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Mathematical Model of Inductive Effect on the Multi-motors Synchronization Systems

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Abstract

Systems of synchronous rotation with AC machines depend on the equality of speed of two or more induction motors (mechanical or non mechanical-shaft connected) with the existence of load differences allocated on these shafts. The most popular ones among non-mechanical-shaft synchronization systems are the synchronization systems with auxiliary machines, electrical shaft systems, and the electromagnetic working shaft systems. In this work, using MATLAB – SIMULINK program, we suggest a mathematical model which represents a synchronous drive with electromagnetic working shaft system. The model will be tested with two similar induction motors 5hp, 50 Hz, 380 line voltage. Principle of operation and advantages related to the synchronous capability and recovery time for the electromagnetic working shaft system in deferent operational stats were also studied.

Keywords: Mathematical Model; Synchronous Capability; Induction Motors; Electromagnetic Shaft

1. Introduction

Systems of synchronous rotation are most used in cranes, cutting tool machines, and lifting machines [1]. The main performance of synchronization systems is very much related to the synchronous capability (speed synchronization, with maximum different loads on the motors shafts), and the required synchronization process time (recovery time).

When difference in load distribution is high, the system requires more synchronous capability. Therefore, the synchronous capability should be determined for any change in rated load, variation in load distribution, and rated power parameters. Accordingly, synchronous capability differs according to the connection, which links up the motors in the system. If the connection is direct mechanical one, then synchronous capability is unlimited. If the connection is non-mechanical, then synchronous capability will depend on the load distribution and the type of the control element connected between the main motors.

Electromagnetic working shaft system is recently the most applicable system compared to other synchronization systems. Each motor in this system is connected to a wounded coil on steel cylinder (inductive reactance element), which is very similar to transformer connections, where primary coils are connected to one motor and the secondary to the other, figure (1).

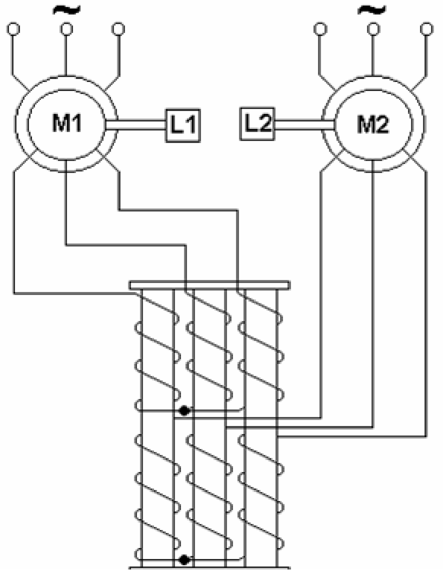

Figure1. Electromagnetic working shaft system.

For the electromagnetic working shaft system, the inductive reactance element parameters and dimensions mainly depend on the rated motors power and loads [2]. If the rotor currents flow inside the inductive reactance from both sides, and electromagnetic connection is generated between them, the main motors' coils fall under a correspondent and continuous influence of the power, where a change in one current of any of the motors leads to a change of the current motor in the other. Therefore the system principle of operation depends on the electromagnetic transformation of energy.

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If the loads on motors shafts are equal, $(L_1 = L_2)$, the rotor currents moving inside the inductive reactance are also equal, and the electromagnetic fields generated in those rotors are equal in quantity and are opposite in direction, so there will be no connection between the rotors, and the motors are operating as individual induction motors.

If the loads and the motors shafts are not equal $(L_1 \neq L_2)$, then the rotor currents and the electromagnetic fields will also change. This will lead to an electromagnetic connection amongst the inductive element of the rotor's coils that will be used to synchronization of the motors speed.

When the system is started with any load difference, there will be a great difference in the starting currents on the inductive reactance terminals, this difference will cause the smallest loaded motor to operate as a generator causing a decrease in the electromotive force value, and therefore the motor speed will decrease rapidly. Therefore the current will increase. The increased current will reverse the previous operation.

This variation will cause a system vibration. And to overcome this effect, the system should start when the loads are equal.

2. System Equivalent Circuit

To derive the control equations for the system, it is possible to use the simplified equivalent circuit given in Figure (2) [3].

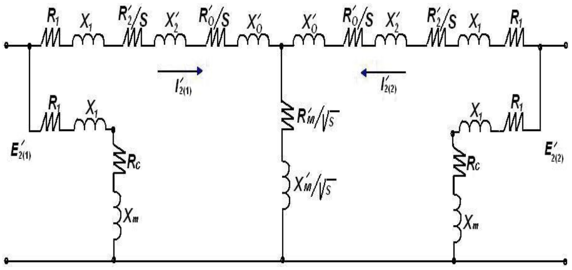

Figure 2. System equivalent circuit.

Where:

R_1, X_1 : Stator resistance and inductive reactance of first and second motors.

R'_2, X'_2 : Rotor Resistance and inductive reactance of first and second motors.

R'_o, X'_o : Resistance and inductive reactance of inductive element.

R'_M, X'_M : Resistance and inductive reactance of magnetizing circuit of inductive element.

R_c, X_c : Resistance and inductive reactance of magnetizing circuit of induction motor.

$E'_{2(1)}, E'_{2(2)}$: Rotor phase voltage in the first and the second motors.

$I'_{2(1)}, I'_{2(2)}$: Rotor current of the first and the second motors.

S: Slip.

When the loads become equal, the rotors and stators phase shift will be equal too ($\alpha_1 = \alpha_2$) and ($\Delta\alpha = 0$).

Where:

$$T_{A(1)} = \frac{\left\langle R_1 + \frac{R'_o + R'_2}{S} + \frac{2R'_M}{\sqrt{S}} \right\rangle^2 . \langle 1 + \cos\Delta\alpha \rangle}{\left\langle R_1 + \frac{R'_o + R'_2}{S} + \frac{2R'_M}{\sqrt{S}} \right\rangle^2 + \left\langle X_k + X'_o + \frac{2X'_M}{\sqrt{S}} \right\rangle^2}$$

α_1, α_2. Phase angles between the stator and rotor windings of main motors.

From the equivalent circuit Figure (2), the balance equations for the phase rotor voltage can be calculated as follows:

$$E'_{2(1)} = I'_{2(1)}\left[Z_d + Z_M\right] + I'_{2(2)} Z_M \tag{1}$$

$$E'_{2(2)} = I'_{2(2)}\left[Z_d + Z_M\right] + I'_{2(1)} Z_M \tag{2}$$

Where:

$$Z_d = (R_1 + \frac{R'_2}{S} + \frac{R'_o}{S}) + J\left(X_k + X'_o\right)$$

$$Z_M = \frac{R_M}{\sqrt{S}} + j\frac{X_M}{\sqrt{S}} \quad , \quad X_k = \left(X_1 + X'_2\right)$$

From (1 and 2) the rotor current for the first motor can be calculated as:

$$I'_{2(1)} = \frac{1}{2}\left[\frac{E'_{2(1)} + E'_{2(2)}}{Z_d + 2Z_M} + \frac{E'_{2(1)} - E'_{2(2)}}{Z_d}\right] \tag{3}$$

Based on [4 and 5], if the first motor is determined as a reference motor of the system, so; ($E'_{2(1)} = E'_2, E'_{2(2)} = E'_2 e^{j\Delta\alpha}$), and the torque of the first motor can be calculated as:

$$T_1 = \frac{mE'^2_2}{2\omega_o}\left[\dot{I}'_{2(1)} + I'_{2(2)}\right] \tag{4}$$

Where:

m: number of phase, $\dot{I}'_{2(1)}$. Conjugate value of the first rotor current.

If we add the value of rotor current ($I'_{2(1)}$) and its conjugate ($\dot{I}'_{2(1)}$), and after some transformations the torque (equation 4) will be:

$$T_1 = \frac{mE'^2_2}{2\omega_o}\left[T_A + T_S . Sin\,\Delta\alpha\right] \tag{5}$$

Where:

$T_A = T_{A(1)} + T_{A(2)}$ - Asynchronous part of the torque.

$T_S = T_{S(1)} + T_{S(2)}$ - Synchronous part of the torque.

$$T_{S(1)} = \frac{\left\langle X_k + X'_o + \frac{2X'_M}{\sqrt{S}} \right\rangle^2}{\left\langle R_1 + \frac{R'_o + R'_2}{S} + \frac{2R'_M}{\sqrt{S}} \right\rangle^2 + \left\langle X_k + X'_o + \frac{2X'_M}{\sqrt{S}} \right\rangle^2}$$

$$T_{A(2)} = \frac{\left\langle R_1 + \frac{R'_o + R'_2}{S} \right\rangle . \left\langle 1 - \cos \Delta\alpha \right\rangle}{\left\langle R_1 + \frac{R'_o + R'_2}{S} \right\rangle^2 + \left\langle X_k + X'_o \right\rangle^2}$$

$$T_{S(2)} = \frac{\left\langle X_k + X'_o \right\rangle^2}{\left\langle R_1 + \frac{R'_o + R'_2}{S} \right\rangle^2 + \left\langle X_k + X'_o \right\rangle^2}$$

If the second motor is determine as a reference ($E'_{2(2)} = E'_2$ and $E'_{2(1)} = E'_2 e^{j\Delta\alpha}$), then the motor torque can be determined similar to the first motor but with negative part of synchronous torque [5].

$$T_2 = \frac{mE'^2_2}{2\omega_o}\left[T_A - T_S.Sin\Delta\alpha\right] \tag{6}$$

3. System Block Diagrams

Using the main equivalent circuit equations, rotational dynamic torque equations, angular speed, and angular positions equations, the mathematical model of the electromagnetic working shaft system has been built [6]. This model (see figure 3) consists of three blocks each of them has a specific functions.

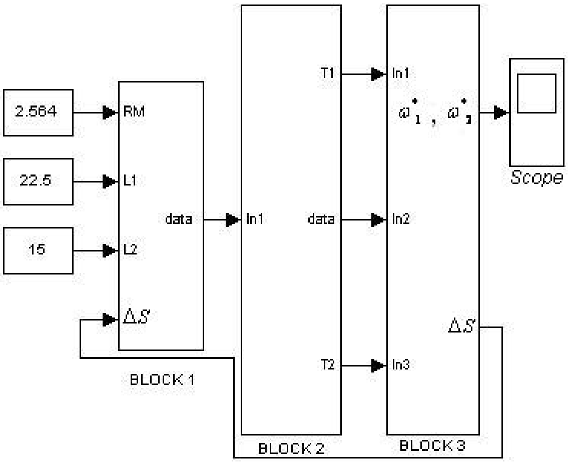

Figure 3. System block diagram.

3.1. Block 1 (General Data Block)

This block was built using difference basic data such as the similar induction motors parameters, (5hp, 4 pole 50 Hz, VL=380*V*, *R1=1.115 Ω*, R'_2 *=1.083 Ω*, *X₁=* X'_2 *= 2.252 Ω*, X_c *= 76.8 Ω., J=0.02 kg.m²)*, inductive element parameters (R'_o, X'_o, X'_M), inputs (R'_M, *L1, L2)*, feedback (Δs . $\Delta\alpha$, *S1, S2*) , and parameters.

Where:

L1. Load torque of first motor. *L2*. Load torque of second motor.

3.2. Block 2 (System Main Equations Block)

The main input of this block is the output data signal of general data block. Using this data, the torque equations, *(5 and 6)* were built Figure (4).

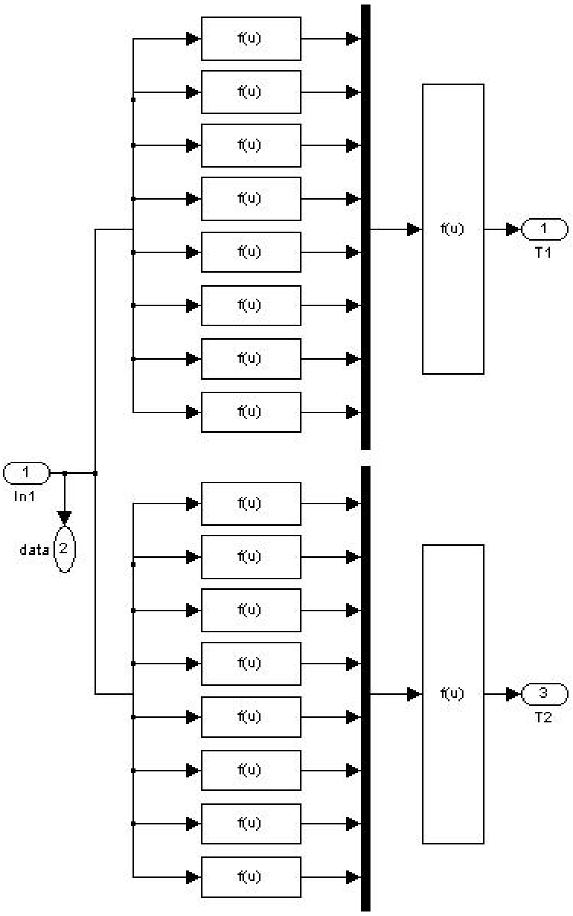

Figure 4. System main equations block

3.3. Block 3 (Error Calculation Block)

The error calculation block input consists of torque equations (*T1, T2*), load torque value *(L1, L2)*, and general data signal incoming from the first block Using dynamic torque equation:

($T_{in} - T_L = J\,\frac{d\omega}{dt}$) and relationships between angular speed, difference between windings phase shift and slip ($\omega_1 , \omega_2 , \Delta\alpha , S_1 , S_2$), the synchronous process, synchronous capability and recovery time of the system are calculated.

The above mentioned output values of this block diagram are presented as the main system response and as the feedback values, which goes back to first block.

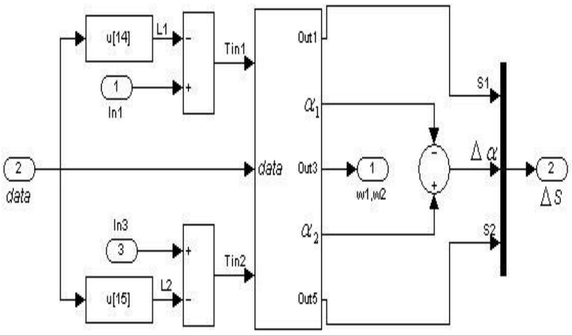

Figure 5. Error calculation block.

4. System Operation and Test

According to [6], and based on practical applications of electromagnetic working shaft systems, the inductive reactance element power factor ($COS\alpha$) ranges between 0.7 and 0.85 , and relationships inductive reactance parameters with resistance R'_M are joined .

$$X'_M = \tan\alpha . R'_M$$

$$X'_o = R'_o = (0.1 - 0.2) R'_M$$

For our system model, using specific method [6], the model will be tested with the below inductive reactance element parameters and dimensions:

R'_M : Rated magnetizing resistance = 2.564 Ω.
La: Axial distance between rods = 243mm.
D: Diameter of the steel rod =125 mm.
Lc: Length of steel core = 496mm.
Oh: Length of turn (half steel rod) =238 mm.

Operation of the system model can represent the inductive reactance magnetizing resistance R'_M effect on the synchronous capability and recovery time of the system.

If the magnetizing resistance is equal to zero, (R'_M = 0), and the loads on the shafts are not equal $(L_1 = 2L_2)$, there will be no relationship between the motors in the control system, and the motors will operate as individual induction motors, Figure (6).

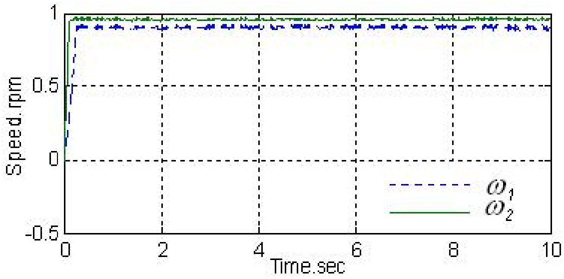

Figure 6. Speed response without rotor connection.

If the magnetizing resistance is not equal to zero, (R'_M ≠ 0), and the loads on the shafts are equal $(L_1 = L_2)$, the electromotive forces generated in inductive reactance coils will be equal in quantity and will be opposite in direction. Therefore, the motors will also operate as individual motors with equal speeds, $(\omega_1 = \omega_2)$,Figure (7).

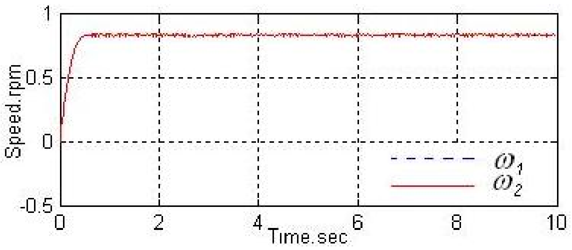

Figure 7. Speed response when equal loads.

If the magnetizing resistance is not equal to zero (R'_M ≠ 0), and the loads on the shafts are not equal, $(L_1 \neq L_2)$, and then the electromotive forces generated in inductive reactance coils will be not equal. This will produce energy difference in the common rotor circuit, $(\Delta E = E'_{2(2)} - E'_{2(1)})$.

This energy will decrease the speed of the motor with the lowest effect until it leads to equality of speeds in both motors. In this case, the system will be tested with three values (0.5, 1.0, 1.5) $R'_M(Rated)$, Figure (8).

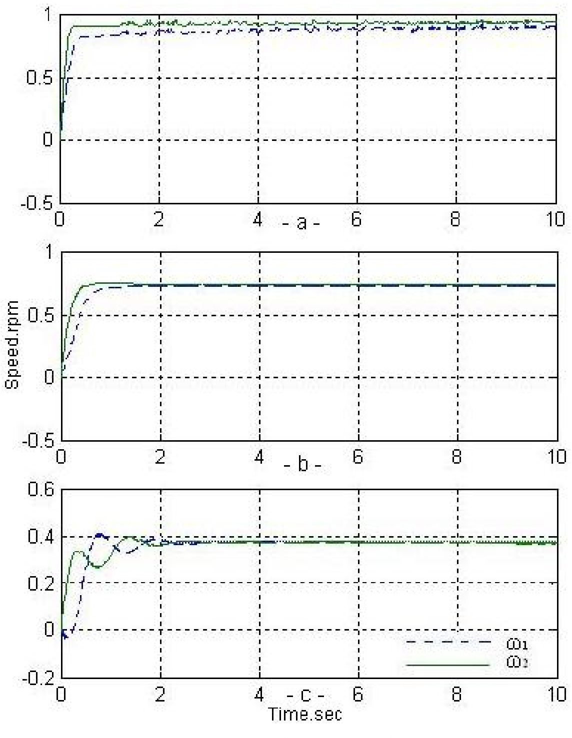

Figure 8. Speed response when $(L_1 = 1.5L_2)$
(a) $0.5R'_M(Rated)$, (b) $R'_M(Rated)$
(c) $1.5R'_M(Rated)$.

Comparing the speed system response, we can see the real role of magnetizing resistance on the synchronization process of the system. For our case, the best synchronous capability and recovery time can be determined only when using rated magnetizing resistance, (see figure 8-b).

Figure (9) shows the effect of load difference on the synchronization process. The figure represents three cases for the load difference on the induction motors shafts. $(L_1 = (1.5 \_ 2 \_ 2.5) L_2)$

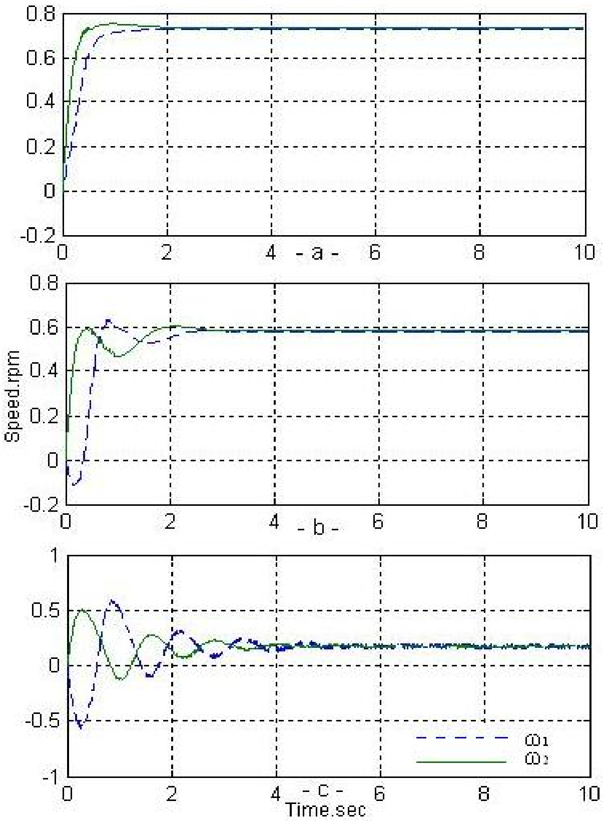

Figure 9. Speed response when rated R'_M ,
(a) $(L_1 = 1.5L_2)$,(b) $(L_1 = 2L_2)$
(c) $(L_1 = 2.5L_2)$.

*In figure 8-a $(L_1 = 1.5L_2)$, the system has the best synchronous capability with the best recovery time.

*In figure 8-b $(L_1 = 2L_2)$, the system has a medium synchronous capability with little vibration.

*In figure 8-c $(L_1 = 2.5L_2)$, the system has the worst synchronous capability with the longest recovery time and high system vibration.

5. Conclusion

The design of the electromagnetic shaft systems depends on the motors power because it depends on the value of R'_M , and by changing this value, the dimensions of the inductive reactance and the synchronous capability will be determined [5].

The effect of R'_M on the synchronous capability and recovery time depends on the load distribution, if the load distribution is greater than the rated value, then the R'_M effect will decrease and the system vibration will increase. Therefore, to have a more stable system with less vibration, the maximum load difference must be determined before choosing the inductive reactance element for the system.

The required recovery time for the synchronization process of the system will be faster in the implementation than the calculated values because of the presentation of the gear box where the speeds are reduced to the tenth of its maximum speed.

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