Study on intelligent control system of EMA-CVT

Abdul Hassan Jaafar, Ataur Rahman

Abstract**: *Continuously variable transmission (CVT) is more efficient in transmitting power from the engine to the wheels than traditional gearboxes as it able to provide an infinite number of gear ratios as per road conditions and car speeds. Current CVT system that utilizes hydraulic actuation mechanism experienced slow acceleration when move from standstill, less torque while climbing the hill and continuously produce unpleasant noise. One of the hydraulic system main problems is that when its fluid temperature is too high, its viscosity falls below the optimum value result in losses of the input power. Electromagnetic actuation (EMA) mechanism, an alternative to conventional mechanism, is discussed in this paper. The EMA is operated by controlling the supply current with a fuzzy logic controller (FLC). A simulation based FLC has been introduced here for identifying the desired current of the EMA actuate on based on UDDS and HWFET driving cycles. The FLC was successfully producing the required current to operate the EMA for the mention driving cycle. The paper also discussed on the development of laboratory scale new EMA as well as its simulation and experiment. The result showed that the EMA with 163 turns and 12.2A current able to generate electromagnetic force of 60N and hence validated the mathematical theory.***

Keywords: Green Transportation; Electromagnetic CVT; Electromagnetism; Fuel efficiency; Green house gas reduction; Intelligent Control System;

1. INTRODUCTION

The ultimate goals for vehicle transmission design engineers are smooth speed change, wider-range speed ratio, simple mechanism and less maintenance[1]. Traditional automatic transmissions are advancing to a new level of drivability and performance but the increasingly popular CVT units bypass the usual gears in favor of a "shiftless" belt-drive system that transmits power from an engine to the driveshaft between its lowest ratio and its highest ratio, which is an overdrive. Different gear ratios are achieved by continuously movement of primary and secondary pulley sheave with accordance to the car speed and road condition. From that point on, the engine stays at the same speed, while the transmission ratio continuously change to provide acceleration [2]. Thus, cars equipped with the CVT system utilized the fuel more efficiently [3]. However, CVTs that utilizes hydraulic actuation mechanism have become an annoyance to many enthusiasts and critics because of several undesirable characteristics such as unpleasant noise, less torque while climbing the hill and slow response of the movable sheaves for fast acceleration time under hard acceleration. According to Tawi et al. [4] CVT that use the hydraulic actuation system possesses some major issues that make it less efficient such as high power consumption, power loss and belt misalignment. The core objective of this paper was to present an intelligent EMA-CVT, which will help to develop the desired traction force in reduction without rattling noises and speed in cruising with setting the minimum gear ratio.

2. METHODOLOGY

An analytical model of the EMA-CVT is formulated based on the vehicle traction force for various road conditions, power requirement to generate the electromagnetic force (F_{em}) and the simplified CVT mathematical models found in literature. Development of new electromagnetic actuator mechanism is presented in this section. A fuzzy logic control system is presented in this chapter as a mean to intelligently regulate the power required by the EMA-CVT for various driving scenario.

2.1 Analytical Model for EMA-CVT

Vehicle traction is required to simulate the developed torque and suitable gear ratio for different road condition. Through this torque a proper size of EMA could be design to operate the CVT operation. For initial condition, the traction torque is computed with the following equation [5-6]:

$$T_{initial} = m_c g \ \mu_R \frac{(l_f + f_r h)/L_w}{1 + \mu_R h / L_w} (r_w) \quad (1)$$

where, μ_R is the adhesion coefficient of the road, m_c is the mass of the car in kg, f_r is the rolling motion resistance coefficient, h is the height of the center gravity in m, L_w is the wheel base in m, l_f is distance of the centre gravity from the front wheel in m, g is the acceleration due to gravity in ms^{-2}, and r_W is radius of the drive wheel. The traction torque during motion is calculation using the following equation:

$$T_{cruising} = \ W \sin \theta_R + f_r W + \frac{1}{2} \rho_a A_f C_D v_c^2 \ \ r_w \quad (2)$$

where, ρ_a is the air density, A_f is the car frontal area, C_D is the drag coefficient, and V_c is the travelling speed. The maximum traction torque calculation is necessary for estimating the clamping force for the pulley. The gear ratio (GR) is gained by the continuously movement of primary and secondary pulley sheave accordingly. The movable of

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the sheave is controlled by the electromagnetic force developed by EMA. In [7], two sets of solenoid with common plunger are used to develop pushing force and pulling force. Normally, the pushing force is higher than the pulling one since it has to move against the rotating belt. Fig.1 shows the basic force acting on the surface of the pulley. The clamping force at pulley sheave can be calculated using equations below [7–9]:

$$\mathrm{F_c} = \frac{\mathrm{T_{out}}\ \cos\left(\theta_b\right)}{2\mu_S R_S} \tag{3}$$

Where is the transmission torque for secondary pulley, is the belt angle, is belt frictional coefficient secondary pulley, is radius for secondary pulley.

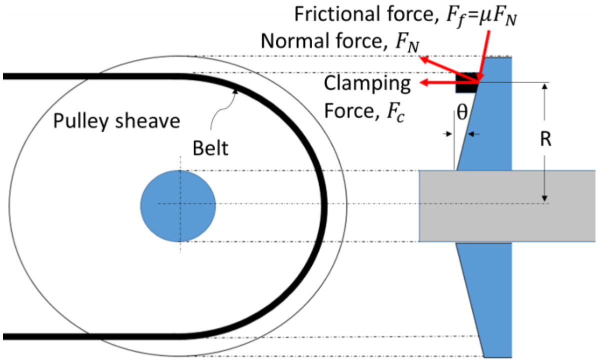

Fig. 1: Force analysis on the pulley surface

The electromagnetic force is designed to be higher than the clamp-ing force. The design is emphasized more on the pushing electro-magnetic force since it is crucial to maintain the belt at its exact position to produce the desired GR. The force generated from electromagnetic actuator could be found by following equation [10–12]:

$$\mathrm{F_{em}} = \frac{A_g B_g^2}{2\mu_o} \tag{4}$$

By substituting the magnetic field strength $\mathrm{H} = \mathrm{F_m}/\mathrm{l_e}$ into magnetic flux density equation $\mathrm{B} = \mu_0 \mathrm{H}$, we get [11]

$$\mathrm{B} = \frac{\mathrm{F_m}\mu_0}{g} = \frac{\mathrm{NI}\mu_0}{g} \tag{5}$$

Substituting into equation (5), yield

$$\mathrm{F_{em}} = \frac{(\mathrm{NI})^2 \mu_o A_g}{2g^2} \tag{6}$$

Where N is number of turns, I is the supplied current, μ_0 is the permeability of free space (has a fixed value of $4\pi\times10^{-7}$), g is the airgap separating between the two ferromagnetic bodies, and A_g is the effective airgap face area. The flux lines consider to be maximum in this area. The effective area of the core in **Error! Reference source not found.** could be found as follows:

$$\mathrm{A_e} = \pi\ \frac{\mathrm{D2^2\quad D3^2}}{4} \tag{7}$$

Where, D2 is outer radius and D3 is the inner radius of the actuator bobbin. From the above equations, the electromagnetic force depends on the number of coil turns, supplied current, effective area of the core, and the gap between the electromagnet and the pulling object. The only controlled parameter is the supplied current. The electromagnetic force produced is directly proportional to the supplied current, which means that the force shall be increased greatly by increasing the current supply. The actuator is designed in such a way that it could produce electromagnetic force, which have equal or more than the clamping force of the CVT. However, over flow of the current may create over heating which will damage the EMA. In practical, for better performance and safety, a cooling system is needed to cool the EMA.

2.2 Electromagnetic actuator design

Solenoid type actuator developed by Rahman [7], the EMA-CVT pioneer, was studied and new electromagnetic was proposed in this study. This new actuator's bobbin is made from iron instead of plastic to increase the stored magnetic energy for the stronger electromagnetic force generation. The bobbin or the core housing of the actuator is functioned as the holder of the copper coil as well as it serves as a guide for the plunger movement. The use of core housing can enormously concentrate the strength and increase the effect of magnetic fields produced by electric currents. Aluminium foil is used both sidewalls and a peripheral wrapping of aluminium foil for preventing magnetic flux leaking. As a consequent all the magnetic flux are bound to be confined; results more concentrate magnetic flux through plunger guider portion of the housing than usual.

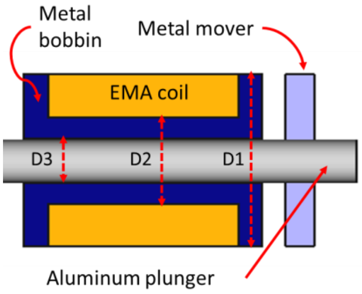

Fig. 2: Cut view of new electromagnetic actuator

A stopper or mover, made of iron, is attached on the non-magnetic (Aluminium) plunger to act as an object of the actuator force. In this study, the area that perpendicular to the coil turn is considered as the effective area of the actuator [11]. Electromagnetic actuator consists of a number of turns of copper wire around the outer radius of the housing. The selection of the wire diameter is made based on the range of maximum current supply in order to develop the desired magnetic force for the EMA.

2.3 Intelligent EMA-CVT system through Neuro-Adaptive learning techniques

As discussed earlier, the generated force to operate the pulley sheave is varied by regulating the supply current to the EMA. The proposed functional block diagram of the intelligent electromagnetic actuator for continuously variable transmission (i-EMA-CVT) is shown in Fig.3. Continuously, a computer based fuzzy logic controller (FLC) will collect the actual data of wheel speeds and road grades from sensors, and calculate the real torque of the car for different driving scenario. Based on these input, a signal is sent from FLC to the digital control switching system (DCSS) to allow a proper current flow to the EMA to generate clamping force at movable sheave. Furthermore, there is a failsafe mode built into the CVT to prevent damage in case some of the sensors malfunction. During failsafe mode, the driver could shift to central manual switching system (CMSS) to set the gear ratio equivalent to first gear. FLC was used as control mechanism due to its simplicity, robustness and effectiveness in providing satisfactory results in solving control problems. Unlike conventional control approach, fuzzy logic control method does not need precise mathematical representation of the controlled system to describe the relationships between inputs and outputs variables, hence is regarded as a model-free technique [13]. Lotfi A. Zadeh, who is considered to be the father of fuzzy logic, once remarked: "In almost every case you can build the same product without fuzzy logic, but fuzzy is faster and cheaper"[14].

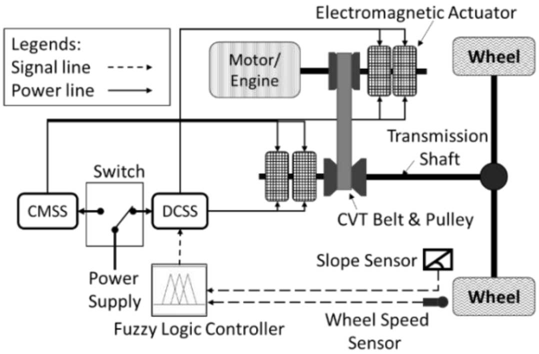

Fig. 3: The proposed functional block diagram of i-EMA-CVT system

In this study, adaptive neuro-fuzzy inference system (ANFIS) techniques was used as a method for the fuzzy modelling procedure to learn information about a data set, in order to compute the membership function parameters. This allow the associated fuzzy inference system to track the given input/output data. The parame-ters associated with the membership functions will change through the learning process. The basic idea behind these hybrid neuro-adaptive learning techniques works similarly to that of neural network. From electromagnetic force equation discussed in previ-ous section, a set of input/output data was produced. The ANFIS then constructs a fuzzy inference system (FIS) whose membership function parameters are tuned using either a backpropagation algo-rithm alone, or in combination with a least squares type of method. This allows the fuzzy systems to learn from the data they are mod-elling [14]. Although fuzzy logic can encode expert knowledge directly using rules with linguistic labels, it usually takes a lot of time for designing and tuning the membership functions which quantitatively define these linguistic labels. Neural network learning techniques can automate this process. Besides it significantly lessen development time and cost while improving performance [15].

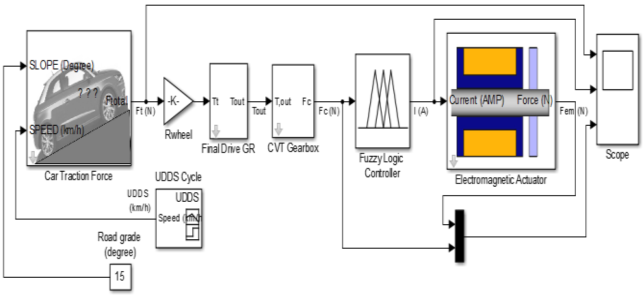

Fig. 4: EMA-CVT simulation block diagram in Matlab

3. RESULT AND DISCUSSION

Simulation result of electromagnetic force and electrical current requirement for operation of EMA-CVT of a passenger car is presented in this section. Proton Preve car with the mass m_c of 1700 kg, maximum speed of 120 km/h or 33 m/s, the road friction coefficient μ_R equal to 0.5, the wheel radius r_w of 0.295 m, the drag area $C_D A_f$ of 0.633, and rolling motion resistance coefficient f_r of 0.02 was considered. In order to validate the result, the mentioned laboratory scale EMA was tested both by simulation and experimental.

3.1 Simulation Result of Preve Passenger Car with UDDS and HWFET Cycles

The traction torque associated with the clamping force that required to operate the EMA-CVT system are modeled in Matlab simulation as described in Figure 4 where the input parameters of the system are vehicle speed and road grades. The required traction was designed according to predefined driving dynamics known as EPA Urban Dynamometer Driving Schedule (UDDS) and EPA Highway Fuel Economy Test Cycle (HWFET) [16]. The UDDS cycle simulates an urban route of 12.07 km with frequent stops. The maximum speed is 91.25 km/h and the average speed is 31.5 km/h. The cycle consists of two phases: the first phase begins with a cold start and run for 505 s (about 5.78 km at 41.2 km/h average speed) and the second phase run for 867 s as shown Fig.5. Furthermore, the HWFET cycles as shown in Fig.6 is a chassis dynamometer driving schedule developed by the US EPA for the determination of fuel economy of light duty vehicles. It simulates a highway route of 16.45 km with average speed of 77.7 km/h at 765 seconds.

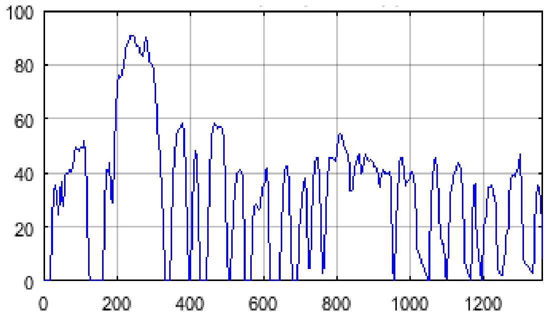

Fig. 5: Urban dynamometer driving schedule (UDDS)

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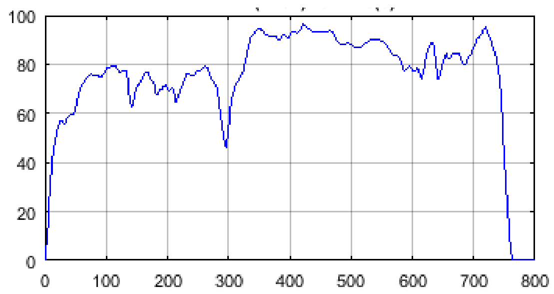
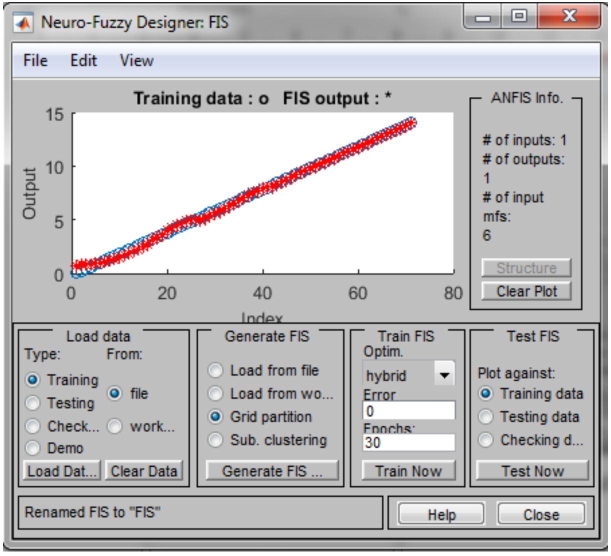


Fig. 6: Highway Fuel Economy Test Cycle (HWFET)

With car speed and road grades input, the model generated the torque requirement to move the car accordingly. The model also estimated clamping force required to operate the CVT pulley sheave in order to gain a proper gear ratio for each road condition based on equation (1) and (2). The required clamping force then become an input to the fuzzy logic controller to generate an enough supply current to operate the EMA. ANFIS, a neural networks type inference system, was used to tune membership functions of fuzzy systems that are employed as decision-making systems for generating current supply. This allowed the fuzzy system to learn the amount of current supply need to flow according to the clamping force requirement.



# of inputs: 1
# of outputs: 1
# of input mfs: 6

Type: ● Training ○ Testing ○ Check... ○ Demo
From: ● file ○ work...

○ Load from file
○ Load from wo...
● Grid partition
○ Sub. clustering

Optim. hybrid
Error 0
Epochs: 30

Plot against: ● Training data ○ Testing data ○ Checking d...

Renamed FIS to "FIS"

Fig. 7: ANFIS interface with current-force loaded data and trained data

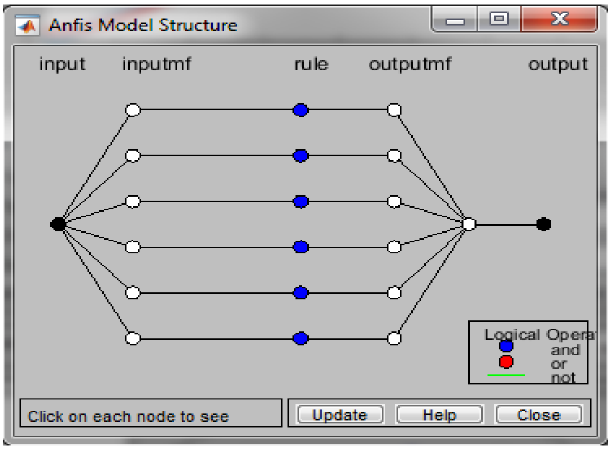
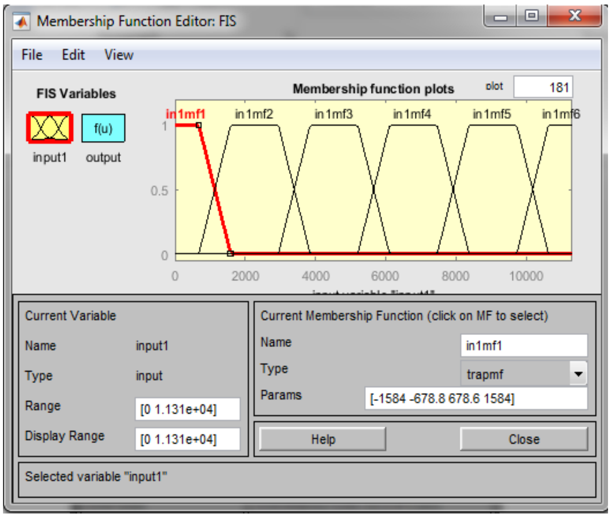


Fig. 8: ANFIS model structure with single input and single output



Current Variable
Name input1
Type input
Range [0 1.131e+04]
Display Range [0 1.131e+04]

Current Membership Function (click on MF to select)
Name in1mf1
Type trapmf
Params [-1584 -678.8 678.6 1584]

Selected variable "input1"

Fig. 9: Membership function of the FLC that generated by ANFIS

Electromagnetic force and supply current relation as in equation (6) become the input data to the ANFIS in order to teach the fuzzy system. ANFIS interface as in Figure 7 shows the loaded supply current and electromagnetic force relation compared with the trained data. Figure 8 shows the network structure for single input and single output with six membership functions. Based on these data, the ANFIS tuned the membership functions of the fuzzy logic controller as shown in Fig.9 and generated the input/output rules accordingly. Figs 10-11 compared the required clamping force and generated electromagnetic force for the UDDS and HWFET driving cycle respectively. The generated electromagnetic force are equal or higher than the required clamping force and this ensure the CVT pulley sheave can maintain its position. The result also shows the supply current requirement to generate the electromagnetic force accordingly. The current requirement is directly proportional to the electromagnetic force and agreed with the equation (6).

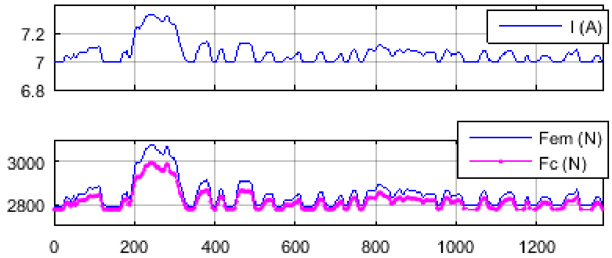


Fig. 10: Simulation result for supply current, required Fc, and generated Fem for UDDS

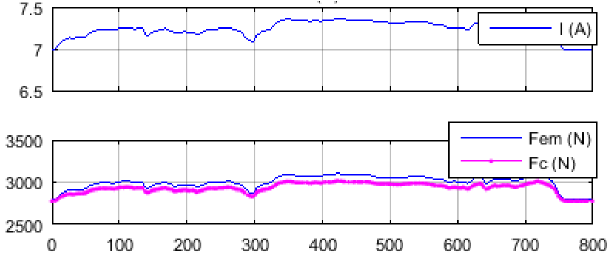


Fig. 11: Simulation result for supply current, required Fc, and generated Fem for HWFET

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3.2 Lab-Scale New Actuator Performance Analysis

Design and fabrication of a laboratory scale electromagnetic actuator for the effectively was discussed in this section. Simulation and laboratory test was conducted on the actuator and the data gained will be analysed in order to develop a full-size actuator that have capability to drive the CVT system of the Preve car. It was made with a hollow housing (bobbin), wounded with copper wire. The bobbin is made from iron to increase the stored magnetic energy for the stronger electromagnetic force generation. A stopper or mover, made of iron, is attached on the non-magnetic (Aluminium) plunger to act as an object of the actuator force. The actuator winding specification is shown in Table 1.

Table 1: Winding specification of the lab scale actuator

Parameters	Values
Wire diameter (d_w)	0.00145 m
Length of actuator (L)	0.065 m
Actuator min. diameter (h_1)	0.030 m
Actuator max. diameter (h_2)	0.050 m
Packing Factor, PF = Actual winding / Theoretical winding	105/200 = 0.525
$N = \frac{L(h_2 - h_1)}{2d_w^2} \times PF$	163 turns

3.2.1 Laboratory Scale EMA Simulation Result

The EMA parameters were considered as follows; the electromag-netic force bigger than the clamping force, number of turn (N) of 163, the effective area ( ) of 0.000625146 m2, and the gap of 5 mm. The EMA simulation diagram consists of input load signal generator, fuzzy logic controller and EMA model as shown in Fig.13.

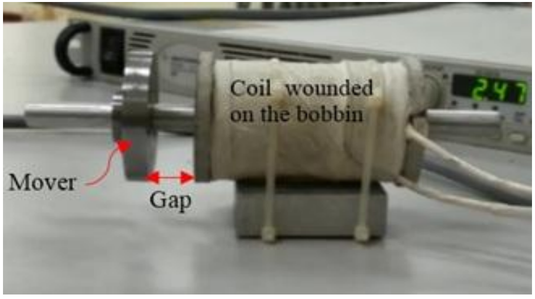

Fig. 12: Lab. scale electromagnetic actuator

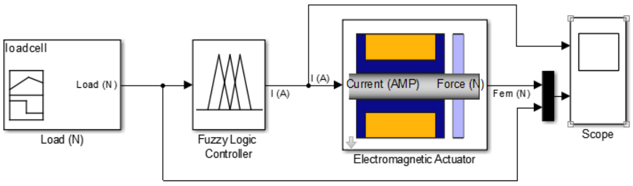

Fig. 13: Lab. scale EMA simulation block diagram in Matlab

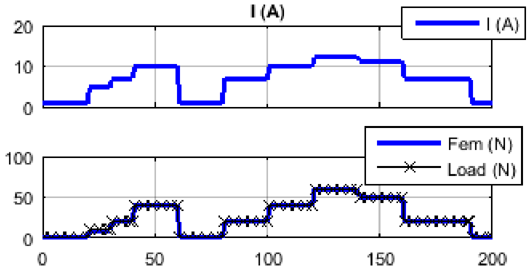

Fig. 14: Simulation result for supply current, load and generated Fem

The load was varied from zero to 60 newton to observed the gen-erated electromagnetic as well as the associated supplied current. The ANFIS used to tune the membership functions of fuzzy logic controller and allowed the fuzzy system to learn the amount of current supply need to flow to generate the required clamping force. Simulation of the force generated by the actuator corresponding the load as well as the supplied current is shown in Fig.14. The force generated increase and decrease proportionally to the supplied current and agreed with the function of as in equation (6).

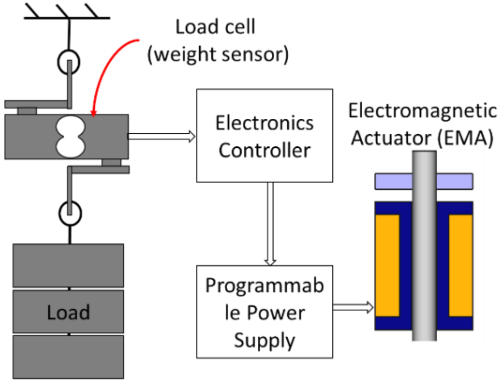

Fig. 15: Electromagnetic actuator experiment setup block diagram

3.2.2 Laboratory Scale EMA Experimental Result

Experimental setup to measure the supplied current with respond to the weight (load) is shown in Figs 15-16. Bending beam load cell using strain gauge based technology was used to measure physical properties of compression, tension, bending or shear and convert it into electrical signal. The computer based controller then convert the signal into an equivalent weight value. The weight become the basis for the controller to send a signal to the programmable power supply and generate the current flow accordingly. Fig.17 shows the experimental result for EMA supplied current based on the input load at the load cell. The current is proportional to the load as well as the actuator electromagnetic force.

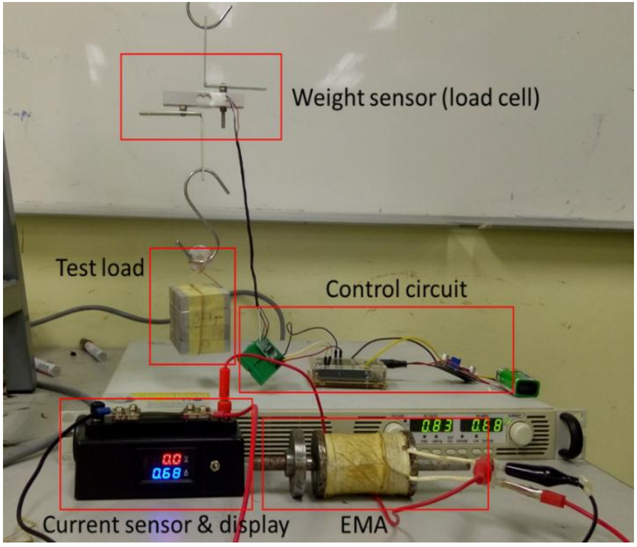

Fig. 16: Electromagnetic actuator experiment setup

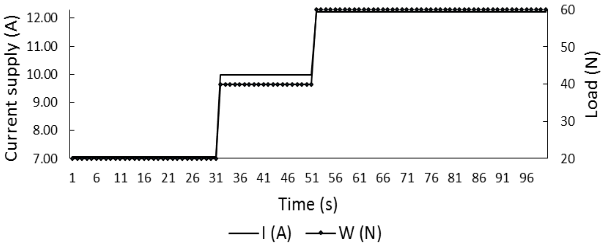

Fig. 17: Experimental result for laboratory scale EMA

4. CONCLUSION

This paper present theoretical and experimental work on the elec-tromagnetic actuator and its feasibility for implementation in CVT. Simulation by Matlab on relation between clamping force, elec-tromagnetic force and current supply was done through ANFIS methods. The developed laboratory scale EMA was studied both in simulation and experimental. The main conclusions drawn from this study are as follows.

Theoretically, the intelligent system is able to develop the elec-tromagnetic for as according to the required clamping force. The current was regulated to meet the traction force due to the vehicle speed pattern of UDDS and HWFET. Besides, for laboratory scale actuator (163 number of turns), the EMA is able to develop elec-tromagnetic force in the range of 0 N to 60 N by supplying current up to 10.50 amps. The FLC are able to generate with accordance to the input load.

Experimentally, the laboratory scale actuator required maximum 12.2A current to generate electromagnetic force due to the varied input load of 20N, 40N, and 60N. These data will be analyzed and become the basis in order to develop a full-size actuator that has capability to drive the CVT system of a real car.

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