Loss Minimization of Asynchronous Machine with Field Oriented Control

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Abstract—**In this paper, the asynchronous machine with flux oriented control (FOC) is studied in order to minimize the electromagnetic losses of the machine using two families of loss minimization methods, the optimization of the control has been performed, firstly under variated rotor flux level, where experimental results are obtained, secondly by the optimization of the relation between the two components of the stator current.**

Keywords- **Asynchronous machine, orientated flux, loss minimization, flux variation.**

I. INTRODUCTION

The asynchronous squirrel-cage machine associated to its static inverter with numerical control unit offers an increasingly advantageous solution in financial terms, dynamic performances and longevity. This explains the increasing use of this machine in industry, electric traction, ventilation, pumping... etc. [1] [2].

The importance of the improvement of the efficiency in the asynchronous machine drives can be announced from the point of view of energy consumption, because it is known that more than 56% of the total electric power generated is consumed by the electric motors.   The asynchronous motors are widely used in the electric drives, and are most responsible for the consumption of the electric motors with approximately 96% [3]. As the very wide use of the asynchronous motors. Reducing losses by only a few percent will relate a major impact to the total consumption of the electric power.

This paper deals with the minimization of losses, by the optimization of the control of the asynchronous machine.

Thus in a first time and after modelization of the asynchronous machine, the rotor flux orientation technique is applied.   In a second time, the various expressions of machine losses are given, then a synthesis of the various objective functions is established, by examining the flux variation, and by the optimization of the stator currents. An experimental validation was carried out for the strategy of flux variation optimization.

II. FIELD ORIENTED CONTROL OF ASYNCHRONOUS MACHINE

A. Asynchronous Machine

The current approach of electric machines modelisation is based on the theory of the two axes which transforms a three-phase system into an equivalent two-phases system of axes d,q (fig. 1), which reduces the model complexity .
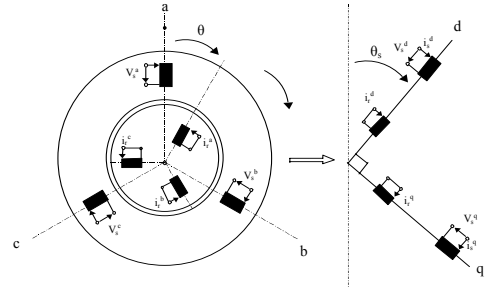

Fig. 1. Park Transformation applied on asynchronous machine

The stator and rotor voltage equations in a *d,q* reference frame rotating at the synchronism speed ω_S are presented below [4],[5]:

$$\begin{cases} V_{ds} = R_s i_{ds} + \dfrac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \\[2mm] V_{qs} = R_s i_{qs} + \dfrac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \\[2mm] V_{dr} = R_r i_{dr} + \dfrac{d\phi_{dr}}{dt} - (\omega_s - \omega_m)\phi_{qr} = 0 \\[2mm] V_{qr} = R_r i_{qr} + \dfrac{d\phi_{qr}}{dt} + (\omega_s - \omega_m)\phi_{dr} = 0 \end{cases} \quad (1)$$

The electromagnetic torque developed by the machine is expressed by:

$$C_{em} = p \frac{M_{sr}}{L_r} (\phi_{dr} i_{qs} - \phi_{qr} i_{ds}) \quad (2)$$

and the general mechanical equation is:

$$J \frac{d\Omega_r}{dt} + f \Omega_r = C_{em} - C_r \quad (3)$$

The two stator currents (i_{ds}) (i_{qs}), the rotor flux, (ϕ_{dr} , ϕ_{qr}), and the mechanical speed (Ω_r) are presenting the state variables, and the two stator voltage (V_{ds}, V_{qs}) as command variables.

B. Priciple of Vector Control

Orientated flux control, was developed in Germany at the beginning of the seventies. Hasse introduces the indirect method of the FOC (Field Oriented Control) and Blaschke the direct method [6], [7].

The objective of this type of control is to lead to a simple model of the asynchronous machine which take into account the separated control of the flux and the torque-producing.

The indirect method consists in using the flux position without its amplitude, it is calculated from the speed measurement and other accessible variables as the stator voltage or the stator current. By regarding the torque C_{em}^* and flux Φ_r^* as references of control, and the two stator currents (i_{ds}, i_{qs}) as command variables, the following equations are obtained:

$$
\begin{cases}
i_{qs}^* = \dfrac{L_r}{pM_{sr}} \dfrac{C_{em}^*}{\phi_r^*} \\[2mm]
i_{ds}^* = \dfrac{1}{M_{sr}}(T_r \dfrac{d\phi_r^*}{dt} + \phi_r^*) \\[2mm]
\omega_{gl}^* = \dfrac{M_{sr}}{T_r} \dfrac{i_{qs}^*}{\phi_r^*} \quad avec \quad \omega_s^* = \omega_m + \omega_{gl}^* \\[2mm]
V_{ds}^* = R_s i_{ds}^* - \omega_s^* \sigma L_s i_{qs}^* \\[2mm]
V_{qs}^* = R_s i_{qs}^* + \omega_s^* \sigma L_s i_{ds}^*
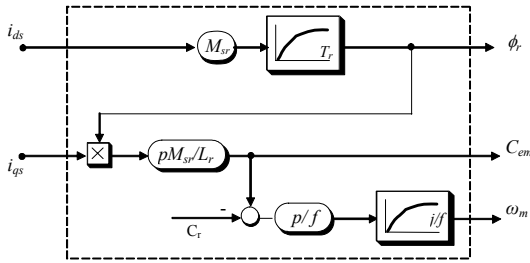\end{cases}
\qquad (4)
$$

Fig. 2. Block Diagram of induction motor

The rotor flux oriented diagram, with the simple equations of the system (4), can be easily established with current-controlled PWM inverter, figure 2.

From the system (4), we can deduce the block diagram of the orientated flux with the inverter current controller, figure 3. The main circuit of the association system represented by figure 3 has, on the network side, a rectifying bridge, followed by a passive filter (inductance and capacity) and an inverter. The generation of the inverter switches logical signals, depends on the used modulation strategies.

Figure 4 represents the simulation of the indirect control of the asynchronous machine under orientated flux.

It is noted that the speed follows the reference variation without going beyond. The decoupling between the flux and the torque is maintained, and the rotor flux remains constant without undergoing the abrupt variations of the speed change.
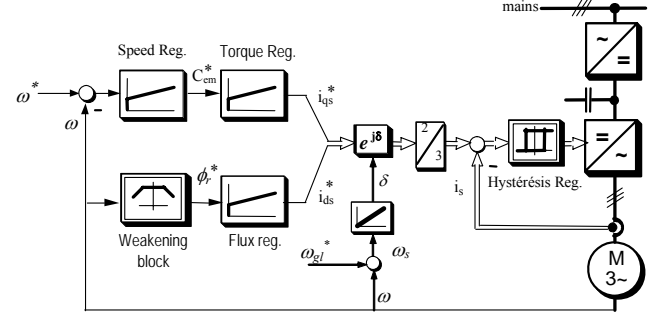

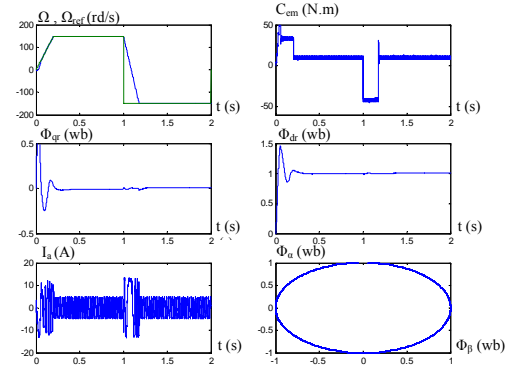Fig. 3. Indirect vector control scheme
current control inverter

Fig. 4. Simulation result for the field oriented control of an induction motor with reverse speed - current control inverter

III. LOSS MINIMIZATION IN ASYNCHRONOUS MACHINE

In this part, two great "families" of optimization are introduced to minimize the electromagnetic losses (copper and iron). The first family recovers the flux optimization methods as a function of the electromagnetic torque, where two methods were elaborated according to different objective functions. The second family synthesizes the methods of optimization according to an expression linking the two stator components of the current, while two methods of loss minimization are used.

A. Study of Asynchronous Machine Losses

This paper aims to minimize the losses (efficiency improvement) of the asynchronous machine by keeping better dynamic performances. To deal with this problem of optimization, a mathematical function must be selected to be minimized, which represents the best of motor total energy.

Several loss models were proposed and used in the literature, among this work those of [8], [9] and [10] which take into account the copper losses of the stator and rotor windings and the iron losses. Based on the traditional equivalent machine diagram.

The following equations present the loss expression in the asynchronous machine.

The total power of the motor P_a is written:

$$P_a = \begin{cases} \sigma L_s (i_{ds}\frac{di_{ds}}{dt} + i_{qs}\frac{di_{qs}}{dt}) - \frac{1}{L_r}\left(\frac{d\phi_{dr}}{dt}\phi_{dr} + \frac{d\phi_{qr}}{dt}\phi_{qr}\right) \\ + R_s(i_{ds}^2 + i_{qs}^2) - R_r\left(i_{qr}^2 + i_{dr}^2\right) \\ -\frac{2R_r M_{sr}}{L_r}\left(i_{qr}i_{qs} + i_{dr}i_{ds}\right) + \frac{M_{sr}}{L_r}\omega_m\left(\phi_{dr}i_{qs} - \phi_{qr}i_{ds}\right) \end{cases} \quad (5)$$

Which can be written in a condensed form by:

$$P_a = \frac{d}{dt}M + \Delta P_{Cu} + P_m \qquad (6)$$

With :

$$M = \frac{\sigma L_s}{2}(i_{ds}^2 + i_{qs}^2) + \frac{1}{2L_r}\left(\phi_{dr}^2 + \phi_{qr}^2\right)$$

is the magnetic energy stored in the machine inductances,

$$\Delta P_{cu} = R_s(i_{ds}^2 + i_{qs}^2) + R_r\left(i_{qr}^2 + i_{dr}^2\right)$$

is the electric power dissipated in the machine windings (copper losses),

$$P_m = \frac{M_{sr}}{L_r}\omega_m\left(\phi_{dr}i_{qs} - \phi_{qr}i_{ds}\right) \qquad (7)$$

is the mechanical power provided to the rotor motor.

According to the equivalent machine diagrams (traditional and parallel), various models from iron losses are distinguishes:

Model A: $\quad \Delta P_{Fe} = \Delta P_{Fe}^s = R_{Fe}\dfrac{\phi_r^2}{M_{sr}^2} \qquad (8)$

with $\quad R_{Fe} = \dfrac{M_{sr}}{L_r}(K_H f_m + K_F f_m^2)$

Model B: $\quad \Delta P_{Fe} = K_{fer}(\omega_s L_s)^2(i_{sq}^2 + i_{sd}^2) \quad (9)$

With $\quad R_{fer} = K_{fer}(\omega_s L_s)^2$

Model C: $\quad \Delta P_{Fe} = R_{fer} I_{fe}^2 = R_{fer}\left[\dfrac{L_m \omega_s}{R_{fer}}I_m\right]^2 \quad (10)$

B. Loss Minimization in Asynchronous Machine

Losses of electric-motor drives can be reduced by the following methods [8]:
- Motor selection and design,
- Improvement of the waveforms of the motor power supply.
- Adjusting voltage, current and/or frequency at each speed and torque operation point, in other term, the use of an adequate control method.

The techniques allowing the improvement of the efficiency (loss minimization) can be divided into two Approaches:

1. Heuristic Approach: these methods give the approximate results. Called Search Controllers (SCs), they are based in the measure of the supply power by introducing an optimum flux research algorithm. This approach does not require the parameters machine knowledge, but it does not have convergence guarantee for any operation [10],[11],[12],[13].

2. Analytical approach: these methods have the advantage of being used directly in real time, since it is an equation giving the optimal trajectory of the control. Called Loss-Model Controller (LMC), This approach is based on the loss model, which consists in calculating the losses by using the model of the machine and the flux level selection, [8],[14],[15],[16],[17],[18]. But they are less robust than the heuristics methods. To attenuate this disadvantage, we can add parameters adaptation mechanisms.

The second approach that we considered in this paper, is generally the fastest, but depends largely on the machine parameters, which are very difficult to obtain in an exact way.

In this part, we develop different objective functions [19], [20], [21], [22], [23].

B.1 Loss Minimization With Flux Level Control

B.1.1. flux Optimization for copper loss minimization

$$\phi_r = f(C_{em})$$

The flux optimization for a minimized energy in steady state consists in finding the trajectory of optimal flux, $\forall\, T \in [\,0,T\,]$, which minimizes the cost function:

$$J = \int_0^T \left\{ r\frac{L_r^2}{R_r^2 M_{sr}^2}(\dot{\phi}_r + \frac{R_r}{L_r}\phi_r)^2 + r\frac{L_r^2}{p^2 M_{sr}^2}\frac{C_{em}^{*2}}{\phi_r^2} + q\phi_r^2 \right\} dt$$

$$= \int_0^T L(C_{em}^*(t), \phi_r, \dot{\phi}_r)\, dt$$

The optimal control (U_1^o, U_2^o) is calculated by using the equations:

$$u_1^o = \frac{L_r}{R_r M_{sr}}(\dot{\phi}_r^o + \frac{R_r}{L_r}\phi_r^o)\ ,\ u_2^o = \frac{L_r}{p\ M_{sr}}\frac{C_{em}^*(t)}{\phi_r^o} \quad (11)$$

The optimization method consists in minimizing the copper losses in steady state while imposing the necessary torque defined by the speed regulator.

The optimal flux is obtained by:

$$\phi_r^o = \alpha\sqrt{\left|C_{em}^*\right|},\ with\quad \alpha = \left(\frac{L_r^2}{p^2 + \frac{q}{r}p^2 M_{sr}^2}\right)^{1/4} \quad (12)$$
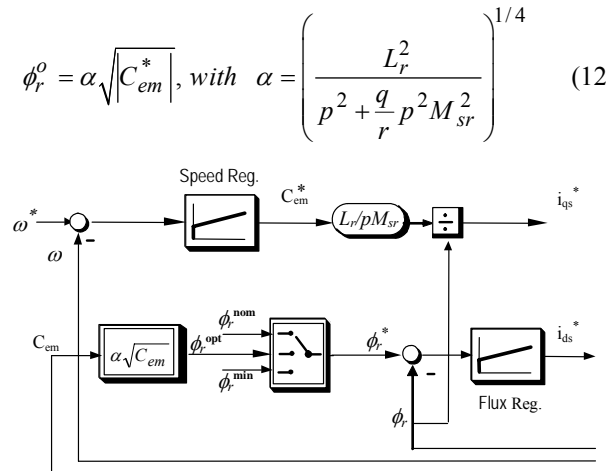
Fig. 5. Optimal control principle with flux variation

To check the simulation results and to evaluate the feasibility and the quality of control, we carried out experimental tests on the copper loss minimization by the flux variation method. It is noticed that the experimental result, figure 6, are similar to the result found by simulation, figure 7.
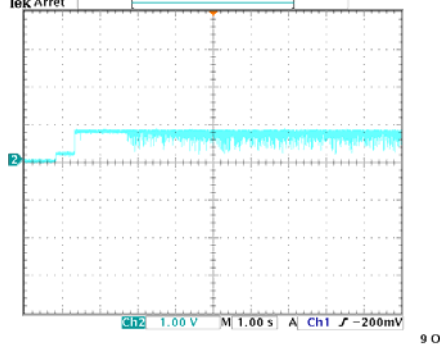

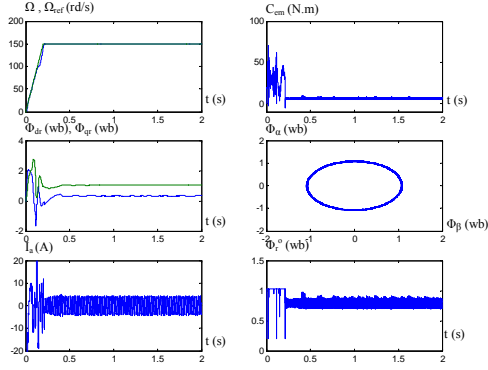Fig. 6. Experimental Result of optimal flux variation

Fig.7. Simulation result of optimal control with flux variation, Cr= 5 N.m.

B.1.2. flux Optimization for copper and iron loss minimization $\phi_r = f\,(C_{em})$

Here the iron losses is taken into account, and by using the model A, the expression of the sum of the losses becomes:

$$Losses = \Delta P_t = \Delta P_{Cu}^s + \Delta P_{Cu}^r + \Delta P_{Fe}^A \qquad (13)$$

Developing this expression, and calculating the optimal flux according to the torque, the following expression is obtained :

$$\phi_r^{opt} = \beta \sqrt{|C_{em}|} \quad \text{with}: \quad \beta = \left(\frac{\beta_2}{\beta_1}\right)^{1/4} \qquad (14)$$

Where $\beta_1 = \dfrac{(R_s + R_f)}{M_{sr}^2}$, $\beta_2 = \dfrac{L_r^2 R_s + R_r M_{sr}^2}{p^2 M_{sr}^2}$

Figure 9 shows a simulation test of the bloc diagram, figure 8, this validates the variation of the magnetic state for the copper and the iron loss minimization. The curves of the losses in nominal and optimal mode with the application of a light load ($C_r = 5\text{N.m}$), enable us to note that during load torque reduction, this method becomes

more effective and it compensates the loss excess by a flux reduction.
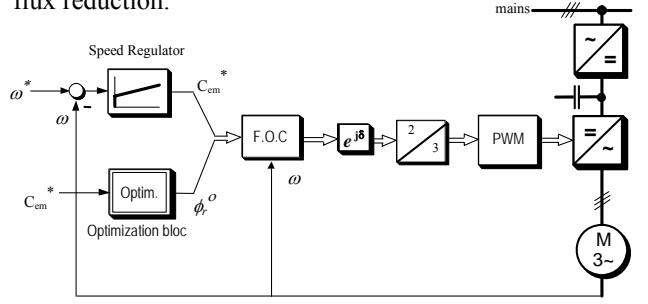

Fig. 8. Block diagram of the indirect vector optimization control asynchronous machine
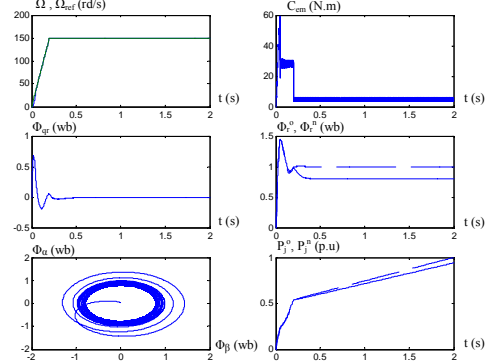

Fig. 9. Simulation result of loss minimization, Cr=5N.m
Comparison between nominal & optimal

B.2. Loss Minimization with $i_{ds} = f\,(i_{qs})$

B.2.1 Copper Loss Minimization , $i_{ds} = f\,(i_{qs})$

The second family of optimization is given here, by using an objective function linking the two components of the stator current for a copper loss minimization. The expression of power losses is written by:

$$\Delta P_t = \left\{ \begin{array}{l} \sigma L_s \left(i_{ds}\dfrac{di_{ds}}{dt} + i_{qs}\dfrac{di_{qs}}{dt}\right) - \dfrac{M_{sr}}{T_r L_r}\Phi_{dr} i_{ds} \\[2ex] + \left(R_s + \dfrac{M_{sr}^2}{L_r T_r}\right)(i_{ds}^2 + i_{qs}^2) \end{array} \right\} \quad (15)$$

In steady state, the minimum of power losses is reached for:

$$i_{ds} = \lambda\, i_{qs} \quad \text{with} \quad \lambda = \sqrt{1 + \dfrac{M_{sr}^2}{R_s L_r T_r}} \qquad (16)$$
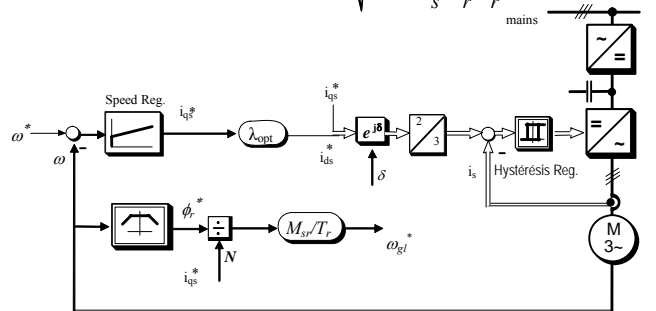

Fig. 10. Block diagram of the indirect vector control asynchronous machine with loss minimization

The behavior of the machine is simulated by using the block diagram of figure 10. The simulation results are presented on figure 11 under light load application. This method shows an increase of the response time speed, an increase reduction of the copper losses according to the reduction of the load torque.
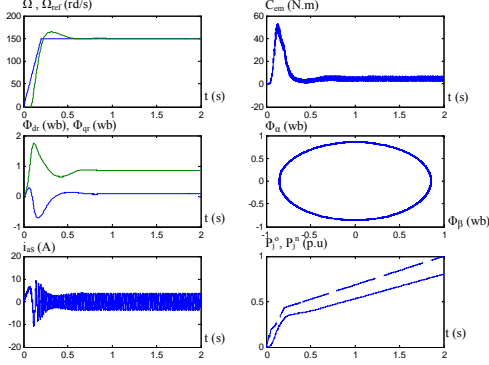

Fig. 11. Simulation result of copper loss minimization, Cr=5N.m
Comparison between nominal & optimal

B.2.2. Copper and Iron Loss Minimization

$$i_{ds} = f(i_{qs}, \omega_r)$$

In this section, another approach of copper and iron loss minimization is presented, by introducing the speed variable into the objective function.

The expression of the copper and iron losses and the relation of optimization are given by:

$$\Delta P = R_s (i_{ds}^2 + i_{qs}^2) + \frac{R_{Fe} R_r}{R_{Fe} + R_r} i_{qs}^2 - \frac{M_{sr}^2 \omega_r^2}{R_r + R_{Fe}} i_{ds}^2 \quad (17)$$

$$I_{ds} = \xi_{opt} \, I_{qs}$$

$$\text{with :} \quad \xi_{opt} = \sqrt{\frac{R_{fe} R_r + R_{fe} R_s + R_s R_r}{M_{sr}^2 \omega_r^2 - R_s (R_{fe} + R_r)}} \quad (18)$$

The simulation results, figure 12, shows that this method of minimization presents a faster response time speed. The block diagram become more difficult to implement.
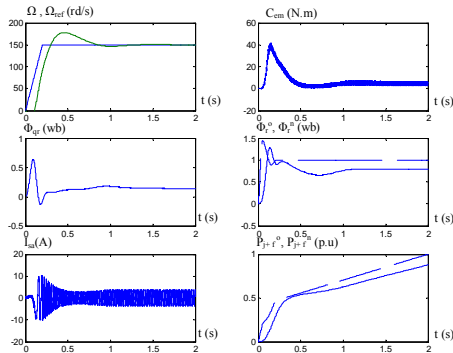

Fig. 12. Simulation result of copper and iron loss minimization, Cr=5N.m Comparison between nominal & optimal

IV. CONCLUSION

The first optimization methods "family", was studied, the strategy used allows, by choosing the magnetic state, to minimize the losses in steady state. The effectiveness is shown by the comparison with the traditional method and by validating this method with experimental tests. It can be said that this strategy can easily be implanted in the control.

The second "family" of loss minimization methods was the optimization of the stator currents. Various objective functions were exploited. Several combinations of copper and iron loss minimization were made and a comparison of the various strategies has been done.

An important criterion can be introduced in the comparison of the different strategies of optimization is the response time speed. According to the results obtained by numerical simulation, the methods according to $i_{ds} = f(i_{qs}, \omega_r)$ are the less powerful with respect to this criterion. Nevertheless all the methods are sensitive to the variations of the asynchronous machine parameters.

APPENDIX
MACHINE PARAMETERS

Rated Power :	P_n= 1.5 kw
Rated Voltage :	U_n= 220 v
Rated speed :	Ω_n= 1420 tr/mn
Rated current :	I_n= 3.64 A(Y) et 6.31A(Δ)
Stator Resistance :	R_s= 4.85 Ω
Rotor Resistance :	R_r= 3.805 Ω
Stator inductance :	L_s= 0.274 H
Rotor Inductance :	L_r= 0.274 H
Rotor time constant :	$T_r = L_r/R_r$
Mutual magnetizing Inductance:	M_{sr}= 0.258 H
Number of poles :	p= 2
Total inertia :	J= 0.031 kg. m^2
Viscous friction coefficient :	f_r= 0.008 Nm.s/rd

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