

MEASUREMENT OF LOSSES IN DIRECT TORQUE CONTROLLED PERMANENT MAGNET SYNCHRONOUS MOTOR BY ANALYSIS AND EXPERIMENTAL SETUP

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Abstract

Direct Torque Control (DTC) appears as an effective and practical control scheme for AC motor drives. The DTC of Permanent Magnet Synchronous Motors (PMSM) Drives attracted great attention, due to many features like high efficiency, quick dynamic performance and provide excellent steady state response. The adjustable speed drives are rapidly introduced in the area of electric vehicle and motion control devices and these devices are often powered by a battery source. Due to the restriction in energy supply, the improvement of motor efficiency is the most important priority, and hence the DTC technique is used to measure the losses in PMSM. In order to measure the losses, the offline and online calculation methods are proposed. In this work, the mechanical losses is depends on rotor speed and friction torque, and it is often uncontrollable but the electrical losses are controllable and hence the electrical losses can be measured certainly. The Offline control method is used for optimizing the steady-state efficiency of PMSM under DTC. In this proposed work, the losses are calculated by offline method for simulation and experimental setup in order to obtain the better steady state efficiency, and also comparatively investigated with analysis and experimental results.

Keywords: Permanent Magnet Synchronous Motors, Direct Torque Control and Electrical Losses

1. INTRODUCTION

The technology has been developed in many industrial driving systems. The development of the switching speeds of the equipment has enabled the control techniques which have high switching frequency and feasibility of high efficiency driving systems.

However, the induction motor's efficiency changes with slip value from its desire reactive current, and it not able to produce high torque / weight ratio which needed for high performance applications such as robotics. The Switched reluctance motor (SRM) [5], has high reliability due to its simple and robust rotor structure. However, the core loss in the solid rotor is very large at super high-speed. Lamination of the rotor can reduce the core loss in the rotor. However, it is not recommended at super high-speeds since it will reduce critical speeds. Therefore, the different solutions are being studied and dissimilar motor designs have been developed. One of these recently urbanized motors is the permanent magnet synchronous motor. In this, the applications where high concert is demanded, some properties of the permanent magnet synchronous motor such as high power, high torque, high efficiency and low noise have made it more popular compared to other alternating current motors.

Especially, because of the high power density the permanent magnet synchronous motor is related for areas such as automation, robotics, and aeronautics technologies. Since the excitation flux is abounding by the magnets and due to the magnet characteristics and position the permanent magnet synchronous motors have both synchronous machine and a direct current machine characteristics

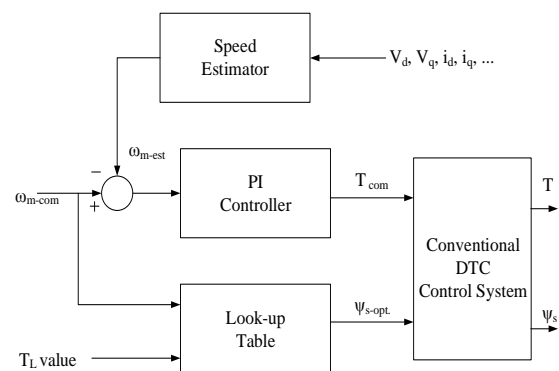


Fig -1: Proposed DTC

The Fig -1 shows the proposed DTC [6] [18] block diagram, for getting the optimized efficiency for a PMS motor drive. The machine terminal voltage and current can be estimated

from the drive and it given to the input of a speed estimator for estimating the speed of a machine. By comparing, the estimated speed and reference speed which has been given to the controller of PI. The output of PI is given to the DTC block for controlling the drive.

The PMSM offers the advantage of high efficiency compared to other types of motors since there is no excitation power loss in the rotor, and low eddy current loss in the stator and rotor [17]. Therefore, there is an increasing interest to consider PMSM for super high-speed applications. For unloaded conditions, the velocity is directly proportional to voltage and it is inversely proportional to the flux and, for loaded conditions it is proportional to the flux and current. The Synchronous motors have three phase windings in their stators, just like the induction motors [3]. Though, the rotor structure is different.

The permanent magnet synchronous motor (PMSM) [14], becoming more and more attractive due to its high efficiency and high torque to current ratio For a PMSM drive system mechanical sensors are often required for correct commutation of the inverters [2]. The use of mechanical sensors however reduces the reliability and increases the cost of the system. To overcome this disadvantage sensor less control scheme is much desirable. Recently the Direct Torque Control (DTC) [9] [10], scheme is increasingly used in PMSM drive systems because of its fast torque response and possibility of eliminating the mechanical sensors if the initial rotor position is known.

2. MACHINE MODEL

The minimization of electrical loss [5] [7], in PMS motor drive necessitates consideration of copper and iron losses in the machine model. An equivalent circuit model of a PMS machine in synchronously rotating reference frame is used through following equations. The d- and the q-axis stator flux linkage components are:

$$\psi_q = L_q i_{oq} \quad (1)$$

$$\psi_d = \psi_m + L_d i_{od} \quad (2)$$

The electro-magnetic torque in terms of the torque producing currents, i_{od} and i_{oq} is given as:

$$T_e = P i_{oq} [\psi_m + (L_d - L_q) i_{od}] \quad (3)$$

The motor drive system dynamics is also signified by:

$$T_e = T_L + B(\omega_m) + J \frac{d\omega_m}{dt} \quad (4)$$

In the steady state we have,

$$\omega_m = (\omega_m)_{com}. \quad (5)$$

$$T_e = T_{ss} = T_L + B(\omega_m)_{com}. \quad (6)$$

Mechanical loss depends on rotor speed and friction torque and often is un-controllable,

$$W_M = T_{mech} \omega_m \quad (7)$$

Electrical loss consists of iron loss and copper loss, therefore, the following equations are,

$$W_E = W_{cu} + W_{fe} \quad (8)$$

$$W_E = R_S(i_d^2 + i_d'^2) + R_c(i_{cd}^2 + i_{cd}'^2) \quad (9)$$

$$W_{LOSS} = W_M + W_E \quad (10)$$

The machine efficiency is a function of output power and loss terms, as:

$$\eta = \frac{P_{out}}{P_{out} + W_{LOSS}} \quad (11)$$

3. PROBLEM FORMULATION

The electrical loss relation has been simplified and appropriate formulation of the loss minimization problem, has been introduced. Fig -2 shows the equivalent circuit for PMSM, we have

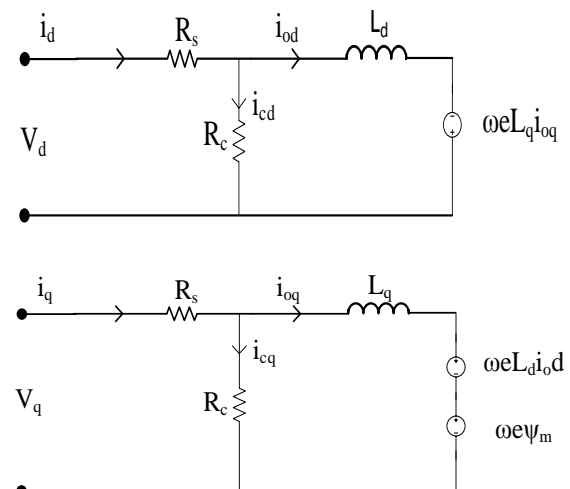


Fig -2: Equivalent circuit for PMSM

$$i_{cd} = \frac{V_d - R_s i_{od}}{R_s + R_c} \quad \text{and} \quad i_d = \frac{V_d + R_c i_{od}}{R_s + R_c} \quad (12)$$

$$i_{cq} = \frac{V_q - R_s i_{oq}}{R_s + R_c} \quad \text{and} \quad i_q = \frac{V_q + R_s i_{oq}}{R_s + R_c} \quad (13)$$

$$W_E = \frac{V_s^2}{R_s + R_c} + \frac{R_s R_c}{R_s + R_c} [i_{od}^2 + i_{oq}^2] \quad (14)$$

$$i_{oq} = \frac{\psi_q}{L_q} \quad i_{od} = \frac{\psi_d - \psi_m}{L_d} \quad (15)$$

Substituting the i_{oq} and i_{od} into equation,

$$W_E = \frac{V_s^2}{R_s + R_c} + \frac{R_s R_c}{R_s + R_c} \left[\left[\frac{\psi_d - \psi_m}{L_d} \right]^2 + \left[\frac{\psi_q}{L_q} \right]^2 \right] \quad (16)$$

Where,

$$V_s^2 = V_d^2 + V_q^2 \quad (17)$$

V_s , is the magnitude of the stator voltage. In DTC method the magnitude of the stator voltage is always constant. The first term in the above equation is always constant. This term represents the “unavoidable electrical loss in direct torque control of PMSM”. Therefore, second term is decreased. The variable part as “Performance Index” has been considered.

Therefore, the optimization problem becomes Minimize

$$J = \left[\left[\frac{\psi_d - \psi_m}{L_d} \right]^2 + \left[\frac{\psi_q}{L_q} \right]^2 \right] \quad (18)$$

This optimization problem is subject to steady state torque generation constraint.

$$T_{ss} = \frac{3}{2} p \psi_q \left[\left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d \right] \quad (19)$$

For different values of T_{ss} obtained from (6), this equation characterizes different hyperbolic trajectories in (ψ_d, ψ_q) plane.

$$\frac{2T_{ss}}{3p\psi_q} = \left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d \quad (20)$$

$$\psi_q = \frac{2T_{ss}}{3p \left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d} \quad (21)$$

Substitute the ψ_q into equation number (18)

$$J = \left[\left[\frac{\psi_d - \psi_m}{L_d} \right]^2 + \left[\frac{\frac{2T_{ss}}{3p \left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d}}{L_q} \right]^2 \right] \quad (22)$$

$$\frac{\partial J}{\partial \psi_d} = 2 \left[\frac{\psi_d - \psi_m}{L_d} \right] - 2 \frac{4T_{ss}^2}{9p^2 L_q^2} \left[\left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d \right]^3 \left[\left[\frac{1}{L_q} - \frac{1}{L_d} \right] \right] \quad (23)$$

4. OPTIMUM STATOR FLUX LINKAGE DETERMINATION

Obtaining the ψ_q component from (19) and substitution in (18), yields the performance index as a function ψ_d of only. Now, it is possible to differentiate J with respect to ψ_d to find the optimum ψ_d

$$\frac{\partial J}{\partial \psi_d} = 0 \quad (24)$$

$$\left[\frac{\psi_d - \psi_m}{L_d} \right] = \frac{4T_{ss}^2}{9p^2 L_q^2} \left[\left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d \right]^3 \left[\left[\frac{1}{L_q} - \frac{1}{L_d} \right] \right] \quad (25)$$

$$\left[\frac{\psi_d - \psi_m}{L_d} \right] = \left[\frac{4T_{ss}^2}{9p^2 L_q^2} \right] * \frac{\left[\frac{1}{L_q} - \frac{1}{L_d} \right]}{\left[\left[\frac{1}{L_d} \right] \psi_m + \left[\frac{1}{L_q} - \frac{1}{L_d} \right] \psi_d \right]^3} \quad (26)$$

The following equation is obtained, for the optimum ψ_d

$$a\psi_d^4 + b\psi_d^3 + c\psi_d^2 + d\psi_d + e = 0 \quad (27)$$

Where

$$a = (L_d - L_q)^3$$

$$b = \psi_m (4L_q^3 - L_d^3 - 9L_dL_q^2 + 6L_d^2L_q)$$

$$c = \psi_m^2 (9L_dL_q^2 - 6L_q^3 - 3L_d^2L_q)$$

$$d = \psi_m^3 (4L_q^3 - 3L_dL_q^2)$$

$$e = \frac{4T_{ss}L_d^4}{9P^2} (L_d - L_q) \psi_m^4 L_q^3$$

It is possible to derive the closed-form solution of (27) for salient-pole PMS machine where $L_d = L_q$. In this case, the solution is as follows:

Steady state torque

$$(\psi_q)_{opt.} = \frac{2T_{ss}L_d}{3P\psi_m} \quad (28)$$

From this, optimum stator flux linkage can be calculated, for the optimized efficiency;

$$(\psi_s)_{opt.} = \sqrt{(\psi_d)_{opt.}^2 + (\psi_q)_{opt.}^2}, (\psi_d)_{opt.} = \psi_m \quad (29)$$

5. ONLINE CALCULATION

In this online calculation, to find the optimum stator flux linkage for obtaining the better efficiency. An important point in DTC is that the magnitude of the stator flux linkage is controlled and there is no control on the components of the stator current or stator flux in d or q axis [18]. That the optimization problem can be solved more easily in terms of ψ_d and ψ_q rather than ψ_s and δ (angle of flux vector in the $\psi_d - \psi_q$ plane). Loss minimization of PMS machines has been dealt with in the vector control framework. As shown before, some parts of electrical loss of DTC strategy are unavoidable and loss minimization procedure deals with another part. Therefore, the optimization here is substantially different from that performed in vector control.

The reference speed and the load torque can be given to the input to the lookup table for calculating the optimized stator flux linkage. The obtained stator flux linkage and output of PI controller can be given to the conventional DTC control system. Normally, for obtaining the optimized solution, they

handle the many algorithms for getting the better efficiency. In this proposed scheme, the conventional DTC has been used to the control system for efficiency optimization of PMS machine. For desired set point and existing load torque, find an optimum stator flux linkage from look-up table. Use the optimized stator flux linkage as an optimal stator flux command in DTC procedure. In this online calculation, the desired efficiency has been obtained from the offline calculation. From, the offline calculation the optimized stator flux linkage had obtained from the PMS machine model.

6. SIMULATION RESULTS

The Simulation Results for ψ_d and ψ_q is shown in Fig -3 and Fig -4.

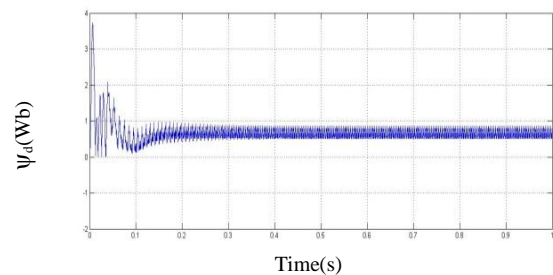


Fig -3: D-Axis Stator Flux Linkage Component

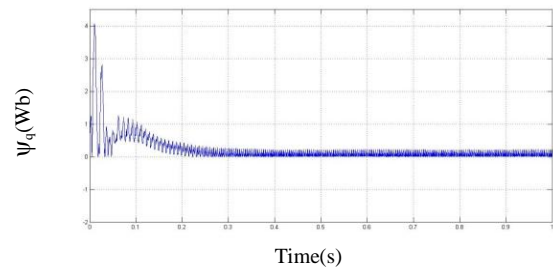


Fig -4: Q-Axis Stator Flux Linkage Component

The stator flux components and electrical losses are depicted in Fig -3 through Fig -4 in addition, flux components and electrical loss are depicted for a typical non optimum ψ_s value ($\psi_s = 1.25$ Wb). Note that although the flux control system only controls the magnitude of stator flux, the ψ_d and ψ_q converges to their optimal values. ψ_d values settles at 1.25 Wb from peak value of 2.75 Wb and ψ_q values settles at 1.25 Wb from 3.25 Wb by online control method.

Fig -5 shows the simulation results for the electrical losses, a desirable torque response shows that the proposed efficiency optimization system does not deteriorate the effectiveness of torque control. The stator flux components and electrical loss are depicted in Fig -10. The electrical loss value is 147.51 (W).

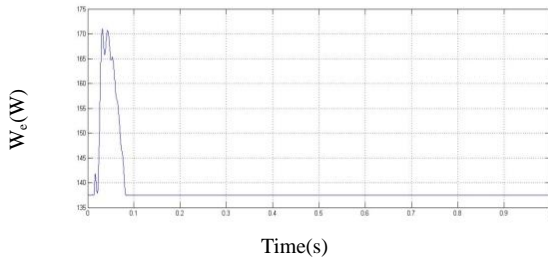


Fig -5: Electrical Loss

The simulation results for PMSM efficiency is shown in the Fig -6. Desirable torque response shows that the proposed efficiency optimization system does not deteriorate the effectiveness of torque control. In addition, flux components and electrical loss are depicted for a typical non-optimum value.

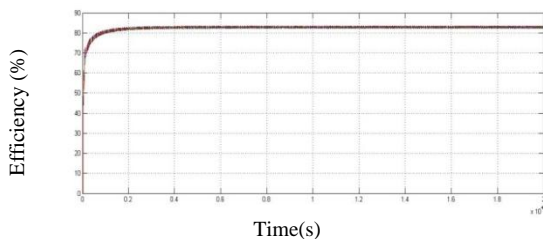


Fig -6: PMSM Efficiency

The efficiency value is 80(%). The load torque is equal to the rated torque of the PMS machine i.e. 3.0 Nm. The desired speed is as before. With these values $T_{ss} = 3.0$ (N.m.) and optimization procedure results $(\psi_d)_{opt.} = 1.25$ (Wb) and $(\psi_q)_{opt.} = 1.25$ (Wb) and consequently. In addition, to verify the robustness of closed loop system to load disturbances, the load torque increased to 3Nm in 0.1 sec at 1 sec period.

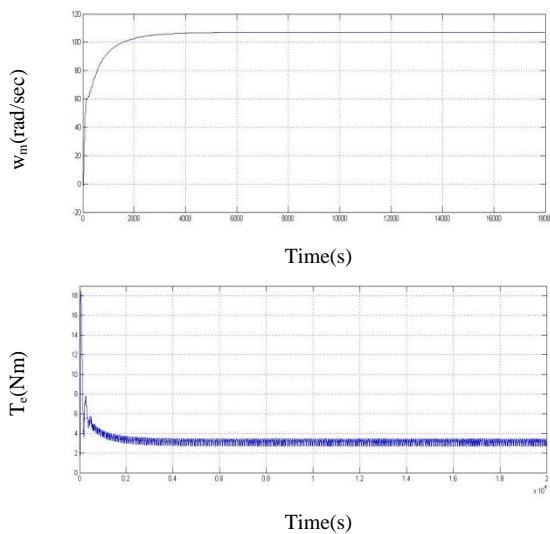


Fig -7: Electro-Magnetic Torque and Hysteresis Bands, Actual Motor Speed

Fig -8 shows Simulation Result for Electro-Magnetic Torque, Hysteresis Bands and Actual Speed. The motor speed control can perform disturbance compensation task and desired speed is obtained after a short transient time. The electro-magnetic torque value is 3 (Nm) and Actual motor speed value is 107 (rad / sec).

In this loss measurement of DTC PMSM used offline control method and online control method to enhance the efficiency of traditional control of the motor. The offline values can be calculated from the machine model. By using the values of offline, for simulate the online control method values of using optimized stator flux linkage ψ_s . This can be achieved from d-axis stator flux linkage ψ_d and q axis stator flux linkage ψ_q .

Table -1: Quantitative comparative study for optimized efficiency

Proposed PMSM	Electrical Losses(W)	Efficiency (%)
Speed = 1000 rpm Torque = No load	120.53	89.30
Speed = 1000 rpm Torque = 1 Nm	127.31	87.35
Speed = 1000 rpm Torque = 1.5 Nm	131.52	86.40
Speed = 1000 rpm Torque = 2 Nm	136.29	85.40
Speed = 1000 rpm Torque = 2.5 Nm	141.72	84.27
Speed = 1000 rpm Torque = 3 Nm	147.51	83.00

Although the flux control system only controls the magnitude of stator flux, the ψ_d and ψ_q converges to their optimal value found due to torque generation constraints. The electrical loss can be depicted through the optimized stator flux ψ_s . The electrical loss can be simulated using the optimized stator flux linkage ψ_s . The flux components and electrical losses can be inferred from the non optimal values. The resulted PMSM efficiency graph shows the motor speed control can perform the disturbance compensation task and desired speed is obtained after a short time. The efficiency denotes the motor speed and motor torque. By varying the load from 0 to 4Nm at a constant speed of 1000rpm has achieved a optimized efficiency. At a speed of 1000rpm and a motor torque of 1Nm has 87.35% of electrical loss is 127.31watts and no load of 89.30% of electrical loss is 120.53watts achieved a better efficiency.

7. EXPERIMENTAL RESULTS

Energy efficient pulse width modulation inverters are widely used to control electrical machine accurately for process needs. The pulse width modulation has adverse effect and produce additional losses in the motor. These losses increases

the motor temperature and degrading of the machine power in converter use. For the performance prediction of the variable speed drives a reliable and reasonably accurate loss model of a PMSM drive system is important. Measurement were taken under no load and load condition for PWM supplies.

7.1 No Load Condition

The motor has been tested under the no load condition as per the motor nameplate data, together with parameter derived from the test are presented in Table -2.

Table -2: No load condition operating at a speed of 50Hz

Operating condition	Without usage of DTC
Voltage(V)	154
Current(A)	0.3
Input power(W)	79.22
Synchronous speed(RPM)	1500
Speed (RPM)	1498
Output power(W)	80

7.2 Load Condition

The motor was tested under the range of load condition, for PWM supply conditions and also the various losses was calculated for rated speed as well as the better efficiency has been achieved for PWM inverter. Table -3 indicates the losses are calculated at 50Hz operating point.

Table -3: Indicates the load condition operating at a frequency of 50Hz

Operating condition	Without usage of DTC
Voltage (V)	151
Current (A)	1.25
Input power (W)	199.42
Synchronous speed (RPM)	1500
Speed (RPM)	1380
Output power (W)	148.85
Efficiency (%)	75
Copper loss (W)	36.57
Iron loss (W)	162.85
Friction and windage loss(W)	2.7
Core loss (W)	17
Total loss	50.57

7.3 Comparative Analysis of Various Losses with Efficiency

Comparative analysis of various losses like(copper loss, iron or core loss called electrical loss and friction and windage loss also called as mechanical loss) with efficiency operating at a frequency of 50Hz.

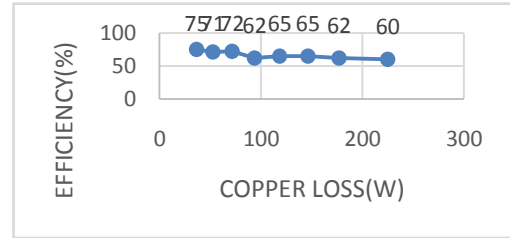


Fig -9: Efficiency Vs Copper Loss

Fig -9 shows that the, Copper losses increase as the value of electrical current passing through the conductors increases. An rise in the temperature of the wire or conductor causes the resistance of the wire to increase causing the copper losses to also increase. Copper losses result from Joule heating stating that the energy lost increases as the square of the current through the wire and is in proportion of the electrical resistance of the conductors.

$$\text{Copper Loss} = I^2R$$

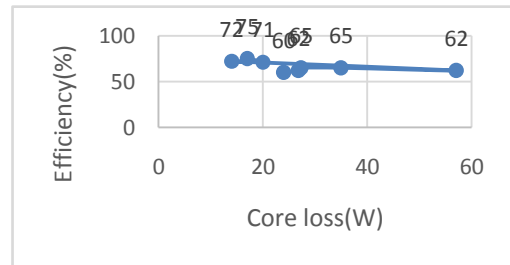


Fig -10: Efficiency Vs Core Loss

Fig -10 shows that the lamination of core area increases the resistance value has to be decreases at a time the iron loss to be more. Since the decreases of core area the efficiency is achieved high.

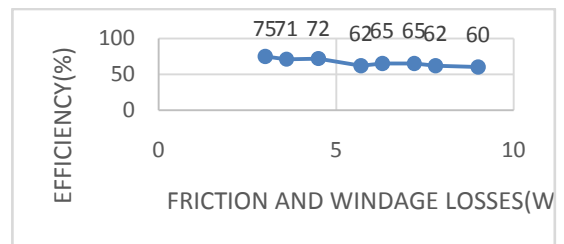


Fig -11: Efficiency Vs Friction and windage Loss

Fig -11 shows that the mechanical losses occur at the bearing and brush friction loss occurs in wound rotor induction motor. These losses happens with the variation in speed. The speed usually remains constant at three phase induction motor. Hence these losses nearly remains constant.

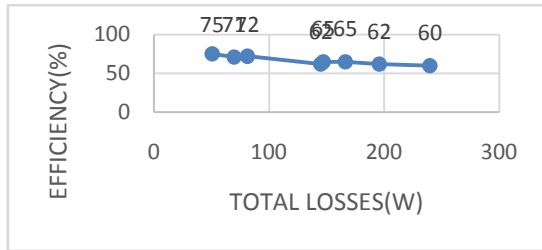


Fig -12: Efficiency Vs Total Loss

Fig -12 shows that the total loss can be calculated by the summation of all above losses.

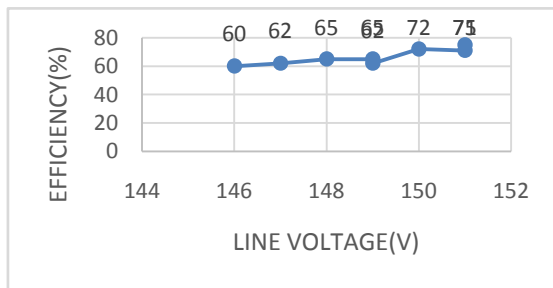


Fig -13: Efficiency Vs Line voltage

In line voltage increases at that time the efficiency gets increased because the efficiency and voltage are directly proportional to each other.

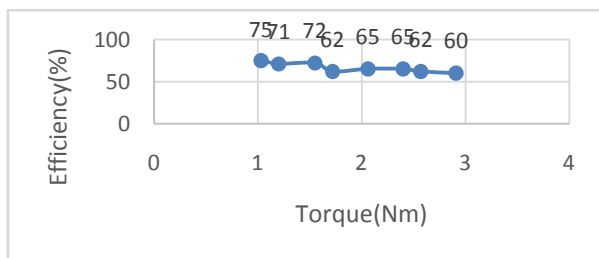


Fig -14: Efficiency Vs Torque

In this fig -14 the torque increases at that time efficiency gets decreased because the torque and efficiency is inversely proportional to each other.

8. COMPARATIVE STUDY

The quantitative comparative study for optimized efficiency of PMSM for both simulation and measured result was compared in Table -4.

Table -4: Shows the comparison of efficiency for Simulation and Experimental setup

Torque (Nm)	Efficiency of measured result (%)	Efficiency of simulation result (%)
2.9	60	83
2	65	85.40
1	75	87.35

9. CONCLUSIONS

In this method the optimization of steady state efficiency in direct torque control of permanent magnet synchronous machines is proposed. The optimum stator flux command is found out at any operating point by an off-line procedure such that the minimum electrical loss is obtained. The On-line computations are limited to find the optimum stator flux linkage command from a calculated offline control method. For PMSM machine, the closed form solution of optimum stator flux has been derived. Although, the flux control system only controls the magnitude of stator flux converge to their optimal values due to torque generation constraint. Lower steady state electrical losses are obtained by efficiency optimization approach. In the outcome, the effectiveness of the optimal flux determination procedure has been verified, and the resulted motor speed, the motor torque and efficiency are depicted and motor speed control can perform disturbance compensation task and desired speed is obtained after a short transient time.

The result which has been obtained from the online calculation was done by MATLAB environment and experimentally. The Simulation results also confirm the machine efficiency over a load changes at constant speed. In the measured value of electrical losses the optimized efficiency has been achieved at a load torque of 1Nm has 87.35% and no-load of 89.30% and as compared to simulation the experimental result efficiency has been decreased by 23% at rated torque.

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