Energy Regeneration from Decelerating Vehicle

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***Abstract*—Up to now most car braking systems use hydraulic braking technology, which converts the excess of kinetic energy into heat, effectively resulting in an energy loss. Regenerative breaking technology supposedly deals with this problem by converting kinetic energy back into electrical energy that can then be reused for example during acceleration. Current hybrid vehicles are equipped with regenerative braking technology which makes them particularly interesting for situations with frequent deceleration, like city traffic. However, the technology used in these vehicles has its limitations and therefore does not stand on its own, but is assisted with conventional hydraulic brakes. This paper looks at removing this limitation and allowing a vehicle to fully rely on regenerative braking technology to deal with any braking situation ranging from simple slow down to full emergency braking. To enable this, multiple generators with different gear ratios are used. The additional benefit of this construction is that the generators can be used as electrical engines and ensure proper acceleration at any speed. The paper shows that the overall efficiency of the system is very close to the efficiency of the generators used while achieving braking performance similar to conventional braking mechanisms.**

I. Introduction

The energy crisis has started quite a while ago and the situation is unlikely to improve in the near future. Hence, an increased effort in determining different technologies to improve on fuel efficiency are being investigated. One of these improvements looks at the use of electrical motors for transportation, largely due to the high efficiency of these motors. The initial implications of the use of electrical motors has translated itself in a set of hybrid vehicles, whereas also fully electrical vehicles are becoming more main stream [1]. Since any electrical motor can also be used as a generator, and vice versa, hybrid vehicles make us of this principle to convert kinetic energy back into electrical energy during braking. However, most current hybrid vehicles are equipped with a single electrical motor [3], which has certain limitations. Since a generator will only be effective within a certain rpm-range, there is a limited spectrum within which kinetic energy will be converted into electrical energy. Consequently, it is impossible to use this generator to deal with all possible braking situations. Considering that especially during city traffic the amount of energy lost in deceleration is quite large, this paper investigates how one can build a system that fully relies on regenerative braking technology for any braking situation.

Regenerative braking technology has been around for quite a while, however most people have looked at a single generator setup [2] and did not consider all possible braking conditions in order to only use regenerative braking for a vehicle. When all braking situations are considered then the system should be able to deal with a minor slow down situation up to a full emergency braking in order to fully replicate the functioning of a current brake-pedal.

The paper starts with giving a description of the problems faced when using regenerative braking as the only braking mechanism combined with the proposed design to overcome these problems in the next section. A test-rig of the proposed design was built and used to test the mechanism, the results of which are presented in the next section. The paper finishes with a conclusion.

II. Proposed Design

A. Design Principles

Current regenerative braking systems have a single generator which is either connected to a load or not. When the generator is connected to the load, then it will extract kinetic energy from the system and turn it into electrical energy. Unless the mass of the vehicle is significantly larger than the braking capacity

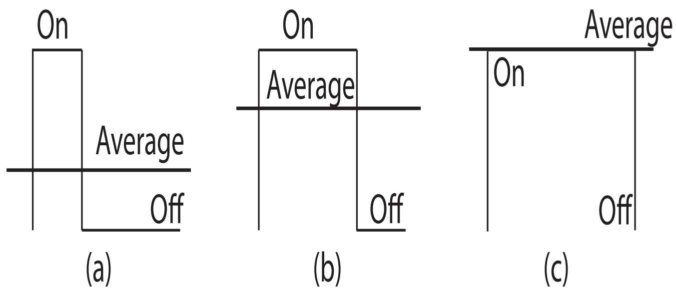

Fig. 1. Pulsing the connection to the load changes the average load to the generator

of the generator, this simple on/off approach would lead to shocks in the driving experience. Considering that current vehicles have a brake-pedal that can be pressed at a variety of stages and consequently deals with a variety of braking conditions this functionality would need to be mimicked. In order to obtain such behaviour one would need to be able to reduce the amount of load presented to the generator. Taking that the energy is supposed to be re-used and would therefore go into a battery or supercapacitor rather than a variable resistor a mechanism was designed to change the amount of load seen by the generator. The solution used in this project is to quickly connect and disconnect the load to the generator. This quick switching behaviour would automatically average itself and therefore lead to a variety of different loads being presented to the generator in relation to the percentage of time that the load is connected within a certain period. Figure 1 for three different switching pulses together with the load that would be experienced by the generator. Within this project, this principle was practically realised using relays in combination with a microcontroller that sensed a variable resistor to simulate the different brake-pedal positions and consequently pulsed the relays between on and off depending on the pedals position.

An additional problem to solve, which is of significant importance for emergency braking and full stop situations is the fact that a generator will be most efficient for a certain rpm, below a certain threshold value it will no longer generate electrical energy, which also means it will not extract kinetic energy from the system. In practice this would mean that the vehicle slows down to a certain speed and then would have to "roll-out", which is clearly not acceptable. To overcome this problem, muliple generators were used, each connected to the shaft with a different gear ratio. These gear ratios allow for at least one generator to be efficiently operating at the spread of speeds that the vehicle can have, consequently efficient braking is possible up to a full emergency stop.

B. Calculations for the Prototype System

The prototype of this design was calculated for use on a trike, which would have a maximum speed of 30 km/h and a maximum total weight of 120kg. In order to determine the amount of energy that could be in the system, one needs to start by looking at the speed of movement and the force related to this.

One needs to start with calculating the speed, which is: $Speed = 30km/h = 8.33m/s$, which is then converted into rpm as follows: $30km/h \times 8.10rpm = 243rpm$. When the trike is at maximum speed, it will go up to $8.33m/s$ and in an emergency brake situation, it would need to decelerate to $0m/s$, hence the total force would be: $F = ma = 120 \times (8.33 - 0)/10 = 100N$ assuming that the vehicle should stop in 10 s. When the trike has 26 inch wheels ($r = d/2 = 0.6604/2 = 0.3302$), then that would mean that the torque is: $\tau = Fr = 100 \times 0.3302 = 33.02Nm$. This means that the overall mechanical load is: $P_{Mech} = \tau\omega = 33.02 \times (243 \times 2\pi/60) = 840Watt$. According to Britisch Standards, the electrical power is 25% higher than the mechanical power, which results in: $P_{Electrical} = 1050W$. In order to deal with the need for different gear ratios, this project used 4 250W generators for its prototype, leading to the overall system as shown in Figure 2. These generators were connected to the central shaft with gear ratios of 0.5, 1, 1.5 and 3 for generators 1 to 4 respectively. Due to technical difficulties to build the system onto the trike, the prototype was constructed as a seperate test rig that was driven by an electrical motor, with a maximum rpm of 130, and the weight for the system was simulated by adding weights onto the shaft with a total value of 30kg.

III. Results & Discussion

Due to the test rig being limited in some aspects in comparison to what the system was originally designed for, the brake values will be particularly low, which also leads to a potentially larger error on the measured results. However, the following results do serve the purpose of indicating the operation of the system. For each of the below tests, the system was run for at least 15s to get proper speed before testing the brake operation.

A first set of tests, tested the full system brake time and this with and without load, meaning before and after the actual weights were mounted. The difference between using the different generators for braking in this situation is shown in Table I. Within this table, one

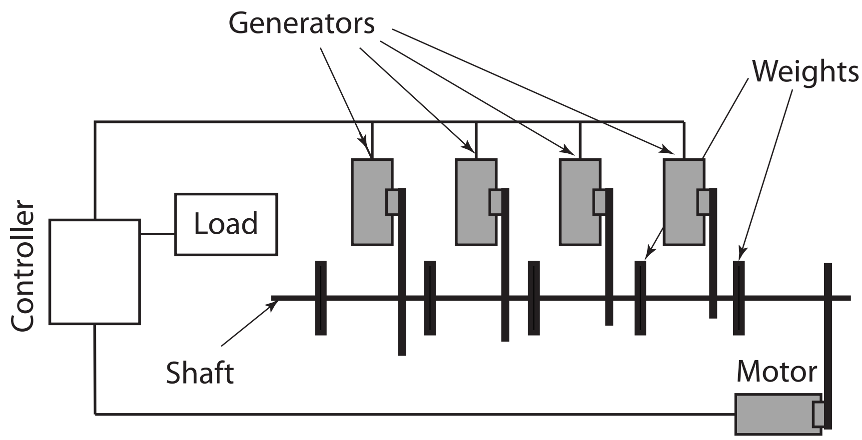

Fig. 2. Block Diagram of the test-rig setup

TABLE I
TIME FOR REGENERATIVE BRAKING WITHOUT LOAD

Generators Used	Time to Completely Stop (s)	
	No Load	With Load
1	1.80	3
1 & 2	1.65	2.7
1, 2 & 3	1.35	2
1, 2, 3 & 4	0.70	1.3

can notice that the values decrease gradually as more generators are used for the braking, as expected with the design. One can also notice that using all generators is not 4 times more efficient than using a single generator, which is related to the fact that not all generators run at optimal efficiency due to their different gear ratios. The difference between loaded and unloaded clearly indicates that if the system is loaded with weight, then it will take longer to extract the kinetic energy from it. Putting these figures in perspective for the vehicle this system was designed for, one needs to consider that the actual rotational speed would be approximately double and the weight would still be larger. When taking these two factors into account, would still reach a proper brake time for the system, which would be close to the value used in the calculation of the system, namely 10s, and also close to that of conventional braking mechanisms.

A second test was performed to specifically determine the advantage of pulsing the connection to the load to obtain a variable load presented to the generator and therefore ensure a smoother braking experience. In this test the difference between no pulsing, short and long pulsing in relation to the braking time was investigated. The results for this test are show in Table II. This table clearly indicates that the pulsing mechanism ensures a

TABLE II
TIME FOR REGENERATIVE BRAKING WITH VARIED LEVELS OF PULSING THE LOAD

Pulsing Level	Time to Completely Stop (s)
None	1.95
Short	2.5
Long	2.2

TABLE III
TIME FOR REGENERATIVE BRAKING WITH DIFFERENT GEAR RATIOS

Generator Used	Time to Complete Stop (s)
2	1.5
4	0.725

clearly different braking time and can therefore be used to ensure the braking is performed more gradually.

Also the second mechanism used was tested seperately so that the influence of the gear system could be evaluated. The results for this are shown in Table III, in each case the system was started at an rpm of 89 and then one generator was switched on completely. As can be seen in the Table, generator 4 brakes the system quite a bit faster than the second generator, which is largely due to the gear ratio linked to generator 4 being large. This results in the generator working in its optimal rpm for a much longer period of time, which means it can brake the system much more efficiently.

As mentioned earlier, the benefit of this system is that it is completely reversible and actually benefits from the additional advantage that during acceleration the different gear ratios will ensure a better acceleration at a variety of speeds. To indicate this point, the time was measured to bring the system from 0 to 50 rpm using the

TABLE IV
TIME FOR THE SYSTEM TO REACH 50RPM USING INDIVIDUAL GENERATORS AS MOTORS

Generator Used	Time to reach 50rpm (s)
1	6.9
2	5
3	4.6
4	3.9

different generators, for which the results are presented in Table IV. The results clearly indicate that the larger the gear ratio, the faster the system would reach its desired rpm. Clearly this is assuming the system starts from 0 rpm, one can easily imagine that the other gear ratios will be more beneficial to provide acceleration at higher rpms.

IV. CONCLUSION

This paper presents a system that allows a vehicle to fully rely on regenerative braking. Hence, it can reuse the energy extracted during deceleration to be used again during acceleration. The system ensures a smooth braking experience, by using controlled connection between the generator and the load. To enable the full braking from any speed to 0, the system exploits the use of multiple generators connected to the shaft with different gear ratios. This setup ensures that there is always one generator working most efficiently and hence extracting the kinetic energy of the system. Additionally, the system can be reversed in which case the generators are used as motors to drive the vehicle. The use of different gears with the different motors then provides the benefit of enhancing the acceleration of the vehicle at any speed.

The results shown indicate that the pulsing mechanism ensures a smooth braking experience, as well as the gear system taking care of easing the deceleration from any speed to stand still. Although the measured results were taken on a test system which was not fully up to the same specification as the system this prototype was designed for, one can easily notice that the braking times obtained with this system would be quite in line with existing braking mechanism with the additional benefit that in this case the energy can be reused. During the conversions from kinetic to electrical and vice versa there will be minor efficiency losses, but it would be considered that these are fairly high considering the high efficiency of electrical motors/generators.

The two principles presented in this paper could also be applied to existing systems, although then they should not be combined onto a single generator system. In case the vehicle has a single generator, one could either use the pulsing mechanism or the gear system. The additional benefit of using the gear system is that it also helps during acceleration and therefore has a larger benefit.

The current system uses relays for the pulsed connection between generator and load, which is not the most reliable system, hence future work would look at the use of other more reliable components to ensure a reliable design, which would not jeapordize safety in any manner. It would also be essential to investigate how this system can easily be integrated in commercial vehicles.

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