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Development and Assessment of Hardware Model for Studying the Mechanism of Regenerative Braking System (RBS)

Abstract

As an increasing number of electric motor vehicles (EV) are reaching consumers, increasing the charge stored by an electric battery and its efficiency has become a priority of the EV industry to compete with combustion (gas) vehicles. The solution car manufacturers are turning to is termed as *regenerative braking system* (RBS). In this project, we build an RBS model to study its efficacy in various conditions, we estimate the mechanical energy generated by the system and its portion that was transformed into electrical energy and stored, and finally estimate real world efficiency. The purpose of this research is (1) learning about how RBS works and is built, (2) designing and building a charging circuit for storage of energy on a capacitor, and (3) analyzing the efficiency of our RBS for various RPMs. Trials of different combinations of capacitors and resistors led us to successfully build and test an efficient experimental configuration with 30% efficiency at 1,000 RMP. Our results predict a possible efficiency of 51% for 2,000 RPM, which corresponds to real-world applications.

Keywords

regenerative braking system (RBS); electric vehicles (EV); permanent magnet synchronous motor (PMSM); revolutions per minute (RPM); "motor-flywheel-generator" system (MFG)

1. Literature Overview

An RBS most commonly involves a brushless motor called Permanent Magnet Synchronous Motors (PMSM) due to its efficient design (described later, in the section: *Theory Behind RBS*) and is used in conjunction with a capacitor to recharge the battery. The system is used to recapture the kinetic energy lost in vehicle braking, thus significantly reducing a vehicle's overall energy consumption, and at the same time increasing battery longevity. The regenerative braking system (or RBS) is an *energy recovery mechanism* associated to slowing down a moving vehicle or object by converting its kinetic energy into electric that can be either used immediately or stored until needed. In our research, an RBS was built by using a motor-flywheel-generator (MFG) system to study the rotational energy of the flywheel, and its conversion into electrical energy. The efficiency of such energy conversion is carefully studied.

2. Preliminary Research

An electric motor in electric vehicles (EV) offers an environmentally friendly solution to the widely common combustion (gas) motor. According to CAR Magazine [1], the longest-range for EV on the market is 379 miles for the Tesla Model S. Compared to a study done in 2016 by the US Dept. of Energy [2], gas vehicles have an average-range of 412 miles with the longest-range vehicle at a staggering 700 miles. The EV industry is behind; however, the solution may not only be found in the battery's storage capacity, but also in the efficiency of energy conversion inside electric motors today. We started by building a model RBS system using a motor, a generator, a cylinder of steel to connect the two pieces, and an RC circuit to test the efficiency of our hybrid RBS system, with the purpose of suggesting an improvement in the EVs' battery-operating electric motors.

3. Materials

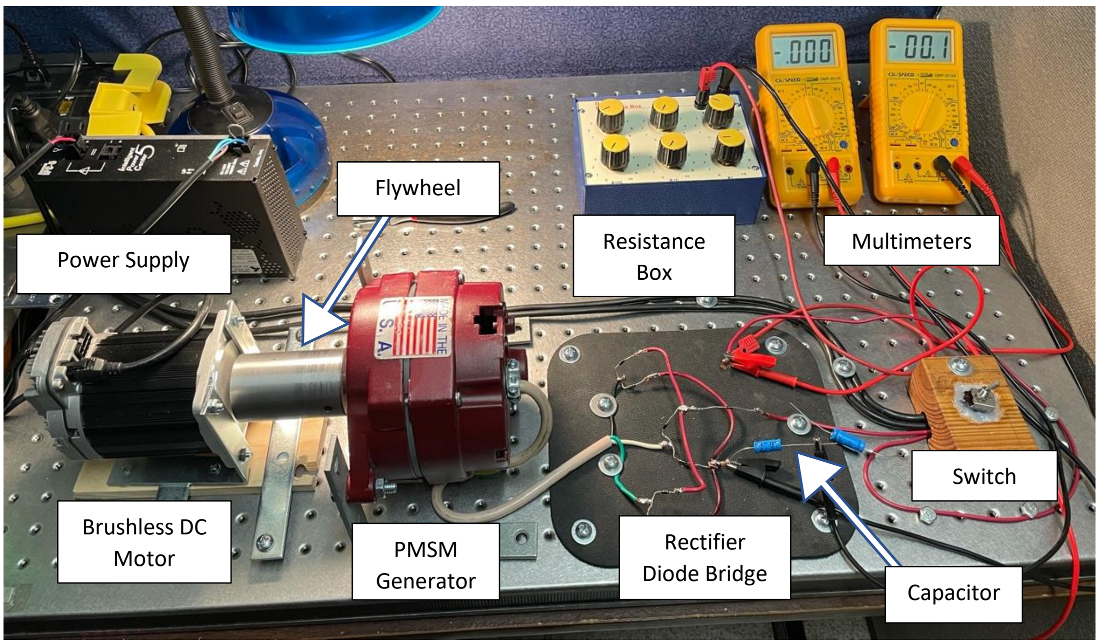

Figure 1 Overview of our RBS model constructed in the laboratory

The first item acquired for the setup was a robust Newport-like breadboard table. Finding an original and functional PMSM motor for the research was not possible. Building a proper PMSM was a difficult task due to the complexity of the motor and needing a very large power supply to power. Our option was to a *create hybrid RBS system:* First, we purchased a brushless DC motor (BLDC) from ClearPath Integrated Servo Motors (Figure 1, bottom left) powered by an IPC-5 DC power supply (Figure 1, top left). The ClearPath Software gave us full control of RPM of the desired RPM while using a computer. The second item acquired was a spare wind turbine PMSM (Figure 1, bottom centered) found in our EE department's storage room. The PMSM served the purpose of acting as a generator for our RBS system, thus demonstrating a complete RBS found in EV.

To build the flywheel (Figure 1, top centered), a steel cylinder was purchased, drilled, and polished to conjoin the shafts of the motor shaft with the generator shaft. In the case of my research, we decided to use only a capacitor to capture the voltage delivered by the generator system. A battery has the capacity to produce electric power through various reactions (i.e. chemical), while a capacitor stores charge for delivering electric power. This option was adopted due to cost, and because for our study, we need to measure the energy produced by the PSMS system and stored for further usage (i.e. for powering a car tractional system). Therefore using a capacitor (Figure 1, bottom right), I was able to store this energy and accurately test the efficacy of the RBS without further loss in energy transfer to car battery. Besides several capacitors (of 100, 500 and 6,300 µF) and wires, we used a 2-phase switch (Figure 1, bottom right) connected the circuits of the motor and of the generator, 4 separate multimeters (Figure 1, top right [two displayed]), 7 diodes to direct and convert AC to DC voltage also called a rectifier diode bridge (Figure 1, bottom centered), rheostat/resistance box (Figure 1, top centered [resistance box displayed]), and finally the "Analog Discovery Kit", allowing us to use an oscilloscope function to display the signal produced by the AC generator as well as rectified in a DC signal by the diode bridge.

4. Process and Experimental Model

4.1 Theory Behind RBS – In real-world applications, RBS works by using a motor-generator system to successfully convert kinetic energy from the rotation of the flywheel (which is a motor's shaft – cylinder coating – generator's shaft) system to recharge the capacitor when it is not being used. The electromotive force (EMF) of an electric motor provides a much greater supply of voltage to a capacitor than a normal car battery recaptures as voltage from a classical alternator. In RBS, the voltage is supplied from the kinetic energy of the wheels which is otherwise lost to thermal energy in physical braking pads. Figure 1 shows the principle of energy conversion from kinetic into electric in RBS. While braking, the EV will naturally slow down due to friction, but the decelerating traction is used toward recharging the capacitor**.** To understand how an RBS works, one must first investigate its components.

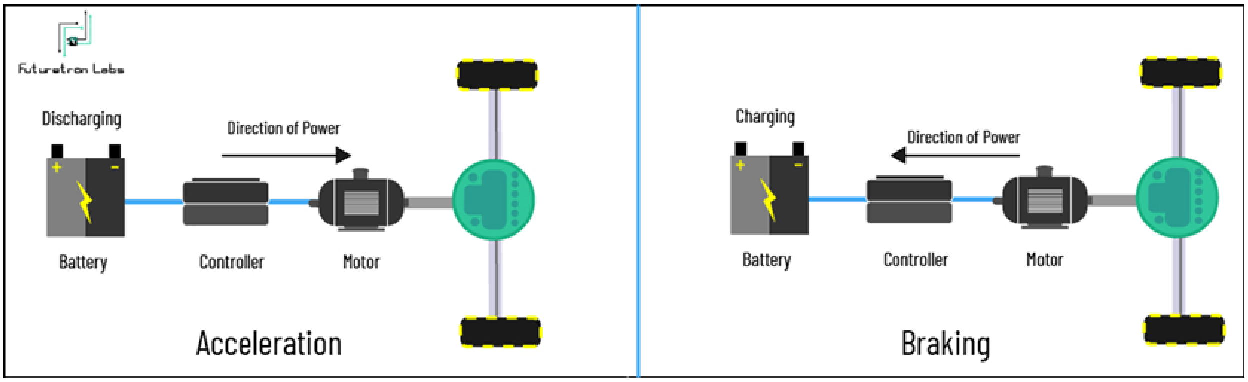

Figure 2 Principle of RBS Diagram (accessed from Futuretronlabs Inc.). The image is from https://futuretronlabs.in/blog/index.php/2019/09/12/regenerative-braking-system/

EV can use either AC or DC motors. A motor is an electrical device that converts electrical energy into mechanical energy. [4] Although there are several types of electric motors, according to *Embitel* [3], the most widely used motors are a brushless DC motor (BLDC) and a AC permanent magnetic synchronous motor (PMSM). Both serve as a better alternative to the standard AC induction motor and have higher power density and efficiency. "BLDCs have high starting torque, high efficiency and low maintenance" according to Ritvik Gupta [5]. There are no differences between BLDC and PMSM besides the driving current and detection of rotor position. Most automotive manufactures use PMSM motors due to their high performance and sinusoidal EMF signal, whereas BLDC generates a trapezoidal signal. "[A] system consisted by PMSMs processes excellent dynamic performance, high precision, and wide speed range."[6] For companies such as Ford and Toyota, they both use PMSM motors in their electric vehicle variations. Tesla Model X also uses PMSM, while their Model S uses the AC induction. Both AC and DC motors can work for an RBS.

A PMSM (shown in Figure 3) is a brushless motor, as opposed to brushing motors found in farm machinery, stair lifts, and chemical injection pumps. For PMSM, the magnetic rotor uses solid magnets. The continuous rotation of the magnets caused by the polarity of the stators and coils allow the motor to smoothly rotate the axle and convert the electromagnetic energy into mechanical energy for generating the rotation of the car wheels.

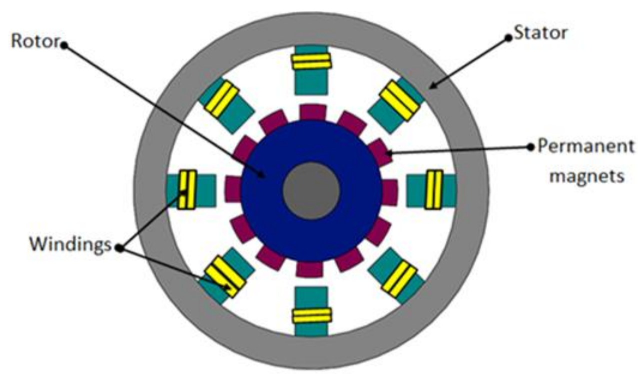

Figure 3 Schematic design of a PMSM (accessed from Embitel [3]). The permanent magnets rotate on the rotor caused by the polarity of the stators allowing the system to generate power. The image is from https://www.embitel.com/blog/embedded-blog/brushless-dc-motor-vs-pmsm-how-these-motors-and-motor-control-solutions-work

4.2 Designing a Circuit for RBS and Understanding its Mechanism- we designed and built the circuit in 2 phases:

Phase 1 *- The power supply is powering the motor and accelerates the flywheel. Figure 4 shows a power supply controlling the RPM of the motor-generator shaft and flywheel. A voltmeter is used to measure the voltage distributed in the circuit.*

Phase 2 *– When the voltage from the power supply is cut off from the motor ~~t~~he kinetic energy (KE) from the wheels is directed into electric energy and stored on the capacitor as voltage,* V_C

(see Figure 4). The generator (PMSM) converts KE into AC which is then converted by a lab made diode rectifier bridge (built with 7 diodes) of with negligible resistance. This newly converted AC to DC voltage is next captured by the capacitor as V_C. The rheostat serves to protecting the capacitor from voltage overload.

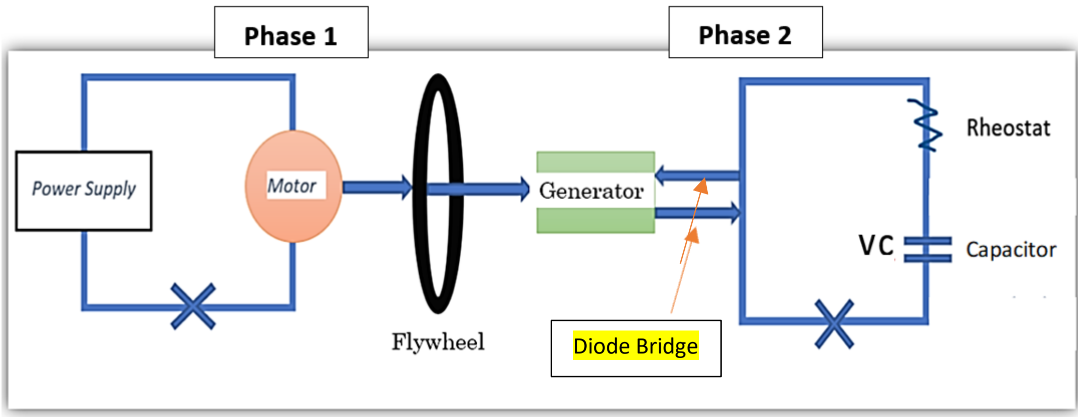

Figure 4 Schematic of the RBS system. Phase 1 consists of the powering of the flywheel system and Phase 2 contains the charging of the capacitor.

5. <u>Methodology and Calculating relevant quantities for our study</u>

5.1 Calculating Moment of Inertia- The energy of rotation (E_r) is given in the equation below

$$E_r = 2I \times (\pi f)^2 \qquad [1]$$

where *f* is the RPM in Hertz, and *I* is the moment of inertia for the flywheel with the two shafts on the motor side and the generator side. From the general formula of moment of inertia for a solid cylinder,

$$\mathrm{I} = \frac{1}{2}\,\mathrm{mr}^2 \qquad [2]$$

we calculate the moment of inertia of the flywheel, which has two chambers (see figure 2) of radii $R - r_1$ and $R - r_2$,

$$\mathrm{I} = \frac{1}{2}\,\sum_{i=1}^{2} \mathrm{m_i}(\mathrm{r_1^2} + \mathrm{r_2^2}) \qquad [3]$$

and where R is the radius of the initial steel solid cylinder.

Figure 5 shows the chambers of the flywheel. For our flywheel *I is 0.003555* $kg\ m^2$. Hereafter, the system built will be called the "motor-flywheel-generator" (MFG) system. Finally, we need to calculate the energy of rotation as:

$$E_r = \frac{1}{2}\,I\omega^2 \qquad [4]$$

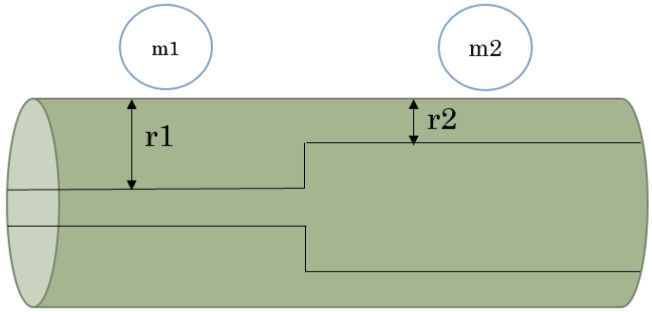

Figure 5 Flywheel Diagram – We have drilled two chambers to fit in the shafts of the motor (left) and generator (right)

5.2 Oscilloscope v. Multimeter Measurements –First tests used an oscilloscope to (1) precisely measure the voltage output from the AC generator, (2) study the sinusoidal AC signal and its root-mean-square (rms) voltage value (labelled V - rms in Table 1), as well as (3) the time of extinction from voltage peak to zero. But the response of the oscilloscope to voltages (lower than 24V) became quickly an issue. Therefore, we had to use multimeters, instead of oscilloscopes for larger voltages. Table 1 shows our comparison study: Using 4 different lower RPMs, the multimeter was found to give a reading comparable to the oscilloscope reading, thus allowing us to read larger voltages and move forward with higher RPM trials toward the real-world RPM values for EV.

5.3 Extinction Time Using the Oscilloscope- Extinction time is the time it takes for the highest peak of the AC sinusoidal signal to reach zero after voltage is cut off (called phase 2 in Figure 4).

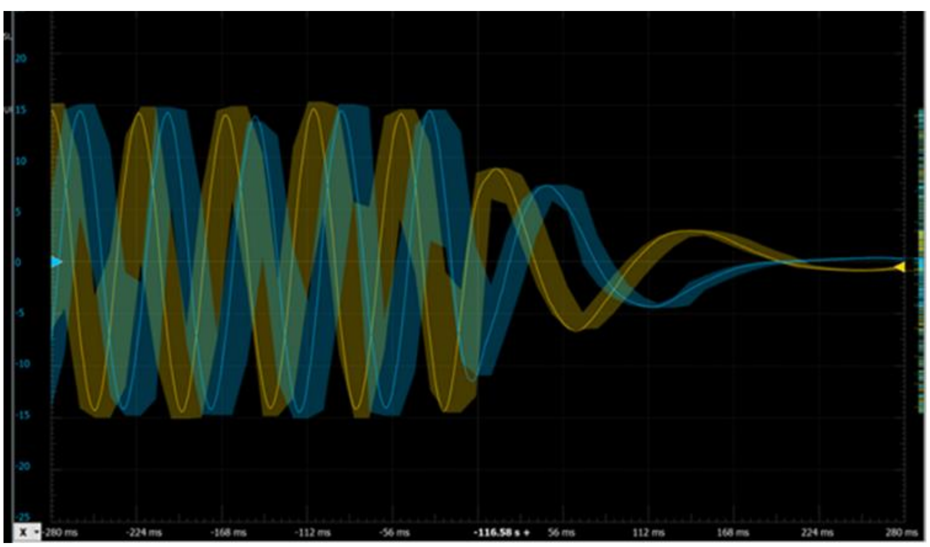

Figure 6 Example of extinction time shown graphically by the oscilloscope

Figure 6 is a signal from the AC PMSM generator before the rectifier diode-bridge, for a random study case at 150 RPM. The two curves corresponded to the two pair channels of the 3-phase AC generator output signal. They were in sync, as they should be. This analysis was also a diagnostic test that the AC generator is functioning normally. We compare the extinction time with the characteristic time (CT) of the RC charging circuit after the rectifier diode bridge.

$$CT = R\ (Ohms)\ x\ C\ (Farad) = t_{1/2}\ /\ ln\ (2), \qquad [5]$$

where $t_{1/2}$ is the time for charging half the voltage on the capacitor. *R* is the Ohmic resistance of the circuit and *C* is the capacitance of the capacitor which receives the mechanical energy of MFG system, as V_C voltage. Reason for this is because as the current flows, the capacitor charges until the voltage reaches *V-rms*. In a typical RC circuit, the complete charging of the capacitor is reached after a time which is about 5 times the $t_{1/2}$ value.

The duration of the voltage peak (DVP) ~~duration~~ is another important time, which is typically very short, of about 0.0001 seconds. In our case, CT needs to be short enough to avoid loss of voltage after the peak voltage has passed. If the CT is too short, then the capacitor cannot capture much voltage from the AC generator. If the CT is too long as compared to DVP, then the voltage from AC generator rectified by the diode bridge is lost in discharging the capacitor mostly through heat dissipation.

Table 1 Study on four lower RPM values for comparing the V - rms reading from the oscilospcope with the voltmeter reading. The extinction time of the AC voltage signal before the diode bridge (from Figure 6) is also reported for each RPM.

RPM	V-rms (volts)	V-meter (volts)	Extinction time (sec)
50	3.308	3.28	0.45
100	6.63	6.61	0.43
150	10.014	10.05	0.4
200	13.36	13.46	0.42

Table 1 indicates that at low RPMs, the extinction time of the rectified voltage signal is 0.42 ± 0.02 seconds. This meant that the characteristic time for the charging RC circuit (that acts as battery in many real-world applications) should be much less than 0.4 seconds. According to equation [5], we can decrease CT, using low R and C, but to store large charge on the capacitor, its capacitance C should be large. Therefore, for practical purposes the only way to decrease CT is by lowering the resistance R of the RC circuit. The final trails of testing different combinations of resistance and capacitance will lead us to optimum results.

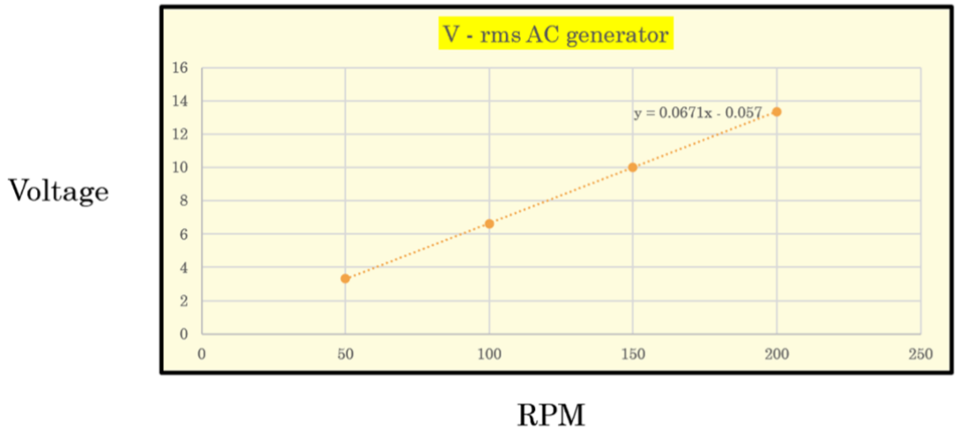

Figure 7 V – rms at low RPMs. The best fitting linear function is reported.

From Figure 7, we observe that V – rms follows a linear trend for these low RPMs. Adopting the linear regression formula V – rms = 0.0671 x rpm – 0.057, generated by the best linear fit, we predicted V – rms values past 200 RPM, where the oscilloscope was not operational. This linear regression allowed us to predict the range of voltages expected at larger RPMs.

5.4 Finding the optimum values for R and C for charging efficiently the capacitor - First, we worked with typical commercial capacitors used in circuitry today (of 100, 500 μF) and larger resistances to protect the RC system. The results of our study is shown in Table 2.

Table 2 Trials for finding optimal R and C for better efficiency

Trial 1 1650 Ohm	One capacitor 100 μF	Capacitor's Energy (Joule)		
V - cap (volts)	Charging time (seconds)		RPM	Efficiency
2.19	0.174	0.000240	100	0.12%
3.206	0.194	0.000514	150	0.12%
5.81	0.214	0.001688	200	0.22%
8.07	0.253	0.003256	250	0.27%

Trial 2 1650 Ohm	Two capacitors in series 50 μF	Capacitor's Energy (Joule)		
V - cap (volts)	Charging time (seconds)		RPM	Efficiency
3.173	0.136	0.000252	100	0.13%
4.98	0.16	0.000620	150	0.14%
7.489	0.172	0.001402	200	0.18%
9.7278	0.204	0.002366	250	0.19%

Trial 3 100 Ohm	Two Capacitors in Series 50 μF	Capacitor's Energy (Joule)	E rotational (Joule)		
V - cap (volts)	Charging time (seconds)			RPM	Efficiency
7.438	0.098	0.001383	0.1949	100	0.71%
9.957	0.096	0.002479	0.4386	150	0.57%
15.099	0.093	0.005699	0.7797	200	0.73%
18.7	0.089	0.008742	1.2183	250	0.72%

Our initial studies used load resistances of hundreds or thousands of Ohms. We choose resistor boxes for having easy to manipulate adjustable resistances. We looked for settings where the CT was at most a quarter of the average extinction time value (of 0.42 ± 0.02 seconds) from Table 1. From the study of efficiency reported in Table 2, we observe that in order to have a better efficiency, and at same time, for lowering the characteristic time we must lower the load resistance.

5.5 Finding the Best Characteristic Time - By lowering the load resistance, we greatly reduce the energy dissipated in the RC circuit. This attempt opened the door for a larger voltage which would go from the AC generator and rectifier (the diode bridge) to the capacitor. But at large voltages, 100 µF or 500 µF capacitors would most likely break down. Thus, we have acquired a large capacitor of 6,300 µF. This choice of large C requires to reduce greatly the load resistance for retaining the peak voltage (see the discussion before). For dropping CT in these circumstances, we moved to using a rheostat (instead of resistor box) which can have a very small resistance.

6. Results and Discussion

6.1 Studies when resistances of 1Ω and 5 Ω are separately used with a 6,300 µF capacitance - First, we chose to study the charging of the capacitor using a rheostat of R = 5 Ω and 1 Ω.

Table 3 Comparing the efficiency in energy transfer between the MFG system and capacitor, for two separate resistances of 1Ω and 5Ω, and a 6,300 µF large capacitor.

RPM	V - rms	V - cap	E - cap	V - cap	E - cap	V - Cap / V - rms	V - Cap / V - rms	Efficiency	Efficiency
	(Joule)	R = 5 Ω	R = 5 Ω	R = 1 Ω	R = 1 Ω	R = 5 Ω	R = 1 Ω	R = 5 Ω	R = 1 Ω
50	2.93	0.82	0.0021	0.71	0.0012	27.99%	24.23%	**4.28%**	**2.51%**
100	6.52	1.64	0.0085	1.73	0.0094	25.19%	26.52%	**4.36%**	**4.84%**
150	9.80	2.51	0.0198	2.69	0.0228	25.62%	27.46%	**4.52%**	**5.20%**
200	13.29	3.50	0.0374	3.67	0.0467	26.30%	27.58%	**4.80%**	**5.99%**
300	19.50	5.78	0.1052	6.23	0.1221	29.64%	31.93%	**6.00%**	**6.96%**
400	26.13	8.12	0.2079	8.36	0.2200	31.08%	31.98%	**6.66%**	**7.05%**
500	32.93	10.40	0.3409	11.32	0.4034	31.59%	34.36%	**7.00%**	**8.28%**
600	39.97	12.97	0.5302	13.75	0.5955	32.46%	34.40%	**7.56%**	**8.49%**
700	46.73	15.68	0.7741	16.84	0.8933	33.54%	36.03%	**8.11%**	**9.35%**
800	53.67	19.41	1.1868	20.45	1.3173	36.17%	38.11%	**9.51%**	**10.56%**
900	60.27	23.10	1.6809	23.63	1.7594	38.33%	39.21%	**10.65%**	**11.14%**
1000	66.87	26.50	2.2121	27.70	2.4170	39.63%	41.43%	**11.35%**	**12.40%**

The AC generated voltage rectified by the diode-bridge, provides V – rms. We have calculated the percentile ratio between the capacitor voltage and the V-rms from the AC generator rectified by the diode bridge, for assessing the voltage transfer from MFG to the capacitor, and reported the results in Table 3, together with the efficiency in energy transfer from the rotational energy of the MFG system into the electrical potential captured by the capacitor for the available RPMs generated by our ClearPath motor. From Table 3, one can see that the efficiency of our system increases with RPM, which is essential for transferring this study to a real-world application in EV industry. The top value is about 12% for the largest RMP we can reach. This value is close to our 16% target value, but at much lower RMP than in real-world cars.

6.2 Comparing results with Two Resistances of 0.02Ω and 1 Ω and the same capacitance of 6,300 µF – As compared to Table 2, in the case of very low resistance used in Table 3 the efficiency is greatly improved to values desired in real-world applications. However, these values are not yet satisfactory.

Therefore, we choose to drop the resistance to a minuscule 0.02 Ω value. With R = 0.02 Ω and C = 6,300 µF, the CT became 0.00012 seconds, and it was comparable with the duration of the peak voltage of the AC generator. From Figure 6, the DVP is about 0.0001 seconds. However, the results reported in Table 4 for R = 0.02 Ω, do not show an improvement as compared to the two cases reported in Table 3. Still a 12% efficiency can be reach at the largest RPM value of 1,000, which in itself is a good result for the efficiency our RBS system.

RPM	V - rms	V - cap	E - cap	V - cap	E - cap	V - Cap / V - rms	V - Cap / V - rms	Efficiency	Efficiency
	(Joule)	R = 0.02 Ω	R = 0.02 Ω	R = 1 Ω	R = 1 Ω	R = 0.02 Ω	R = 1 Ω	R = 0.02 Ω	R = 1 Ω
50	2.93	0.72	0.0021	0.71	0.0012	22.16%	24.23%	3.32%	2.51%
100	6.52	1.55	0.0085	1.73	0.0094	22.97%	26.52%	3.88%	4.84%
150	9.80	2.75	0.0198	2.69	0.0228	26.96%	27.46%	4.67%	5.20%
200	13.29	3.33	0.0374	3.67	0.0467	24.72%	27.58%	5.50%	5.99%
300	19.50	5.83	0.1052	6.23	0.1221	29.08%	31.93%	6.10%	6.96%
400	26.13	8.68	0.2079	8.36	0.2200	32.34%	31.98%	7.28%	7.05%
500	32.93	10.93	0.3409	11.32	0.4034	32.58%	34.36%	7.72%	8.28%
600	39.97	13.01	0.5302	13.75	0.5955	32.29%	34.40%	7.60%	8.49%
700	46.73	14.80	0.7741	16.84	0.8933	31.39%	36.03%	7.22%	9.35%
800	53.67	19.90	1.1868	20.45	1.3173	37.05%	38.11%	9.99%	10.56%
900	60.27	24.27	1.6809	23.63	1.7594	40.33%	39.21%	11.75%	11.14%
1000	66.87	27.60	2.2121	27.70	2.4170	41.44%	41.43%	12.31%	12.40%

Table 4 Same structure as Table 3, but for 0.02 Ω and 2 Ω resistance and 6,300 µF capacitance

6.3 Comparing All Three Resistances with Capacitance at 6,300 µF - When we looked to the experimental peak voltage absorbed by the capacitor (shown in Figure 8) as a function of the RPM range from Table 1, we observe for all three cases defined by the three resistances of 0.02 Ω, 1 Ω, and 5 Ω a perfect parabolic variation (a polynomial of order 2) for larger RPMs than 300, as opposed to the simpler linear variation from Figure 7. In Figure 8, we give an example for R = 5 Ω and take 3 trials for checking the consistency of our results. As one can see in Figure 9, the best fitting with a polynomial of order 2 has a high R^2 precision.

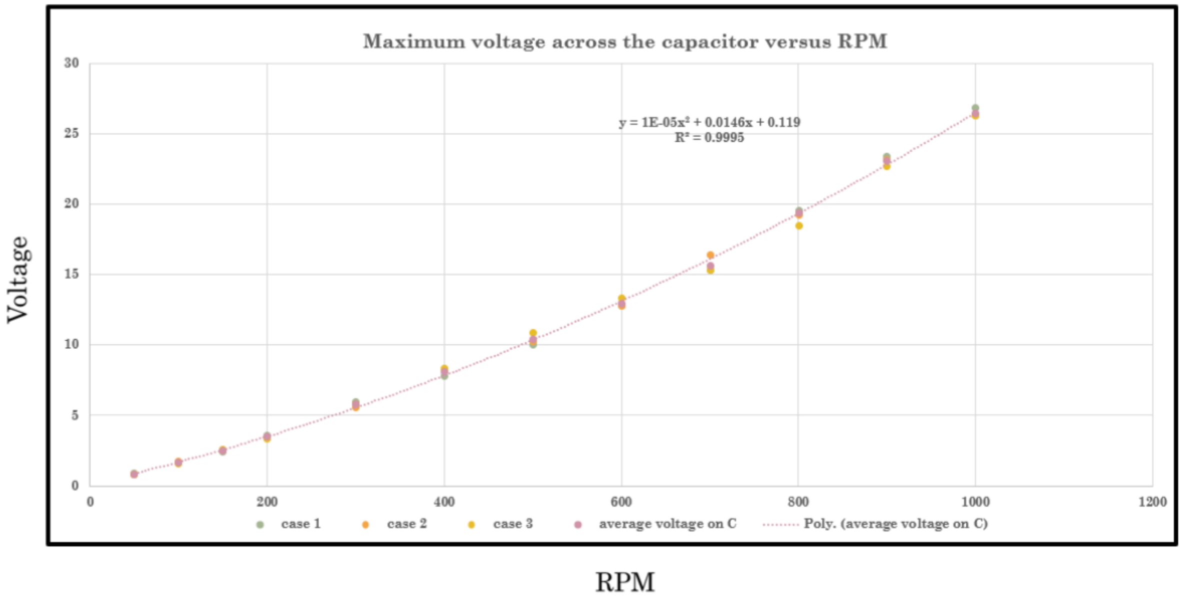

Figure 8 Parabolic trend-line for voltage capacitance (V-cap) versus RPM for a wide range of RPMs allowed by our ClearPath motor.

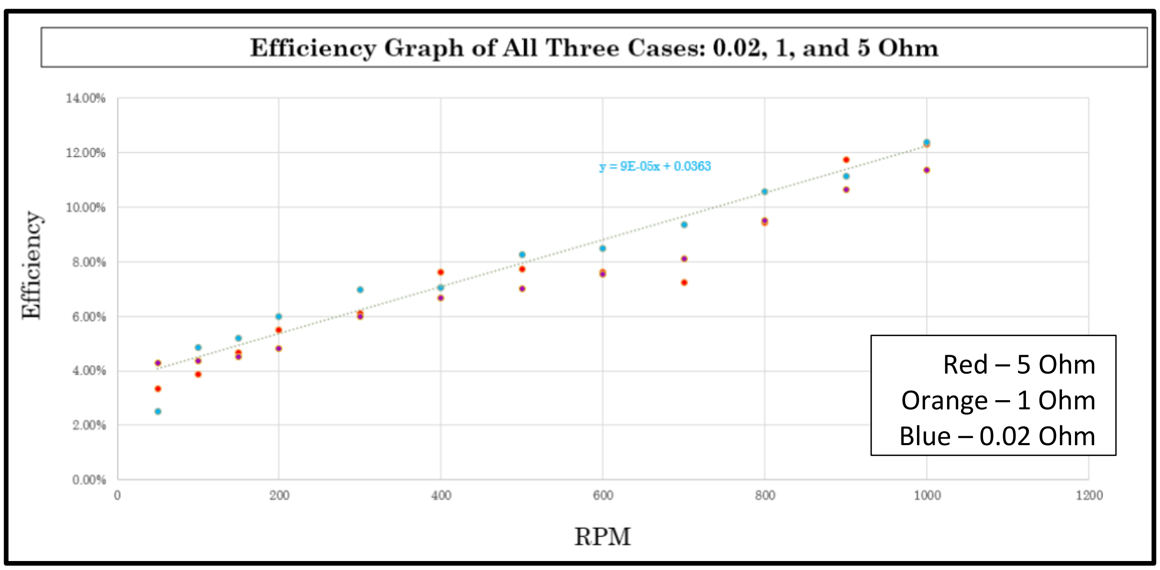

Figure 9 The efficiency for the three resistances included in Tables 4 and 5, and using the same 6,300 µF capacitance. The best fitting function is shown for the case at 1 Ω, as an example.

6.4 Comparing Three Capacitances with the Lowest Load Resistance of 0.02Ω - The impact of using a combination of capacitors on the efficiency of charging a large capacitor.

We took the analysis route with two case studies in mind. If two capacitors are wired in parallel, the equivalent capacitance increases. If they are wired in series, the equivalent capacitance decreases. In the former wiring case, we offered more room for energy to be transferred from the

AC generator to the capacitors, but we lose the critical parameter, CT, which naturally increases for two identical capacitors wired in parallel. Thus, CT doubles, according to equation [5]). For a series combination, we decrease the equivalent capacitance, and with the two identical capacitors, we half the CT value.

Using the lowest load resistance available, of 0.02Ω, we minimize the energy lost through dissipated heat (i.e., due to collisions in the load resistance). The results are shown in Table 5 for efficiency. Here, the parallel and series combination of two capacitors of 6,300 µF are compared with measurements using one similar capacitor. All the measurements are done with R = 0.02 Ω.

Table 5 Comparing the efficiency for three Capacitances at same load resistance 0.02 Ω

RPM	Efficiency % for R = 0.02Ω in All Three Cases		
	12,600 µF	3,250 µF	6,300 µF
50	1.45%	6.81%	3.32%
100	1.83%	14.22%	3.88%
150	2.20%	15.89%	4.67%
200	2.33%	17.10%	5.50%
300	2.65%	17.73%	6.10%
400	2.84%	18.30%	7.60%
500	2.98%	19.98%	7.72%
600	3.38%	22.12%	7.60%
700	3.49%	22.29%	7.22%
800	3.76%	23.80%	9.44%
900	4.03%	28.66%	11.75%
1000	4.68%	29.97%	12.31%

One can see that a series combination can significantly increase the efficiency as revealed in the previous study reported in Tables 3 and 4. With a resistance of R = 0.02 Ω and two 6,300 µF capacitors in series (equivalent to 3,150 µF), we reached a maximum of **29.97% efficiency at 1000 RPM for the system**, which surpasses greatly the goal of 16% energy regain in an efficient RBS as discussed in [6].

6.5 Expanding from Our Results to Real-World Situations – "Automobile engines that can have rotational speeds of 500–7000 RPM" [7]. Domestic cars run typically at 2,000 RPM moving forward, and idle at 1000 RPM. From the best polynomial fitting function for a series combination of capacitors, we found that at 2,000 RPM: (1) from Figure 10, the maximum voltage delivered can be 133 volts (an increase by 7.7 times from 17 volts at 1000 RPM), and (2) from Figure 11, the efficiency can reach an astonishing 51% (from about 30% at 1,000 RPM)! These numbers encourage further exploration on the implementation of these ideas in car industry and successfully demonstrate the effectiveness of RBS in real-world applications.

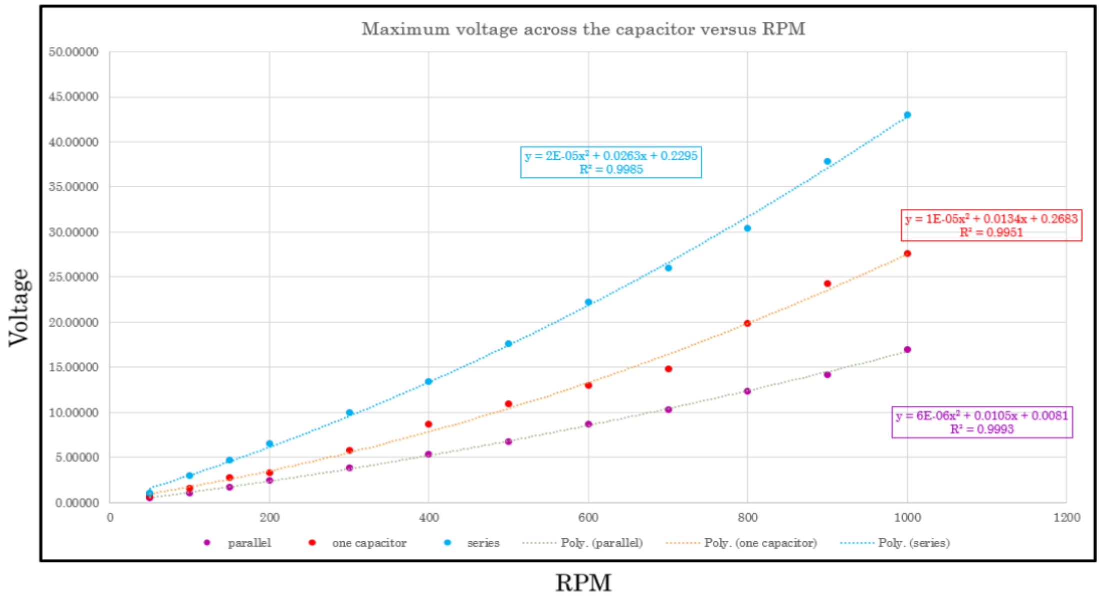

Figure 10 The maximum capacitor voltage extracted from the rectifier diode bridge at the peak voltage from the AC generator for R = 0.02 Ω and C = 6,300 μF (from Table 5). A similar parabolic-trend-line of different curvatures can be observed, which increases in slope as the capacitance decreases (the lowest curve is for the highest C value of 12,600 μF).

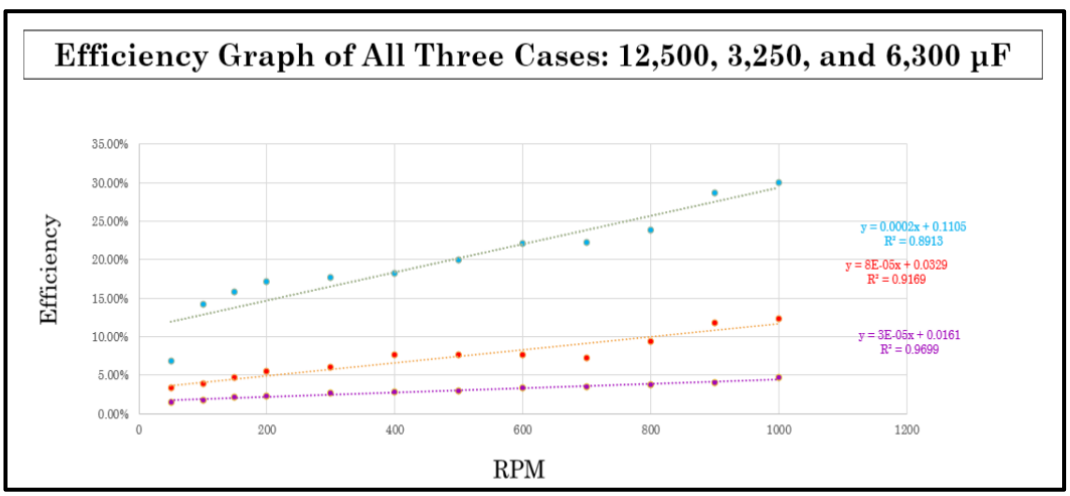

Figure 11 Plot of the efficiency in charging the three capacitors from Table 5 using the same 0.02 Ω resistance. In each case, the best polynomial fitting function is reported.

Conclusion:

According to Doyle "Regenerative braking allows the range of the EV to be extended; however, the efficiency of capturing this energy is reported to vary from 16% to 70% [8]". Our hypothesis that we can build an RBS system with efficiency greater than 16% has been proved to be accurate.

When using our RBS to real-world RPM, we find nearly 30% efficiency at 1,000 RPM. When extrapolating our data beyond 1,000 RPM, we find 51% efficiency at 2,000 RPM. This research suggests that an RBS can increase the overall single charging of a battery to meet and surpass the average gas-mileage consumption for combustion vehicles. Thus, EVs with RBS are presumably more efficient than combustion vehicles, on top of being more environmentally friendly, and can extend the lifespan of a physical braking system. EV manufacturers and any industry that uses electric motors can take advantage of our findings and inspire others to utilize RBS in their applications. This research helped demonstrate that the EV industry can meet range demands, benefit all forms of electric motors, and further help the environment by making EVs the transportation standard of the future.

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