# A Hydraulic Motor-Alternator System for Ocean-Submersible Vehicles

Harry O. Aintablian, Thomas I. Valdez, Jack A. Jones
Jet Propulsion Laboratory, California Institute of Technology.

**Abstract**

An ocean-submersible vehicle has been developed at JPL that moves back and forth between sea level and a depth of a few hundred meters. A liquid volumetric change at a pressure of 70 bars is created by means of thermal phase change. During vehicle ascent, the phase-change material (PCM) is melted by the circulation of warm water and thus pressure is increased. During vehicle descent, the PCM is cooled resulting in reduced pressure. This pressure change is used to generate electric power by means of a hydraulic pump that drives a permanent magnet (PM) alternator. The output energy of the alternator is stored in a rechargeable battery that powers an on-board computer, instrumentation and other peripherals.

The focus of this paper is the performance evaluation of a specific hydraulic motor-alternator system. Experimental and theoretical efficiency data of the hydraulic motor and the alternator are presented. The results are used to evaluate the optimization of the hydraulic motor-alternator system. The integrated submersible vehicle was successfully operated in the Pacific Ocean near Hawaii. A brief overview of the actual test results is presented.

## 1 Introduction

NASA JPL and Scripps Institute of Oceanography have developed and demonstrated an underwater vehicle that is capable of being powered by natural thermal energy of the ocean. The underwater vehicle (Figure 1) takes advantage of the temperature differences at different ocean depths. Key to its operation is a phase change material (PCM) that melts and expands as the vehicle ascends to warm water causing the pressurization of oil inside the vessel. The PCM solidifies and contracts as the vehicle dives into cold water thus lowering the pressure of oil. The pressurized oil periodically drives a hydraulic motor – alternator thus generating electric power.

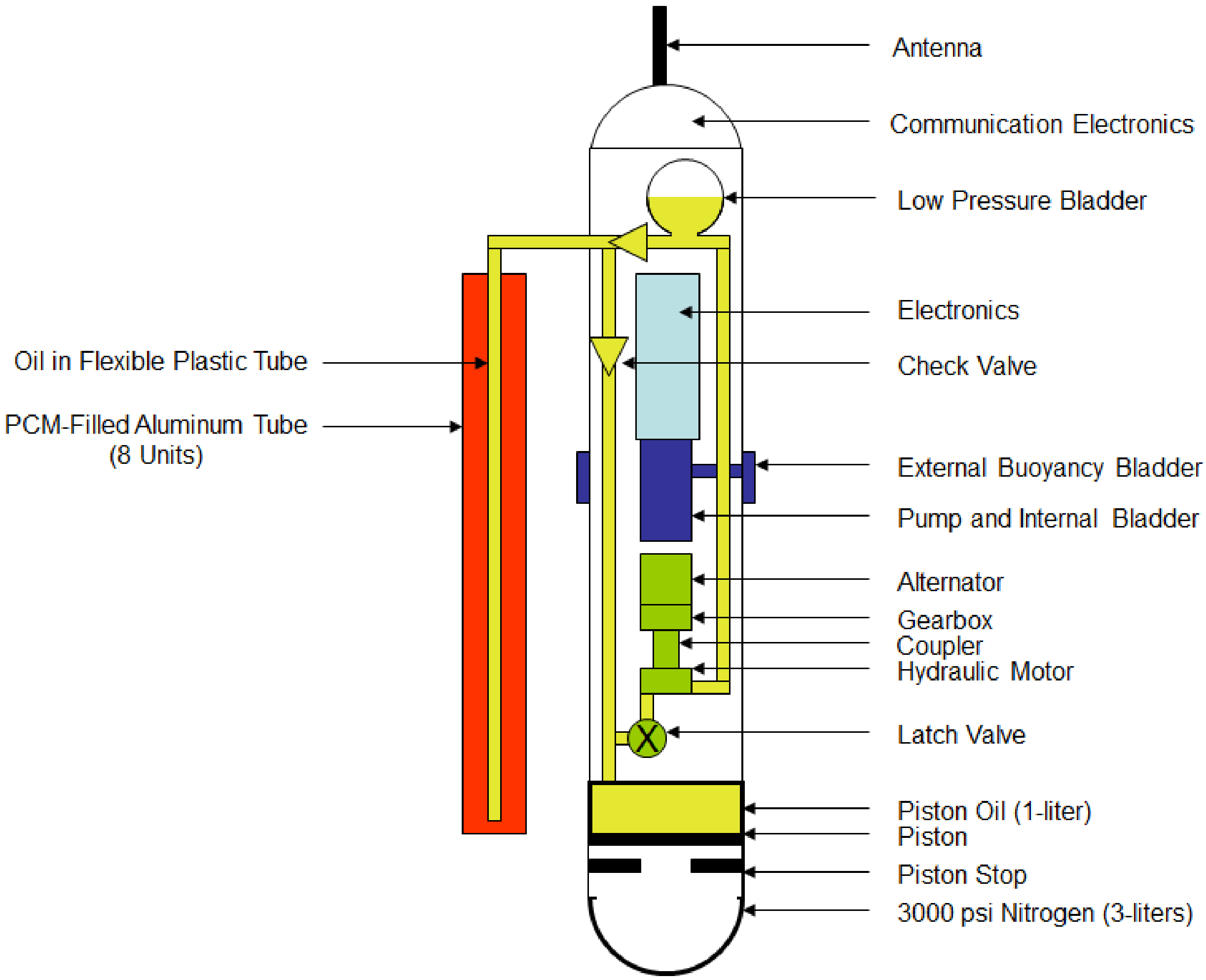


**Figure 1: Submersible Vehicle Functional Diagram**

## 2 Design Description

Figure 2 shows the functional diagram of the hydraulic motor- alternator system.

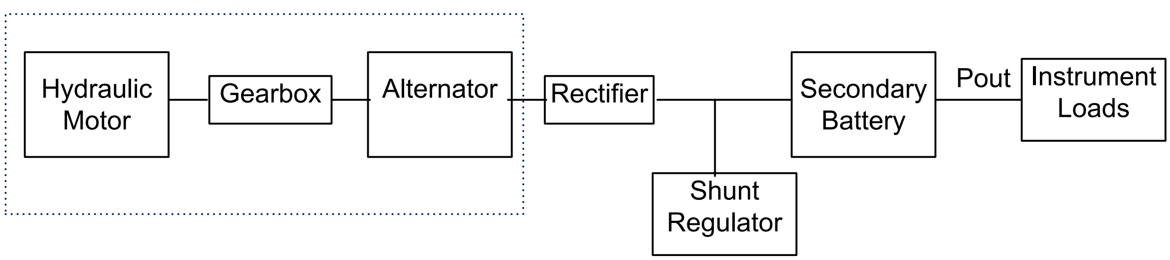


**Figure 2: Functional Diagram of end-to-end System**

The hydraulic motor provides the mechanical power to the permanent magnet 3-phase alternator. A gearbox matches the speeds at the hydraulic motor-alternator shafts. A 3-phase full wave rectifier converts the alternator output voltage into dc. Electrical energy is stored in a secondary battery which supplies power to instrument loads. A shunt regulator diverts any excess power to a shunt load thus preventing the battery from overcharge. The major components of the system are described in the following paragraphs.

Table 1 summarizes the characteristics of the hydraulic motor. Table 2 lists the major parameters of the alternator. Even though the hydraulic motor is rated at 6,000 rpm, the fluid power system could enable speeds of up to 1,200 rpm. To match the speed and torque of the hydraulic motor and the alternator, a gearbox with a 1 to 4 ratio is used.

**Table 1: Hydraulic Motor Specifications**

| | |
|---|---|
| Displacement | 1.4 $cm^3$/rev |
| Maximum Pressure | 200 bars |
| Maximum Speed | 6,000 rpm |
| Maximum torque | 2.5 N-m |

**Table 2: PM Alternator Specifications**

| | |
|---|---|
| Output Power | 400 W |
| Nominal Voltage | 48 V |
| No Load Speed | 5,370 rpm |
| No Load Current | 0.733 A |
| Nominal Speed | 4,960 rpm |
| Nominal Torque | 0.747 N-m |
| Maximum Efficiency | 86% |
| Maximum Current | 9.38 A |

A three-phase full-wave rectifier converts the alternator output voltage from ac to dc (Figure 2). The energy of the hydraulic-electric system is stored in a Li Ion battery for subsequent power delivery to the instrument loads. A shunt regulator provides battery charge control. When the battery voltage exceeds a given threshold, the current is shunted away from the battery.

## 3 Efficiency Estimation

A renewable energy system such as the one described in this paper is preferred to non-renewable systems such as the ones that employ primary batteries. However, in order to make a renewable system feasible, it has to be competitive in term of power, mass and cost. Efficiency, mass and cost are correlated. Emphasis is placed on improving the overall efficiency of the system, in particular the efficiency of the hydraulic motor – alternator.

### 3.1 Optimization of Hydraulic Motor

The efficiency of a hydraulic machine is the product of the volumetric and mechanical efficiencies (Appendix). Volumetric efficiency, $\eta_v$, relates to flow losses within the hydraulic motor.

$$\eta_v = \frac{Q_{actual..}}{Q_{theoretical.}} \qquad \text{(Eq. 1)}$$

Where, the flow Q is expressed in $m^3/s$. The mechanical efficiency, $\eta_{m,}$ relates the frictional losses within the hydraulic motor.

$$\eta_m = \frac{\tau_{actual..}}{\tau_{theoretical.}} \qquad \text{(Eq. 2)}$$

Where, the torque τ is expressed in N-m. For an ideal motor, the relationship between flow rate and speed is given by Eq. 3 (Appendix).

$$Q = V\ n \qquad \text{(Eq. 3)}$$

Where, V is the displacement and it is expressed in $m^3/rev$. For an ideal motor, torque is related to displacement and the pressure drop within the motor by Eq. 4.

$$\tau = V\ \Delta p \qquad \text{(Eq. 4)}$$

Gear motors are of the fixed displacement type. In a displacement motor, the shaft speed varies only with the flow rate. On the basis of equations 1 and 3, the volumetric efficiency of an ideal motor is expected to increase as the motor speed is increased. On the basis of equations 2 and 4, the mechanical efficiency of an ideal motor would increase with increasing inlet to outlet pressure drop.

However, in the presence of leakage, the overall efficiency of a ”real” hydraulic motor would decrease as its rotational speed is increased. The leakage is the result of excessive clearances within the motor mechanism resulting in reduced volumetric efficiency. Thus, it is imperative to characterize a given hydraulic machine to determine its optimum speed and pressure drop operation ranges.

### 3.2 Optimization of PM Alternator

Efficiency of a generator is defined as the ratio of electrical power generated to mechanical power consumed. It can be shown that the expression for efficiency of a PM dc machine is given by (Appendix)

$$\eta = \left(1 - \frac{I_{nl}}{I}\right)\left(1 - \frac{I}{I_s}\right) \qquad \text{(Eq. 5)}$$

Where $I_{nl}$ is the no load stator current and $I_s$ is the stall current. Figure 4 shows the relationship of efficiency to stator current. The losses of a dc machine are primarily due to friction and armature $I^2$ R losses. Frictional loss increases with increasing current since torque and current are directly proportional. There is an optimum operating point where the most useful work is received while a minimum amount of power is dissipated in the stator windings. It is noteworthy that maximum efficiency occurs at a current (or torque) that is equal to a fraction (typically ~1/7) of the stall current while maximum generated power is at 50% stall current (Appendix).

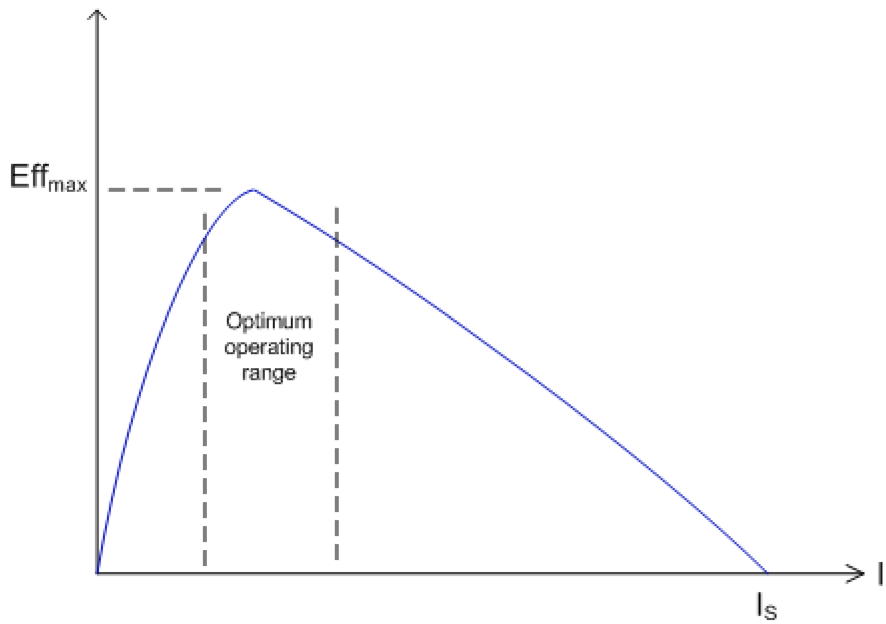


**Figure 3: DC Machine Efficiency versus Current**

### 3.3 Experimental Results

At first, the hydraulic motor and alternator were characterized individually. The hydraulic system performance is verified using oils of varying viscosities. Pressure, flow rate and speed were increased in order to establish optimum regions of operation. Similarly, the 3-phase alternator was characterized using a dc motor as its prime mover. Load, speed and torque were varied in order to determine the alternator optimum operating range.

The thermal energy system described in Figure 1 was constructed in order to assess its performance. Figure 4 shows the laboratory set up. Pressure change is achieved by pumping oil into a tank until a desired pressure is reached. The hydraulic motor is activated by opening a valve to allow flow. By measuring the volume of the displaced fluid and the elapsed time, the flow rate is calculated.

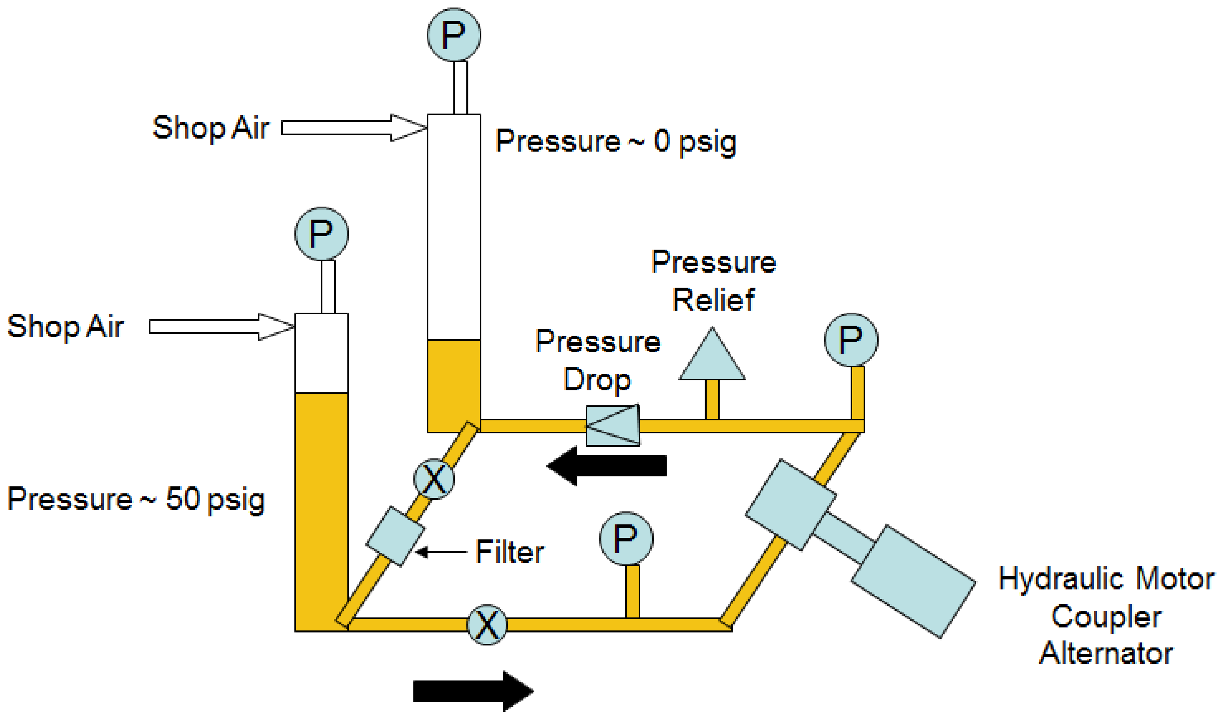


**Figure 4: Experimental Setup**

Table 3 summarizes the test data obtained under the conditions of maximum experimental efficiency of 58%. Using Eq A- 14 (Appendix) the efficiency of the alternator is estimated at 0.85. The gearbox efficiency is approximately 0.9 when operating near rated torque (Figure 5). The efficiency of the hydraulic motor under the conditions described in Table 3 is approximately 0.75.

**Table 3: Experimental Data for Hydraulic Motor – Alternator System**

| **Hydraulic Motor** | |
|---|---|
| $\Delta p$ | 2,195 psi (or 1.5 x $10^7$ pa) |
| Q | 1.2 GPM (or 7.5 x $10^{-5}$ $m^3/s$) |
| Speed | 1,554 rpm |
| $P_{in} = Q\ \Delta p$ | 1,136 W |
| **PM Alternator** | |
| Speed | 6,216 rpm |
| $V_{LN}$ | 21.5 V |
| $I_{line}$ | 10.2 A |
| $P_{out} = 3\ V_{LN}\ I_{line}$ | 655 W |
| **System** | |
| Efficiency | 58% |

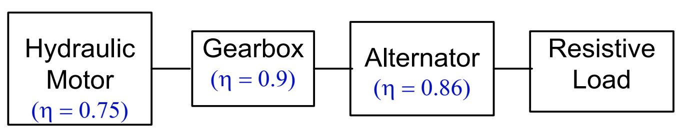


**Figure 5: System Efficiency Breakdown**

## 4 Optimization of Hydraulic Motor Alternator System

An off-the-shelf hydraulic motor and an off-the-shelf PM synchronous generator were integrated to convert hydraulic energy into electrical energy. A gear box with a ratio of 1 to 4 was used to match the torques of the hydraulic motor and the alternator. Frictional losses of the gear box resulted in the reduction of the overall efficiency of the system.

The proper optimization of the hydraulic motor alternator system would require a custom designed system. The system would eliminate the need for a gear box by matching the torques of the hydraulic motor alternator unit. The rated torque of the hydraulic motor would match the torque of the PM generator in its optimum operating range.

## 5 Prototype Testing in Ocean

The autonomous underwater vehicle described in Section 1 of this paper was deployed in the Pacific Ocean near Hawaii in 2009. The 84 kg vehicle successfully completed at least 300 dives from the ocean surface to a depth of 500 meters producing 1.7 W-hr of energy per dive (Figure 6). This effort was the first successful demonstration of a submersible thermo-electric generation rechargeable system. Such a system is capable of operating in the ocean for many years while conducting science measurements.

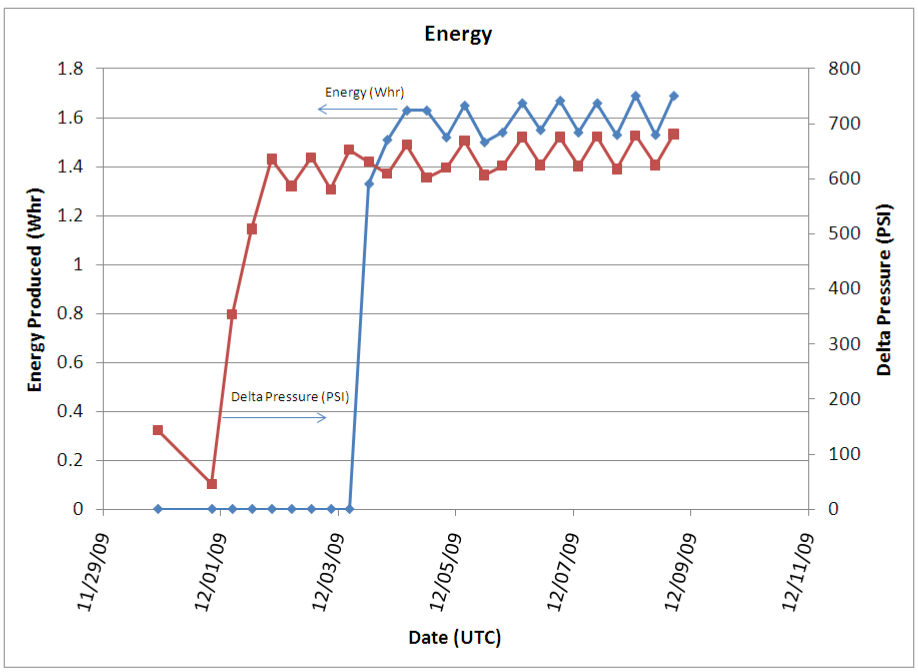


**Figure 6: Energy and Pressure Test Results of Prototype Vehicle**

## 6 Conclusions

A hydraulic – electric power generation system for use in ocean applications is described. Analytical results are presented for optimizing the performances of a hydraulic motor coupled to a PM synchronous generator. 58% efficiency was achieved for the combined hydraulic – electric system in a laboratory setting. The operation of an integrated submersible vehicle was successfully demonstrated in the Pacific Ocean.

It is recommended to custom design and build a hydraulic – electric generator set to further optimize system performance.  Such a system would have a direct drive architecture with the system torque matched for optimum performance.

## 7 Acknowledgments

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## 8 References

[1]

# 9 Appendix A: Derivation of Equations

## 9.1 Hydraulic Motor

In a hydraulic motor, pressure (p) and flow (Q) are converted to torque (T) and speed (n).

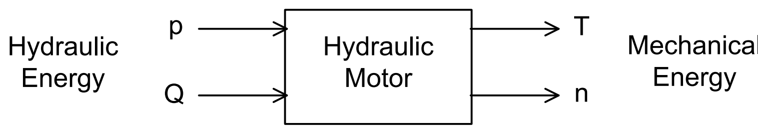


**Figure 7: Hydraulic Motor Functional Diagram**

Hydraulic power is proportional to the product of pressure drop and flow.

$$P = \Delta p\, Q \qquad \text{(Eq. A-1)}$$

Where p is in $N/m^2$, Q is in $m^3/s$ and P is in Nm/s or W. Mechanical power is proportional to the product of torque and speed. Thus, the efficiency of the hydraulic motor is

$$\eta_o = \frac{T\, n}{\Delta p\, Q} \qquad \text{(Eq. A-2)}$$

The displacement V of a hydraulic motor is defined as the volume of fluid required to produce one revolution. Thus, flow rate Q is equal to

$$Q = \frac{V\, n}{\eta_v} \qquad \text{(Eq. A-3)}$$

Where V is in $m^3/rev$ and n is in rps. $\eta_v$ is the volumetric efficiency of the hydraulic motor, which comprises leakage and compressibility losses.

The torque developed by a hydraulic motor can be calculated using the following equation

$$T = V\, \Delta p\, \eta_m \qquad \text{(Eq. A-4)}$$

Where V is displacement, $\Delta p$ is the pressure drop and $\eta_m$ is the mechanical efficiency of the motor, which comprises flow and frictional losses. By combining equations A-1, A-2, A-3 and A-4, it can be shown that the overall efficiency of the hydraulic motor is equal to the product of mechanical and volumetric efficiencies.

$$\eta_o = \eta_m\, \eta_v \qquad \text{(Eq. A-5)}$$

## 9.2 Permanent Magnet DC Machine

Figure 8 shows the equivalent circuit of a PM dc motor.

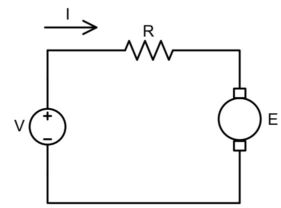


**Figure 8: Equivalent Circuit of DC Motor**

R represents the armature resistance and E represents the back emf. Kirchhoff's voltage law yields

$$V = E + I\,R \qquad \text{(Eq. A-6)}$$

The back emf of a dc machine is proportional to its speed.

$$E = K_e\ \omega \qquad \text{(Eq. A-7)}$$

Similarly, torque is proportional to armature current.

$$T = K_t\ I \qquad \text{(Eq. A-8)}$$

Combining equations A-6, A-7 and A-8 yields the expression for the angular velocity.

$$\omega = \frac{V}{K_e} - \frac{R}{K_e\ K_t}\,T \qquad \text{(Eq. A-9)}$$

Equation A-9 indicates that, for a given voltage, there is a linear relationship between speed and torque. Figure 9 is a graphical representation of the torque speed characteristics of PM dc machine.

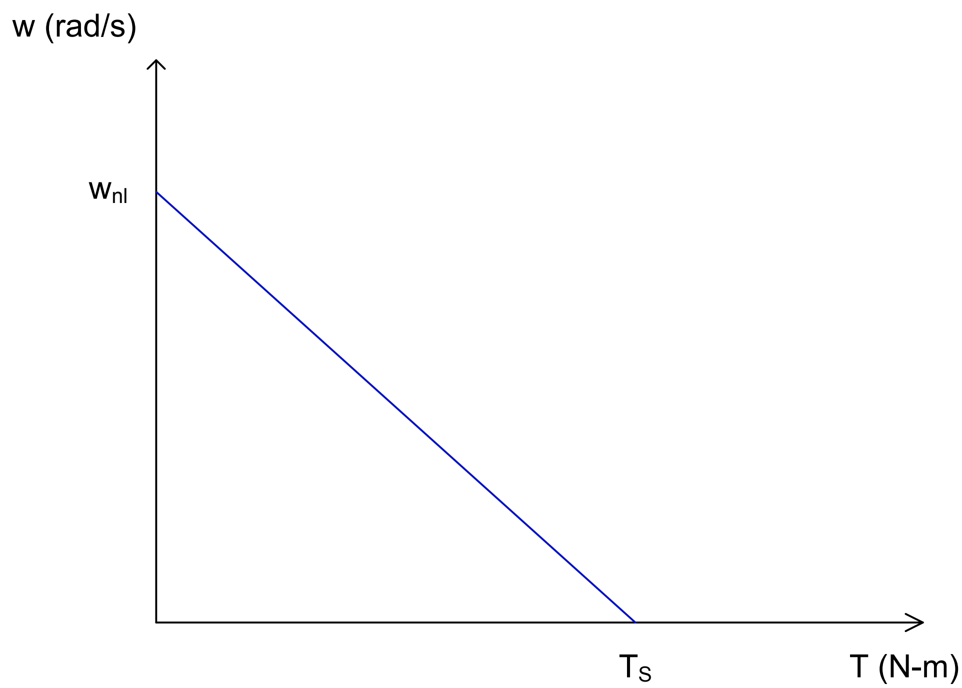


**Figure 9: DC Motor Torque-Speed Curve**

Given the parameters defined in Figure 9, the angular velocity can be expressed as a function of torque (Eq. A-10).

$$\omega = \frac{\omega_{nl}}{T_s}\left(T_s - T\right) \qquad \text{(Eq. A-10)}$$

Where $w_{nl}$ is the no load angular velocity and $T_S$ is the stall torque. The mechanical power of a dc machine, which is equal to the product of torque and angular velocity, is expressed by Eq. A-11.

$$P = \omega_{nl}\, T - \frac{\omega_{nl}}{T_s} T^2 \qquad \text{(Eq. A-11)}$$

Maximum power occurs at $T = T_s / 2$ (Figure 10).

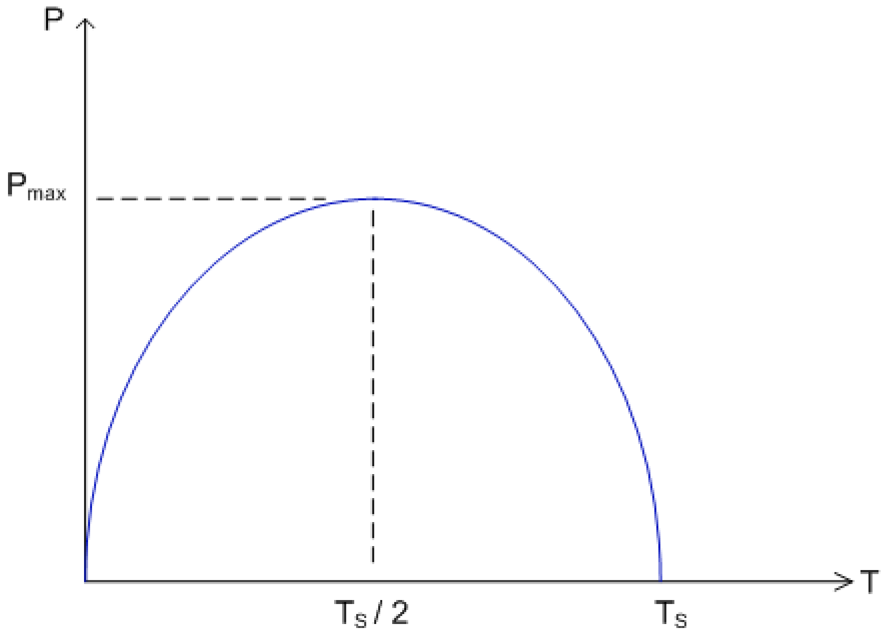

**Figure 10: Dc Machine Power Vs. Torque Curve**

The efficiency of a dc motor is given by Eq. A-12.

$$\eta = \frac{P_{mech..}}{P_{elect.}} \qquad \text{(Eq. A-12)}$$

Eq. A-12 can be expanded to

$$\eta = \frac{T_{load\,.}\,\omega}{V\,I} = \frac{\left(T_{mech.} - T_f\right)\omega}{V\,I} \qquad \text{(Eq. A-13)}$$

Where $T_f$ is the frictional torque and eddy current losses are ignored.

Combining Equations A-7, A-8 and A-13, substituting $V = I_s R$ and performing further simplifications, an expression for efficiency as a function of stator current is obtained.

$$\eta = \left(1 - \frac{I_{nl}}{I}\right)\left(1 - \frac{I}{I_s}\right) \qquad \text{(Eq. A-14)}$$

Figure 11 is a graphical representation of efficiency versus stator current of a PM synchronous machine. At low values of current or torque, the developed mechanical power is low with most of the electrical power used to overcome friction. At high values of current or torque the stator $I^2 R$ losses are high and hence efficiency is low.

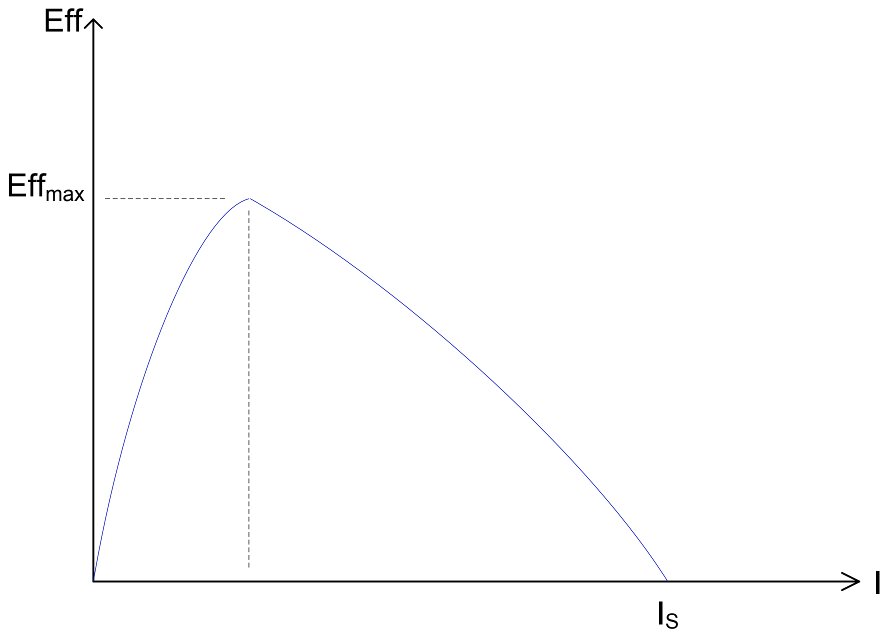


**Figure 11: PM DC Machine Efficiency Vs. Current Curve**

It can be shown that the expression for maximum efficiency is

$$\eta_{\max} = \left(1 - \sqrt{\frac{I_{nl}}{I_S}}\right)^2 \qquad \text{(Eq. A-15)}$$