Chapter 3

Experimental Setup and Data Acquisition

3.1 Introduction

AMT system is based on an electronic control unit (ECU) that supervise the use of the clutch and the gear shifting, allowing the driver to change gear without using the clutch, either sequentially or fully automatically. The *e*-AMT is in effect a conventional 5 speed countershaft gearbox with a motor employed to do all the shifting and clutch work. There are three electromechanical actuators; the shift and select actuators which move the selector rod in the same way as the 'H' movement of a manual gearbox, and the clutch actuator which moves the clutch pushrod with the help of electronic control modules (ECM). This system uses PMDC motors to control the clutch and gears. For an actuator the input control signal is reciprocated to a linear movement, thus helping in achieving a remarkably improved performance during clutch actuation as shown in Fig. 3.1.

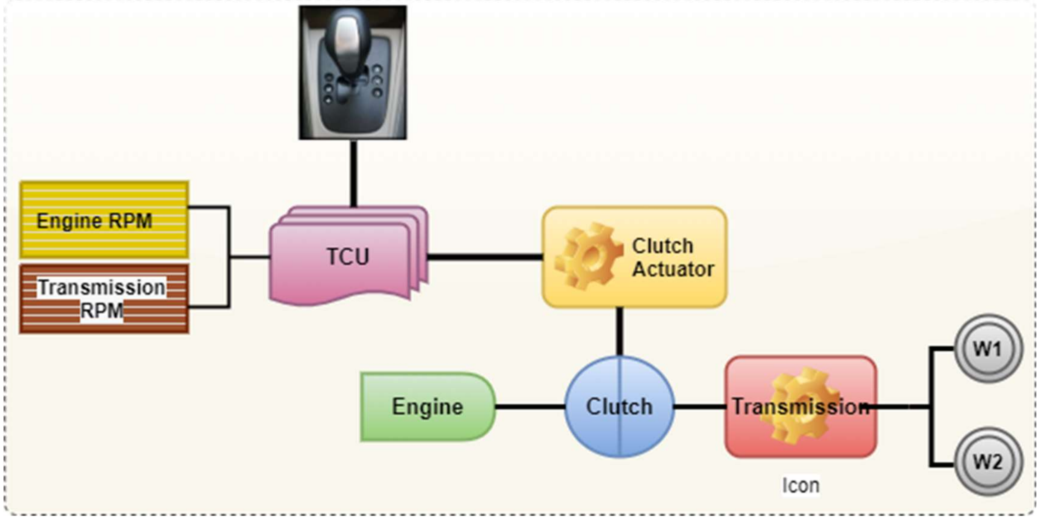

Figure 3.1 Components of an *e*-AMT set-up

To automate clutch actuation and gear shifting, the DC motor-based *e*-AMT includes a conventional MT, actuators, and a processor known as transmission control unit (TCU). The TCU receives the driver's gear shift order, and after processing all input signals via a gear shifting control strategy, generates the corresponding command for actuators. TCU also processes vehicle-related signals from the engine control unit, such as torque requirement, engine rpm, and throttle angle, as well as driver change commands.

The present study emphasizes on clutch operation of an *e*-AMT vehicle that require high accuracy and consistency in order to provider driver comfortability besides maintaining durability of the system. The performance of the system largely relies on how the electric motor functions. One of the prime parameters is the duty cycle that helps in the selection of an actuator. Therefore, three strategies are developed for data collection by changing the duty cycle load. The first is named as "Strategy-I" that uses 50% duty cycle for clutch engagement and a 70% duty cycle for clutch dis-engagement. "Strategy-II" uses 75% duty cycle for clutch engagement and an 80% duty cycle for clutch dis-engagement whereas, during "Strategy-III" an 80% duty cycle was used for clutch engagement while an 85% duty cycle for clutch dis-engagement. A relatively increasing range of duty cycles data for the system implies that a smaller amount of time is required for completing both the clutch operations. The effect of rise in temperature of the motor is neglected for prognosis as it is not possible to mount a sensor inside the clutch assembly. Each individual strategy with a respective duty cycle input is used while collecting the data from the degraded PMDC motor for 5 respective days. The data is collected for a total of 15 days. The cumulative data for each individual strategy is then prepared for prognosis of the system any further.

3.2 Preparation of Experimental Setup

The experiments carried out to conduct life prediction of motor and motor controller system in an HIL setup consists of following components:

a. Clutch Assembly
b. Electromechanical Actuator
c. Electronic Control Unit
d. Battery
e. Sensors

The first member of an automobile drive train is the clutch. In order to change the speed and torque of an automobile, the clutch connects the gearbox and the engine. Power is transmitted from the engine to the wheels during clutch engagement, while it is disrupted during disengagement. The clutch assembly together comprises of a driving member to which the flywheel is mounted on the engine crankshaft, while another is the driven member also known as a pressure plate, mounted on the transmission shaft. Whole assembly is kept under clutch housing and is connected to the operating member/electromechanical actuator.

The PMDC motor replaces the knob of the mechanical actuator to provide linear movement by converting the rotary motion of the motor. The electromechanical actuator is preferred for being capable in handling variations in operating load along with varying speeds, thereby, assisting in higher mechanical efficiency. The capability to have complete control over the motion profile make its futuristic use. The velocity and position are encoded in the control strategy thereby providing additional benefit of reconfiguring the motor while in action, without complete shutdown. The operating principle is the recast of an inclined plane. The lead screw's threads act as a ramp, magnifying the slight rotational force over a long distance to transform it. This makes it possible to carry a big load over a short distance. Additionally, they offer significant cost savings by consuming power only while performing work. The work required to be done is performed on the car’s memory often termed as ECU. All the control logics are programmed into the ECU and a feedback loop is also initiated for passenger safety. The Fig. 3.2 describes the *e*-AMT system schematic comprising of the sensors, actuators that are connected to the memory (or, ECU).

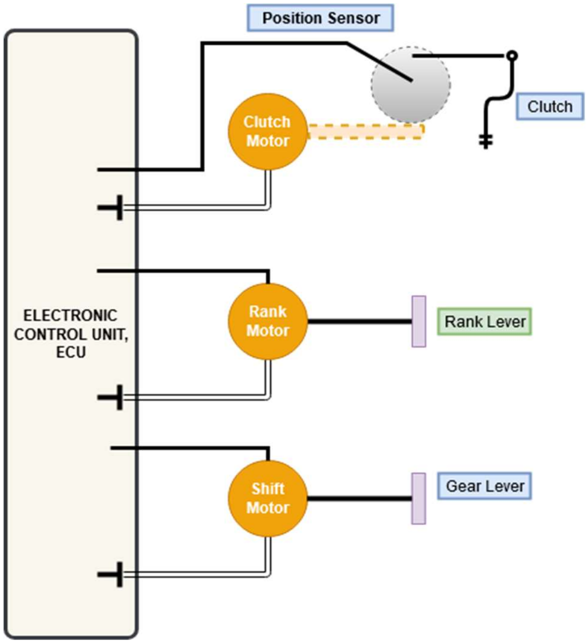

Figure 3.2 System Schematic of *e*-AMT consisting of ECU, Sensors and Actuators

The ECU electronically controls the automobile engine by controlling the electrical requirements of the systems or subsystems as per the duty cycle load. There exist various categories of ECU for individual system, that are:

i. Power control unit
ii. Transmission control unit
iii. Engine control unit
iv. Battery management system, etc.

The heart and intelligence of the gear control system is the TCU (Transmission Control Unit) (see Fig. 3.3 for TCU architecture). TCU sends an order signal to the H-Bridge circuitry, which guides the linear actuators. The program for the microcontroller is designed to send pulse width modulation (PWM) signals to the driver IC. Taking into account the driver's requirements and the operating conditions of the vehicle, the TCU manages the gear changes by controlling the clutch, the gears and the engine. The PWM is sensed by the motor from the BTN/H-Bridge. The voltage across the loads are guided using the electronic circuit of H-bridge. The microcontroller in H-Bridge circuitry receives analogue feedback signals from actuators in order to analyze and monitor linear actuator movement. Inhibit signal (i.e., gate) works as an enabling pin for PWM to H bridge. IN is current drawn by the BTN. IS current sensed feedback to the micro controller from BTN. The microcontroller is connected to a 12V DC source. The closed loop circuit transmits the current to the BTN from the microcontroller using PID control. Working of the PID control is as per the required position 'θ' of the actuator, thus, the duty to the controller is computed as:

$$error, \varepsilon_\theta = \theta_{actual} - \theta_{required} \tag{3.1}$$

where, θ is the actuator position and the respective duty is computed as:

$$duty = K_P(\varepsilon_\theta) + K_I \int \varepsilon_\theta dt + K_D \frac{d\varepsilon_\theta}{dt} \tag{3.2}$$

K_P, K_I, and K_D are the respective proportional, integral and derivative constants. There is always a steady state error besides an increase in oscillation while using the proportional control. A use of integral control helps in disappearing the steady state error. Finally, the filtering of noise in the system is carried out by the derivative controller, thus amplifying the high frequency response.

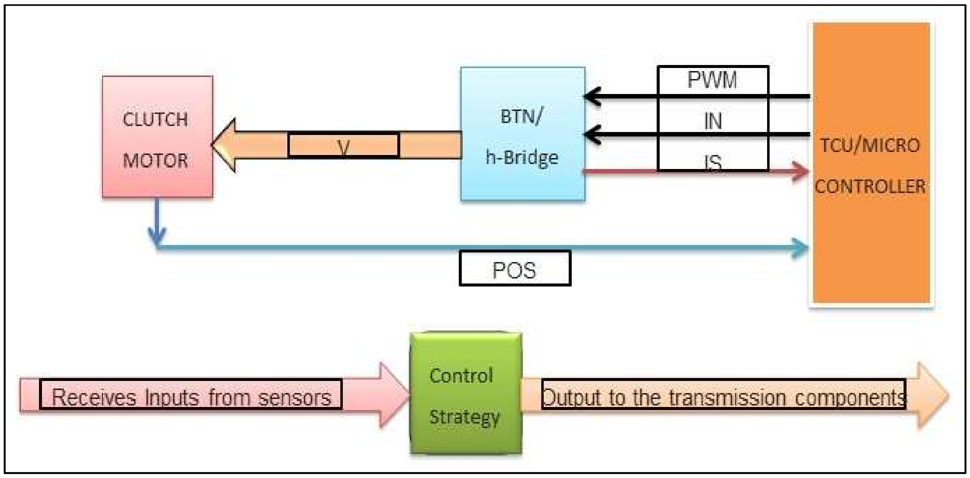

Figure 3.3 Transmission Control Unit Architecture

Together, all the control units make up the ECU. In general, the ECU suffices a closed-loop control whereby it monitors the output by controlling the input. Key elements comprising of an ECU are:

a) Microcontroller
b) Flash memory
c) Digital inputs
d) H-bridge
e) Controller Area Network (CAN)
f) Bootloader

The in-house built ECU is a 32bit controller with megabytes of allocated memory. Correct power management is crucial for the working of an ECU as it offers full control over the whole system. With the correct voltage, the microcontroller starts to read the programs and begins a self-check. In the process, the experiment is said to begin and the ECU reads data from different sensors transmitting over CAN bus, which triggers other control units to respond accordingly. CAN allows the connected ECUs on the bus to receive digitally encoded signals.

The 12volts battery was retained under constant charging, and after a span of every 15 minutes the voltage across the terminals were checked using multimeter. Additionally, the HIL comprised of the ETAS modules, the INCA module for data logging using CAN communication protocol and the LEM current sensor on the motor side. The experimental setup was carried out in a sophisticated HIL laboratory under accelerated loading circumstances in order to obtain degradation motor data that would be utilized for RUL estimation. The complete experimental setup along with its labelled components can be found in Fig. 3.4.

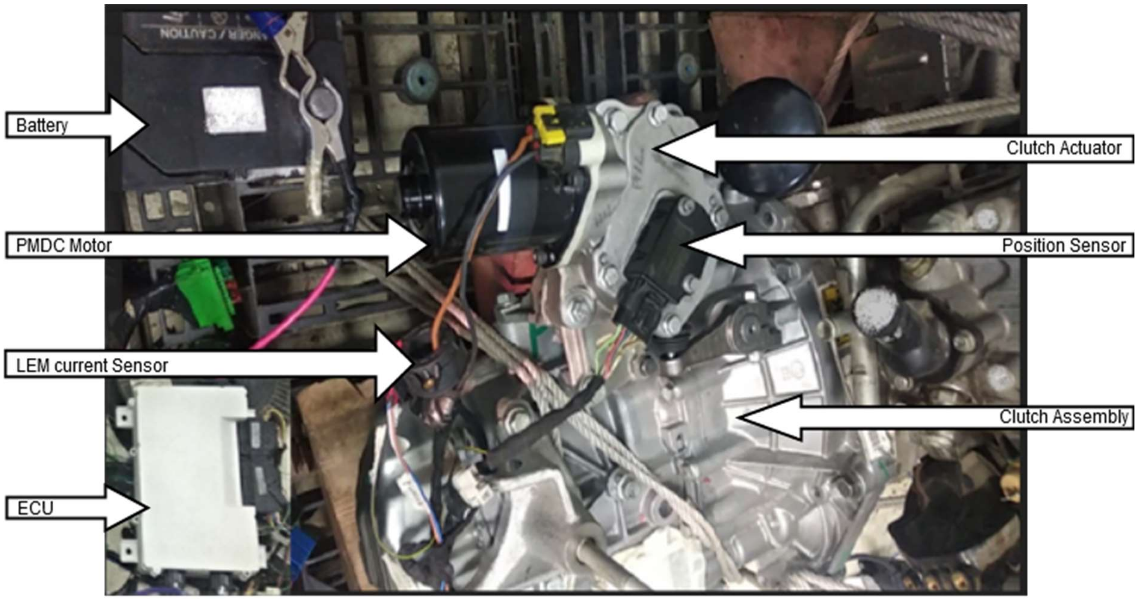

Figure 3.4 Experimental Set-up

The benefits of ALCT has been that the time to failure is just not directly observed, yet this degradation can even be precisely monitored, thus shortening the testing times (Crk 2000). To ensure the reliability of rapidly emerging electric mobility and advanced driver assistance systems (ADAS), HIL testing has gained importance. An HIL must include sensors and actuators that is synchronized in a way to act simultaneously. Upon actual loading conditions it enables a feedback signal to the end user. Under altered conditions, the changes in the algorithms input parameter, assists in developing an optimal control strategy.

The duty cycle data is used to configure the speed as well as the road-load conditions by increasing or decreasing the input voltage. However, in the case of emergency braking or a sudden halt, the clutch actuator must withstand severe dynamic demands, which are also addressed in the ALCT tests. Following this step, the system is certified to be fault-free under all operating loads, ensuring its dependability. Target is to achieve product reliability via accelerated testing methodology using the commonly used degradation factors like vibration, voltage, current, duty cycles or a combination of any two. Aiming towards higher prediction accuracy of the RUL one of the accelerated degradation factors is considered. Furthermore, with this degradation process established, the degradation trend will be accelerated. The present work uses 3 different duty cycle combinations as the stress factor for conducting the ALCT test. The modified Indian drive cycle (MIDC) is the adopted benchmark strategy in the process of data collection. A drive cycle resembles the relationship between the speeds at different instant of gear shifting.

ALCT is conducted in a HIL laboratory for an auto-clutch setup under accelerated loading conditions. The data were logged using the sensors and the INCA software by ETAS and were stored in ASCII and DAT format. A sensor is an electrical/electronic device that responds to a measurable output in the form of a signal/encoded feature. Awareness of the assets' failure mechanisms is needed for a successful sensor selection. The reliability of the sensor, the accuracy, and the resolution are amongst the few considerations that needs to be taken into account while selecting respective sensors for tracking a signal to enhance product reliability (Mishra et al. 2002). The use of indirect sensors enhances the reliability in terms of monitoring the process by making it resilient against multiple sensor failures (Goebel 1996). A few of the variables can be directly measured while for the rest of the variables the sensors are mounted at different locations. The temperature data logged using the thermocouples were found not so accurate, hence is neglected in the present study. The in-house developed control strategy helped the rotating machinery in producing a mechanical clutch actuation for an e-AMT vehicle. Table 3.1 below summarizes the list of advanced sensors used to monitor the *e*-AMT system's performance variables using direct and indirect measurement.

Table 3.1 Sensors used during experimentation

Measured Variable	**Direct/Indirect Measurement**	**Sensor technology**	**Sensor mounting location**
PWM (%duty)	D	From control strategy	N/A
Battery Voltage	D	CAN communication	N/A
Environment temperature	I	Thermocouple, ETAS thermo-module	Ambient
Actuator current	I & D	LEM current sensor (hall-effect)& feedback from BTN (H-Bridge name)	Clutch motor supply side
Actuator position	I	Position sensor	Actuator
BTN temperature	I	K-type thermocouple	Surface of the BTN
Motor temperature	I	K-type thermocouple	Enclosures of motor
Clutch conditions	D	Mechanically	N/A

3.3 Data Generation

Prognosis can be described as the timely prediction of a fault indicator in a long-term use, for a component, system or a subsystem and, are generated with a view to estimate the RUL of a failing equipment/system. The proposed strategy for motor prognosis uses a degradation model to predict the state of health or RUL of the actuator motor to enable PdM. Experiment were carried out on HIL test setup. The Fig. 3.5(a) shows the schematic layout for a conventional clutch operation with the use of PMDC motor. Clutch engagement and disengagement are the two set of operations during clutch actuation while the actuator changes its position (*see* Fig. 3.5(b)). The change in respective position is the displacement generated by the actuator due to its linear movement and has been recorded in degrees. The control strategy has been developed using the thumb rule of directions i.e., 'Zero' for engagement (that starts from 18degrees) while 'One' for disengagement (ends at 34degrees). The position of 34 and 18degree corresponds to complete disengagement and complete engagement. A 5seconds dwell time at the end of each respective operation had been chosen. It is perceived that the actual clutch operation lasts for less than 200milli-seconds. Considering the dwell period and the actual time of operation, the total cycle time ranges from 1 to 1.4seconds. These set of rules further helped in sampling the data and generating the respective number of cycles. Accelerated loading strategy helps in time to failure under higher stress in less time, besides a much higher tendency towards degradation of the rotating equipment. Proposed work uses current (I_a) data as one of the prime variables out of the whole dataset for the prognosis workflow.

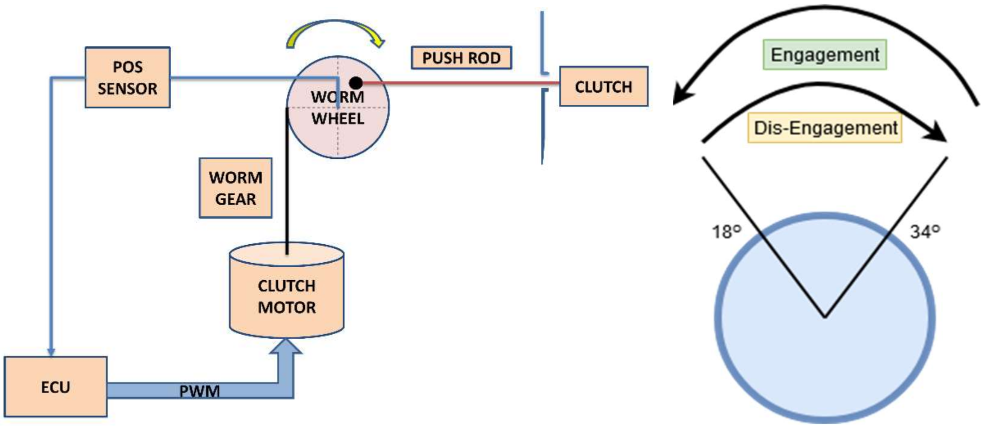

Figure 3.5 (a) Schematic diagram of 12V, 0.5kW PMDC clutch motor actuator assembly with electronic control unit (b) Clutch sensor position during engagement-disengagement

Clutch motor, clutch stroke sensor, worm shaft, worm wheel, push rod, and assist spring make up the clutch actuator. The clutch motor's rotation is transmitted to the worm shaft and worm wheel's reduction gears, causing the worm wheel to rotate. The clutch release lever is actuated by this movement, which causes the push rod to move through a fulcrum given on the worm wheel. When the clutch is engaged, the worm wheel has an assist spring that provides a force to assist the movement of the push rod. As the clutch is released, this reduces the load on the clutch motor. The clutch actuator is stopped by the ECU based on signals from the clutch stroke sensor. The clutch stroke sensor is made up of two Hall ICs and a magnetic yoke that rotates in perfect agreement with the worm wheel's rotation. The two Hall ICs transform variations in magnetic flux induced by clutch motor rotation into electric signals, which are then sent to the ECU. These electric signals are used by the ECU to calculate the clutch stroke's span (*see* Fig. 3.5(b)). The clutch motor's rotation is transmitted to the worm shaft and worm wheel's reduction gears, causing the worm wheel to rotate. The clutch release lever is actuated by this movement, which causes the push rod to move through a fulcrum given on the worm wheel. When the clutch is engaged, the worm wheel has an assist spring that provides a force to assist the movement of the push rod. As the clutch is released, this reduces the load on the clutch motor.

The TCU on the other hand produces output instruction signals to the clutch actuator after receiving the input signals. The linear actuator in our system is powered by DC motors that adds to weight reduction besides cost benefits. H-bridge circuitry is required for DC motors. TCU sends an order signal to the H-bridge circuitry, which guides the linear actuators. PWM and polarity are used to track and adjust the torque, rpm, and direction of the motor. The speed and location of the actuators are fed back to the transmission control module via hall sensors. The aim is to mimic a driver's use of the clutch and gears in order to prevent them from being misused. If we need to consider the amount of control it takes to maneuver a car up a ramp. The driver (control strategy) must be able to detect forward and backward direction, acceleration, clutch biting point, and engine rpm, among other things. During experimentation the motor produces a back electromotive force (emf), that has been corrected prior to data collection for generating good quality of data. The transmission control module includes data from a variety of sensors to accomplish this.

Besides accuracy, reliability, consistency the data generated should also meet the limiting uncertainties associated with the data and its statistical properties. The dependency of data quality assessment (DQA) in data-driven modeling were perceived targeting decision-making benefits (Pritchard 2020). Accuracy in the data generation have been perceived with the correctness in sampling. Reliability was attained with the in-house control strategy and the communication protocols generating a robust experimental data. Correct precision of the actuators and calibration of the sensors and unbiased system once again helped in achieving data integrity. Data anomalies were verified for all the operational datasets and no extreme variation and gaps were found between the continuously recorded data. Literary works (Pritchard 2020) with data quality suggests quality resistant inference to mitigate poor data quality with the use of robust estimators e.g., dispersion for univariate dataset while covariance for a multivariate measure. The use of such robust metrics increases the ability in detecting the outliers. System data from real world experiments encounter anomalies corresponding to error structures which provides a room to the present research in developing a robust intelligent methodology. Dependency on the Bayesian inferential statistics helps in incorporating the priors adaptively. The present scope of the work is derived towards building a predictive model that will incorporate the noise present in the data. The adherence to a good quality of data will therefore quantify the decision making ability and its correctness. Keeping in mind about the resource allocation tailored to a particular application, the data required for experiment to be performed is collected in-vitro majorly due to the adaptability to desired changes whenever required. The advantages of in-vitro data collection over in-situ are:

a) economical in nature,
b) less time required, and
c) increased throughput

Table 3.2 presents sample datasets in case of a single cycle collected by means of sensors in an HIL setup during experimentation. The initial and the final part of the dataset in the table is the dwell cycle when the actuator is seen to be fully engaged position (>35degrees), thereafter a PWM of 50%duty is sensed which moves the actuator position to attain complete disengagement. The position of 21 to 24degrees represents partial engagement while 25 to 28degrees represents partial clutch disengagement. The data generation along with collection was carried out for a span of 5days for each strategy. There were three strategies developed in order to collect data from the degraded motor with varying PWMs.

Table 3.2 Sample dataset from HIL experiment

Serial number	PWM (duty)	Actuator Current (Amperes)	Actuator Position (degrees)
1	0	0	35.63085
2	0	0	35.94213
3	0	0	36.04589
4	0	0	36.09777
5	0	0	36.09777
. . .	. . .	. . .	. . .
527	50	16.60351	23.54284
528	50	15.25585	23.07592
529	50	15.22656	22.73870
530	50	14.96289	22.19396
531	50	14.66992	21.93457
. . .	. . .	. . .	. . .
1065	70	41.56250	32.56994
1066	70	39.44335	32.95904
1067	70	37.93945	33.40002
1068	70	38.14453	33.84100
1069	70	43.10058	34.25604

. . .	. . .	. . .	. . .
1367	0	0	35.99401
1368	0	0	36.01995
1369	0	0	36.01995
1370	0	0	35.99401
1371	0	0	35.99401

The present data quality assessment will also favor in distinguishing the good motor and bad motor reliably. The selection of a good motor will also provide the reuse potential of the motor which is beyond the scope of the present study. Present study will only focus on finding the RUL of the motor. The indirect measurement of data and its associated metrics in the process will help us to reliably indicate the degradation parameter.

3.4 Role of Motor

A PMDC motor is used in a wide variety of industrial and commercial applications by many OEM's. A brushed DC motor is chosen for a number of reasons such as portability, high starting torque, bi-directionality, high reliability and for having the ability to fine tune the speed to match the requirements. The ability to handle the load is one of the primary considerations for the design of the brushed motor. Matching the actual load to the brushed DC motor design is extremely important for motor longevity. Running a motor at a lower current than the original design will actually shorten the motor life. A motor running at a higher current than the original design will create excess heat reducing motor life prematurely. A well-matched motor/current profile will produce the optimum motor life for that design.

3.4.1 Advantages of PMDC motor

1. No external field circuit, so no field circuit copper loss
2. No field excitation is required, so efficiency as compared to wound field motors is high
3. Good for low power applications providing good starting torque

The time varying currents and voltages resulting from the sudden application of sources are called transients. Clutch motor in the recently developed technology cars is one of the sources that works in such dynamic conditions. An integro-differential type equation describes the circuit analogy. Aperiodic current for such a short time can produce electromagnetic disturbance. Prior knowledge of the current and voltage harmonics is always a limitation where intensity of such variables changes continuously with time. Currently observed system is one such in which the range of operation time lies from 100-200 milliseconds.

Motor current signature analysis (MCSA) (Miljković 2015) using spectral approach revealed the presence of higher harmonics in the current signal. The use of digital filters can be seen in industry to lower the harmonics. The particular response obtained can be seen to produce individual amplitude out of the filter set during frequency analysis. The use of electrical signature analysis (ESA) (Bonnardot et al. 2011) can also be seen in use besides MCSA. In ESA the fast Fourier transform is done over voltage signal besides current that has been seen in MCSA. These conventional approaches towards PdM for condition monitoring limits its use for a non-periodic signal, which is another aspect of importance in our present study.

The use of PMDC motors (see Fig 3.6(a)) in the low power applications with high torque delivery promotes their use in terms of choice. Spectral response reveals that much higher current has been used to perform the same operation while experimenting with the motor. DC powered devices mostly favors using R_a-L_a circuits. The use of resistance (R_a) and inductive (L_a) circuit as shown in Fig. 3.6(b) for a 0.5kW rated Johnson Electric made PMDC motor in the present study. The series representation of an R_a-L_a circuits makes it favorable towards voltage driven thereby assisting in our present experimental strategy. These kind of circuits exhibit the behavior of analogue electronics where the signal is said to vary between two levels. The present experiment is driven by an in-house built control strategy which is being developed using the two levels 0 and 1 that refers to the two respective clutch operations.

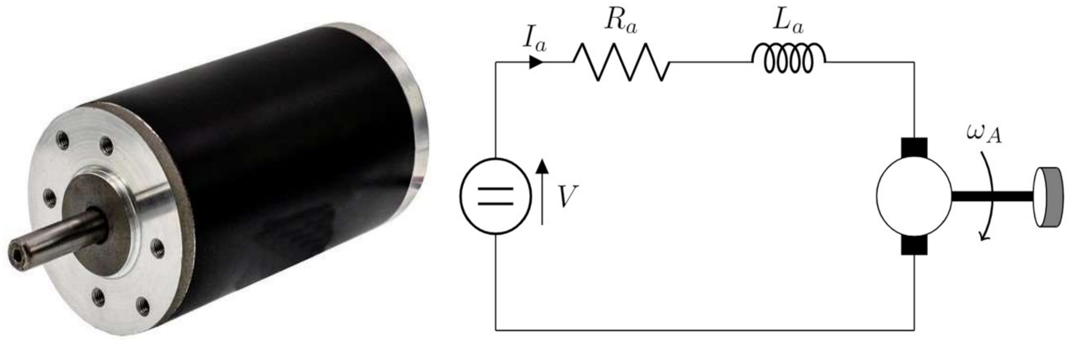

Figure 3.6 (a) PMDC Motor (b) Circuit diagram of a PMDC motor

The notations can be described as; I_a denotes the current drawn from a voltage source V. The speed of rotation for the motor is given by ω_a. PMDC motors have seen an increasing use in low power applications. The principle of working is a mechanical torque is created when fixed magnetic field generated by the permanent magnets interact with the perpendicular field induced by the currents in the rotor windings.

The present study uses electromechanical actuator for an automated clutch operation. The motor operates at 2kHz frequency (i.e., 0.5milli-sec) while the feedback current is collected at 10milli-sec intervals to micro-controller. This time interval is long enough to damage the motor control unit (MCU). Proposed methodology involves the use of data-driven approach (Coble 2010; Jouin et al. 2016; Lei et al. 2018; Zhu et al. 2020) for meaningful interpretation of changes in this period of transient operation.

The Table 3.3 and 3.4 below summarizes the *e*-AMT vehicles actual motor and controller specifications used during experimentation for data generation. It is worth mentioning that the in-house built controller (*name not disclosed due to company rights*) presently encounter the product development stage by undergoing rigorous experiments.

Table 3.3 Specifications of Motor

Motor		
Make		JOHNSON ELECTRIC
Diameter & Length (mm)		74±1 128±1
Source		DC
Rated Voltage (V)		12
Rated torque		1 Nm
Rated speed		4023 rpm
Power		0.5 kW
At no load	**Speed**	5178 Rpm
	Current	4.66 Amp
Resistance		0.055 Ohms

Table 3.4 Specifications of Motor Controller

Controller	
Make	In-house
Source	DC
Temperature limit	110 degrees
Voltage/Current	9-12 V

The current flows through brush, the commutator half ring, round the coil, and out through the other commutator half ring and brush. The rotation is upwards at one time, while the direction reverses when the current (I_a) flows back from the commutator to the brush, thus, helping the coil to turn. The coil turns with the commutator which ensures that even if the current changes its direction, same directional force is exerted. Adding more wires to the coil will help in getting increased force, thus contributing to the torque. More than a pair of magnets will help in getting turning force. Permanent magnet machines are becoming more common in actuation systems due to high power density, compactness and current availability needed for effective control.

3.5 Evaluation Criterion

A dataset is considered to be good if the measurements are found to be consistent within their range during each repetitive set of experiments. Although the section 3.3 discusses general aspects that has been considered in the present study prior to data generation, few more points are listed below which helped us in further evaluating the quality of the dataset.

1. Higher motor current is drawn for a constant voltage supply and increasing load input. This will also result in a corresponding increase in torque requirements.
2. The motor current has been found to increase but under a finite rate, for a same load and increasing input voltage.
3. The back-emf has been constant for all the experimental test strategies.

The above points are some of the factors that rule the manifestation of a good data. The present experiment is an anecdote of a real-time performing AMT clutch. Experiments conducted in the beginning were found to lack finite degradation measures. The errors were raised due to uneven set values in the control strategy that tripped the system, so the initial part of the data were eliminated. The uneven shutdown led to the presence of faulty data in the cache memory so a necessary boot was performed to erase the cache memory files before starting the subsequent experiment. However, a flash program was made to run before start of the experiment at every instant of the data collection. At the time of starting of the motor the back-emf was found to be 0, so an extra resistance has been added to the circuit during the lab experiments. The same was mimicked using a logic developed to build the control strategy. There were no further changes to the control strategy or throughout the experiment, and the data collection ran smoothly. Since the data is represented as a signal property. So, subsequent chapter 4 will try to explore the computation required along with the associated mathematics to extract the signal characteristics, which will drive towards a plausible data-driven model development.