Electromagnetic Contactless Torque Transducer: Torque Measurement and Shaft Impediment Approach

Ataur Rahman, Mohiuddin AKM, Badrul Md Daud

chtorque on a rotating power transmission system such as Static torque is relatively easy to measure but dynamic torque is difficult to measure, since it requires transferring some torsional effect in terms of electric signal or magnetic inductive voltage. The several torque transducers has been made with slip ring and metallic resistance strain gauges to measure the dynamic torque of the power transmission shaft. However, the slip ring method brushes are prone to wear and tear and need to be replaced frequently while the strain gauge chemical properties is disturbed due to heat and provided the significant error of the signal output which emphasis this study to develop an electromagnetic non-contact (EMNC) torque transducer to measure the dynamic torque of the power transmission shaft. The EMNC torque transducer has been made from this study with a permanent magnet and two cylindrical coils. The first coil serves as the electromagnet, which causes the force (attractive) and second coil gets the voltage induction due to the changing of the magnetic field. The measured voltage of the second coil represents the torque applied on the shaft.

Keywords: Non-contactless torque transducer; Magnetism effect; Dynamic torque; Induction voltage.

I. INTRODUCTION

The torque transducer is a device that converts a torsional mechanical input into an electrical output signal. In general, a signal can be a function of time, distance, position, temperature, pressure, torque, etc., and it represents some variable of interest associated with a system. For examples, in an electrical system the associated signals are electric current and voltage while in mechanical system, the associated signals may be force, speed, or torque [1]. The most important quantity of rotating machine is the acting mechanical power. There are many widely used measuring methods and more or less standardized instruments for measuring the rotational speed; however the torque measurement needs every occasion a special solution and most important is measuring the torque directly on the rotating shaft and measuring the rotational speed. For many years metallic resistance strain gauges have been used as the principal sensors for measuring torque on a shaft [2]. Metal foil strain gauges are bonded onto a flexure or structural member that deforms when a torsional or twisting motion is applied. In most cases, four metal foil strain gauges are used to obtain maximum sensitivity and temperature compensation. Two of the gauges are usually in tension, and two in compression, all four strain gauge are wired in a Wheatstone bridge configuration with compensation adjustments that correct for temperature errors.

There are two types of torque, which is static and dynamic [3]. Dynamic torque involves acceleration while static torque does not. Remember that in physics, the term acceleration refers to any change in speed, not necessarily an increase. *For example, when you unscrew the lid from a glass jar, you apply both static and dynamic torque. The torque is applied initially of the static variety because the lid is stationary. Once the lid begins to turn, however, the applied torque is said to be dynamic.* In generally, it is more difficult to measure dynamic torque than to measure static torque of the system. The metallic resistance strain gauge is an example of a passive transducer that converts a mechanical displacement into a change of resistance. A metallic resistance strain gauges torque transducer (Fig.1) has been developed to measure the torque of an off-road wheel vehicle [7].

The metallic strain gage is a thin electrical wafer-like device is attached (bonded) to a variety of materials to measure applied strain. The resistance of the wire or metal foil changes with the length as the material to which the gage is attached undergoes tension or compression. This change in resistance is proportional to the applied strain and is measured with a specially adapted Wheatstone bridge. The sensitivity of the strain gage is described in terms of a characteristic called the gage factor S_g, can be defined as the unit change in resistance per unit change in length. The gauge factor of the strain gauge has been computed using the equation, $S_g = \frac{\Delta R / R}{e}$ with $e = e_a + e_L$ where, axial strain, and lateral strain. The instantaneous output volatge of the torque transducer due to the instanteneous applied torque has measured with considering all the strain gauges are in active using the equation [7].

$$T(t) = \frac{r}{m(1+r)^2} * nS_g * v_{in} = \frac{r}{m(1+r)} * nS_g * \sqrt{p_g R_g} \quad (1)$$

where, r is the resistance ratio, S_g is the gauge factor, n is the number of active gauge, v_{in} input voltage, p_g power disspation of the gauge and R_g is the gauge factor and m is the slope of the calibration curve of the transducer.

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Fig. 1: Strain gauges embedded torque transducer [7]

There are two main torque measurement methods, which is inline and reaction. Inline torque measurements are taken by inserting the torque transducer between the agent of rotation and the object being rotated. While the reaction torque is measurements take advantages of Newton's Third Law of Motion, which tells the every action, there is an equal and opposite reaction [4]. For a reaction torque measurement, the amount of torque that is being experienced by a rotational system is not measuring. However, the amount of torque required to stop the rotation. The electromechanical conversion devices use rotating shafts. A dynamic system's torque measurement is the main feature used to monitor safe operation and prevent if there has any chance to damage due to the excessive torque applied. The torque measurement of a rotating shaft is essential for selecting the shaft of the dynamic system and assembling machines precisely, improving machine performance and controlling power transmission systems.

II. MATHEMATICAL ANALYSIS

Electromagnetic induction is the process of generating electromagnetic field (induced voltage) by subjecting a conductor in to a magnetic field. Induced voltage is explained using the Faraday's Law. Induced voltage of a closed circuit is defined as the rate of change of magnetic flux through that closed circuit. Induced formula is given as,

$$e_{ind} = N\frac{\partial \phi}{\partial t} \qquad (2)$$

where: e_{ind} is the induced voltage in volts (V), N is the numbers of series-connected turns of wire in turns, dϕ/dt= rate of change in flux in Webers/second (Wb/s).

The magnetic energy stored in the coaxial cable is given by

$$W_n = \frac{1}{2}\int_v \mu_r H^2 dv \qquad (3)$$

Since the H is a function of r only, we choose dv to be a cylindrical shell of length l, radius r, and thickness dr along the radial direction. Thus dv = $2\pi r^2 l$ and

$$W_n = \frac{\mu_r I^2 l}{4\pi} ln\left(\frac{b}{a}\right) \qquad (4)$$

After that, we refer to the basic power equation, $P = T\omega$ where, P is the power, T is the torque, and ω is angular rotational speed of the shaft. And using equation of magnetic energy in a coaxial cable,

$$T = \frac{\eta I^2 l}{4\pi w}\ln\left(\frac{b}{a}\right)\int_0^t dt \qquad (5)$$

After we get the value of voltage induced at second coil, we can simply put that value of into the equation that already derived. To make sure that we get correct value of torque, again we will derive new equation to compare the value of torque.

Motors supposed to do some work and two important values define how powerful the motor is. It is motor speed and torque – the turning force of the motor. Output mechanical power of the motor could be calculated by using the following formula:

$$P_{out}(t) = V_{rating} * I_b(t) * \eta_m \qquad (6)$$

and the motor torque can be estimated as,

$$T(t) = \frac{V_{rating} * I_b(t) * \eta_m}{\omega} \qquad (7)$$

where P_{out} is the output power, Watt, T is the torque, Nm, and ω is the angular speed, rad/s.

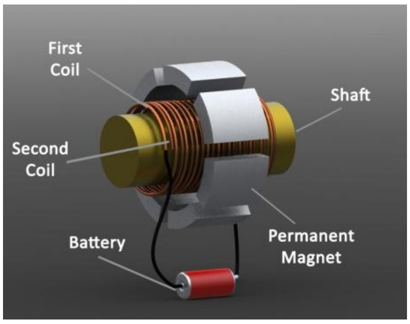

Fig. 2: Electromagnetic contactless torque transducer.

III. MODEL OF EMC TORQUE TRANSDUCER

The EMC torque transducer model (Figure 2) has been developed by using a cylindrical permanent magnets attached to the polypropylene wrapped magnetic field insulated rotating power transmission shaft and placing two coils between the permanent magnet and the rotating shaft. The relative movement between the magnets due to deformation resulting from torsion will increase or decrease the magnetic field strength. By measuring the resulting magnetic field strength in terms of voltage induction into the second coil, it is possible to determine the applied torque of the shaft. The electromagnetic contactless torque transducer has been designed in Solid Work Software. The material of the components will be selected accordingly to the function of the components. The design consists of the shaft, copper coil, magnets, and power cable and battery.

3.1 Principle of operation

The shape of a bar magnet giving a distinct North and South pole can formed by using a copper coil with supplied current, which may greatly intensified a static magnetic field. The magnetic flux developed around the copper coil being proportional to the amount of current flowing in the copper coils windings (Fig.3). If additional layers of wire

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are wound upon the same coil with the same current flowing through them, the static magnetic field strength would be increased.

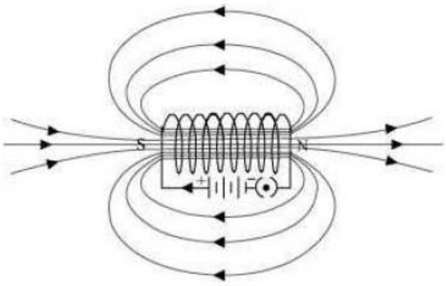

Fig. 3: Magnetic lines of force.

Therefore, the magnetic field strength of a copper coil is determined by the *ampere turns* of the coil. With more turns of wire within the coil, the greater the strength of the static magnetic field around it.

The permanent magnets produce a good and sometimes very strong static magnetic field, in some applications the strength of this magnetic field is still too weak or need to be able to control the amount of magnetic flux that is present. By using a copper coil with supplied electricity a much stronger and more controllable magnetic field can be produced. By using coils of wire wound around shaft, very strong electromagnet is produced. This use of coils of wire produces a relationship between electricity and magnetism that gives another form of magnetism called electromagnetism**.** The electromagnetism effect may enhance by using a sensor and potentiometer by controlling the current supply to the coil as the magnetic field strength is the function of number turns of the coil and current supply, $H = f(N,I)$. The sum of the magnetic filed of the PM and EM will induce the voltage into the second coil with magnetic field induction, $e_{ind}(t) = N\frac{dj}{dt}$, where $e_{ind}(t)$ is the instantaneous voltage induction, dφ/dt is the rate of changing of the magnetic flux and N is the number of turn. The applied torque on the shaft is determined with measuring the instantaneous voltage induction of the coil.

Meanwhile, magnetic forces attract and repel like electric forces and when two lines of force are brought close together the interaction between the two magnetic fields causes one of two things to occur:

- *When adjacent poles of the copper coil and permanent magnet are the same, (north-north or south-south) they repel each other.*
- *When adjacent poles of the copper coil and permanent magnet are not the same, (north-south or south-north) they attract each other*

IV. RESULT AND DISCUSSION

A dynamic torque of a power transmission system has been made with an electromagnetic non-contact rotary torque transducer (Figure 4). The torque signal is produced by magnetic field induction techniques, which is made by using a pair of cylindrical coils and permanent magnet. The first coil serves as the electromagnet, which strengthen the magnetic strength of the permanent magnet. Its electromagnetic field is control by a sensor and fuzzy controller. While, the voltage induces to the second coil due to the induction of the magnetic field of the permanent magnet and electromagnet. The measured voltage of the second coil represents the torque applied on the shaft. The fuzzy controller disconnects the power supply to the electric motor if the applied torque on the shaft exceeds the threshold values based on the feedback system.

The EMNC torque sensor is able to measure torque of the rotary shaft in both clockwise and anti-clockwise direction with voltage signal output. The input voltage 5 to 5V and output 3 to 5V represents the applied torque of the sensor. The experiment of the laboratory scale torque transducer has been conducted with dead load 200, 400, 600, 800, 1000, and 1200 grams. A 12V DC battery is used to make the first coil of the torque transducer as electromagnet.

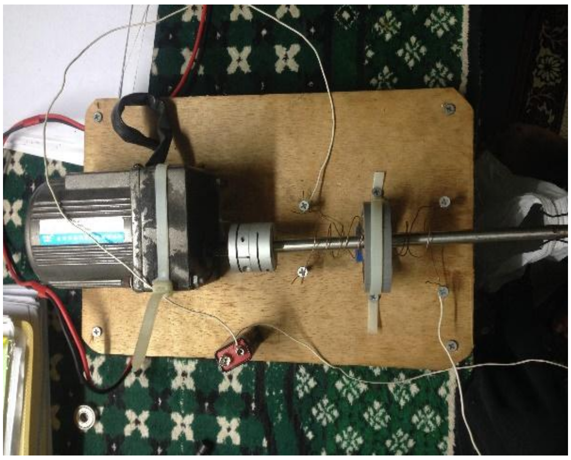

Fig. 4: A laboratory scale EMC torque transducer.

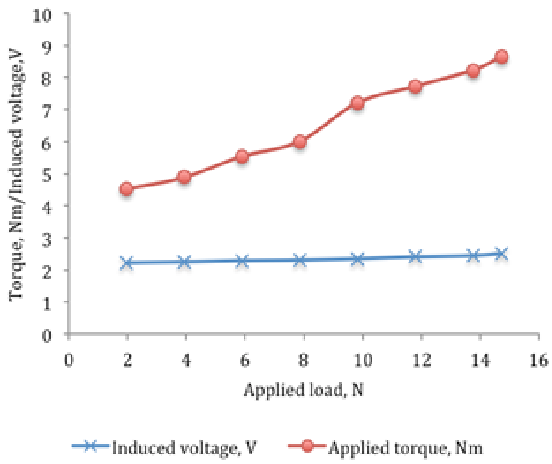

Fig. 5: Applied torque of the shaft based on the EMNC transducer

After setting the mechanical and electrical parts and conducted trail test, the experiment has been to determine the performance of the prototype. The test was run 3 times to take the average of the outcomes. Figure 5 shows that the highest voltage induces 2.31V when the 7.85 N load is applied to the motor shaft. For the lowest voltage induced is 2.23V when the minimal load (2N is applied. The graph

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pattern shows that the voltage induction will increase when the load applied to the motor is increased. The maximum current flow through the coil is 4.79A and the minimum current flow through the coils is 4.30A.

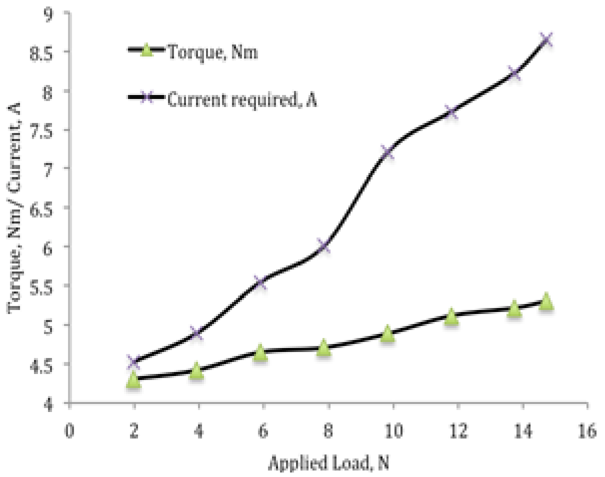


Fig. 6: Current required to develop the motor torque

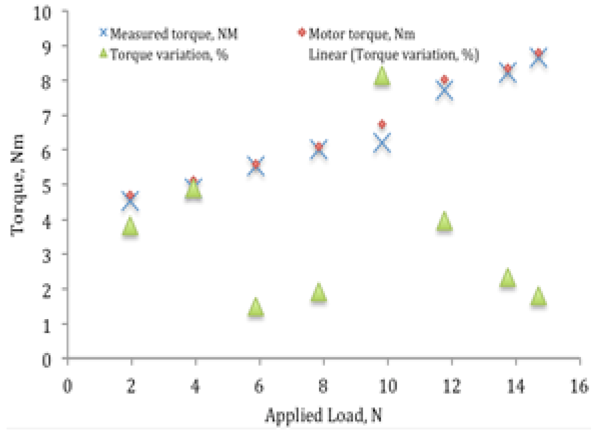


Fig. 7: Variation of the torque.

Figure 7 indicates the relationship between the load applied to the motor and the torque produced. Figure shows that the value of torque increases with increasing the applied load to the shaft. The motor develops torque to operate the torque with required rotation speed. The minimum torque produced 5.0 Nm to operate the load 1.96 N with 11.25 rad/s. The corresponding measured torque was recorded as 4.5 Nm by the torque transducer. The maximum torque produced by the motor 8.81 Nm to operate the load 14.72 K with angular speed of 8.07 rad/s. The variation of the torque is 1.81%. The maximum torque variation is recorded 8.14% for the motor torque 6.76 Nm and the corresponding measured torque 6.21 Nm. However, all of the torque variation are considered as the transmission losses or magnetic field losses due to the air gap between the secondary coil and the PM and EM.

Table 1 shows that the detailed experiment results of the torque transducer for the corresponding the applied loads. The torque was calculated by considering the measured torque by the torque transducer and motor torques in respect of the applied load. The torque variation of 8.14% was considered as the transmission losses, which is significantly higher values in any mechanical system. Table 1 also shows that the slight difference between the measured torque from the coil and torque measured directly from motor shaft. The overall percentage error is shown less than 5%. The highest percentage error was at load 4.0 N, which is 4.5% and the lowest percentage error is at load 6.0 N, which was 1.25%. Table 2 shows the performance of the torque transducer for various applied torque on the shaft, which was considered as the axle of the vehicle.

Table 1: Comparison of torque between the motor torque and TT measured torque.

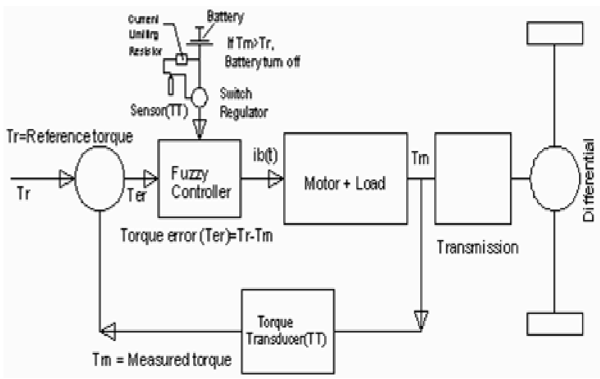
Shaft Subjected		Measured Torque		Torque Variation (%)
Applied load, N	Rotating Speed, rad/s	Transducer Torque (Nm)	Motor Torque (Nm)	
1.962	11.25	4.52	4.7	3.83
3.924	11.03	4.89	5.12	4.89
5.886	10.68	5.54	5.61	1.49
7.848	10.46	6.01	6.1	1.91
9.81	10.00	6.21	6.76	8.14
11.772	9.55	7.73	8.05	3.97
13.734	8.87	8.23	8.34	2.34
14.715	8.07	8.65	8.81	1.81

Table 2: Torque transducer's performance

Shaft Subjected		Transducer's Potential Measured Parameters			
T_a (N)	ω (rad/s)	e_{ind} (V)	I_b (A)	T(t) (Nm)	E_m (J/s)
1.962	11.25	2.23	4.3	4.52	46.87
3.924	11.03	2.25	4.42	4.89	49.68
5.886	10.68	2.29	4.65	5.54	55.01
7.848	10.46	2.35	4.71	6.01	58.21
9.81	10	2.41	4.89	6.21	63.5
11.772	9.55	2.48	5.12	7.73	68.27
13.734	8.87	2.56	5.22	8.23	72.19
14.715	8.07	2.61	5.31	8.65	72.56

Notifications: T_a = Applied torque, Nm; ω = Angular speed, rad/s, I_b = Battery current, A; T(t) = Transducer torque, Nm; E_m = Magnetic energy store, J; $e_{ind.}$ = Induce voltage, V; TT=Torque transducer.

V. TRANSDUCER CONTROL STRATEGY



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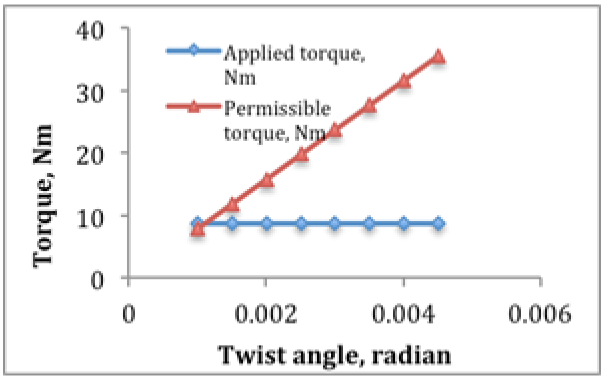
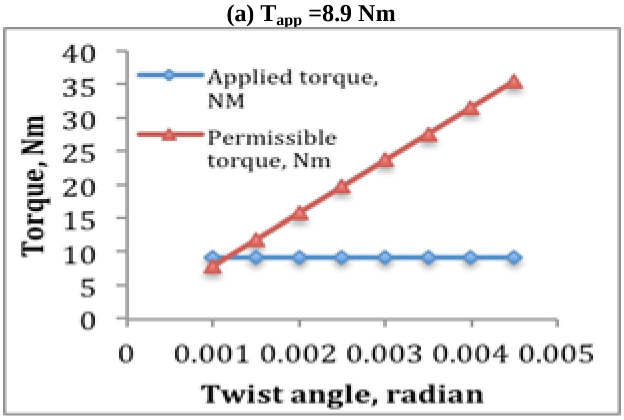
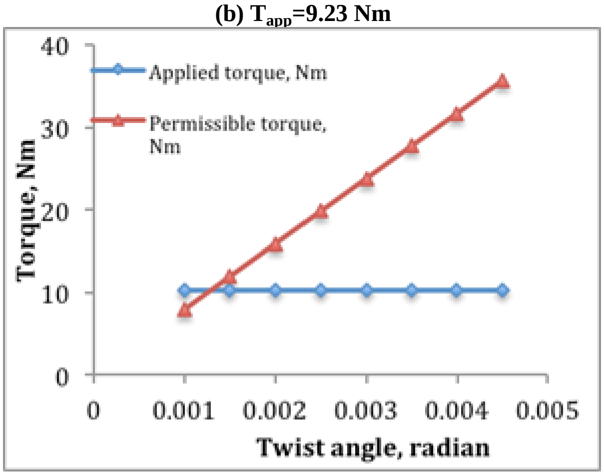


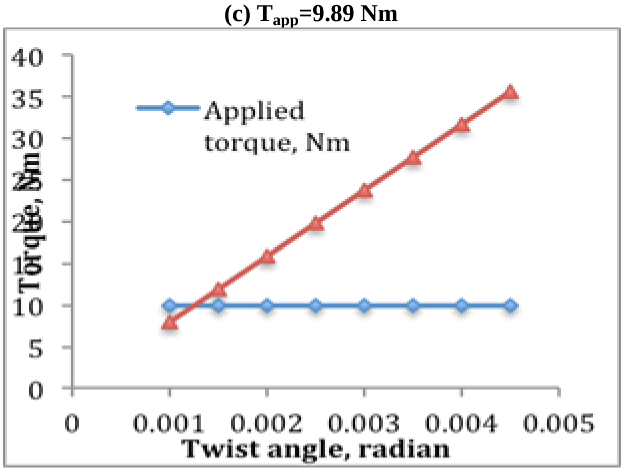
(a) T_{app} =8.9 Nm



(b) T_{app}=9.23 Nm



(c) T_{app}=9.89 Nm



(d) T_{app}=10.65 Nm

Fig. 9: Relationship between permissible torque and applied torque to the shaft.

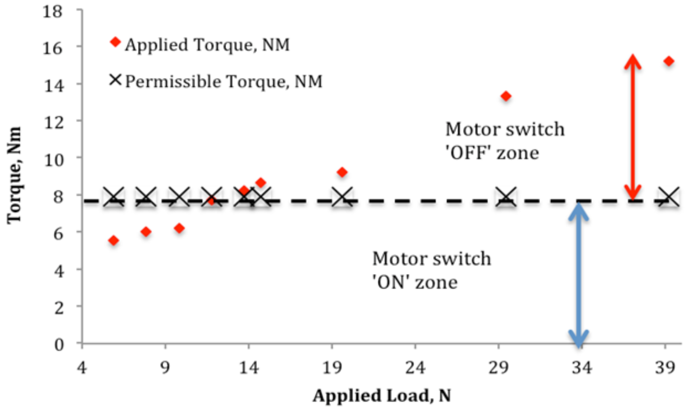


Fig. 10: Transducer operating characteristics

The closed loop fuzzy controlling system has been developed for controlling the operation of the transducer with the feedback sensor (Figure 8). Reference torque of the rotating power transmission shaft has been selected based on the maximum power requirement of the system to operate. In the transducer model, the maximum torque of the shaft is estimated by using the equation: $T = \frac{GJ}{L} * f_t$ with polar moment of inertia, $J = \frac{1}{2}\pi R^4$ and twist angle, $f_t = 0.001\text{-}0.75^0$ and modulus of rigidity, $G = 7.9\text{x}10^{10}\ N/m^2$. By using G equals to 7.9x10^{10} N/m^2, ϕ equals to 0.0015 radian, R equals to 0.01 m, the computed values of the shaft maximum permissible torque 7.9 Nm. The battery field current (I_{bf}) controlled DC motor has been used to torque delivered to operate the load. This relationship may be written as T_m = T_L (s) + T_d (s), where, T_L(s) is the load torque, and T_d(s) is the disturbance torque, which is often negligible. The transfer function (G(s)) of the motor-load combination with T_d(s) = 0,

$$G(s) = \frac{T_L(s)}{V_f(s)} = \frac{k_m I_{bf}(s)}{s(\tau_f s+1)(\tau_L s+1)} \quad (8)$$

where, $\tau_f = L_f / R_f$ and $\tau_L = J/b$, and $\tau_L > \tau_f$; V_f is the field voltage of the motor, k_m is the motor constant. The system has controlled the torque applied of the shaft based on the reference toque and output torque of the transmission.

Figure 9 shows the relationship between the applied torque and paermissible torque for the different loading conditions. While the operating characteristics of the transducer has been made by the switching operation. It is concluded that the applied torque on the motor depends on the output signal of the sensor. If the applied torque of the motor to the shaft is more than the permissible torque of the shaft, the motor power flow controlling switch will be trigger-off automatically and vise-versa (Figure 10).

VI. CONCLUSION

The electromagnetic contactless torque transducer has been developed using electromagnetic mechanism. It's tested result shows that it effectiveness on measuring the torque of the rotating shaft is acceptable, which can be justified based on the measurement error. The measurement

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percentage error between calculated torque directly from the motor and measured torque from the coil is less than 5%. It shows that the prototype torque measurement has closed agreement with the theoretical analysis. However, the concept of the prototype development can be validated by developing a full-scale model and testing with a real transmission system such as crankshaft.

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