

Torque Analysis of 2 KW BLDC (Brushless Direct Current) Motor with Speed Variations in Electric Cars E-Falco

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Abstract. The motor releases torque and power to drive an electric car by carrying the load from a start position until it travels at the desired speed. The KMLI E-Falco electric car uses a BLDC type electric motor with a power capacity of 2 kW. To find out the amount of torque of a 2 kW BLDC motor when driving with variations in speed, it can be done by manual calculations using the torque equation and doing a dynotest. The dynotest results show that the motor torque at the speed: 1 km/h is 1 Nm, 10 km/h is 131 Nm, 13 km/h is 228 Nm, 20 km/h is 225 Nm, 30 km/h is 219 Nm, 40 km / h is 188 Nm, 50 km / hour is 145 Nm, 60 km / h is 113 Nm, and 70 km / h is 85 Nm. From the results of the dynotest, it shows that the peak torque occurs at a speed of 13 km / h at 228 Nm. Racing software installed in the controller can increase the motor torque by 3 to 4 times at a speed variation of 13-70 km/h based on the results of the dynotest above.

Keywords: motor; BLDC; torque; speed; acceleration

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1. Introduction

To reduce dependence on the use of fuel oil so that it is useful to reduce pollution and greenhouse gas emissions, one thing that can be done is to apply electric car technology [1].

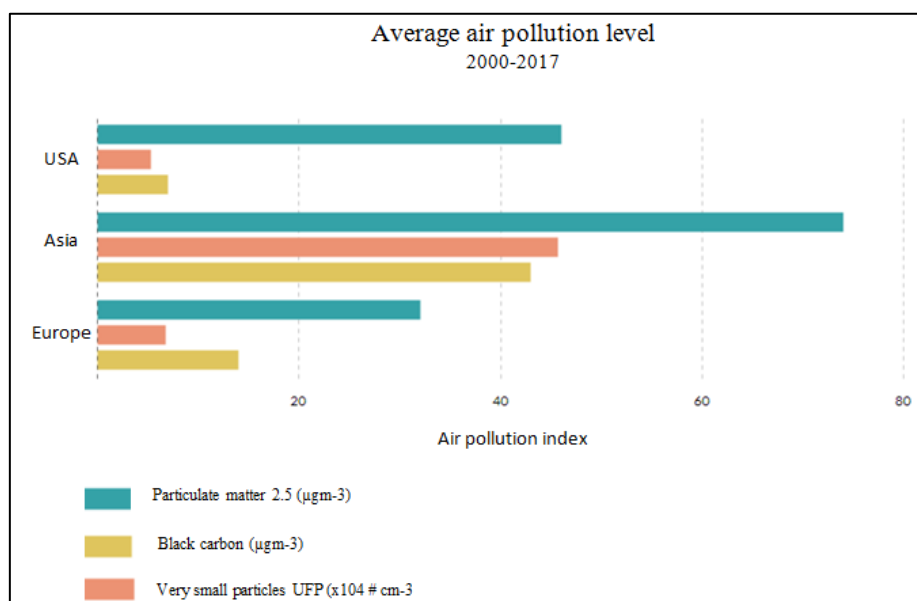


Figure 1. Average air pollution level 2000-2017

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A pure electric vehicle or Battery Electric Vehicle (BEV) uses a motor as the only source of propulsion by taking into account challenges such as dynamic road conditions, control systems and torque accuracy [2].

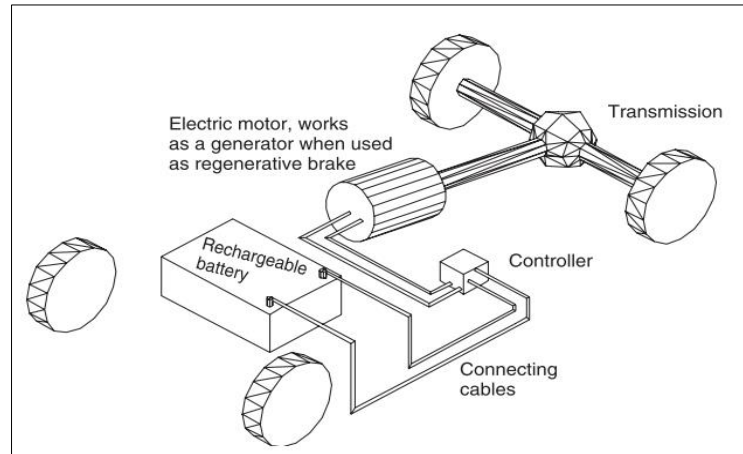


Figure 2. Battery Electric Vehicle

The driving motor used in the KMLI electric car (Indonesian Electric Car Contest) is a BLDC motor with a power of 2 kW because this type of motor meets the criteria and specifications required by this car. BLDC motor is a type of DC motor that does not use a brush so it does not require brush replacement maintenance and this motor has many advantages such as high efficiency, high power, high torque, high speed operation, simple drive method and low cost [3].

The motor driving the KMLI E-Falco car must be able to produce torque to move the car from the start position to speed up with a responsive acceleration speed. The motor speed-torque characteristic of electric vehicles shows that when the motor speed is still in low speed, the motor will produce high torque and when the motor speed is higher, the torque produced by the motor will decrease [4].

An electric car is a vehicle that uses an electric motor as a propulsion engine that gets energy from a battery and this car is classified into several types, namely Pure Electric Vehicle (PEV), Hybrid Electric Vehicle (HEV) and Fuel Cell Electric Vehicle (FCEV). The electric car is based on its energy source [5].

The KMLI E-Falco electric car is BEV electric car because the motor is the only driving force for the car that gets its electric power supply from the battery. The concept of a battery electric vehicle is basically simple consisting of a battery, a motor and a controller where the controller functions to control the electric power of the battery to the motor to drive the car wheels by getting an input signal from pressing the accelerator pedal [6].

The working principle of the Battery Electric Vehicle (BEV) on the KMLI electric car is the electric power from the battery is transferred to the controller then the controller determines the amount of electric power sent to the driving motor based on the accelerator pedal variable pressing, the power output varies from zero to full, based on needs [7].

2. Methodology

The method used to determine the amount of motor torque with variations in speed is using torque calculation and using a dynotest. The torque results from those two methods then analyzed to know the conclusions.

2.1 Technical Data Collection

The technical data will be used as a parameter for calculating and the dynotest. The technical data collected are dimensions, weight, motor specifications and air drag parameters.



Figure 3. Electric Car KMLI E-Falco

a. Weight and Size Vehicle Data

Table 1. Vehicle Data

Data	Description
Vehicle weight	188 kg
Length	245 cm
Width	134 cm
Height	70 cm
Ground clearance	10 cm
Wheelbase	169 cm
Thread	124 cm

b. Motor Specification Data

Table 2. Motor Specification

Data	Description
Rated Power	2 kW
Rated Voltage	48 V
Maximum Torque	150 Nm
Maximum Rpm W/O Load	1000 rpm
Peak Current	120 A
Speed	45-80 km/h
Maximum Efficiency	88 %

c. Gear Ratio Data

Table 3. Gear Ratio Data

Data	Description
Driver Gear Diameter	147 mm
Driven Gear Diameter	180 mm
Driver Gear Teeth	36
Driven Gear Teeth	44
Gear ratio	1.2 : 1

2.2 Motor Torque Calculation

Calculate the motor torque in accordance with variations in speed based on weight, acceleration and travel time that can be achieved by the vehicle using the motor torque theory equation [8].

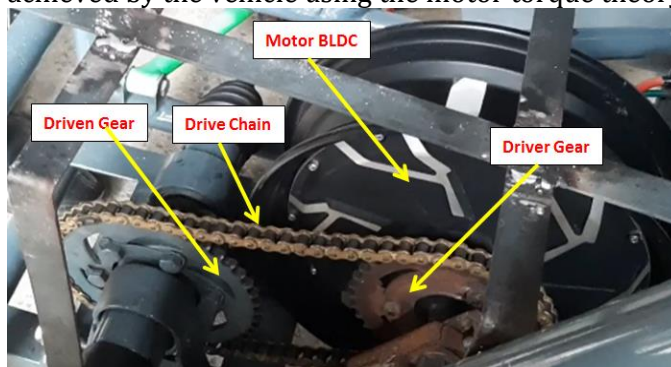


Figure 4. Drive system

a. *The Rotation Calculation of Motor and Wheel*

$$\text{Wheel (rpm)} = \frac{v \cdot 60}{2 \cdot \pi \cdot wr}$$

$$\text{Motor (rpm)} = \frac{v \cdot i \cdot 60}{2 \cdot \pi \cdot wr}$$

Where v is vehicle speed (m/s), i is gear ratio, wr = wheel radius (m).

The calculation of motor and wheel rotation (rpm) is starting from the speed 1 km/h then continued until 70 km/h as explanation below:

$$1 \text{ km/h} = 1000 \text{ m} / 3600 \text{ s} = 0.28 \text{ m/s}$$

- Wheel rotation (rpm) at speed 1 km/h is:

$$\text{Wheel rpm} = \frac{(0.28) \cdot (60)}{(2) \cdot (3.14) \cdot (0.25)} = 11 \text{ rpm}$$

- Motor rotation (rpm) at speed 1 km/h is:

$$\text{Motor rpm} = \frac{(0.28) \cdot (1.2) \cdot (60)}{(2) \cdot (3.14) \cdot (0.25)} = 13 \text{ rpm}$$

b. *The Torque Calculation Without Motor Controller*

This calculation is to know the motor torque based on the motor rotation without any load applied on the motor. The electric power source is direct connected to the motor and without a controller to supply the electric current to the motor and the torque result is based on the motor rotation from starting rotation to high rotation. The purpose of this calculation is to know what torque difference between the BLDC motor with the controller and without the controller. This simulation as the BLDC motor characteristic below:

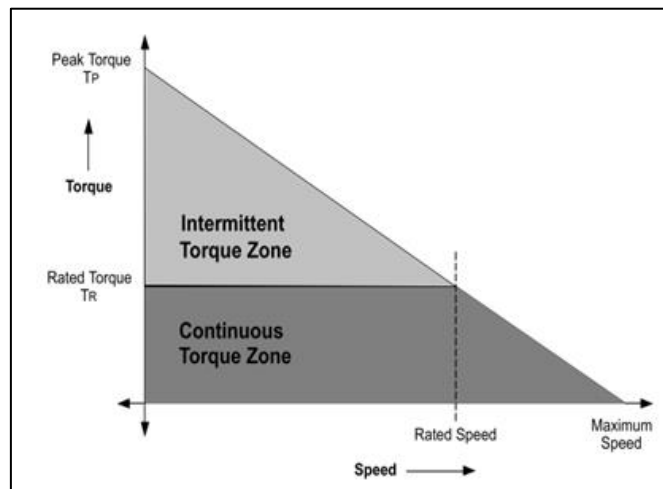


Figure 5. BLDC Motor Torque-Speed Characteristic

The torque calculation in this subject starts from the speed of 1 km/h with motor rotation is 13 rpm.

$$T = \frac{P}{\frac{2 \cdot \pi \cdot n}{60}}$$

Where T is motor torque (Nm), P is power (Watt), n is motor rotation (rpm).

$$T = \frac{2000 \text{ watt}}{(2) \cdot (3.14) \cdot (13)/60} = 1470 \text{ Nm}$$

c. *The Motor Torque Calculation Based on The Vehicle Acceleration*

Acceleration travel time used to calculate the motor torque is using the travel time of the dynotest results that have been installed the racing software in the controller. Because the results of the acceleration travel time from the dynotest are the right data as same as the travel time according to the speed under researched.

Table 4. Travel Time According to Speed Variations

Vehicle Speed (km/h)	Travel time (s)
0 to 1	0.04
0 to 10	0.77
0 to 13	1.00
0 to 20	1.56
0 to 30	2.41
0 to 40	3.40
0 to 50	4.84
0 to 60	7.30
0 to 70	13.63

$$a = \frac{\Delta V}{\Delta t} = \frac{(V_1 - V_0)}{(t_1 - t_0)}$$

$$F = m \cdot a$$

$$T_{\text{wheel}} = T_L = F \cdot r$$

$$T_{\text{motor}} = \frac{d_1}{d_2} \cdot \frac{T_L}{\eta}$$

Where a is acceleration (m/s^2), ΔV is change in speed (m/s), Δt is change in time (s), F is Force (N), r is wheel radius (m), d_1 is diameter of driver gear (m), d_2 is diameter of driven gear (m), T_L is load torque (wheel torque) (Nm).

The torque calculation based on the vehicle acceleration starts from the speed of 1 km/h = 0.28 m/s.

- Vehicle acceleration (a)

$$a = \frac{(0.28) - (0)}{(0.04) - (0)} = 7 \text{ m/s}^2$$

- Force during acceleration (F)

The vehicle mass is 188 kg and the driver mass is 65 kg

$$F = (243) \cdot (7) = 1701 \text{ N}$$

- Total torque on the wheel (T_L)

$$T_L = (1701) \cdot (0.25) = 425 \text{ Nm}$$

- Motor torque (T_{motor})

$$T_{\text{motor}} = \frac{147}{180} \cdot \frac{425}{0,88} = 395 \text{ Nm}$$

d. Perform the Dynotest

Torque testing uses a dynotest machine which is a product of the Mustang Dynamometer and this is a chassis dynamometer type. The controller condition in this test is already inputted with the racing software. The purpose of racing software is to improve the torque and acceleration during driving so that this electric car will have good performance when performing the contest. The software will manage the supply of the current amount to the motor when the driver doing fast acceleration.



Figure 6. Dynotest

The table below is the result of the dynotest when the electric car has accelerated from the speed of 0 km/h to 70 km/h with fast acceleration. The below data is the same as a printout from the computer of dynotest machine.

Table 5. Dynotest result

Time (s)	Speed (km/h)	Wheel Rotation (rpm)	Torque on the Wheel (Nm)	Power (hp)
0,00	0,5	7	0	0
0,50	6,6	89	25	4
1,00	13,0	177	279	7
1,50	19,3	263	276	10
2,00	25,3	346	270	13
2,50	31,0	424	267	16
3,00	36,4	498	250	17
3,50	41,0	561	224	17
4,00	44,8	613	202	17
4,50	48,0	658	187	17
5,00	50,9	697	174	17
5,50	53,3	731	163	17
6,00	55,5	760	155	16
6,50	57,4	786	147	16
7,00	59,1	810	142	16
7,50	60,6	830	136	16
8,00	61,9	849	132	16
8,50	63,1	865	127	15
9,00	64,2	880	123	15
9,50	65,2	893	119	15
10,00	66,0	905	117	15
10,50	66,8	915	114	15
11,00	67,4	925	112	15
11,50	68,1	933	110	14
12,00	68,6	941	108	14
12,50	69,1	947	106	14
13,00	69,5	953	104	14
13,50	69,9	959	104	14
14,00	70,3	964	102	14
14,50	70,6	968	101	14
15,00	70,9	972	101	14

The dynotest table data above can be used to find the travel time, speed, wheel rotation, and wheel torque by using an interpolation formula:

$$Y = Y_1 + \left(\frac{X-X_1}{X_2-X_1}\right)(Y_2 - Y_1).$$

3. Results and Discussions

The torque data that has been obtained will be used for analysis so that the results of the analysis can be used to improve the acceleration speed capability.

3.1 The Result of Torque Calculation Based on the Motor Without Controller

The table below is showing the result of the torque calculation without motor controller and the torque calculation is based on the motor rotation from low to high rotation speed when the motor is connected to an electric power source directly.

Table 6. Torque without Motor Controller

Speed (km/h)	Speed (m/s)	Motor Rotation (rpm)	Torque (Nm)
1	0,28	13	1470
10	2,78	127	151
13	3,61	166	115
20	5,56	255	75
30	8,33	382	50

40	11,11	510	38
50	13,89	637	30
60	16,67	764	25
70	19,44	892	21

3.2 The Result of Torque Calculation Based on the Acceleration

The table below is showing the result of the torque calculation based on the vehicle acceleration.

Table 7. Torque Based on the Acceleration

Speed (km/jam)	Motor Torque (Nm)
1	395
10	204
13	204
20	201
30	195
40	184
50	162
60	129
70	80

3.3 The Torque Based on the Dynotest Result on the Speed of 1 km/h, 10 km/h, 13 km/h, 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h and 70 km/h

The table below is showing the torque of motor based on the dynotest result on the Speed of 1 km/h, 10 km/h, 13 km/h, 20 km/h, 30 km/h, 40 km/h, 50 km/h, 60 km/h and 70 km/h.

Table 8. Torque Based on the Dynotest

Speed (km/h)	Travel Time (s)	Wheel Rotation Based on Dynotest (rpm)	Motor Rotation Based on Wheel Rotation (rpm)	Wheel Torque (T_L) Based on Dynotest (Nm)	Motor Torque (Nm), $= \frac{D_1}{D_2} \cdot T_L$
1	0,04	14	17	2	1
10	0,77	136	167	160	131
13	1,00	177	217	279	228
20	1,56	273	334	275	225
30	2,41	410	502	268	219
40	3,40	547	670	230	188
50	4,84	685	839	178	145
60	7,30	822	1006	138	113
70	13,63	960	1176	104	85

The table above showing that peak torque appears at the speed of 13 km/h with the motor torque is 228 Nm.

3.4 The Torque Comparison Between the Result of Torque Calculation and the Dynotest

This subject will explain the torque based on the calculation and dynotest result. The table and the graph below are showing about the numbers of torque based on the calculation and dynotest result.

Table 9. Torque Comparison between the Result of Torque Calculation and the Dynotest

Vehicle Speed (km/h)	Torque Calculation Based on The Motor Rotation (Nm)	Torque Calculation Based on The Vehicle Acceleration (Nm)	Torque Based on The Dynotest (Nm)
1	1470	395	1
10	151	204	131
13	115	204	228
20	75	201	225
30	50	195	219
40	38	184	188
50	30	162	145
60	25	129	113
70	21	80	85

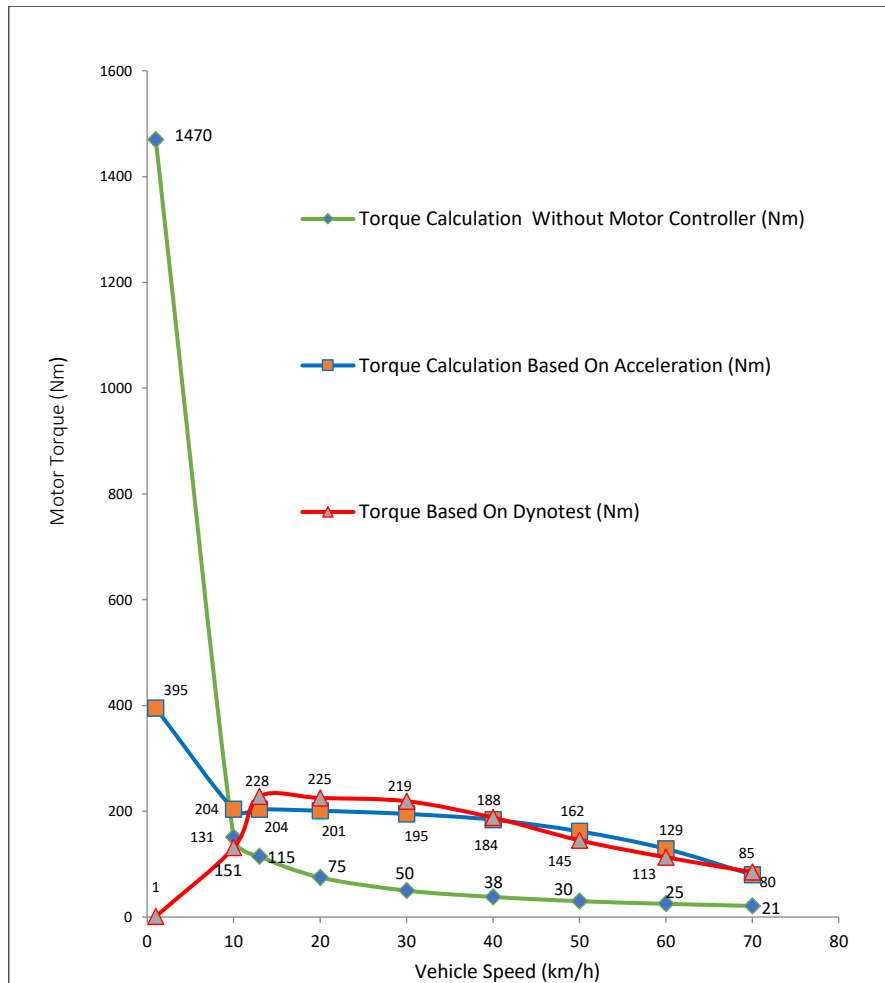


Figure 7. Graphic of Torque Comparison

3.5 The Analysis of Torque Between Motor Specification and Dynotest Result

The information from table 2 is mentioned that the maximum torque/ peak torque of BLDC motor used for this electric car is 150 Nm with a peak current 120 A. But if we see from the data of dynotest result, the motor peak torque can reach 228 Nm at speed of 13 km/h and at speed of 70 km/h can reach 80 Nm. This can happen in the motor torque because the working principle of the motor is different from the Internal Combustion Engine (ICE) which the torque of ICE is dependent on the size of the crankshaft journal and piston stroke. The Electric motor torque and rotation are based on the electric induction process accordingly to the amount of electric current supplied to the motor by the controller. Because this car is for race competition so that the setting of the controller is set up with a large electric current flow to the motor accordingly with the driving condition to get the fast acceleration. The software of the motor controller can be set up by inputting the normal software program so that the motor will rotate with normal torque and the motor can use a more long life. Inputting the software racing to the motor controller will possibly make the usage of motor life will be short. Figure 9 is showing that the vehicle speed is 52 km/h and the motor controller supplied the electric current with an amount 269 Ampere and the output torque from the motor is 141 Nm.

3.6 Torque Analysis Between the Manual Calculation and the Dynotest

The data that has been obtained shows that the results of torque calculation and the results of the dynotest have difference results.

a. Torque Analysis From the Speed of 1 km/h to 13 km/h

This phase is a situation where the acceleration pedal is on the way to being fully depressed, when the pedal is pressed a little, the electric power received by the motor is still small, resulting in small power output and motor torque, when the pedal is fully pressed, the electric power received by the

motor is large, resulting in the power and torque output of the motor increases. This is making the motor torque at a speed of 1 km/h until before 13 km/h is smaller than manual calculations.

b. Torque Analysis Between the Torque Calculation without the Motor Controller and the Dynotest Result

The analysis of torque at a speed of 13 - 70 km/h against these two methods because the pedal is fully depressed and the peak torque in the dynotest occurs at a speed of 13 km/h. It can be seen that the motor torque without motor controller compared with the results of the dynotest shown by the table below:

Table 10. Torque Comparison between Torque Calculation without motor controller and Dynotest Result

Motor Torque	Vehicle Speed (km/h)						
	13	20	30	40	50	60	70
Without Motor Controller (Nm)	115	75	50	38	30	25	21
Based on The Dynotest (Nm)	228	225	219	188	145	113	85

Table 10 above shows that the racing software installed in the controller according to the results of the dynotest test is able to increase the torque up to an average of 3 - 4 times from the motor torque without the motor controller.

c. Analysis of the Phenomenon on the Graphic between Torque Calculation Based on the Acceleration and the Dynotest

It can be seen that motor torque between calculation based on the acceleration compared to the results of the dynotest in the speed 13 km/h - 70 km/h as shown to the table and graphic below:

Table 11. Torque Comparison between Manual Calculations Based on Acceleration and Dynotest

Motor Torque	Vehicle Speed (km/jam)						
	13	20	30	40	50	60	70
Torque Calculation Based On Acceleration (Nm)	204	201	195	184	162	129	80
Torque Based On Dynotest (Nm)	228	225	219	188	145	113	85

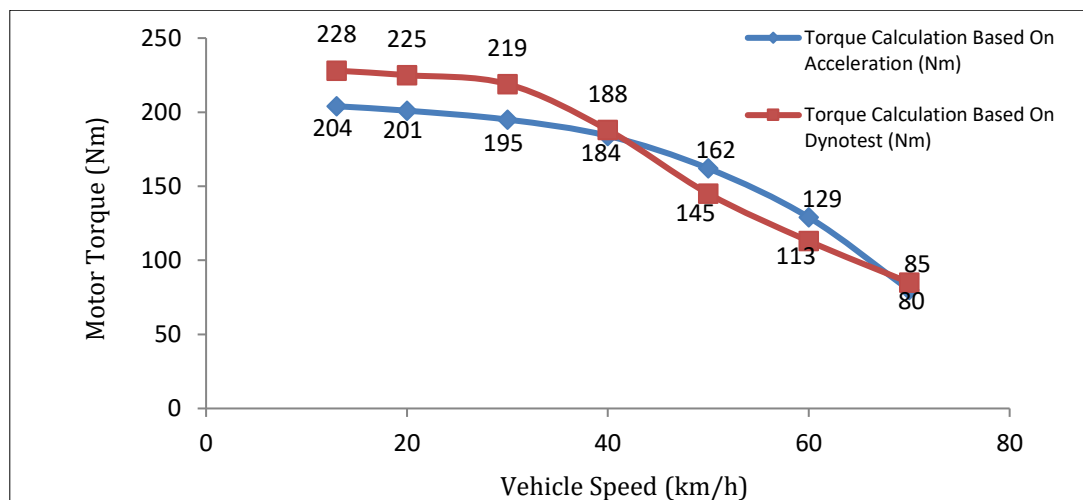


Figure 8. Graphic of Comparison between Torque Calculation Based On Acceleration and Dynotest

This phenomenon occurs because of the amount of the electric power supply from the controller to the motor at speed variations after 40 km/hour to before 70 km/hour which makes the torque figure below the graph based on calculations. It is proven by the print shot results of the electric power supply at a speed of 52 km / h with the following calculations:

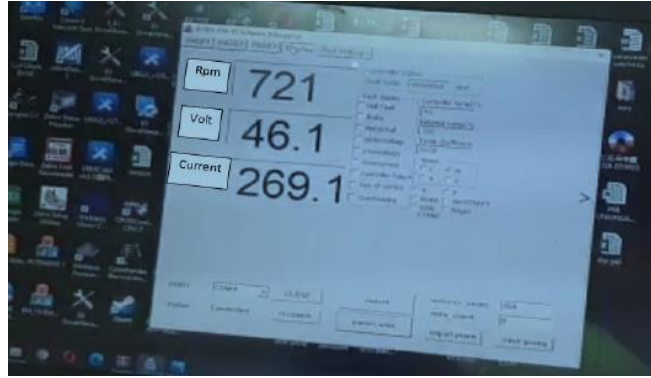


Figure 9. Current and Voltage Supply From Controller to Motor

From that above data that total current supplied to the motor is 269.1 ampere with voltage 46.1 volt and motor rotation is 721 rpm. Motor rotation 721 rpm is equal with vehicle speed 52 km/h. From those data we can proofed the torque is below then torque calculation based on the acceleration.

Motor power, $P_{el} = 46 \text{ volt} \times 269 \text{ ampere} = 1241 \text{ Watt}$

Torque of motor,

$$T_{in} = \frac{169}{1,2} = 141 \text{ Nm}$$

When compared with the torque calculation based on the acceleration at 52 km/h is 155 Nm, it is evident that the torque number of the dynotest results is below the torque calculation on the graph with the electric power supply to the motor is 1241 Watt.

4. Conclusions

From the results of the research and analysis above, This research concludes as follows:

1. The results of manual calculations based on motor rotation (without racing software in the controller) show that motor torque at speeds: 1 km/hour = 1470 Nm, 10 km/hour = 151 Nm, 20 km/hour = 75 Nm, 30 km/hour = 50 Nm, 40 km/hour = 38 Nm, 50 km/hour = 30 Nm, 60 km/hour = 25 Nm, and 70 km/hour = 21 Nm.
2. The results of manual calculations based on acceleration (installed racing software in the controller) show that the torque released by the motor at speed: 1 km / h = 395 Nm, 10 km / h = 204 Nm, 20 km / h = 201 Nm, 30 km / hour = 195 Nm, 40 km/hour = 184 Nm, 50 km/hour = 162 Nm, 60 km/hour = 129 Nm, and 70 km/hour = 80 km/hour.
3. The results of the dynotest test (installed racing software in the controller) show that the motor torque at speed: 1 km/h = 1 Nm, 10 km/h = 131 Nm, 20 km/h = 225 Nm, 30 km/h = 219 Nm, 40 km/h = 188 Nm, 50 km/h = 145 Nm, 60 km/h = 113 Nm, and 70 km/h = 85 Nm. Peak torque occurs at a speed of 13 km / h is 228 Nm.
4. The racing software installed in the E-Falco electric car controller is able to multiply the motor torque up to 3-4 times compared to the motor without racing software.

Acknowledgments

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