Study on the development of electromagnetic two speed gearbox for EV

Ataur Rahman, Nurul Hassan, Abdul Hassan Jaafar, AKM Mohiuddin, Sany Ihsan Izan

Abstract: ***Electric drive vehicle uses one or more electric motors or traction motors for a propulsion. A multispeed electric vehicle (EV) transmission adds weight, complicacy, and friction reduce the vehicle traction efficiency. Among epicyclic transmission (ET) with a single motor gear shifter or manual transmission or automatic transmission (AT) and continuously variable transmission (CVT), the ET is a complex transmission because most of the driver doesn't know properly the transmission option. The efficiency of the gearbox is an important factor of the inverter and driving manner. The aim of this study is to develop of electromagnetic 2-speed gearbox (EM-2SGB), which would contribute on the reduction of the vehicle transmission losses from 15% to 5%. This proposed 2-speed gearbox would be able to improve the vehicle transmission shift quality and acceleration time in 250 ms to reach the speed of 35 km/h in 15% road gradient. The lighter and compact energy efficient EM-2SGB is expected to increase the vehicle overall performance about 25%.***

Keywords: ***Electromagnetic actuator, two speed gearbox, Fuzzy logic controller, wheel speed sensor, low cost transmission.***

I. INTRODUCTION

The automotive industry, an electric vehicle is a vehicle, which is power up by an electric motor instead of a gasoline engine. The electric motor gets energy from the controller, which produced the power like as accelerator pedal. It is getting charged from household electricity then stored in its rechargeable batteries [1]. An electric vehicle acts as an opposite to internal combustion engine vehicles because of it decrease the pollutant to the environment. For these reason automotive companies started to improve each component in their product [2].

The 1st modern fully electric vehicles were developed by the leading carmakers which are designed by a two-wheel drive layout with a centrally located electric motor drive which coupled to the wheels through a single speed gearbox, a differential and half shaft [3]. A basic single speed transmission represents the cost-effective solution but not signifying performance limitation and that is fully improved by an electric vehicle which is the future standard solution [4][5][6]. The compact gearbox can replace the multispeed transmission and provide less than 1/3 the size and weight of the transmission. It's leads ICE to EV brings user from 25% to 85% workable [7][8]. Multispeed transmission could improve the EV traction performance but it also increases the weight, cost and reduce efficiency. The EV doesn't require clutch for gear changing and not require a complicated gear shifter and rods [9]. A 2-speed gearbox is the best option for EV because bolted directly to the motor. Therefore, a two-speed gearbox probably a right transmission for EV. One used for traction and other used for high speed.

There are two examples of cars with gear shifting mechanism. Firstly, the Exagon Furtiv e-GT has two motors, each with a two-speed gearbox. When starting, both motors are in first gear and acceleration is begun one motor switches to 2nd gear. When the driver keeps his right foot down, 2nd motor also switch to the 2nd gear. Here without any torque flows interruption in gear changing process because of one motor always in gear. It is very complex and expensive like manual transmission [10]. Secondly, Toyota PRIUS, when the driver moves the shifter with change the gear position, he doesn't know the transmission actually shift in gear or not or if in gear which gear. The Volt, Ampera, Auris, Fusion and C-Max operating as a single speed transmission which has many moving parts and complicated [11] [12]. Literature review has reported that the electromagnetic actuated CVT system which offers an opportunity to meet the challenge because of improving its automotive drivability and provide great fuel economy. This system can also help EV to reduce the greenhouse gas emission [13] [14].

This study focuses on the development of electromagnetic two-speed gearbox, which increases the working capability of about 5-10% without the negotiating the driver style. It is more effective and functional of the sets of speed sensor and controller. The specialty of this development is that the proposed gearbox would reduce weight, frictional power loss and improve working capability range and the first operation, which hasn't any obstruction of power transfer. It would be the OE-type single speed for AC and brushless DC motors as it minimizes space requirement and allows design flexibility and it would be an effective gearbox, which minimizes both factor such as 1st acceleration and cruising.

II. METHODOLOGY

In-vehicle system, transmission is the main part which performance related to gear efficiency, gear noise and gearshift comfort during gear change and it also determine

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the behaviour of power and fuel economy of a vehicle. For the stability of transmission and comfort for the user, synchronizer mechanism must allow gear changing in a smooth way, noiseless and without vibration. This study guided on the development of electromagnetic two speed gearbox for EV which improve the dynamic shift quality and decrease the shifting time and effort (Fig: 1).

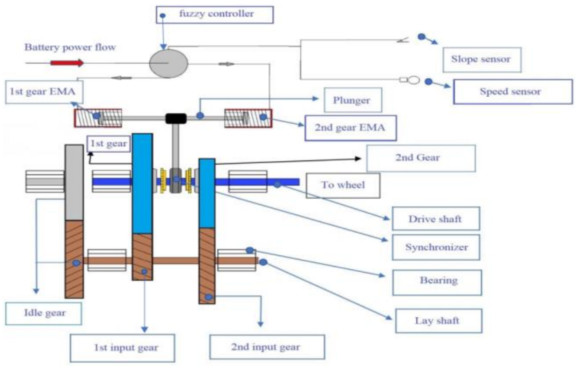

Fig. 1: Model of electromagnetic two speed gearbox.

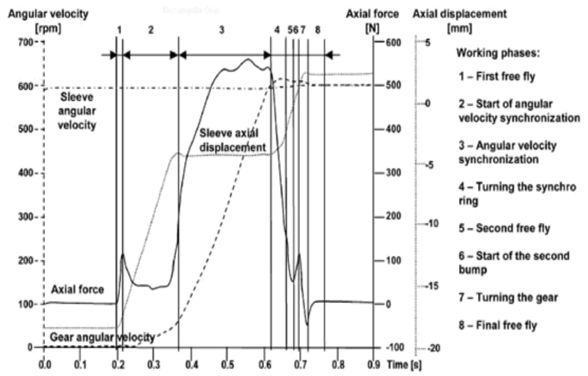

Fig. 2: The shift force or axial force and angular velocity of the gear during gear shifting [5].

The electromagnetic transmission transfer power from the electrical motor to the drive shaft in an electric vehicle. The simulation of this study considering the actuation force maximum 550N for gear shifting. This force considered as the axial force of the synchronizer. When investigating the actuator gear shifter performance by the laboratory test by using different loads equivalent to the vehicle load both in 0% to 15% gradient. The aim of the laboratory scale is needed to check the actual parameter of gearbox and actuator size EM2-SGB for the passenger car. The laboratory scale is also developed for EV to place the inverter, fuse, contactor, energy renewable capacitors, auxiliary battery and others.

The electromagnetic actuator known as solenoid uses for gear shifting process and also maintain gear ratio. In (Fig 1) EMA-2SGB is developed by copper coil wounding. Current is supplied to the coil to develop the magnetic flux in actuator. If magnetic flux ϕ exists in a component due the presence of magnetic field intensity H, given by H=Fm / *l*, where Fm is magneto -motive force and *l* is the length of the component. The shift force of synchronizer can be calculated by this following equation [14]:

$$F_a = \frac{2J\Delta\omega\sin\alpha}{N_c \mu d_m t_f} \quad (1)$$

where, F_a is the shiftin force, N, J is the polar moment of inertia, $\Delta\omega$ is changing of the angular velocity of the synchronizer ring, N_c is the number of cones, d_w is the mean cone diameter, t_f is the slip time. The working phase of gear changing has shown in (Fig. 2) [2].

2.1 Electromagnetic force

The actuator has been designed to develop the maximum electromagnetic force which is must be greater or equal to the axial force needed of the synchronizer to engage and disengage the gears. EMA developed by two solenoids with different number of turns and stoppers along with a common plunger. The mathematical representation is developed for the EMA by considering the dynamic behavior of the magnetic flux, density, strength, electromagnetic force and energy according Faraday's Law, Ampere's Law, Lenz's Law and Maxwell's dynamic condition. From Fleming's LH rule the total electromagnetic force at the magnetic field by this general equation,

$$F_{em} = BiL_{wire} \quad (2)$$

where, F_{em} is the electromagnetic force for the total solenoid coil length L_{wire}, B is the magnetic flux density, and i is battery current supply to the coil. The properties of EMA depends on the geometry of the magnetic core, amount of air gap in the magnetic circuit, core material and solenoid temperature. The magnetic flux density along the z direction considered as circular loop although the turns look like helical in shape (Fig. 3) [16].

The magnetic concentration is gathered in the center P of the solenoid. Here, overall magnetic flux density can be expressed as:

$$\vec{B}_z = \hat{z} \sum_{a={h_1}/{2}}^{{h_2}/{2}} \sum_{z=-{L_{solenoid}}/{2}}^{{L_{solenoid}}/{2}} \left(\frac{\mu \left(\iint_{S(r,l_{segment})} J dS_{wire} \right) a^2}{2.\sqrt[3]{a^2+z^2}} \right) \int dz \quad (3)$$

where, h_2, h_1 is the outer and inner radius of the solenoid from the centre P. $L_{solenoid}$ is the length of the solenoid. It is noted that the development of F_{em} is the function of supplied current

$$F_{em} = f^n \left(\iint_{S(r,l_{segment})} J dS_{wire} \right) \quad (4)$$

The supplied current of the solenoid is controlled with the controlling the voltage for the desired F_{em}. The main purpose of controlling current is to prevent the actuator from temperature spike and unnecessary power loss. Fig.3 shows the development of electromagnetic force. It also shows that the magnetic flux (B) develops with supplying current to each loop of the EMA solenoid. The magnetic flux squeezes along the *x* direction and expands along the *z* direction of the solenoid. The largest F_{em} is generated in the middle of the solenoid due to magnetic field concentration, which causes the plunger to attract and to repel. The total *B* at point P can be estimated by using the equation [16]:

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$$B=\hat{z}\sum_{a=h_1/2}^{h_2/2}\sum_{z=-L_{solenoid}/2}^{L_{solenoid}/2}\left(\frac{\mu\left(\iint\limits_{S(r,l_{segment})} JdS_{wire}\right)}{2}\right)\int\frac{a^2}{\sqrt[3]{a^2+z^2}}dz \quad (5)$$

$$=\hat{z}N_{loop}\frac{\mu N_{wind\,per\,length}I}{2L_{solenoid}}(\sin\alpha_2-\sin\alpha_1)$$

where, μ is magnetic permeability (degree of magnetization of a material in response to magnetic field), $N_{wind\ per\ length}$ is the number of turns in a single loop, N_{loop} is the number of loop in solenoid housing, $N{=}N_{wind\ per\ length}.N_{loop}$ is the total number of turns in the solenoid. $I=\iint\limits_{S(r,l_{segment})} JdS_{wire}$ is the total supply current, $L_{solenoid}$ is the solenoid length and $\alpha=\tan^{-1}\left[\frac{L_{solenoid}/2}{a/2}\right]$ is the limiting angle with radius (a) for the first loop of the solenoid depends on solenoid inner dimension (h_1).

Therefore, the electromagnetic force develops by the solenoid can be estimated as:

$$F_{em}=N\frac{\mu I^2}{L_{solenoid}}(\sin\alpha_2-\sin\alpha_1)l_{singlewinding} \quad (6)$$

If the solenoid length is much larger than its radius, then $\alpha_2\cong 90^\circ$ and $\alpha_1\cong(-)90^\circ$ in which Equation 3.19 reduced to:

$$F_{em}=N\frac{\mu I^2}{L_{solenoid}}l_{singlewinding}=N\frac{\mu I^2}{L_{solenoid}}2\pi a \quad (7)$$

Boundary conditions of the electromagnetic force assisted to figure out the maximum I while a is the distance between the wire segment centre and the centre of the solenoid and $L_{solenoid}$ is the length of the solenoid are assumed to be defined and play around N for satisfying with desired magnetic force.

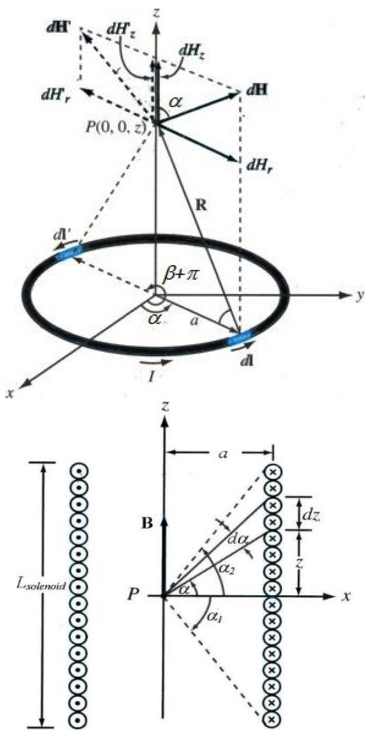

Fig. 3: Magnetic field of single and multiple coil winding.

2.2 Electromagnetic energy

Electromagnetic energy that has been developed in EMA of this study is defined as the energy which is from a magnetic field that is produced by the motion of electric charges such as electric current. The electromagnetic energy stored in the solenoid $E_{eng\cdot Li}$ due to its inductance and it is estimated by using the following equation:

$$E_{eng.L_i}=\int pdt=\int\int i(t)L_i\frac{di}{dt}dt=L_i\int_0^I i(t)di \quad (8)$$

the self inductance of the solenoid coil can be defined as the ratio of the magnetic flux linkage $L_i=\frac{\phi_{total}}{I}$ with total magnetic flux linking $\phi_{total}=\phi_{loop}n$ .where, L_i is the self inductance in Henry. The magnetic flux ϕ_{loop} linking a surface area of the coil is defined as the total magnetic flux density passing through the cross-sectional area of the solenoid coil loop can be represents as,

$$\phi_{loop}=\int\limits_{A_{solenoid}} B.dA_{solenoid} \quad (9)$$

In a solenoid with an approximately uniform magnetic field given by equation 3.18, the flux linking a single loop [16]:

$$\phi_{loop}=\mu\frac{NI}{L_{solenoid}}(A_{solenoid}) \quad (10)$$

where, μ is magnetic permeability, N is the number of turns per loop, I is the supply current, $L_{solenoid}$ is the solenoid length, $A_{solenoid}$ is the surface of the coil and α is the limiting angle. Total magnetic flux linking for n number of loop in the solenoid can be defined as:

$$\phi_{total}=\sum_{n=1}^{n}n\phi_{Loop}=\mu\frac{NI}{L_{solenoid}}(A_{solenoid}) \quad (11)$$

The inductance became:

$$L_i=\mu\frac{N}{L_{solenoid}}(A_{solenoid}) \quad (12)$$

The electromagnetic energy stored in the solenoid due it inductance can be estimated as:

$$E_{eng.L_i}=\frac{1}{2}\mu\frac{N^2A_{solenoid}}{L_{solenoid}}\left(\frac{BL_{solenoid}}{\mu N}\right)^2$$

$$=\frac{1}{2}\frac{B^2}{\mu}Vol^m_{solenoid} \quad (13)$$

where, $Vol^m_{solenoid}$ is the volume of the interior of the solenoid, with, $Vol^m_{solenoid}=L_{solenoid}\,A_{solenoid}$, $L_{solenoid}$ is the length of the solenoid, $A_{solenoid}$ is surface of the coil or cross-sectional area of the solenoid loop. Again Energy stored in the solenoid coil can be find out by combining the Equation 3.16 and 3.24 is:

$$E_{eng.Li}=\frac{1}{8}\frac{\mu N^2I^2A_{solenoid}}{L_{solenoid}} \quad (14)$$

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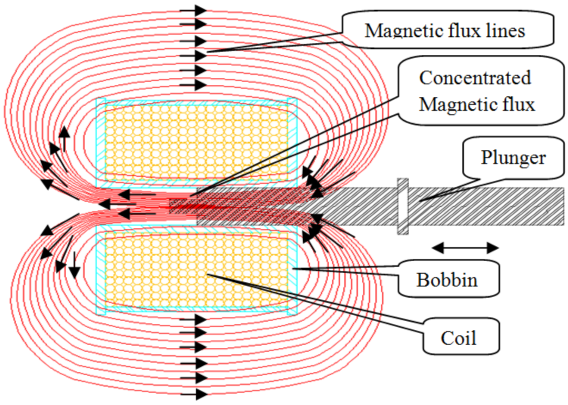

Fig.4: Simple Solenoid with Plunger.

2.3 Electromagnetic actuator design

Electromagnetic actuator acts like medium which converts electrical energy to mechanical energy. Solenoid uses the same way to generate electromagnetic force. It is important to know the core principle of electromagnetic force generation then how force generated in solenoid actuator. It is a coil of wire with an outer flux return path of permeable material and magnetically plunger, which is attacked by the centre of the coil when current is passing through the winding (Fig. 4).

A magnetic field strength H_{out} and H_{in} is developed both outside and inside the coil after passing the current through the coil. In here, the magnetic field is always $H_{in}>H_{out}$ and considerable magnetic energy is stored in the interior, which is used to do mechanical work. The pulling / pushing of the EMA plunger greatly increased by the current which is supply to the EMA. Excessive current sometimes damage the EMA by overheating. Solenoid is designed by considering the core housing, number of winding and diameter of the copper wire, HCS (high carbon steel) plunger and power-pack.

A number of turns of copper wire are rounded outside the solenoid. It must be following that large diameter wire causes considerable void, which affect the magnetic flux due to low magnetic permeability of air. Conversely low diameter wire can't be used because it causes high resistance. Total length of wire of the EMA can be expressed as,

$$l_{wier} = \pi \times \frac{h_2 - h_1}{2} \times \frac{L_{solenoid}}{d_w} \times \frac{h_2 - h_1}{2d_w}$$

$$l_{wire} = \pi \frac{L_{solenoid}(h_2^2 - h_1^2)}{4d_w^2} \qquad (15)$$

where, h_2 and h_1 is largest and smallest diameter of the solenoid respectively. d_w is the wire diameter and $L_{solenoid}$ is the length of the solenoid.

Again, the wire resistance,

$$R = \frac{4\rho l_{wire}}{\pi d_w^2} \qquad (16)$$

where, R is the wire resistance in Ω , ρ is the resistivity of conductor in Ωm, l_{wire} is the total length of the conductor and d_w is the wire diameter. In combine the Equation 3.34 and 3.34 can be written as:

$$d_w = \sqrt[4]{\frac{\rho L_{solenoid}(h_2^2 - h_1^2)}{R}} \qquad (17)$$

III. DEVELOPMENT OF EM-2SGB

The laboratory scale EMA -2SGB has been developed and fabricated (Fig.5). The main objective of this transmission is to identify its potentiality on the shifting operation of the gear during traction and cruising speed. It has been made with electromagnetic mechanism for the shifting operation of the 1^{st} gear to 2^{nd} gear and vise-versa. The first gear of this transmission of gear ratio 3.58 is for the vehicle traction while the 2^{nd} gear of gear ratio 1.92 is for the vehicle cruising speed. Each of the EM is considered as solenoid, which is made with metal bobbin inner diameter of 30 mm and outer diameter of 47 mm. It is wounded with copper coil diameter of 1.44 mm. The 1^{st} gear shifting EMA coils turn is 600 while for the 2^{nd} gear shifting EMA is 500. The 1^{st} gear needs more force and 2^{nd} gear needs less force for adjustment the speed. The main objective of the solenoid development is to develop the electromagnetic force of 500 N with supply current in the range of 3.5 - 4.5 A with a 12 V DC battery. The electromagnetic force is limited by the axial force requirement for the shifting of the gear from one gear to the other.

The number of turns of copper coil is 600 for getting the EMF 550 N with maximum supply current 16A to ensure the axial force. The temperature develops if the current supply is more than 16A to the EMA.

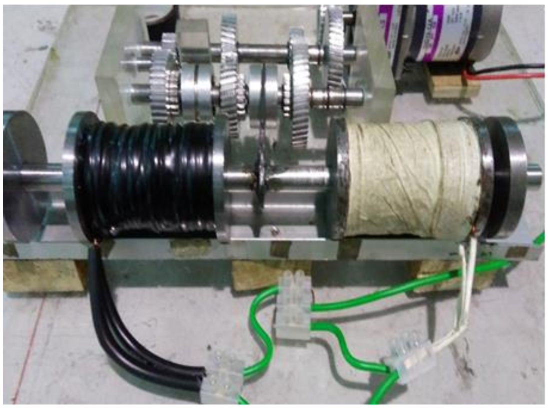

Fig. 5: Laboratory scale Electromagnetic actuator two speed gearbox.

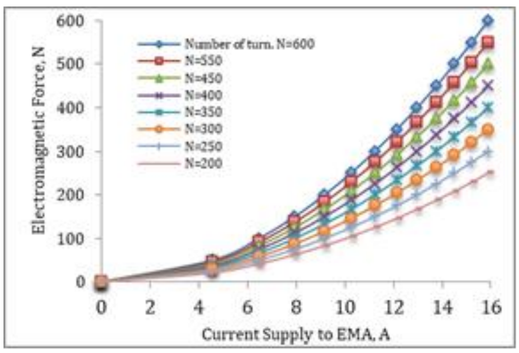

Fig.6: Electromagnetic force of the solenoid.

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IV. RESULTS AND DISCUSSION

PERFORMANCE INVESTIGATION OF EM-2SGB

The simulation of the study of EMA-2SGB has been guided to estimate the $F_{em} \geq F_{ax}$ by using the EMF with considering permeability, $\mu = 1.25 \times 10^{-6}$, effective area 0.0019 m^2. Magnetic force, F_{em} is considered in this study 70N for lighter vehicle [18] and 550 for heavier vehicle [19].

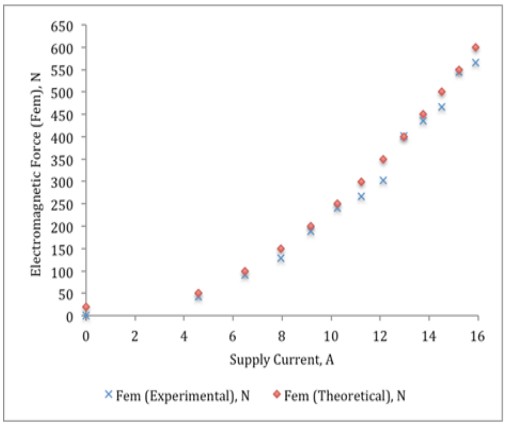

Fig. 7: Electromagnetic shifting force.

The simulation of this study is guided for the gear shifting time, which refers to the time interval between gear changes in a transmission which power delivery is breakout. Figure 7 shows the electromagnetic force of the gears develops by the EMA based on the supply current. EMA is capable to develop electromagnetic force to change the gear in 120-150 ms for the supplied current range 10-16 A. The maximum current supply to the EMA is 15A based on the recommendation from the experiment, it was found that shifting gear from 2nd to 1st in 110ms with supplied current of 14A with developing force 50N. By equation 6, the number of coil winding has been determined which generate much force is about 75N (120) turns.

The copper wire required, length of 99 m, solenoid length of 0.2m, height of 3 cm and wire diameter of 1.44 mm. Table 1, shows the gear shifting time from neutral to 1st gear or 2nd gear and 1st gear to 2nd gear and 2nd gear to 1st gear for heavy-duty operation. Gear shifting time for the 2nd gear engagement is 25% more than the 1st gear, which might be due to the speed variation of the vehicle. Table 2, shows that EMA-2SGB accelerating time over automatic, manual, conventional CVT and electromagnetic CVT. Results shows that EMA-2SGB has lowest time taken compared to other transmission. The EMA-2SGB can reduce power loss occur while gear shifting.

Table 1: Gear shifting time for the 15A supply to the EMA for heavy duty operation

Gear Shifting position	Distance (mm)	Current (A)	Gear shifter time (ms)
1st gear engagement from neutral position	7	10	75.5
2nd gear engagement from 1st gear position	14	8.5	150.5
1st gear engagement from 2nd gear position	14	8.5	120.25

Table 2: Acceleration time for gear shifting of the transmission.

Type of transmission	Acceleration time (from speed 0 to 30 km/h)	Performance comparison of other transmission over the automatic transmission			
		[a]Energy losses (kWh)	Energy saving (kWh)	[e]Emission on generation of additional power to compensate the losses (kg)	
				Coal plant	Petroleum plant
Automatic[c]	10.86	3.3	-	3.89	2.80
Manual	10.25	3.11	0.20	3.66	2.64
Conventional CVT[15]	7.55	2.29	1.04	2.70	1.95
EMA-CVT[11]	3.50	1.06	2.24	2.64	0.90
EMA-2SGB[d]	2.79	0.85	2.46	3.29	0.72

Notification: [a]Neglect the weight of the transmission, [b]Prime mover brake power has considered to be 33 kWh [WTO, 2012], [c]Automatic transmission power lose has considered to be15% due to slip (2%), friction (3%) and gear shifting delay (10%) , [d]EMA-2SGB laboratory scale , [e]Based on EV battery power charging electricity generation (CO_2 emission for coal plant 1.18kg/kWh and 0.85 kg/kWh for petroleum plant) [17].

V. CONCLUSION

The laboratory scale of EMA-2SGB shows that the reduction of transmission losses and fuel consumption and emission due to the fastest time gear shifting. The flux leaking could be the bad impact of the EMA-2SGB on the environment and passenger. It could be prevented by using a polypropylene shield with the aluminum alloy outer shell. Higher current supply to the EMA-2SGB will develop heat and may damage the EMA.

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