the vehicle is not enough and the conventional brake is then initiated.

Fig. 4 shows the Complete System Configuration Simulink Diagram

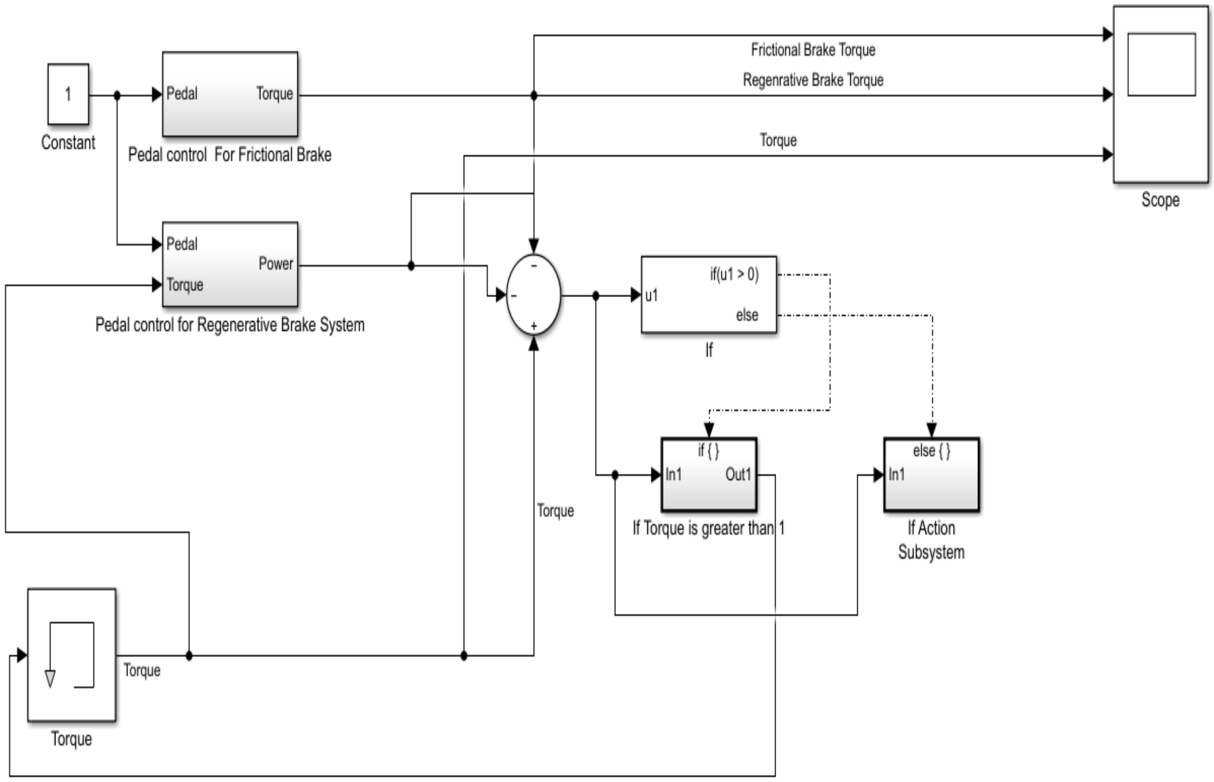

Fig.4: RBS and friction brake Simulink block diagram.

Different approaches have been applied over time to improve the state of the RBS technology. As a way of progress, the method and design proposed in this project are the means to better the RBS.

1.2 Operation of the Regenerative System Design

The design uses four electric motors to effectively halt or retract the vehicle's motion. The four electric motors can either engage simultaneously or progressively depending on the degree to which the pedal is depressed. The electric motor engagement could either be on wheel or gearbox engagement. This is done with the use of a motor controller which is designed to respond to the pedal angle position.

From our proposed system design, two electric motor engages first, one at the front right wheel and the other at the left rear wheel as in Fig. 5 and Fig. 6. Depending on the type of drive, whether front-wheel drive or rear-wheel drive, the third electric motor engages at the drive wheel, as shown in Fig.7 and Fig. 8. Fig. 9 and Fig. 10 show the fourth electric motor in engagement with the dead axle. This engagement of the electric motors is all controlled by the brake pedal design. One of the advantages of this design is that it gives far better stability to the vehicle than other design configurations. This is due to the even weight distribution of the electric motor, unlike the other configuration which has an uneven distribution which also calls for a design that will eliminate this disadvantage. Also, the engagement sequence order is great for stability. The outer thicker arrow indicates the electric motor is engaged at a particular interval/instant of pedal depression.

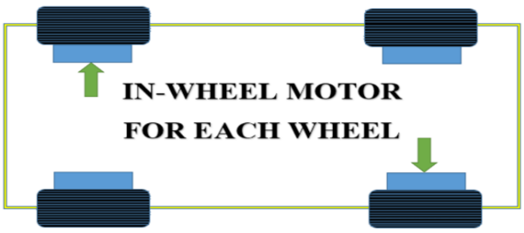

Fig. 5: Four electric motors on wheel design (two motors in engagement).

Fig. 6: Four electric motor gearbox design. (two motors in engagement).

Fig. 7: Four electric motor gearbox designs (three motors in engagement).

Fig. 8: Four electric motors on wheel design (three motors in engagement).

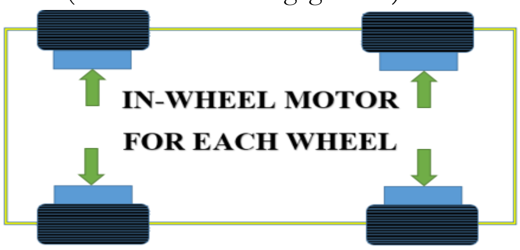

Fig. 9: Four electric motor gearbox design (four motors in engagement).

Fig. 10: Four electric motors on wheel design (four motors in engagement).

2 Theory and Calculation

The regenerative brake system is an improvement on the conventional brake system which takes advantage of the electromagnetic principle in recovering of the energy that would have been lost to the surroundings. First, according to Faraday's law, an induced magnetic field (e.m.f.) occurs in a conductor anytime there is an electric or magnetic field and the conductor cuts it at a variable rate, or when a fluctuating electric or magnetic field cuts a conductor, [1]. The e.m.f.'s intensity and level are dependent on a few variables such as the speed of the conductor if it's the one moving, rate of change of the electric/magnetic flux, strength of the flux, the number of turns if more than one, and the presence of material with high susceptibility, e.g., iron, [14].

Considering these factors, one can incorporate ideas such as these in electric motors which produce electric current from the driving force which moves the shaft around to cut the varying flux of the field or as a dynamo which acts as a motor by application of electromotive force via current to the motor which makes it undergo rotary motion. When this is utilized, the car's wheels and electric motor are linked, and the electric motor rotates in tandem with the wheels. Electrical energy produced by the motor's action is expended in one way or another. How frequently, how hard, and how long the brakes are used determines how much energy is wasted overall in the process. The energy can be stored or used directly by the car system. Using the latter is not the best as energy will be lost at one point or the other due to storage of energy and later being converted to the form in which it is now being needed, a process that is not 100% efficient, leading to another source of energy loss. But the former case uses up the energy directly and does not cause energy loss since no storage process is required which will then in turn call for conversion back to the needed form. If connections were made from the electric motor to the battery, the battery will be charged up which can be used later by the car.

2.1 Working Principle of the Regenerative Brake System

When the vehicle is in motion and there is a need to bring it to rest, the brake pedal is depressed. The brake system having both the regenerative brake system and the conventional brake system actuates the regenerative brake system through the use of sensors or the brake system configuration in some cases which may have modifications to the initial brake settings. In some cases, the design may be in the form of telescopic shock absorber, [10]. The action of the brake pedal causes the electric motor of the regenerative brakes to mesh with the wheel shaft. This causes the rotational motion of the wheel shaft to be transferred to the electric motor. This action through the rotation of the electric motor induces an electromotive force in the electric motor in accordance with Faraday's law of electromagnetism, [1]. This e.m.f. drives current through a circuit and it always acts in a direction that opposes the source producing it in accordance to Lenz's law. This is because, in this regard, the electric motor functions as a generator. The electromagnetic force (EMF) is called back and, in line with the Lorentz force law, it produces an electromagnetic force that applies a negative torque to the wheel shaft, causing it to decelerate was the implication from the theory of [14]. The energy that the regenerative braking system produces during braking can be immediately supplied into the flywheel as kinetic energy or stored in a battery. The latter is better as it does not abhor energy losses due to storing and converting back to the form it is now needed, [1]. The conventional braking system, or friction braking, is required to apply the remaining braking force to stop the vehicle if the regenerative brake system is unable to do so because of the vehicle's high speed or the necessity for a quick descent when the regenerative brake system cannot absorb as much energy as the instant requires. This situation arises due to some limitations of the electric motors.

Unlike most model of regenerative brake models, the design of a circuit system that controls the braking action is introduced. The braking system/style is usually complicated and requires new braking sense as the old conventional braking style differs from the new one. This could lead to serious trouble in case of emergency or accident area as explained by [10].

To avoid this, a better system of new brakes is proposed which will not introduce complications during braking. From careful study of the brake pedal in relation to the braking conditions, a new brake pedal can be modeled. From the analysis of [10], it is observed that from 0^0 to 18^0 the braking force required is normal somewhat like in stop-and-go situations. Beyond 18^0, the braking is an emergency and needs prompt action. The brake pedal is designed such that from 0^0 to 10^0 the front right and rear left electric motors will engage action. When further barking force is required, the front left electric motor will engage, and join the braking action once the brake pedal is decreased beyond 10^0 to 15^0 to produce further the back e.m.f. When the pedal is depressed between 15^0 to $19^{0,}$ the rear right electric motor engages to contribute its back e.m.f. Beyond 19^0, the conventional frictional brake is introduced to help halt the vehicle by supplying the additional necessary braking torque required.

2.2 Mathematical Expressions and Symbols

The brake is used when a vehicle has to be stopped or its speed reduced. The ground contact area of the tire experiences braking force as a result of the braking torque applied by this brake, which continues until the ground contact region is no longer able to bear the force. This means that the amount of braking torque needed to stop or slow down a vehicle depends on its speed. It is a function of the vehicle's acceleration and speed. The car's weight and the tire's ground contact area determine the adhesive ground coefficient's maximum value. The braking force is determined using equation (1)

$$F_b = \mu W \qquad \dots (1)$$

Where W is the vehicle's weight, μ is the coefficient of ground contact area, and F_b is the braking force. This force is the highest braking power the brake system is capable of providing. This is due to the car's constant weight and constant coefficient of ground contact area. This indicates that the braking force cannot be applied any higher once it reaches this maximum level. The braking force stays constant at its highest amount, but the braking torque can now grow even more. Because the aerodynamic and air resistance forces are negligible when compared to the braking force, they may be disregarded.

The combined braking force of the vehicle's front and rear wheels is the overall braking force, and it is computed using equation (2).

$$J = \frac{F_{bf} + F_{br}}{M} \qquad \dots (2)$$

Where M is the vehicle's mass, J is the deceleration, F_{br} is the force applied to the back wheels, and F_{bf} is the force applied to the front wheels.

Momentum is moved from the back to the front during braking.

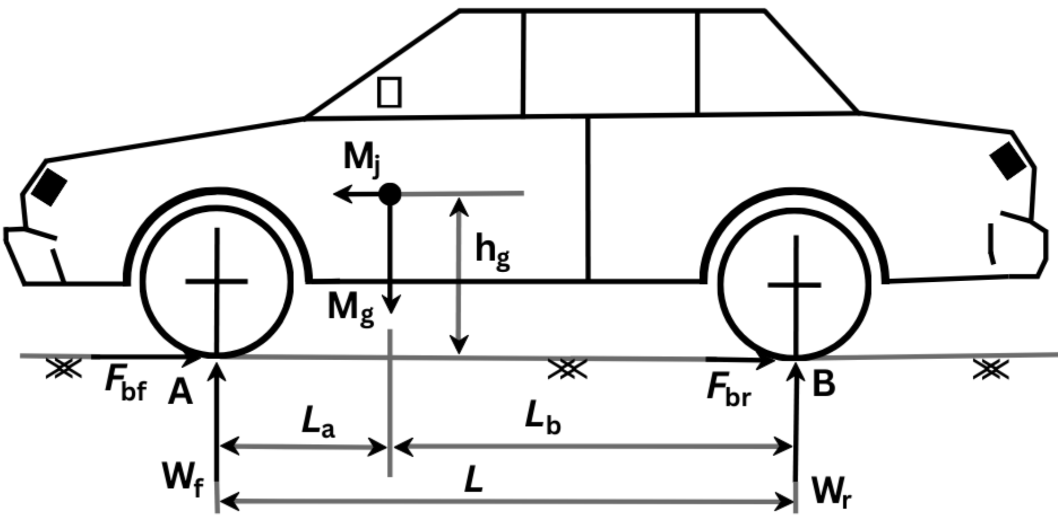

Fig. 11: Vehicle schematic, Price [9].

Weight is transferred from the rear axle to the front axle while braking. The moment balance between points A and B may be used to define the weight over the front and rear axles depicted in equation (3) as follows:

$$W_f = \frac{Mg}{L}\left(L_b + \frac{h_g J}{g}\right) \quad \text{... (3)}$$

Where g is the acceleration brought on by gravity and W_r and W_f, respectively, are the normal loads on the front and rear axles.

From the above equations, we get the ratio of the normal forces presented in equation (5) as;

$$\frac{F_{bf}}{F_{br}} = \frac{W_f}{W_r} = \frac{L_b + \frac{h_g J}{g}}{L_a - \frac{h_g J}{g}} \quad \text{... (5)}$$

It is possible to determine the front and rear braking forces by plugging equation 2 into equation 5. These are exemplified by

$$F_{bf} = \frac{JM}{L}\left(L_b + \frac{h_g J}{g}\right) \quad \text{... (6)}$$

$$F_{br} = \frac{JM}{L}\left(L_a - \frac{h_g J}{g}\right) \quad \text{... (7)}$$

This point is the road adhesive coefficient, or μ, for that particular road. The rear wheels will lock up first if the road adhesive coefficient is larger than μ. Nevertheless, the front wheels will lock before the back wheels if the road adhesive coefficient is below μ. This may have a significant impact on the stability of the car. The car will lose directional stability if the back wheels lock up since they can no longer withstand side stresses. The vehicle will spin out of control if an external source—such as wind or centrifugal force—introduces a slight side force as explained by [10]. Alternatively, the car will lose directional stability but not control if the front wheels lock up. This implies that while the car will still travel straight ahead, the driver will not be able to manoeuvre it left or right. You can restore directional control by releasing the brakes a little bit. Therefore, it is crucial that the rear wheels avoid locking up initially since, even with the brakes fully released, control of the vehicle cannot be regained if the back wheels lock up and the car has spun out to some extent.

3 Results and Discussion

The following results ranging from Fig. 12 to fig. 15 were obtained from the MATLAB Simulink model, the simplified form of these results were tabulated in table 2 to table 5.

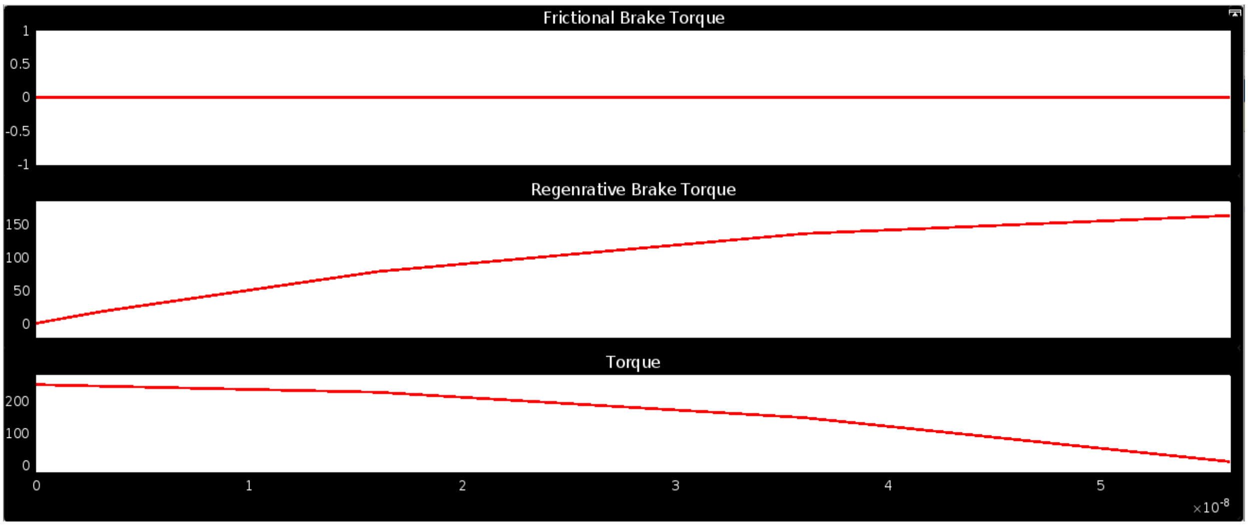

Fig. 12: First graph of friction, RBS, and car torque respectively.

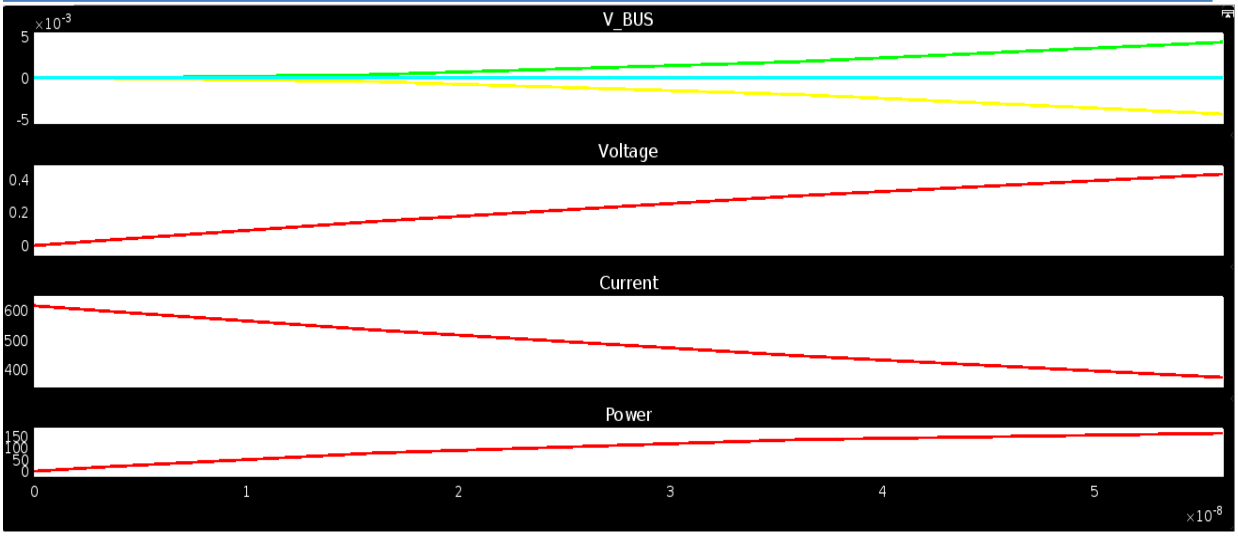

Fig. 13: First graph of RBS voltage, current, and power respectively.

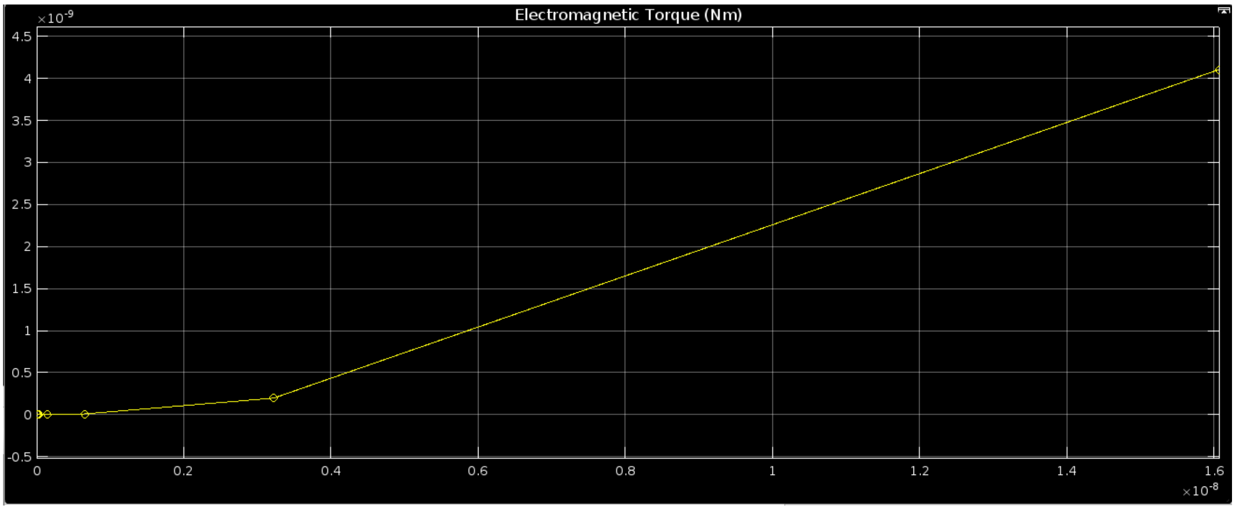

Fig. 14: Electromagnetic Torque

Table 2 *Vehicle torque, regenerative torque, and friction torque first simulation value.*

S/N	VEHICLE TORQUE (Nm)	REGENERATIVE BRAKE TURQUE(Nm)	FRICTION BRAKE TORQUE(Nm)
1	249.470512000000	0	0
2	249.470512000000	1.89520579146143e-20	0
3	249.470512000000	0.0981236533678309	0
4	249.372388346632	0.0981236533678327	0
5	249.274264693264	0.221452198487101	0
6	249.052812494777	0.837095272059369	0
7	248.215717222718	3.89042765502236	0
8	244.325289567696	18.5483526495518	0
9	225.776936918144	78.1676850233441	0
10	147.609251894800	135.335085755821	0
11	12.2741661389788	147.609251894799	0

Table 3: *Regenerative current, voltage, and power first simulation value.*

S/N	VOLTAGE(V)	CURRENT(A)	POWER(W)
1	0	614.154724136377	0
2	3.08587676196168e-23	614.154724136377	1.89520579146143e-20
3	0.000159793150896642	614.066703217459	0.0981236533678309
4	0.000159793150896645	614.066703217459	0.0981236533678327
5	0.000360697159500652	613.956036675416	0.221452198487101
6	0.00136467423192907	613.403003056688	0.837095272059369
7	0.00637101057780120	610.645298342143	3.89042765502236
8	0.0310671008975420	597.041632906895	18.5483526495518
9	0.146536103602119	533.436355286123	78.1676850233441
10	0.302353537714073	447.605431638122	135.335085755821
11	0.350584249742345	421.037887478635	147.609251894799

From Fig. 12 and Fig. 13, it is apparent that the behaviour of the system is different for the new pedal position. When the brake is applied, the wheel's torque starts to reduce progressively from 249.47Nm to 12.27Nm while the torque gained by the regenerative motor brake starts to increase progressively as well from 0Nm to 147.61Nm.

At the same instant, the graph of the voltage from the terminal of the electric motor starts at its peak at 0V relative to the speed/torque of the moving vehicle. This voltage of the RBS increases due to the braking effect of the regenerative motor(s) which necessitate generation of the voltage to drive current. It finally reaches 0.35V. Fig. 12 and Fig. 13 also shows that the current harvested from the vehicle starts from 614.15A and progressively decreases as long as the vehicle is in motion to 421.04A. This current manifest as eddy current, and is in a direction as to oppose its source in order to bring about the braking effect.

From the results of the graphs plotted via the scope as seen in Fig. 12 and Fig. 13, it is apparent that the torque of the moving vehicle wheel was at a high level of 294.47Nm from just before the brake was applied. The energy harvested is also reflected in the electromagnetic torque shown in Fig. 14 where there is progressive increase in the in graph generated. This reduces progressively as the torque of the regenerative brake increases to 12.27Nm while the regenerative brake system gained this torque which is reflected in the value, from 0Nm to 147.61Nm as seen in Table 2.

The power as referenced from Table 3 increases as well from 0W to 147.61W, showing that considerable amount of power (work is done in on the RBS motors within the scope of time of application of the brakes) is recovered from the energy that would have been otherwise lost to the environment via conventional braking. This shows that energy is always recovered via a regenerative braking system.

This graph also indicates that the friction brake is inactive during this braking operation as long as the brake pedal does not get depressed beyond 19^0, showing that the need for the friction brake is greatly reduced and will not be needed when there is no need for heavy braking. Hence, energy is saved.

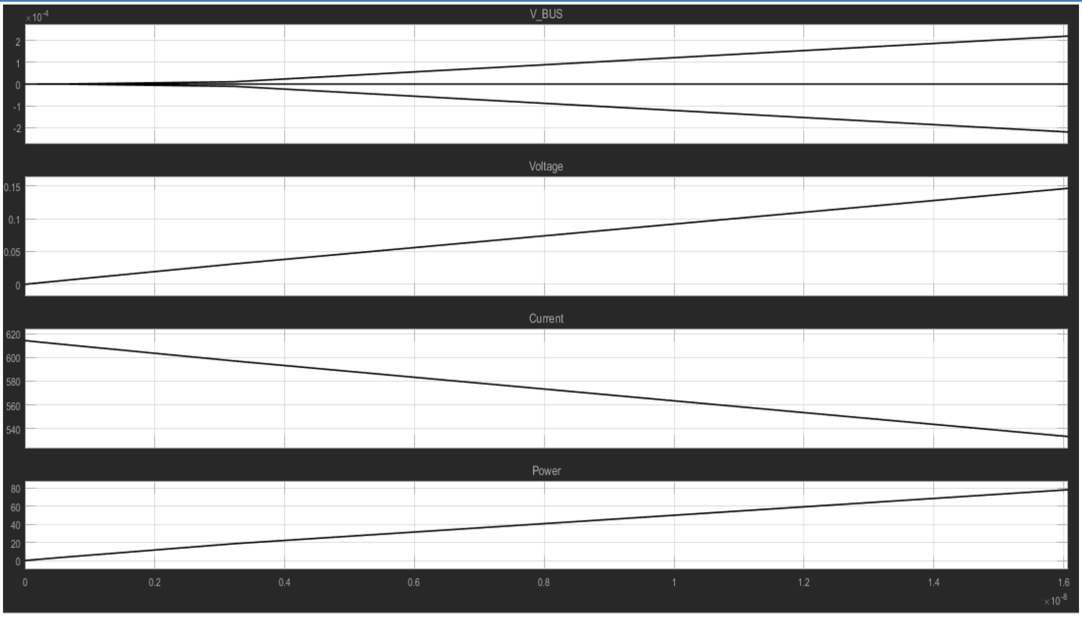

Fig. 15: Second graph of RBS voltage, current, and power respectively.

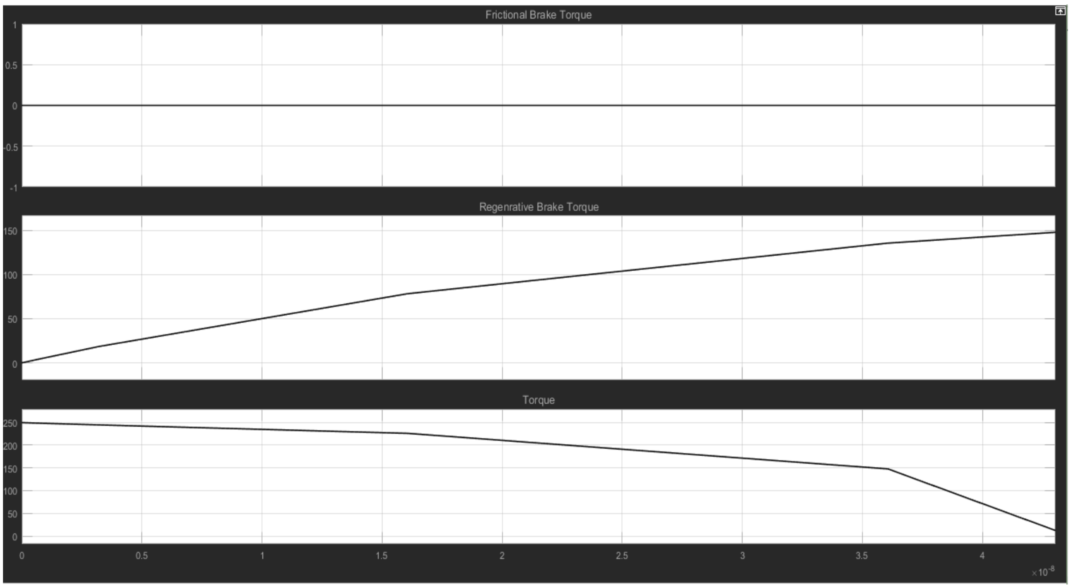

Fig. 16: Second graph of friction, RBS, and car torque respectively.

Table 4: *Vehicle torque, regenerative torque, and friction torque second simulation value.*

S/N	VEHICLE TORQUE (Nm)	REGENERATIVE BRAKE TORQUE(Nm)	FRICTIONAL BRAKE TORQUE(Nm)
1	249.470512000000	0	18
2	231.470512000000	1.8952e-20	18
3	213.470512000000	0.1019	18
4	195.368645374381	0.1019	18
5	177.266778748761	0.2252	18
6	159.041585601642	0.8408	18
7	140.200759486288	3.8941	18
8	118.306651197009	18.5518	18
9	81.7548611733931	78.1701	18

Table 5: *Vehicle torque, regenerative torque and friction torque second simulation value.*

S/N	VOLTAGE(V)	CURRENT(A)	POWER(W)
1	0	614.154724136377	0
2	3.08587676196168e-23	614.154724136377	1.89520579146143e-20
3	0.000165889441910402	614.063345118979	0.101866625619422
4	0.000165889441910405	614.063345118979	0.101866625619424
5	0.000366792351846367	613.952679182130	0.225193147119592
6	0.00137076393390386	613.399648587733	0.840826115353367
7	0.00637707290201582	610.641958954033	3.89410828927962
8	0.0310730281681783	597.038367912087	18.5517900236155
9	0.146541399416448	533.433438124523	78.1700825182947

The data obtained from the second simulation is quite different from the first due to the introduction of the friction brakes. Looking through Table 5, the voltage is quite smaller compared to that of Table 6, which shows that there less torque available to high enough voltage as it was when the friction brakes are not activated. This means that less current will be delivered to the battery from the RBS terminal for the given time frame.

From the new results from the second simulation, as shown in Table 4, we can see that the friction brake took the torque of the vehicle at the rate of 18Nm while that of the regenerative brake system varied based on the value of the car torque remaining. It can also be observed that the time frame of the process is shorter compared to the first simulation in which the friction brake is not activated. This is because in the first simulation, only the regenerative brake system is doing the work unlike in the second case in which the torque available is also being consumed by the friction brake.

The power derived from the braking process when the friction brakes are activated alongside the regenerative brake system is 78.17W, which is smaller compared to 147.60W when not activated, i.e. about 47.04% of the energy saved from the case of only regenerative braking is lost when the friction brake is activated. The results show that the regenerative brake system is not only germane in energy recovery that would have been lost to the environment but also a potential means of revolutionizing the transportation industries by increasing the driving range of vehicles, especially electric vehicles which promises to be more environmentally friendly.

4 Conclusions

The regenerative brake system is certainly an added advantage to the automobile industry. The regenerative brake design with four electric motors in this design has greater braking output due to the additional back electromotive force from the other three electric motors against the other single electric motor design. From the simulation results, it was obvious that the design has rendered to a large extent the redundancy of the conventional friction brake system and added advantage of saving 48.67% of the energy, however, they could have been energy losses due to friction. The choice of design and the meshing order not only improve the state of the technology but also help ensure safety.

Furthermore, the use of additional components such as MOSFET, rectifier, etc. has improved the level of energy harvested from the system.

5 Declarations

5.1 Study Limitations

Some of the limitations of the project are, that increases weight to around 25-30 Kg, and when the battery is fully charged, the braking becomes ineffective. Also, the limitation posed by unavailability of required equipment needed for the fabrication of the designed RBS.

5.2 Acknowledgements

All acknowledgments (if any) should be included in a separate section before the references and may include list of peoples who contributed to the work in the manuscript but not listed in the author list.

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