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A Fuzzy-Logic-Controlled Two-Speed Electromagnetic Gearbox for Electric Vehicles

Ataur Rahman[1*], Sany Izan Ihsan[1], Nurul Hassan[1]

[1]*Department of Mechanical Engineering, International Islamic University Malaysia, 50728 Kuala Lumpur, Malaysia*

Abstract. Epicyclic transmission (ET), five-speed manual gearbox (5-SMT), automatic transmission (AT), and continuously variable transmission (CVT) are all possible transmission options for electric vehicles (EVs). The ET is so complex that motorists may be unaware that they are in gear. As the 5-SMT, AT, and CVT transistors are heavier, they consume more energy. Although a single-speed gearbox is lighter, it is not capable of developing enough torque for acceleration. Therefore, this study presents a fuzzy-logic-controlled electromagnetic two-speed gearbox (AEM-2SGB) model for EVs. The electromagnetic actuator is modelled in terms of electromagnet size, number of coil turns, supply current, and electromagnetic force needed to shift gears. The parametric analysis of AEM-2SGB is conducted using Matlab Simulink and a fuzzy simulation model. According to the results, the AEM-2SGB has a first-gear shift time of 110 ms at 300 Nm motor torque and a second-gear shift time of 116 ms at 110 km/h vehicle speed, with a maximum current supply of 16 A using a 24 V lithium ion battery. The AEM-2SGB reduces weight by 37%-66%, transmission losses by 40%–90%, and battery life by 5%.

Keywords: AI-embedded IoT controller; Compact and low-cost transmission; Electromagnetic gearbox; Energy efficient; Fuzzy logic controller

1. Introduction

The market share of electric vehicles (EVs) will be boosted by their ability to reach higher ranges and their target to increase design efficiency and reduce manufacturing costs to become affordable to more customer segments (Bottiglione et al., 2014). In one study, the adoption of two-speed transmission over single-speed transmission gave rise to a reduction in energy consumption over numerous driving cycles of up to 4% for the case study vehicles (Jose et al., 2021). The power transmission of Evs mostly a single-speed transmission system, while MT, AT, and CVT are the transmission options for hybrid electric vehicles (Miller, 2006; Jaafar et al., 2020). A novel two-speed inverse automated manual transmission was examined, and the gear ratios were optimized using dynamic programming. Gear shift control was addressed, and a smooth shift process without a torque hole was achieved through feed-forward and feed-back control of the clutch and the motor. The performance of a two-speed transmission EV was compared with that of an EV

*Corresponding author's email: ataur7237@gmail.com/arat@iium.edu.my , Tel.: +603-64214544, Fax: +603-64214455
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with a fixed-ratio gearbox, and two-speed automated manual transmission with a rear-mounted dry clutch was found to have better performance in terms of acceleration time, maximum speed, and energy economy (Spanoudakis et al., 2019). It has two main advantages. When using two-speed transmission, the first gear ratio can be chosen to increase the low-speed torque to improve acceleration on a road grade, while the second gear ratio is for cruising (Miller, 2006).

The power requirement of EVs depends on the traction power, which mostly depends on the weight of the EVs. The power loss of EVs is 5%–15% for manual transmission due to gear shifting from the first to the fifth gear, 15%–20% for automatic transmission (AT) due to slow pressure development in the torque converter, and 15%–25% for CVT (Rahman et al., 2012). Sorniotti et al. (2011) examined the performance of EVs using single-speed transmission and two-speed transmission and found a significant advantage in adopting a two-speed transmission system over a single-speed transmission system.

The power of EVs is limited compared to that of an internal combustion engine, as it requires much time to refuel energy. Therefore, it is important to save the power of EVs by decreasing transmission weight and reducing transmission loss by eliminating the number of gear shifts. Moreover, manual transmission, AT, and CVT are bulky and unsuitable in the available space of EVs because their power train space is limited in order to maintain vehicle performance (Sorniotti et al., 2011; McKeegan, 2020). According to a report, it could benefit EVs and make them 5% energy efficient, but it caused much transmission power loss due to the slower motor response (Porsche, 2019). Tesla originally planned to put a two-speed gearbox in the original Roadster manufactured by the gear manufacturing company ZF (Germany).

According to a review of EV powertrains on the road, EVs can be equipped with epicyclic transmission, a five-speed manual gearbox (5-SMT), AT, or CVT. Energy usage and gear shifting are issues with the aforementioned transmission methods for EVs. Although a single-speed gearbox is lighter, it is not capable of developing enough torque for acceleration. As a result of transmission problems, a technological innovation to solve them should emerge (Berawi, 2021, Rahman et al., 2019).

This study aimed to present a two-speed fuzzy-controlled electromagnetic gearbox (EMA2SGB). This aim was achieved by (i) examining the vehicle's dynamic torque requirement in traction and speed while cruising and (ii) analyzing the electromagnetic force equivalent to the gear shifting axial force. The gearbox was designed based on the outcome of the first sub-objective outcome, and the second sub-objective outcome was used to design the electromagnetic actuator (EMA) as the gear shifter.

2. Mathematical Model

2.1. Vehicle Dynamics

The design and development of the fuzzy-controlled EMA2SGB are made with a comprehensive understanding of gear shifting based on vehicle dynamics under different load and road conditions.

(i) Starting mode

The vehicle dynamics torques has ben estimated using the equation 1 (Rahman et al., 2018):

$$T_{w(s)} = mg\left[\frac{m_R L_f}{L + m_R h} \pm \sin q_R\right](r_w). \tag{1}$$

(ii) Dynamic mode

The traction torque in dynamic mode can be estimated by simplifying the following equation 2 (Wong, 2001):

$$T_{w(d)}(t) = m\frac{\partial v}{\partial t} * r_w + \left| \begin{matrix} f_r W & 0 < v \le 120\,km/h \\ W\,Sin\theta_R & 0 < G \ge 20\%,\ 0 < v \le 40\,km/h \\ \frac{\rho}{2} C_d A_f v^2 & G = 0\%, 40 < v \le 120\,km/h \end{matrix} \right| * r_w \tag{2}$$

where T_s is the starting torque, T_d is the dynamic torque, m is the car mass, v is the vehicle speed, f_r is the rolling motion resistance coefficient, C_d is the drag coefficient, A_f is the vehicle frontal area, r_W is the wheel radius, L is the wheelbase, L_f is the location of the center of gravity from the front wheel, μ_R is the road friction coefficient, θ_R is the road slope, ρ is air density, and G is the gradient.

Torque computation

(i) The computation of T_S is performed with $f_r = 0$, $\theta_R = 0$, $\mu_R = 0.4$; L =2.0 m, and L_f = 1.2 m flat road. The slope of the road needs to be considered if vehicles need to climb a slope.

(ii) T_d (t) on slope is made by considering $f_r = 0.012$, $\theta_R = \sin^{-1}G$, and $C_D = 0$.

(iii) T_d (t) on a flat road is made by considering $f_r = 0.012$, $\theta_R = 0$, $\rho = 1.18$ kg/m^3, and $A_f = 1.18$ m^2.

The required gear ratio of the vehicle is estimated using the following equation 3 (Rahman et al., 2014):

$$GR = N_g = \frac{T_{w(s/d)}}{T_e N_d \eta_t} \tag{3}$$

where N_g is the gear ratio, T_W is the driving wheel torque, N.m, T_e is the engine torque, N.m, N_d is the differential speed constant, and η_t is the transmission efficiency. The gear ratio of the EMA2SGB is adjusted using a fuzzy controller to actuate the gear shifter based on the sensor input signals.

3. EMA Development

This study used an EMA to generate the requisite axial force to engage the synchronizer with the matching gear. This section simulates the number of coil turns, the length of the EMA, and the power source used to supply current to the EMA.

3.1. EMA Force Modeling

The actuator should be designed to create an electromagnetic force that is equivalent to or greater than the axial force required to engage the synchronizer with the gear, $F_{em}(t) \ge F_{axial}(t)$, to change the gear ratio in the range of $1.12 < GR \ge 2.35$. EMA force modeling is created by simplifying Gauss's law, Maxwell's equation, Ampere's circuital equation, Faraday's law, and Poynting's equation.

The EMA considers thin coaxial cylindrical conducting closed shells with radii a and c. The current I is supplied with a number of turns N per unit length. According to Gauss's law, the electric field, E, takes the following form equation 4:

$$E = \begin{vmatrix} Q/(2\pi\varepsilon_0 r l) & for\ a \le r \le c \\ 0 & Otherwise \end{vmatrix} * e_r \tag{4}$$

Similarly, according to Ampere's circuital law, the initial magnetic field of the EMA due to the supply current is as follows equation 5:

$$B_z = \begin{vmatrix} \mu_0 NI & for\ r \le c \\ 0 & Otherwise \end{vmatrix} \tag{5}$$

The initial momentum density of the electromagnetic field is

$$g_\theta = \begin{vmatrix} \mu_0 NIQ/(2\pi r l) & for\ a \le r \le b \\ 0 & Otherwise \end{vmatrix} \tag{6}$$

Any change in the current flow in the EMA winding generates an inductive electric field, which is defined as follows equation 7:

$$E_\theta = \begin{vmatrix} -\mu_0 NIr/2 & for\ r \le b \\ -\mu_0 NI\, b^2/2r & Otherwise \end{vmatrix} \tag{7}$$

The EMA develops the magnetic force, and F_{em} is the function of the supplied current and the number of coils, as stated in Equation (8). Therefore, the electromagnetic force is

$$\begin{aligned} F_{em} &= \frac{E_{eff(EMA)}}{d} \\ &= \frac{1}{d}\left[\frac{1}{2\mu} B^2 V_{EMA} + \frac{1}{2}\varepsilon_0 E^2\right] \\ & with\ \ B = \mu NI \\ & d = gear\ shifter\ moval\ distance, m \end{aligned} \tag{8}$$

where μ is the magnetic permeability (degree of magnetization of a material in response to a magnetic field), and V_{EMA} is the EMA volume, m^3.

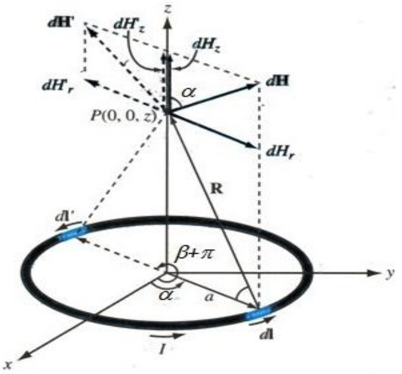


Figure 1 Magnetic flux density for a single coil

Figure 1 shows the magnetic flux density for a single coil. If the current is allowed to flow to the coil of the windings of the EMA, the coil turns to the electromagnet and develops a magnetic field (H) and a magnetic force (F). An instantaneous magnetic field is exerted around the coil. Therefore, the magnetic flux density develops, which is defined as dB = μdH=μNdI/lc. The magnetic force is dF = dB.dI.dl_{ema}, where l_{ema} is the length of the conductor. The direction of the dF is perpendicular to the current flow and the conductor, l_{ema}.

The electromagnetic force can move the shifter in any direction, either to the first gear or the second gear, based on the electrical power supply to the EMA. The F_a of the synchronizer can be calculated using the following equation 9 (Faid, 2015):

$$F_a = \frac{2 \sin a . J . \Delta w}{n_c . m d_m . t_F} \tag{9}$$

where α, J, Δω, n_c, μ, d_m, and t_F are the shift force, engagement ring cone angle, polar moment of inertia, angular velocity of synchronizer ring, number of cones, coefficient of friction of cone, mean cone diameter, and slipping time, respectively.

3.2. Vehicle Dynamic Torque

Equations (1) and (2) are used to calculate vehicle dynamic torques as shown in Figure 2. The first gear ratio is appropriate for accelerating an electric vehicle from a stop or for driving on a slope that requires for the development of more wheel torque. The maximum torque of 200 to 190 Nm can only be achieved in the lower range of motor speeds (500–1,500 rpm). This means that the acceleration and slope phases are only applicable up to the specified rpm. The first gear ratio provides more torque, allowing the car to maintain traction in the starting mode, while the second gear ratio allows the vehicle to reach a top speed of 120 km/h at a motor speed of 5,500 rpm.

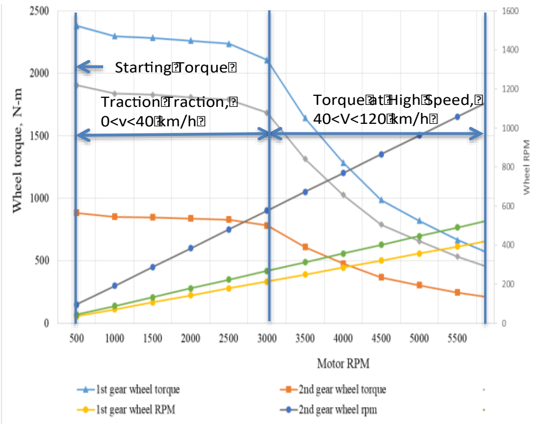


Figure 2 Simulated performance of the EMA2SGB

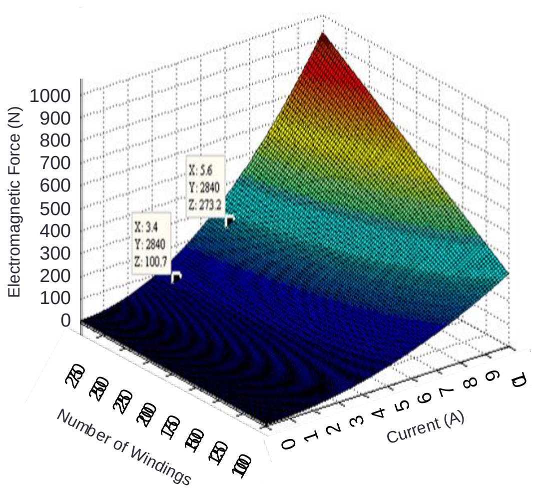


Figure 3 Electromagnetic force vs. number of windings and current

3.3. Electromagnetic Force

A simulation study of the electromagnetic actuator is conducted to estimate $F_{em} \geq F_{ax}$. The relative permeability for iron (0.2 impurity), μ_r, is 5,000 (this material is chosen for the gear shifter because of its higher magnetic permeability). Thus, the permeability for such a metal is $\mu = \mu_o \mu_r = 1.26 \times 10^{-6} \times 5000 = 6.3 \times 10^{-3}$ in N/A. Using Equation (8) and varying the supply current in the range of 1–16 A, the electromagnetic force is computed considering the number of turns of the EMA coil of 163, the length of the solenoid of 0.075 m, and the inner radius of the EMA of 0.02 m.

Figure 3 shows the maximum and minimum electromagnetic forces required to move the gear shifter from the first to the second gear and from the second to first gear for a vehicle mass of 1,330 kg. The electromagnetic force is calculated by altering the amount of current supplied for the different numbers of coil turns. The axial force of the gear shifter should be 100 N in the first gear and 230 N in the second gear. With a supply current of 5–10 A and a total number of turns of 1,300, the EMA can create electromagnetic forces in the range of 100–300 N.

4. Electromagnetic Actuator Model

Figure 4 illustrates a lab-scale electromagnetic actuator for the proposed 2SGB, which was developed to produce an electromagnetic force equivalent to a maximum axial force of 6.5 N to shift the gear of a powertrain with a blast load of 25 kg. Two identical EMAs, each with 163 coil turns and a magnetic disk, are fabricated: one for first gear shifting and the other for second gear shifting. Both EMAs are capable of producing a 4–6 N electromagnetic force with a supply current of 5–10 A using a 24 V DC.

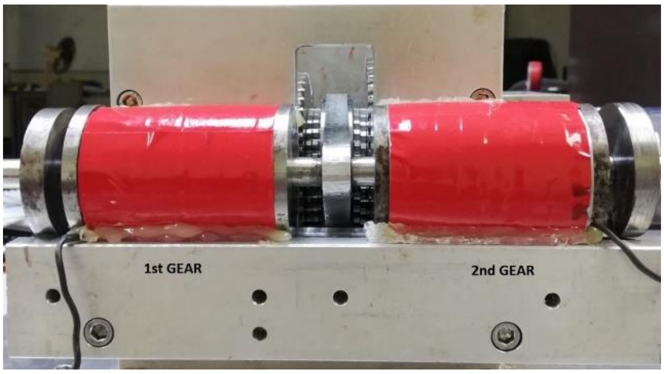


Figure 4 An electromagnetic actuator with 163 coil turns

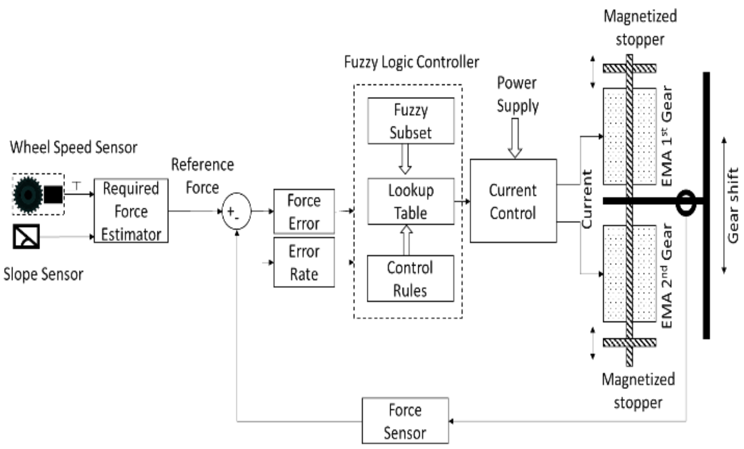
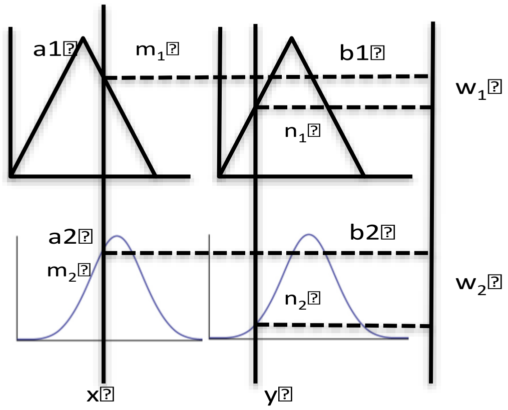


Figure 5 Fuzzy logic controller for the AEM-2SGB

5. EMA Control Strategy

The goal of the control system is to allow the AEM-2SGB to automatically shift gears as needed, based on the traction or slope sensor and wheel speed sensor data. To test the fuzzy controller's behavior, ADVISOR software is used. The EMA's shifting force is generated by supplying a current of 7–15 A using a fuzzy control system, as shown in Figure 5. A force error and a force rate of change error are considered the input fuzzy logic controller (FLC) variables in the FLC simulation, and the supply current in the EMA is considered an output.



where, a1 =motor speed (x), very low (vL), b_1=wheel speed (y), very low (vL),

Figure 6 Fuzzy inference system

A total of 25 rules are set up based on the input and output membership functions of the fuzzy controller. For simplicity, we assume that the fuzzy inference system under consideration has two inputs, x_1 and x_2, and one output, P. For example, the rule base contains two fuzzy if-then rules:

Rule 1: If x is a1 and y is b1, then $A_1 = r_0 + m_1 x_1 + n_1 y_1$

Rule 2: If x is a_2 and y is b_2, then $A_2 = r_0 + m_2 x_2 + n_2 y_2$

where m and n are defined as the degree to which the given satisfies the quantifier of the membership function of a and b, respectively, r_0 is the constant input value, and A is the output current to the corresponding EMA, as shown in Figure 6.

The fuzzy controller collects actual data from the sensors fed to the EMA for different driving scenarios (denoted as Ia). The reference or required current is estimated based on the gear-shifting force generated. With reference to the reference current level (denoted as Ir), the error is calculated based on the road profile. The current error (E) and its derivation (RE) are the main inputs to the FLC for estimating a proper current to operate the electromagnetic actuator to yield a suitable gear ratio for driving the car. Based on the signal from the FLC, the current control acts as a gate to allow a proper amount of current to the EMA. Each rule generates one output function, as shown in Figure 7. For more than one rule, the output functions from each rule are aggregated into a single output function and then defuzzified into a single numeric value. The fuzzification of the gear ratio error (E), rate of error (RE), and servo motor is conducted using the following functions:

$$E(i_1) = \begin{Bmatrix} i_1; & -9.6 \le i_1 \le 9.6 \\ 0; & otherwise \end{Bmatrix} \tag{10}$$

$$RE(i_1) = \begin{Bmatrix} i_2; & -1 \le i_2 \le 1 \\ 0; & otherwise \end{Bmatrix} \tag{11}$$

The recommendations for each rule are considered independently. Later, all recommendations from all the rules are combined to determine the flow rate for the installation. At this stage, the degrees of truth (μ) of the rules are determined for each rule by using the minimum and then taking the maximum between the working rules. The input variables RPM and slope gradient, as well as the output variable current, are restricted to positive values. Therefore, for the different crisp measurements of the RPM and the slope, different values of $\mu_{premise}$ and $\mu_{\inf erence}$ function are obtained. By combining all the recommendations of all the rules, we determined the control action. This is done by aggregating (combining all operations) the fuzzy sets outputted.

6. AEM2SGB Performance Investigation

By integrating the motor speed sensor, wheel speed sensor, and controller, we develop an FLC system to regulate the operation of the EMA2SGB in self-mode. The current flow in the EMA is controlled by an FLC module embedded in an Arduino Mega 2560 controller. We evaluated the EMA2SGB on a test bed using a 36 V DC motor and a speed sensor because of the lack of an actual car powertrain.

Table 1 Performance of the fuzzy logic controller for first gear shifting.

Input range		Fuzzy variable	Shifting time from second gear to first gear (Traction) (ms)
sensor signal (V)	Current flow (A)		
0–1	0–.5	XS	300
0.5–1.5	5.0–7	S	300
1.0–2.5	6.5–8.5	M	200
2 .5–3.5	8.5–10.5	L	151
3.0–4.5	10–12	XL	92
4.0–5.0	12–16	EL	39

Table 2 Performance of the fuzzy logic controller for second gear shifting.

Input range		Fuzzy variable	Shifting time from first gear to second gear (Higher speed) (ms)
sensor signal (V)	Current flow (A)		
0–1	0–.5	XS	300
0.5–1.5	5.0–7	S	300
1.0–2.5	6.5–8.5	M	150
2 .5–3.5	8.5–10.5	L	131
3.0–4.5	10–12	XL	120
4.0–5.0	12–16	EL	66

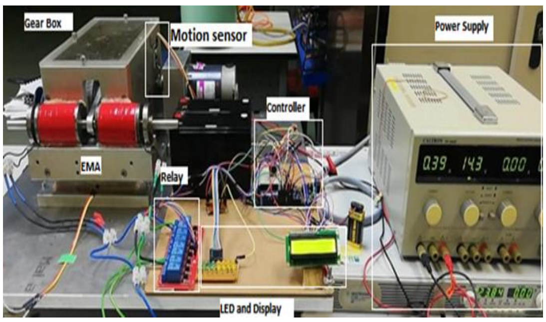


Figure 7 EMA2SGB testing (a) without a fuzzy controller and (b) with a fuzzy controller

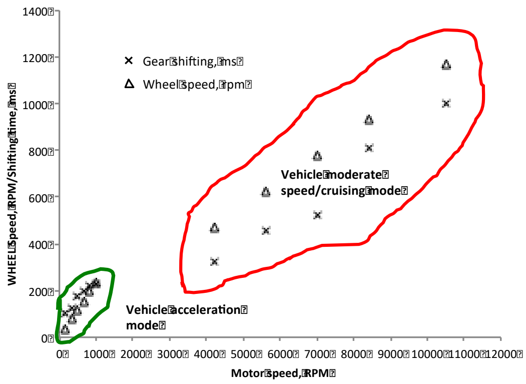


Figure 8 AEM2SGB dynamic testing with varying loads

6.1. Theoretical EMA2SGB Performance Investigation

Tables 1–2 show a simulation of the characteristics of the AEM-2SGB for shift times in the first and second gears. Table 1 shows the fuzzy subsets of Xsmall (XS), Small (S), Medium (M), Large (L), Xlarge (XL), and Extreme Large (EL) used to describe the linguistic value of electromagnetic force. The linguistic values for the voltage of the sensor, the universe of discourse, V, are equal to 0–36 V, while the linguistic values of the current, the universe of discourse, I, are equal to 0–16 A for switching from the second to the first gear and from the first to the second gear. This result implies that the time it takes to shift from the second to the first gear is shorter than that required to shift from the first to the second gear. The reason is that engaging the synchronizer with the gear with the lower spin of the first gear requires less axial force. This is more noticeable when shifting from the first to the second gear, which is due to the higher spin of the gear.

6.2. Experimental EMA2SGB Performance Investigation

During the testing of the EMA2SGB in the self-operating mode, the controller transfers power from one EMA to another based on the motor speed input, as shown in Figure 7. When the motor speed reaches 200 rpm or higher, the controller switches the power system to the EMA of the second gear to achieve a gear ratio of 1.3. When the motor speed reaches 500 rpm, the current flow increases to 16 A. The increased current supply from the EMA generates a higher electromagnetic force, necessitating the gear changer to activate the second gear to achieve a gear ratio of 1.3. When the motor speed decreases to 200 rpm, the controller switches the power system to the EMA for the first gear, with a gear ratio of 3.5. The reduced electromagnetic force developed by the EMA causes the first gear to engage when a current flow of 7 A is recorded. The gear shifter requires a stronger axial force to engage the synchronizer, with the second gear at higher speeds, based on the degree of current flow. The gear shifting force is lower when traveling at lower speeds or in the first gear. Using a 24 V DC power system, the experiment was conducted with and without an FLC.

Figure 8 shows that shifting time is directly related to the vehicle climbing slope and speed and the effectiveness of the fuzzy autonomous system. In the first gear on a 30% slope, the minimum gear shifting time is 110 ms due to the synchronizer's easier engagement, and the maximum gear shifting time is 1200 ms due to the synchronizer's difficulties at a motor speed of 11,000 rpm, which is equivalent to a vehicle speed of 90 km/h.

Figure 9 shows the performance of the EMA laboratory scale for work with a load, which is considered the driving force of the gear shifter to move from the first to the second gear or vice versa. The EMA performance is tested by developing a laboratory-scale, two-speed gearbox. The axial force required to shift the gear shifter from the first gear to the second gear is greater than 5 N and that from the second gear to the first gear is less than 3 N. The shows that the EMA develops an electromagnetic force equivalent to the axial force of 3.5 N for the supply current 6 A and 5.2 N for 10 A. This indicates that the electromagnetic force development of the EMA is proportional to the current flow. The EMA develops less electromagnetic force as a result of the reduced current flow, which takes longer to accelerate due to the longer gear-shifting time. As a result, the car starts to lose traction and slows down. The AB zone in the diagram depicts the sluggish acceleration caused by gear shifting timing (first to second gear), also known as the dead zone. As the EV's motor power does not flow to the driving wheels, traction losses are common in this zone. The vehicle's momentary action causes a modest variation in acceleration.

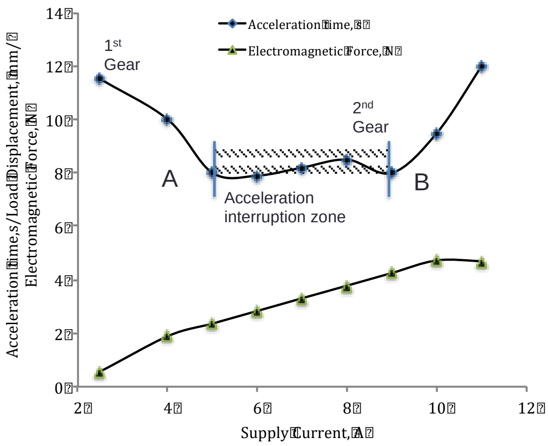


Figure 9 Performance of the laboratory-scale EMA to maintain acceleration time

Table 3 Performance of the laboratory-scale EMA2SGB with an EMA and 163 turns

EMA2SSGB -without Fuzzy Controller			EMA2SSGB -Fuzzy Controller		
Neutral to first Gear (Motor speed, 0–200 rpm)					
Voltage, V	Current, A	Time, ms	Voltage, V	Current, A	Time, ms
24	10	754	24	10	916
24	11.1	627	24	11.1	241
24	12	167	24	12	161
24	14	111	24	14	95
24	16	68	24	16.11	65.5
First gear to second gear (motor speed, 200–500 rpm)					
24	12	965	24	13.08	930
24	14	500	24	14	364
24	15.35	527	24	15.19	260
24	15.98	369	24	16.11	137
Second gear to first gear (motor speed, 500–75 rpm)					
24	13	973	24	13	650
24	14	404.6	24	14	259
24	15	375.3	24	15.1	167
24	16	297.2	24	15.98	110

Table 4 Advantages of 2-SAEMT for the EVs

ELECTRIC VEHICLE BATTERY POWER DENSITY OF 8.9 kWh							
						2-SAEMT ES[c] (%)	
Gear Shifting mode	Transm. Type	[a]W_T (kg)	[b]ST (ms)	Acceler. (m/s^2)	[c]TL (Wh)	RST	W_S
1st Gear to 2nd Gear	5-SMT	48	150	214.14	356	92.29	37.50
	2-SMT	33	800	276.03	190	85.54	9.09
	2-SEMT	36	850	283.41	202	86.39	16.67
	2-SAEMT	30	116	1735.56	28	0.00	0.00
	4-	91	150	405.96	356	92.29	67.03
	7-SDCT	89	200	2977.82	48	42.17	66.29
2nd Gear to 1st Gear	5-SMT	48	700	458.86	166	83.48	37.50
	2-SMT	33	770	286.79	183	84.98	9.09
	2-SEMT	36	800	301.13	190	85.54	16.67
	2-SAEMT	30	110	1825.02	26	0.00	0.00
	4-SAT	91	140	434.96	332	91.74	67.03
	7-SDCT	89	320	1861.14	54	46	66.29

Notification:
1. 5-SMT- five speed manual transmission, AT-automatic transmission,
AEMT- autonomous electromagnetic transmission, DCT- dual clutch transmission
EMT- electromagnetic manual transmission,
2. W_T-Transmission weight, ST-Shifting time, TL- Transmission losses,
RST-Reduction shifting time, W_S-Weight saving,
3. a-actual values, b-experimental values, c-calculated
4. ES – Energy saving
Electric vehicle mass 1300 kg

The performance of the proposed EMA2SGB without and with fuzzy controller is presented in Table 3. To engage either the first or second gear, the shifter travels a distance of 28 mm. To carry out the controller operation, the wheel speed sensor and motor speed sensor are linked to the controller. Only the motor speed sensor is used because of system constraints. A lower motor speed is considered for vehicle traction in which the gear spins at a slower speed, whereas a higher motor speed is considered for a vehicle's greater speed in which the gear spins at a faster speed. Compared to the EMA2SGB without the fuzzy controller, the EMA2SGB with the fuzzy controller takes less time to shift gears. This is because the fuzzy controller's behavior is dependent on sensor input, preventing human attempts to change gears. However, compared to manual control or fuzzy logic control, the actuation of gear shifting at a lower current utilizing a fuzzy control method is not considerably different.

Table 4 shows that 2-SAEMT (2-SAEGB) has a power savings advantage over 5-SMT and SDCT. Quantitative data for 5-SMT and SDCT, such as transmission weight, power losses due to transmission, and shifting time, were taken from published research (National Research Council, 2015; Ho-Chang et al., 2015). For example, if the 5-SMT is replaced with a 2-SAEMT, the EV will save 0.93*356 or 331 Wh in transmission loss and 1.1*0.375 or 412 Wh in weight savings for a 90 km/h EV. As a result, gross battery power savings of 743 Wh are achieved. Conversely, if the SDCT and SAT are replaced with a 2-SAEMT, the EV will save 1,245 Wh and 1,500 Wh of battery power, respectively. Therefore, a total power savings of 743 Wh is achieved. A similar conclusion can be made if the SDCT is replaced by the 2-SAEMT; the EV will obtain a total power savings of 1,245 Wh. As a result, the EV will gain 6–8 km of extra mileage, battery life span of 5%, and battery charging power savings of 10%.

7. Conclusions

The potential of AEM2-SGB is obvious in changing from the first to the second gear and from the second to the first gear because of the efficacy of the fuzzy controlling mechanism using sensors and magnets. The AEM-2SGB is a prospective gearbox for EVs owing to its weight reduction of 37%–66%, transmission loss reduction of 40%–90%, and battery life enhancement of 5%.

- For traction, AEM-2SGB's autonomous fuzzy intelligence system allows it to shift gears from the second to the first in 110 ms and from the first to the second in 116 ms. As a result, it eliminates the issue of vehicle traction control interruption and reduces transmission loss by 42%–93%.
- In terms of energy savings, compared to other potential gearboxes, an EV will save 743 Wh, 1,245 Wh, and 1,500 Wh of battery power if the 5SMT, 7SDCT, and 4SAT are replaced with 2-SAEMT, respectively. As a result, the EV will gain an additional 6–8 km of mileage and a 15% boost in battery life due to a 10% reduction in battery charge frequency.

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References

Berawi, M.A., 2021. Philosiphy of Technology Design: Creating Innovation and Added Value. *Internation Journal of Technology*, Volume 12(3), pp. 444–447

Bottiglione, F., Pinto, S.D., Mantriota, G., Sorniotti, A., 2014. Energy Consumption of a Battery Electric Vehicle with Infinitely Variable Transmission. *Energies*, Volume 7(12), pp. 8317–8337

Faid, S., 2015. A Highly Efficient Two-Speed Transmission for Electric Vehicles. *EVS28*, pp. 3–6

Ho-Chang, J., Deok, JK (2015) Analysis of Energy Consumption Performance for Electric Vehicle Considering Transmission Shifting Pattern', EVS28, KINTEX, Korea, May 3-6, 2015

Jaafar, AH, Rahman, A., 2020. EMA-CVT Performance for UDDS and HWFET Cycles with Fuzzy Logic Approach. *Test Engineering & Management*, Volume 83(March-April, 2020), pp. 13775–13781

Miller, J., 2006. Hybrid Electric Vehicle Propulsion System Architectures of the e-CVT Type. *IEEE Transactions on Power Electronics*, Volume 21(3), pp. 756–767

McKeegan, N. 2020. Antonov's 3-Speed Transmission for Electric Vehicles Boosts Efficiency by 15 Percent. Available Online at http://www.gizmag.com/antonov-3-speed-transmission-ev/19088/, Accessed on January 17, 2020

National Research Council, 2015. Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles. National Academies Press, Washington, D.C

Rahman, A., Hassan, N., Jaffar, A.H., Mohiuddin, AKM., Izan, S., 2019. Study on the Development of Electromagnetic Seamless Two Speed Gearbox for EV. *International Journal of Recent Engineering and Technology*, Volume 7(6S), pp. 147–152

Rahman, A., Sharif, S., Mohiuddin, A.K.M., Rashid, M., Altab, H., 2014. Energy-Efficient Electromagnetic Actuator for CVT System. *Journal of Mechanical Science and Technology*, Volume 28(4), pp. 1153–1160

Rahman, A., Mizanur, R., Ahmad, F.I., Sany, I.I., 2018. Design Optimization of Electric Coaster. *International Journal of Electric and Hybrid Vehicles*, Volume 10(2), pp. 272–278

Rahman, A., Sazzad, B. S., Hossain, A. 2012. Kinematics and Non-linear Control of Electromagnetic Actuated CVT System. *Journal of Mechanical, Science, and Technology*, Volume 26(7), pp. 2189–2196

Sorniotti, A., Subrahmanyan, S., Turner, A., Cavallino, C., Viotto, F., Bertolotto, S. 2011. Selection of the Optimal Gearbox Layout for an Electric Vehicle. *SAE International Journal of Engines*, Volume 4(1), pp. 1267–1280

Sorniotti, A., Pilone, G.L., Viotto, F., Bertolotto, S., 2011. A Novel Seamless 2-Speed Transmission System for Electric Vehicles: Principles and Simulation Results. *SAE International Journal of Engines*, Volume 4(2), pp. 2671–2685

Spanoudakis, P., Tsourveloudis, N.C., Doitsidis, L., Karapidakis, E.S., 2019. Experimental Research of Transmissions on Electric Vehicles' Energy Consumption. *Energy*, Volume 12(388), pp. 2–15

Porsche Taycan, 2019. Why the Porsche Taycan EV's Two-Speed Transmission Is a Big Deal. Available online at https://www.caranddriver.com/news/a28903274/porsche-taycan-transmission/ Accessed on July 2, 2020

Wong, J.Y., 2001. *Theory of Ground Vehicle*, 3rd Edition. John Wiley & Sons: New York