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ORIGINAL RESEARCH ARTICLE

TWIN SYNCHRONOUS MOTOR GRINDING MILL DRIVES: PERFORMANCE COMPARISON OF TWO OPTIONS

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ABSTRACT

The major challenge of twin synchronous motor drives, as seen in the large grinding mills of the mineral and cement industries are motor overheating and gear wearing, due to certain inevitable manufacturing errors/tolerances on the gear which prevents the two motors from sharing the mill load equally. This paper models a typical gear-driven grinding mill load which accommodates the manufacturing error located on the girth gear circumference, and applies it to two twin synchronous motor drive configurations, namely two three-phase series-connected six-winding synchronous motors (Drive A) and two conventional three-phase synchronous motors (Drive B). The motor equations were mentioned, and the drives simulated in the MATLAB/SIMULINK environment. Results obtained for the two configurations were compared. It was observed that while the risk of motor overheating was removed in Drive A, it was obvious in Drive B. However there is a risk of motor shaft breakage due to the mechanical coupling of the motors.

1.0 Introduction

In large grinding mills such as the mineral and cement industries where twin motor drives are used, the two major challenges which limit the use of two synchronous motors connected direct on line and mechanically coupled to the same mill are motor overheating – due to the fact that the two motors do not share the mill load equally, and the increased rate of wear of the gear teeth on the account of non alignment of the rotor positions of the two motors (Hoffmann and Trasky, 1972). The reason for these problems has been attributed to small inaccuracies in tolerances and manufacturing circumferential error, pitch diameter error, or rim face run out on the girth gear. Again, due to manufacturing tolerance or difference in wear, the girth gears do not mesh with the pinions exactly the same way, and so the rotors of the motors are not rotated at the same relative angular positions at the time of starting or during running (Valentine *et al.*, 1977). A similar issue is small errors of tolerance in the gear tooth angle. Moreover, whereas it is important that the two motors in dual motor grinding mill drives should be electrical duplicates of each other, in practice, motor characteristics may not match perfectly. Hence there is a load sharing problem between the two motors.

If the two major challenges mentioned earlier must be overcome in such drives, then it is critical that the two synchronous motors should rotate coordinately because they are mechanically coupled together to drive the same mill load through a pinion-driven speed reduction gear. The slip-ring induction motors have a better performance in this respect. But such advantages of using a synchronous motor over the induction motor as lower current for the same power levels, higher efficiency, and power factor correction ability renders the synchronous motors far more attractive than the slip-ring induction motors (Seggewiss *et al.*, 2014).

A number of schemes have been implemented which mitigates these problems such that synchronous motors remains the choice of motor for dual motor drives (Valentine *et al.*, 1977; Seggewiss *et al.*, 2014; Mular *et al.*, 2002; Rodriguez *et al.*, 2005). All these solutions require the use of expensive circuitry, complex stator frame, or complex rotor system. Odnokopylov *et al.* (2015) were interested in load balancing of two-motor asynchronous drive using variable

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frequency drives (VFD) while the present study is focused on a synchronous drive. Recently, Onwuka and Obe (2019) studied a special drive comprising of two synchronous motors whose stator windings are series-connected and whose shafts were coupled to a common load shaft by gearing. The winding connection is presented in Figure 1. They observed that the system was able to deal with the issue of motor overheating by equal load sharing, but the slow varying rotor position persisted. Some series connected motors have been studied before with a different objective than the present study (Levi *et al.,* 2007).

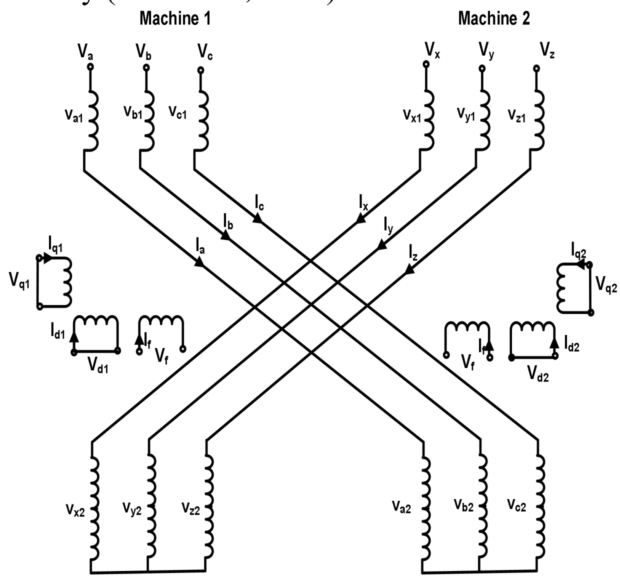

Figure 1: Motor Winding Connection of Drive A (Onwuka and Obe, 2019)

It is tl by Onwuka and Obe (2019) (designated as Drive “A” in this study), with that of a mill drive with two conventional three-phase synchronous motors (designated as Drive “B” in this study), by imposing the same load model on the two drives, implementing their respective mathematical models on MATLAB/SIMULINK environment, and then comparing important performance indices.

2. Materials and Methods

2.1 System Description

The mechanical coupling of the drive motors is shown in Figure 2, which holds true for the two systems under comparison. The motors rotate in the same direction while the girth gear rotates in the opposite direction. An important assumption made in this study is that both Motor 1 and Motor 2 are identical machines. For proper comparison, the parameters of the motor units in *Drive A* where obtained from known parameters of a conventional three phase synchronous motor (Ojo *et al.*, 1990), which represents the *Drive B,* by phase belt split (Rich, 1982; Singh and Singh, 2012). The parameters are presented in Table 1.

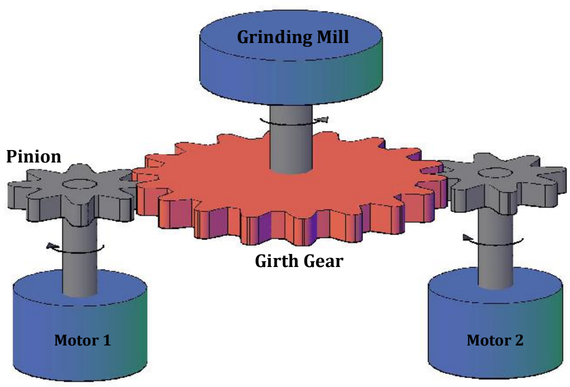

Figure 2: Two Synchronous Motor Mill

Consideration has been made in Table 1 that one set of three phase winding on the stator, the *s1*, is the reference winding for *Drive A*. The second set of three phase winding on the stator is designated *s2*.

The special configuration of the windings of the motors of *Drive A,* as shown in figure 1 has been described in (Onwuka and Obe, 2019). Motor units with two three-phase stator windings is the usual six-phase or quasi six-phase machines and have been studied by several authors. The articles of Singh and Singh (2012) and Palavicino and Valenzuela (2015) however were found helpful. The windings of the motors of *Drive B* need no introduction.

Table 1: Parameters of the Motors under study (Onwuka and Obe, 2019)

Parameter	3-ϕ Motor	3-ϕ Six-Winding Motor
Winding Pitch factor, k_p	0.9659	0.9659
Winding Distribution factor, k_d	0.9598	0.9937
q-axis magnetizing reactance, X_{mq}	1.483Ω	0.3974 Ω
d-axis magnetizing reactance, X_{md}	2.42Ω	0.6485 Ω
Rotor q-axis leakage reactance, X_{lqr}	0.597Ω	0.1600 Ω
Rotor d-axis leakage reactance, X_{ldr}	0.574Ω	0.1538 Ω
Field winding leakage reactance, X_{lfr}	0.6291Ω	0.1686 Ω
Rotor winding resistance for q-axis, r_{qr}	0.0904Ω	0.0242 Ω
Rotor winding resistance for d-axis, r_{dr}	0.0993Ω	0.0266 Ω
Field winding resistance, r_{fr}	0.0662Ω	0.0171 Ω
Stator winding resistance, r_s	0.0667Ω	$r_{s1} = 0.0333\ \Omega$ $r'_{s2} = 0.0333\ \Omega$
Stator leakage reactance, X_{ls}	0.1212Ω	$X_{ls1} = 0.0358\ \Omega$ $X'_{ls2} = 0.0358\ \Omega$
Leakage reactance mutual to the two winding sets, X_{lm}	0	0.0088
Leakage reactance between the q- and d-axes of the two winding sets, X_{ldq}	0	0
Number of Poles, P	6	6
Rated voltage, $V_{Line\text{-}to\text{-}Line}$	208V	208V
Rated current, I_{rated}	57.8A	57.8A
Inertia of unloaded motor, J	0.08kg-m^2	0.08kg-m^2

2.2 Mathematical Model

The mathematical model used for this study was adopted from Onwuka and Obe (2019), for *Drive A*, and from textbooks (Krause and Sudhoff, 2000; Krause *et al.*, 2013; Lipo, 2012), for *Drive B*. From Figure 1, the applied voltages in *Drive A* are given by Eqn. 1.

$$V_n = v_{ns1} + v_{ns2} = (r_{s1} + r_{s2})i_n + p(\lambda_{ns1} + \lambda_{ns2}) \tag{1}$$

where: *n = a, b, c, x, y, or z*-phases of the stators and the three rotor windings of each motor, and the subscripts *s1* and *s2* refers to the two stator winding sections. It is pertinent to mention that zero degree angular displacement was considered for the two sets of three-phase stator windings.

In characterizing the flux linkages in Eqn. 1, the interactions of all the current-carrying conductors were carefully considered. Park's equations were used to transform the time varying

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inductances to constant inductance terms in the rotor reference frame, for ease of computer simulation.

With s_2 windings referred to s_1 windings, Eqn.1 will be modified as follows:

$$V_n^{'} = r_s i_n + p\lambda_n^{'} \quad (2)$$

$$\text{Where } V_n^{'} = v_{n1} + v_{n2}^{'} \quad (2a)$$

$$r_s = r_{s1} + \frac{N_{s2}}{N_{s1}} r_{s2}^{'} \quad (2b)$$

$$\lambda_n^{'} = \lambda_{n1} + \lambda_{n2}^{'} \quad (2c)$$

Eqn. 2 is a compact matrix of twelve (12) voltage equations, representing the six interconnected stator windings and the three rotor windings of each motor unit, developed to describe the system of *Drive A*.

The motors in Drive B were conventional three-phase synchronous motors, and their model equations are available in many textbooks (Krause and Sudhoff, 2000; Krause *et al.*, 2013; Lipo, 2012).

Another important model for this study is the load model. In the load model, the major consideration is on how to factor in the load variation between the two motors in the drive due to imperfect gearing. If it is assumed that the imperfection of the gear is due to circumferential error in manufacturing, then Figure 3 will be an exaggerated schematic for the system, while Table 2 presents the load torque, T_{L1} and T_{L2} perceived by the two motors in the drive for one rotation of the gear.

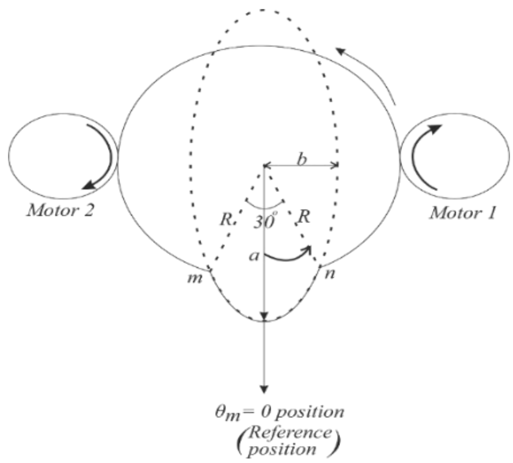

Figure 3: An Exaggerated Schematic of the imperfect gear (Onwuka and Obe, 2019)

Table 2: Variation of the Load Torque T_L of the Motors as the Girth Gear rotates (Onwuka and Obe, 2019)

Position	T_{L1}	T_{L2}
$0 \le \theta_m \le \frac{5}{12}\pi$	$\frac{T_{LM}}{2}$	$\frac{T_{LM}}{2}$
$\frac{5}{12}\pi \le \theta_m \le \frac{7}{12}\pi$	$\frac{T_{LM} \times R}{R + \sqrt{x^2 + y^2}}$	$\frac{T_{LM}\sqrt{x^2 + y^2}}{R + \sqrt{x^2 + y^2}}$
$0 \le \theta_m \le \frac{17}{12}\pi$	$\frac{T_{LM}}{2}$	$\frac{T_{LM}}{2}$
$\frac{17}{12}\pi \le \theta_m \le \frac{19}{12}\pi$	$\frac{T_{LM}\sqrt{x^2 + y^2}}{R + \sqrt{x^2 + y^2}}$	$\frac{T_{LM} \times R}{R + \sqrt{x^2 + y^2}}$
$\frac{19}{12}\pi \le \theta_m \le 2\pi$	$\frac{T_{LM}}{2}$	$\frac{T_{LM}}{2}$

where: θ_m refers to the angular position of the gear as it moves on its axis.
$T_{LM} = Mill\ Load\ Torque$
$R = radius\ of\ the\ symmetric\ part\ of\ the\ gear.$
$x = a\cos\theta_m$
$y = b\sin\theta_m$

To obtain this load model, the grinding mill speed is selected to be 20 rpm, while the motors are 1000 rpm, resulting to a gear ratio of $k = 50$.
The grinding mill speed in rad/sec will be:

$$\omega_m = \left(\frac{\omega_{r1}+\omega_{r2}}{2}\right) \times \frac{2}{P} \times \frac{1}{k} \tag{3}$$

where: ω_{r1} and ω_{r2} are the respective speed of the first and second synchronous motors, P is the number of poles of the motors and k is the gear ratio. The displacement angle, θ_m is:

$$\theta_m = \omega_m t \tag{4}$$

3. Results and Discussion

The Embedded MATLAB Function tool was used to simulate the machine equations. The varying load torque was imposed on the motors (the Embedded MATLAB function) using the Switch found in the Library/SIMULINK/Signal Routing tool box. The Load torque was applied 3 seconds into the simulation, after the steady state has been observed, and the simulation was allowed for 4 revolutions of the grinding mill. The pattern of the load torque is shown in Figure 4, where it will be observed that the load pulsations are 180^o out of phase in the two motors of the drive and occurs twice in each revolution of the mill. It is further observed that when one motor unit drops some load, the other unit picks it up, hence the pulsations.

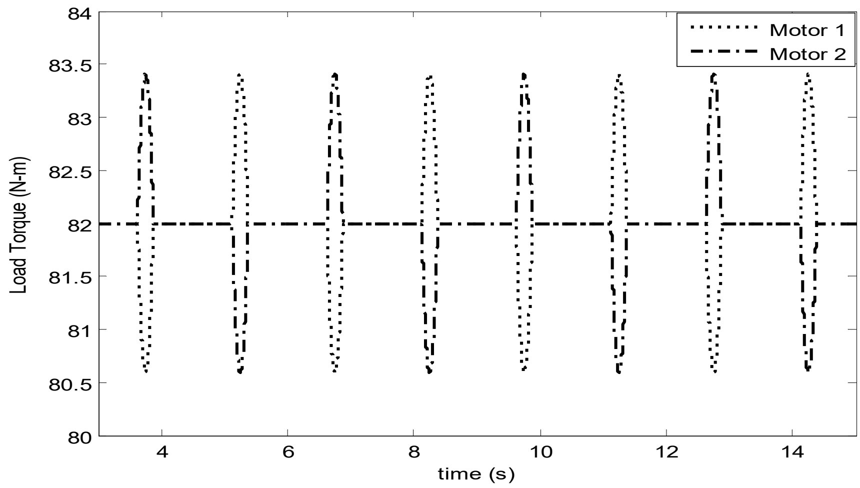

Figure 4: Load Torque Applied to the two motors of each of Drive A and Drive B

The rotor speed observed for the two drives is shown in Figure 5. As the two motors attempt to adjust themselves to the changing load, a maximum speed difference of 1.74 rad/sec is observed during each load pulsation for the motors in Drive A, while for the case of the motors in Drive B, a maximum speed difference of 0.26 rad/sec was observed. Similarly, the observation of the load angle shown in Figure 6 is that the Drive A motors have, with respect to each other, diverging load angles, while the load angles of Drive B motors are fairly constant, with a maximum difference of 0.3 radians observed during each load pulsation.

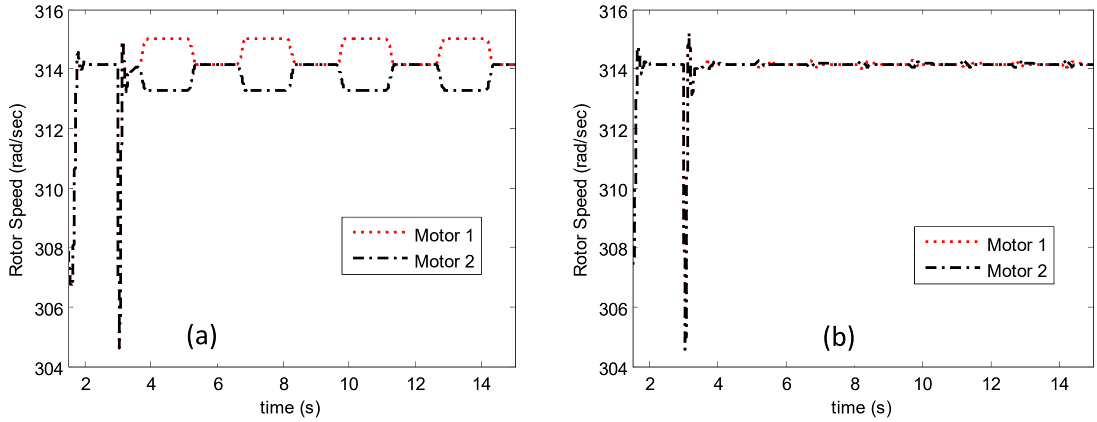

Figure 5: Rotor Speed of the two motors for: (a) Drive A and (b) Drive B

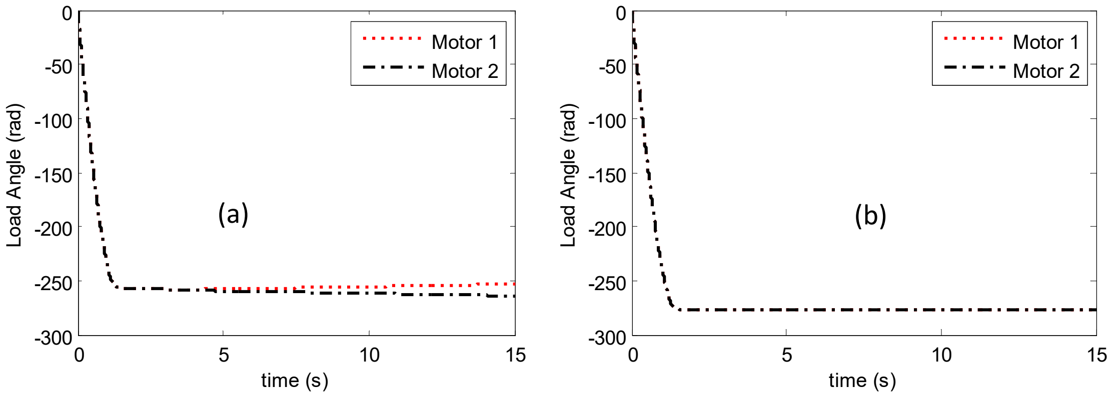

Figure 6: Load Angle of the two motors for: (a) Drive A and (b) Drive *B*

In Figure 7 however, Drive A motor Units were observed to develop equal and constant torque for the varying mill load, a situation considered desirable, while the Drive B motors developed torque according to the applied load torque, which varies during mill revolution. In the same vein, the stator currents were observed for both Drives and reported in Figure 8. While those of Drive A were expectedly constant despite the changing load, those of Drive B changed with the changing load, overshooting the rated current of 57.5A by 1.15A.

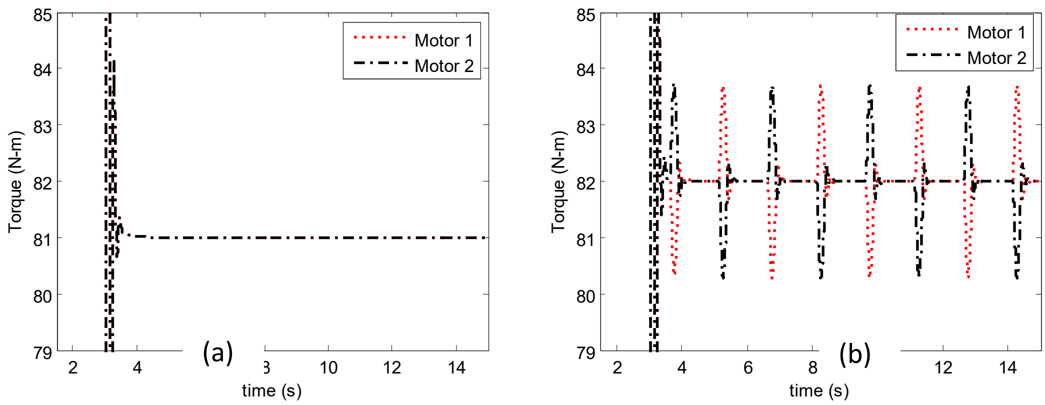

Figure 7: Torque Developed by the two motors for: (a) Drive A and (b) Drive B

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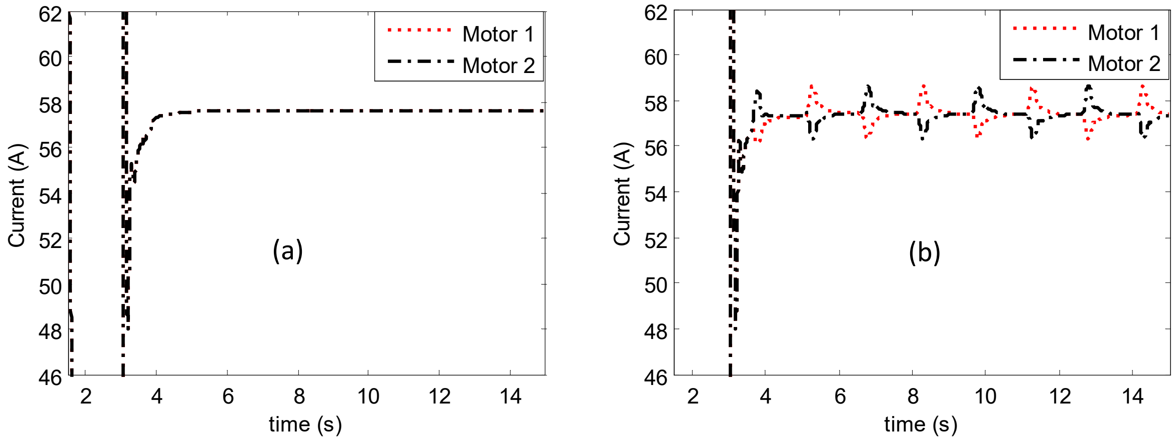

Figure 8: Stator a-phase Current of the two motors for: (a) Drive A and (b) Drive B

4. Conclusions

Twin pinion driven grinding mill has been presented which has load pulsations 180° out of phase in the two motors driving it. Two synchronous motor drive options have been presented as Drive A (six-winding motors with series stator winding connections and parallel field winding connection) and Drive B (conventional three-phase motors). The stator currents and developed torque of the Drive A motors were observed equal despite the changing load, thereby forcing their speeds to mismatch, resulting in diverging load angles. While this condition is good for the stator windings, there will be increased risk of shaft breakage due to the mechanical coupling of the motors. Contrariwise, while the stator currents and developed torque of the Drive B motors fluctuated in response to the applied load, their speed, and hence load angle, pulsated about an average value. This condition can lead to fast deterioration of the stator winding insulation and gradual wear of the gear. Hence, power electronic option of load balancing remains the better technology.

One of the limitations of this study is the use of 25HP motors, as practical applications of this technology is for motors in megawatts ranges.

Notations

T_{em}	Electromagnetic Torque in N/m
δ	Load angle in rad
λ	Flux Linkages
p	The differential operator dy/dx
P	Number of Poles
L	Inductance in Henrys
X	Reactance in Ohms
r	Resistance in Ohms
V	Voltage in Volts
ω	Angular Speed in rad/sec
θ	Angular position in radians
N_s	Winding function of the specified winding
s1	First 3-phase winding set on the stator
s2	Second 3-phase winding set on the stator
k	Speed ratio between the motor and gear
J	Inertia of unloaded motor
T_{L1}	Load torque of motor 1
T_{L2}	Load torque of motor 2

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