Performance of Super Capacitor as Solar Energy Storage and Electric Tricycle's Power Source

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***Abstract*—Recent developments and projects in the Philippines gave way for the introduction of electric tricycles (e-trikes) with lithium-ion batteries as its power source and which use the power grid for charging stations. This paper studied the workability of super capacitor as lone substitute to Li-ion batteries for electric tricycles and charging it by means of power from an alternative source that is solar panel. Specifically, this study is aimed to determine the power needed by super capacitor to fully charge, the time of its full charging, and the distance run by electric tricycle. The electric tricycle is assembled using electric bicycle mounted with a passenger side car. The solar panel is mounted on a support which houses charge controller and other accessories. The super capacitor used has a rating of 48 V, 165 F, modular type while the solar panel is rated 100 W. Various tests were conducted such as distance test and charging time test. From test results, the super capacitor employed in this work requires 68 W of solar panel power to become fully charged in more than 6 minutes. The electric tricycle with a fully-charged super capacitor can run up to 600 meters with driver and passenger load of not more than 118 kgs. A remarkable short average charging time, accounted by its high power density, validates that super capacitors are good storage medium for harvesting power from sporadic energy sources. On the other hand, the result for short distance travelled conveys that super capacitors are said to be suitable only for vehicle transportation requiring short distances such as point-to-point transport services.**

***Index Terms*—Electric Tricycle; Solar Energy Charging; Super Capacitor; Ultracapacitor.**

I. Introduction

In the Philippines and abroad, electric vehicle (EV), in general, is becoming an interest to many. Studies on increasing transportation efficiency is surfacing nowadays because of environmental issues and limited fossil fuels [1]. Combined efforts of the government, various private funding sectors, and foreign and local manufacturing companies are paving way to make the Philippines the leading hub of EV in Asia. Tricycle, a popular transportation in the country and most common means of transport from rural areas to small towns and cities, especially where jeepneys are not capable of entering, is among the vehicles which are being developed into electric tricycle (e-trike). The Philippine government and Asian Development Bank have forged partnership to promote this development [2]. There are a lot of reports nowadays that gives positive remarks on e-trikes; they run silently and produce less or no emission at all [3], which makes them a promising environment-friendly vehicle. They can be an alternative solution to fuel problems, lessening degradation effects of gasoline-run tricycles to the environment [4].

These electric tricycles use lithium-ion batteries as source of power. They are well known to have superior energy density and their small sizes can store more energy than other storage medium. However, this type of battery has low power density, limiting its life and charging cycles. It has long charging time and some safety hazards, too. On the other hand, super capacitor has very high power density, can be charged in a matter of minutes accounted by its double-layer charging composition [5], can be charged and discharged over several hundred thousand times, doesn't overcharge nor explode, is easy to maintain because it doesn't age or degrade, and is environment friendly because it doesn't have chemical actions inside. At present, super capacitors have become more and more popular and have widened their field of applications like energy harvester in regenerative braking, energy storage in hybrid electric vehicles [6], as energy storage in microgrid systems [7], and as back-up power for a short time. Yet, it has drawback and it lies in its low energy density, that is, it is easily discharged. It offers power over short time. Despite these, super capacitor has found its great application as energy storage systems to renewable energy generation, solar, in particular [8]. Super capacitor fits the need of solar power for a quick charge and discharge energy storage system to bring rapid storing of solar energy.

II. Literature Review

A. *Environmental Effects of Conventional and Electric Tricycles*

Several reports are claiming some unfavorable environmental effects of the rampant use of gas-powered tricycles.

According to a news article by [3], motor tricycles, being considered the king of the Philippines' side streets, have drawbacks. Commuters have to bear with the noise and smog they are emitting.

There are also approximately 3.5 million combustion engine tricycles and motorcycles running in the Philippines, which contribute to carbon dioxide emissions to the environment, millions of tons in quantity, annually. These vehicles are noted to cause drastic effect to air quality, affecting health and climate changes risks [9].

On this online news report in CNN Philippines, [10] mentioned that in a report published by Ateneo de Manila University, 45% of all volatile organic compound (VOC) emissions are accounted by tricycles and motorcycles. These VOCs contain benzene and chlorofluorocarbons (CFCs) known to destroy ozone layer, carbon dioxide which is a greenhouse effect contributor , and a toxic gas in the name of carbon monoxide.

In the same news report, it was quoted that when 100,000 gas-powered trikes will be replaced under the joint-project of ADB and the government, there will be a dramatic decrease of annual CO2 emissions by 260,000 tons in the country, alongside with a saving of $110 million a year in fuel imports.

On the other hand, there is a lot which speaks very optimistically of the electric tricycle. Reported by [3], e-trikes run silently and produce less or no emission at all. In her report, [2] said that e-vehicles, (which includes e-trikes), have earned Department of Environment and Natural Resources (DENR) certification that they do not emit harmful chemicals. Recounted by [11], replacement of gasoline trikes with electric tricycles in the country is the solution for air and noise pollution. A similar context is noted by [12] in which she wrote that electric vehicles are the alternative solution to fuel problems which greatly affects degradation of the environment. In addition to overwhelming positive remarks regarded to electric vehicles as a whole, [13] mentioned numerous advantages public operators realized in using electric vehicles, which includes quiet and convenient to use, less maintenance, and way cheaper to operate.

Tricycle is not only famous in the Philippines but also abroad. A version of it in Thailand and Cambodia is named Tuk-tuk, bajaj in India and Indonesia, keke Napep or Maruwa (in Nigeria), and many other terms used to refer a three-wheel cabin vehicle. [14] cited that Tuk-tuks have been used for more than 60 years now in Asia, Europe, Central and South America, and in some parts of Africa. Despite its low oil consumption, flexibility, excellent maneuverability, and inexpensive operational cost, obviously as compared to four-wheel vehicles, this tricycle is a pollution threat because of inefficient combustion engines.

B. Super capacitors as Power Source

Super capacitors are also known as ultracapacitors or electric double-layer capacitors. In terms of capacity, it can hold up to tens of thousand farads and its power density is 10 times superior than battery. Its storage is also higher than electrolytic. Super capacitors operate in a wide range of temperature. In addition, it can be charged and discharged quickly [15], [16].

Because of the many advantages of super capacitor, it has become the best choice, among the very few, for microgrid applications. Super capacitors paired with an intelligent energy storage system may serve as energy buffer of batteries, may improve microgrid's power quality, and in general, plays a significant role in the economic performance of the microgrid [15].

Super capacitor can act as a key player in the compensation of power fluctuations caused by hybrid renewable energy systems (such as wind and solar) by providing buffer power necessary when there are abrupt and unexpected load changes [17].

C. Super capacitor for Renewable Energy Storage System

Super capacitors are now making its way in energy storage systems for renewable energy generation because of numerous technological advancement and increase in energy storage capacity.

In the paper of [18], they used super capacitors as photovoltaic energy storage to overcome the intermittency in the solar energy source. A study by [17] shows that the hybrid storage system composed of a battery connected in parallel to super capacitor for wind and solar integration compensates fluctuations triggered by sporadic harnessing of energy inherent to renewable sources.

D. Super capacitor in Electric Vehicles

Several studies were already done on super capacitors and battery hybrid energy system for electric vehicles. The work of [19] focused on the design of the compact electric vehicle intended for a hybrid energy storage and its corresponding three-layer control. A follow-up study was also done by [20] which presented another control mechanism that is bidirectional power flow for the same hybrid storage system and electric vehicle. In the work of [21], test results of charging and discharging capacities result showed that the super capacitor had a very quick delivery time, making it useful for high currents. A simulated study on electric vehicle which is powered by super-capacitors by [22] verified that super capacitors can be applied on electric vehicles primarily because of its higher power density, longer life cycle, and safer operation. Simulation result on travelling distance indicates a possibility that a maximum distance per cycle may be attained.

III. Objectives

This work is aimed to develop a charging system for electric tricycles through super capacitors, the e-trike's energy storage medium, which harnesses energy from solar power. Alongside with it, this study is aimed to determine (a) the power needed by the super capacitors for full charging; (b) time of charging for the super capacitors to become fully charged; and (d) the distance run by the electric tricycle using fully-charged super capacitor. It is expected that this system is not close to how far the electric tricycle can run using the usual Li-ion battery, but instead, this is focused on the sufficiency of the system to run on short distances taking advantage of the super capacitor's fast charging time.

IV. Research Methodology

A prototype of electric tricycle is accomplished by assembling an electric bicycle with a one-passenger metal side car attached to it. The electric bicycle's manufacturer-supplied Li-ion battery is swapped with super capacitor, mounting the latter to the electric tricycle. A mini structure is built where solar panel is mounted and where charging can be done. This structure also houses the charge controller and other electrical accessories.

A. Sizing of Super capacitor and Solar Panel

The super capacitor used in this model is rated 48 V, 165 F matching the 48-V battery requirement of the electric bicycle. The super capacitor is in module form comprised of 18 pieces of 2.7-V 3,000-F individual super capacitors, as calculated. As for the solar panel size, its power and current ratings were calculated as 4.4 A and 105.6 W, respectively. Thus, a readily-available solar panel with manufacturer rating of 100 W (maximum power), 22.27 V (open circuit voltage), 6.06 A (short circuit current), 18.4 V (voltage at maximum power), and 5.43 A (current at maximum power) is chosen.

B. Charging Set-up

The charging test was divided into two set-ups, through the use of an e-bike charger plugged in to the utility power source and through the use of the solar panel. A simple wiring connection was made for both tests. Figure 1 shows the wiring diagram of the super capacitor connected to the e-bike's charger via male-to-female plug and alligator clips clipped to the super capacitor's terminals with the e-bike charger then plugged in to the utility outlet while Figure 2 is the wiring diagram for the super capacitor connected to the charge controller via wires and alligator clips clipped to the super capacitor's terminals with the charge controller connected to the solar panel.

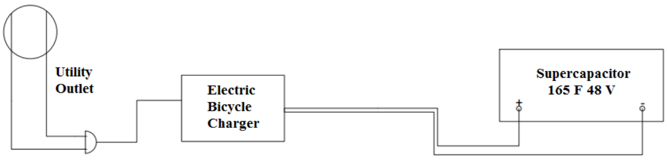

Figure 1: Wiring diagram for charging time test when utility is the main power source

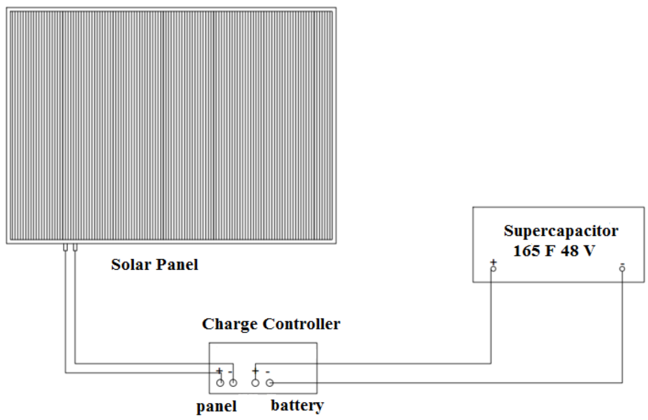

Figure 2: Wiring diagram for charging time test when solar panel is the main power source

V. Testing and Analysis

Different testing and analysis were done to see the capability of the prototype. Measuring of how much power the solar panel generate and also how fast can the super capacitors be fully charged from a discharged state were managed. After that, the super capacitor was connected to the e-trike motor and driven to see the duration of how long the e-trike can travel using super capacitors as its sole power source.

A. Distance Test

Distance test was conducted to determine the distance travelled by the e-trike using the fully charged super capacitor. This test is performed by driving the e-trike around MCL track and field oval, with and without passenger (load), until the super capacitor delivers no more power to the e-trike's motor. Load is fixed to 53 kg for the driver and 65 kg for the passenger. Data taken were super capacitor voltage at the start and at the end of the run, e-trike's speed as indicated by its speedometer, and the distance travelled. The latter is measured by multiplying the number of laps run by the e-trike to 400 m (total perimeter of the inner track). However, the speed is maintained at 30 kph as well as the voltage at start, 48 V as nominal rating voltage, to limit the factors to be treated for analysis.

B. Charging Time Test

Charging time test, on the other hand, determines the time needed for the super capacitor to become fully charged. It tells how fast the super capacitor is charged versus the conventional Li-ion battery using solar power. Power generated by the solar panel (in watts) and time of charging (in minutes) were taken, obtaining 25 trial data. Initial charging time was also obtained, that is, when the super capacitor is charged via the electric tricycle's charger connected to the utility power. This is to establish a baseline reference to compare the charging time when solar panel provides power to the charging circuit.

C. Mathematical Treatment of Data

For the interpretation of results where multiple inputs and varying outputs were produced, regression was used. Regression analysis is used in observing a data to quantify the relationship of one variable to another. Through regression, equations were formulated which can answer the following hypotheses: (a) the super capacitor's voltage at start or end has significant contribution to the distance that the e-trike can travel; and (b) the amount of power derived from the source (i.e., solar panel) has significant relation to the time of charging the super capacitor, whether it will be shortened or lengthened. Furthermore, regression analysis yielded several model equations which can predict the distance that the e-trike can travel with any starting and ending voltage and as well as the time of charging it needs for a given amount of power.

VI. Results and Discussions

Test results for distance test are shown in Table 1 and Table 2. It can be seen that the average distance travelled by the e-trike without passenger load is 831 meters and that the average distance travelled with passenger load is 581 meters. It can be seen that having additional loads can affect the distance that the e-trike can travel.

Regression was performed to further verify those results and it shows that for these tests, there is relation between variables *voltage at start*, *voltage at end*, and *distance*. The super capacitor's voltage at start or end has significant contribution to the distance that the e-trike can travel and the relation (for each test) is represented by Equation (1) and Equation (2):

$$d_1 = 1.8980082 + 0.0314281x_1 - 0.0619538y_1 \quad (1)$$

$$d_2 = 3.5622791 + 0.0139840x_2 - 0.0875621y_2 \quad (2)$$

where:
d_1 = Distance travelled, without load
x_1 = Voltage at start, without load
y_1 = Voltage at end, without load
d_2 = Distance travelled, with load
x_2 = Voltage at start, with load
y_2 = Voltage at end, with load

That is, the distance travelled when the voltage at start is 48 V and voltage at end is 42 is predicted to be 804 meters without passenger load and 560 meters with passenger load (as determined by Equations (1) and (2), respectively). As shown in Table 3, variables were statistically significant. The fit is said to be relatively good at 74% (R square) and confidence level of 95%.

Table 1
Data for Distance Test Without Passenger Load and Starting Voltage Close to Super capacitor's Nominal Rated Voltage (48 V)

Without Passenger Load (Driver's Body Weight – 53 kg)			
Run	Voltage at Start (V)	Voltage at End (V)	Distance Travelled (km)
1	48.6	41.7	0.84
2	48.2	41.7	0.84
3	48.4	41.8	0.84
4	48.6	41.8	0.85
5	48.5	41.7	0.84
6	48.3	41.8	0.85
7	48.5	41.7	0.83
8	48.6	41.9	0.84
9	48.1	41.9	0.83
10	48.3	41.9	0.84
11	48.6	41.8	0.84
12	48.1	41.9	0.81
13	48.4	41.7	0.84
14	48.2	41.8	0.81
15	48.6	41.7	0.84
16	48.6	41.7	0.84
17	47.2	41.8	0.85
18	48.5	41.9	0.81
19	48.5	41.7	0.82
20	48.6	41.9	0.81
21	48.5	41.8	0.83
22	48.3	41.8	0.83
23	48.4	41.7	0.81
24	48.4	41.7	0.82
25	48.3	41.9	0.82

Table 2
Data for Distance Test With Passenger Load and Starting Voltage Close to Super capacitor's Nominal Rated Voltage (48 V)

With Passenger Load (Driver's Body Weight – 53 kg and Passenger's Body Weight – 65 kg)			
Run	Voltage at Start (V)	Voltage at End (V)	Distance Travelled (km)
1	48.6	41.7	0.59
2	48.5	41.7	0.59
3	48.6	41.7	0.59
4	48.6	41.8	0.6
5	48.6	41.7	0.59
6	48.4	41.8	0.6
7	48.4	41.8	0.58
8	48.6	41.7	0.59
9	48.2	41.8	0.58
10	48.6	41.7	0.59
11	48.5	41.7	0.59
12	48.1	41.9	0.56
13	48.6	41.7	0.59
14	48.1	41.9	0.56
15	48.5	41.7	0.59
16	48.4	41.8	0.6
17	48.3	41.8	0.6
18	48.3	41.9	0.56
19	48.2	41.9	0.59
20	48.2	41.9	0.56
21	48.3	41.7	0.56
22	48.6	41.7	0.59
23	48.5	41.8	0.55
24	48.5	41.9	0.56
25	48.4	41.9	0.56

Table 3
Regression Results for Distance Test With Passenger Load Considering Super Capacitor's Starting and Ending Voltage

Summary Output					
Regression Statistics					
Multiple R	0.8595475627				
R Square	0.73882201261				
Adjusted R Square	0.71507855921				
Standard Error	0.006504677851				
Observations	25				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.0026331	0.00131	31.116	0.000000386
Residual	22	0.0009308	0.00004		
Total	24	0.003564			

On the other hand, if simply the difference of voltage level at start and end is considered, then the relationship is represented by Equation (3) and Equation (4):

$$d_3 = 0.5607858 + 0.0407742 z_1 \quad (3)$$

$$d_4 = 0.3359407 + 0.0368557 z_2 \quad (4)$$

where:
- d_3 = Distance travelled considering voltage difference, without load
- z_1 = Voltage difference, without load
- d_4 = Distance travelled considering voltage difference, with load
- z_2 = Voltage difference, with load

With an average voltage difference of 6.6 V, the distance travelled is 830 meters without passenger load and 579 meters with passenger load (as determined by Equations (3) and (4), respectively). Fit quality is 70% at 95% confidence level.

It can also be observed that at the range of 41.7 – 41.9 V, e-trike stops from running because super capacitor is no longer able to supply the required current to run the motor, although at that voltage level, the super capacitor still has considerable charge. This is the result of having a low energy density.

Results for charging time are presented in Table 4. The average charging time of the super capacitor when its power was derived from the utility is 8 minutes and 52 seconds at an average power of 66 W. While that of when power is from solar panel, its average charging time is 6 minutes and 34 seconds at 69 W (average).

Table 4
Data for Charging Time Test Using Two Different Power Sources

	Charging thru Utility Power Source Using E-trike Charger		Charging thru Solar Panel	
Run	Measured Power (W)	Charging Time (seconds)	Measured Power (W)	Charging Time (seconds)
1	68.13	558	76.22	375
2	65.16	548	73.44	383
3	67.58	558	62.00	421
4	70.87	548	86.10	356
5	66.67	558	81.12	372
6	62.56	528	76.32	350
7	62.24	538	76.22	391
8	72.90	558	83.60	363

Run	Charging thru Utility Power Source Using E-trike Charger		Charging thru Solar Panel	
	Measured Power (W)	Charging Time (seconds)	Measured Power (W)	Charging Time (seconds)
9	59.95	508	89.04	349
10	75.74	558	71.40	410
11	70.33	548	55.16	438
12	64.38	488	43.24	476
13	71.81	558	48.50	414
14	60.93	488	64.32	405
15	68.13	548	73.80	393
16	65.16	528	78.81	327
17	67.33	518	78.66	400
18	66.79	508	60.32	425
19	64.50	498	52.92	413
20	61.79	518	64.32	401
21	65.58	538	68.34	406
22	67.21	528	47.38	445
23	68.17	518	56.28	434
24	62.22	508	69.70	387
25	64.19	548	74.90	323

Regression is also used to verify such above result. Equations to describe relationship of power to charging time are represented by Equation (5) and (6):

$$c_1 = 277.999577 + 2.824635 p_1 \quad (5)$$

$$c_2 = 562.95744 - 2.46300536 p_2 \quad (6)$$

where:
c_1 = Charging time via power outlet
p_1 = Measured power via outlet
c_2 = Charging time via solar panel
p_2 = Measured power via solar panel

For an average power of 68 W, charging time of super capacitor when power outlet is used is 8 minutes and 57 seconds while when solar panel is used, charging time is 6 minutes and 35 seconds. As shown in Table 5, variables were statistically significant. The fit of the line is considerably good for the latter equation (70%); 95% confidence level for both tests. It has clearly shown that super capacitors have high power density and are superior in fast charging applications.

Table 5
Regression Results for Charging Time Test and Solar Panel as Power Source

Summary Output					
Regression Statistics					
Multiple R			0.83900956		
R Square			0.70393704		
Adjusted R Square			0.69106474		
Standard Error			20.5593851		
Observations			25		
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	23115.21	23115.2	54.686	0.0000001608
Residual	23	9721.831	422.688		
Total	24	32837.04			

VII. CONCLUSION

This paper attempted to develop the charging system of the e-trike with super capacitor as its power source. Super capacitor was charged through solar panel and the utility power source. The e-trike was tested to run at a smooth oval track with driver and passenger load.

Regression analysis was used to predict the distance travelled by the e-trike as well as the duration of charging the super capacitor up to full level. Based on test results, the following parameters are determined specific only for super capacitor which is rated 48 V and 165 F, 100 W solar panel (with V_{OC} = 22 V and I_{SC} = 6 A), e-trike's load of 53 kg (driver) and 65 kg (passenger), and e-trike's maintained speed of 30 kph: (a) the power needed by super capacitors for full charging is 68 W; (b) it only takes 6 minutes to fully charge the capacitors using the solar panel and 8 minutes using the e-bike charger; and (c) for a full charged super capacitor, e-trike can run up to 850 meters loaded with the driver only and 600 meters loaded with driver and passenger.

It can be noted that super capacitor's average charging time is remarkably short to completely charge, with its power coming from solar panel, even without reaching the maximum power. This can be accounted to the capacitor's high power density. On the other hand, the distance travelled by the e-trike with super capacitor as its lone power source is quite short. This can be accounted to the super capacitor's low energy density.

Super capacitors are said to be suitable only for vehicle transportation requiring short distances such as point-to-point transport services. In addition, they are good storage medium for harvesting energy from intermittent sources such as solar and wind energy sources.

The use of super capacitors with higher voltage and capacity, which can be obtained through paralleling, is recommended to be able for vehicles to run much longer and farther. The use of the newest advancement in technology of super capacitors, if already available in the market, is also recommended for a higher energy density.

Also, since super capacitors are great for recapturing the lost kinetic energy during brakes, it is recommended that a regenerative braking system be added. Harnessing this energy will serve as another source of power to charge the super capacitor.

Similarly, solar panels may be embedded as roofing to the e-trike to allow super capacitors to charge while being used. This will enable a longer and farther run.

Specialized motor or transportation system may also be built, through engineering and design, to fit the performance of the super capacitor under study. Likewise, another study may be conducted to determine the most compatible motor suitable to super capacitors in order to maximize their efficiency.

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