# Speed Synchronization of Single-Phase Induction Motors by Electromagnetic Shaft System

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*Abstract:* - This paper presents a mathematical analysis and simulation of electromagnetic shaft synchronization system with two capacitor-start single-phase induction motors. The main synchronization quality parameters (the synchronization capability and recovery time) have been analyzed. The desired synchronization quality parameters have been obtained by optimizing the parameters of the stator capacitor and the rotor additional inductive element. Analysis has been based on determination of the relationship between the capacitor and inductive element parameters, loads difference and the response time of the angular speed of the motors. The proposed system has been mathematically modeled and simulated using MATLAB/Simulink. It has been designed and tested for various load conditions. Results of the dynamic processes of the suggested electromagnetic shaft synchronization system have been illustrated.

*Key-Words:* - electromagnetic shaft, multiple-motor system, single-phase capacitor-start induction motor, recovery time, synchronization capability

## 1 Introduction

The induction motor is the most widely used motor in industry because of its robustness, reliability, low cost, high efficiency and good self-starting capability [1-2]. Squirrel-cage induction motors are employed in almost all applications. They always operate at low lagging power factor, which ultimately results in less efficiency [3-4].

Slip-ring induction motors have better starting characteristics compared to squirrel-cage motors. They are used in applications, where the motor speed can be controlled by different approaches [4-7]. When two or more wound-rotor induction motors are used in the synchronization system applications, speed synchronization and speed control of these motors become a challenge. In [8], authors made a comparative study between three different approaches of traditional synchronization systems with two three-phase slip-ring induction motors. Results show the advantages and disadvantages of each approach in terms of different synchronization quality indicators.

Usually, in industrial applications, single-phase induction motors (SPIMs) are not widely used, but due to the availability of single-phase power, they can be used in some industrial applications, especially for small loads. SPIMs include: split-phase, capacitor-start, capacitor-start and capacitor-run, two-value capacitor and shaded-pole motors [9-10]. SPIMs are used in different drives applications such as: pumps, mowers and others. Speed synchronization system that uses SPIMs requires some inefficient and complex electrical or mechanical methods for a complete direct synchronization. To simplify this process, the electromagnetic shaft system is suggested, where squirrel-cage rotors are replaced by slip-ring rotors as shown in Fig.1.

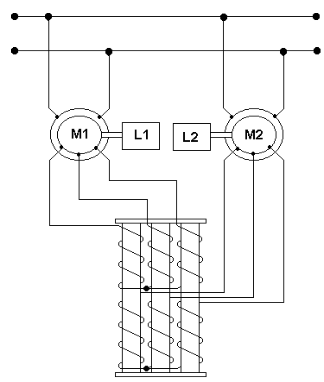


Fig.1 Electromagnetic shaft system with two single-phase induction motors

The operation of the traditional electromagnetic shaft system is based on the principle of electromagnetic transformation of energy. Each motor, in this system, is connected to three-phase wounded coils on a ferromagnetic cylindrical core,

*Fulbright visiting scholar at Wayne State University, Detroit, USA which is very similar to the transformer connection. One side (the primary coils) is connected to the rotor circuit of the first motor and the other side (the secondary coils) is connected to the rotor circuit of the second motor [4].

This work presents a speed synchronization system of two identical capacitor-start single-phase induction motors (CSSPIMs) based on the electromagnetic shaft system, where rotor circuits of the motors are connected together to the common additional inductive element (*RL*-element). The additional three-phase *RL*-element, in the rotor common circuit, plays a main role in determining the synchronization capability and recovery time of the system [4]. The capacitor in the stator circuit adjusts the starting torque, which in its turn will enhance the synchronization capability and the recovery time. The control ability of the starting torque of CSSPIMs makes it possible to use them in two-motor synchronization systems.

Electromagnetic torque and, consequently, speed synchronization of both motors in this synchronization system can be optimized by adjusting the capacitor in the stator circuit by a factor of $K_c$, and the *RL*-element in the rotor circuit by a factor of $K_m$. In such systems, the designer should know the maximum load of the system in order to choose the power of the motors. Then, according to the given application, the maximum possible difference in loads should be considered in order to calculate the *RL*-element dimensions [11]. Finally, according to the maximum possible difference in loads, for example 40%, the system synchronization capability should be tested.

This work aims at designing a synchronization system of two CSSPIMs with electromagnetic shaft system, and determining its optimum parameters to achieve the best synchronization capability and recovery time.

## 2 System Modeling

To develop the equivalent circuit of the system with the additional three-phase *RL*-element in the common rotor circuit, the forward and backward sequence circuits are considered [10], [12-13]. Therefore, the equivalent circuits can be presented as shown in Fig.2, where $R_S$, $X_S$ are the resistance and inductive reactance of both the stator winding and the inductive element; $R_F$, $X_F$ are the forward resistance and inductive reactance of the rotor; $R_B$, $X_B$ are the backward resistance and inductive reactance of the rotor; $X_C$ is the capacitive reactance of the starting capacitor in the stator circuit; $E_{F2(1)}$, $E_{F2(2)}$ are the forward induced voltages in the rotors of the two motors; $E_{B2(1)}$, $E_{B2(2)}$ are the backward induced voltages in the rotors of the two motors; $I_{F2(1)}$, $I_{F2(2)}$ are the forward currents flowing in the rotors; $I_{B2(1)}$, $I_{B2(2)}$ are the backward currents flowing in the rotors; $R_m$, $X_m$ are the resistance and inductive reactance of the magnetization branch; $S$ is the slip of the motor; $R_M$, $X_M$ are the resistance and inductive reactance of the magnetization branch of the *RL*-element.

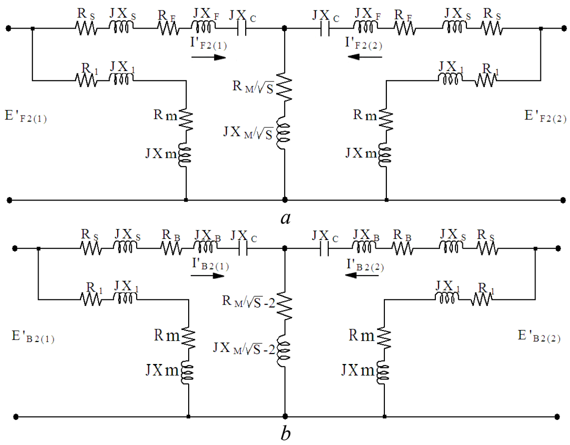


Fig.2 Forward (*a*) and backward (*b*) sequence circuits

According to [14-15], $Z_F = R_F + JX_F$ and $Z_B = R_B + JX_B$, they may be calculated as follows:

$$Z_F = \frac{1}{2}\left( \frac{\left(\frac{R_2 X_m (X_2 + X_m)}{S}\right) - \left(\frac{R_2 X_2 X_m}{S}\right)}{\left(\frac{R_2}{S}\right)^2 + (X_2 + X_m)^2} \right) + J\left( \frac{\left(\frac{R_2^{\,2} X_m}{S^2}\right) + (R_2 X_2 (X_2 + X_m))}{\left(\frac{R_2}{S}\right)^2 + (X_2 + X_m)^2} \right)$$

$$Z_B = \frac{1}{2}\left( \frac{\left(\frac{R_2 X_m (X_2 + X_m)}{(2-S)}\right) - \left(\frac{R_2 X_2 X_m}{2-S}\right)}{\left(\frac{R_2}{(2-S)}\right)^2 + (X_2 + X_m)^2} \right) + J\left( \frac{\left(\frac{R_2^{\,2} X_m}{(2-S)^2}\right) + (R_2 X_2 (X_2 + X_m))}{\left(\frac{R_2}{(2-S)}\right)^2 + (X_2 + X_m)^2} \right)$$

where $R_2$, $X_2$ are the resistance and inductive reactance of the rotor respectively.

In case if the motors are operating at different speeds, a difference in the phase angles between the stator and the rotor windings ($\alpha_1$, $\alpha_2$) appears. The difference in loads may be represented by the difference in the phase angles. At equal loads, this difference will be equal zero $\alpha_1 - \alpha_2 = \Delta\alpha = 0$ [16-17]. Based on the equivalent circuits shown in Fig.2, the rotor balance voltage of the forward and backward sequences can be determined as follows:

$$E'_{F2(1)} = I'_{F2(1)}\left[(R_S + R_F) + j(X_S + X_F - X_C)\right] + I'_{F2(2)}\left[R_M/\sqrt{S} + JX_M/\sqrt{S}\right] \quad (1)$$

$$E'_{F2(2)} = I'_{F2(2)}\left[(R_S + R_F) + j(X_S + X_F - X_C)\right] + I'_{F2(1)}\left[R_M/\sqrt{S} + JX_M/\sqrt{S}\right] \quad (2)$$

$$E'_{B2(1)} = I'_{B2(1)}\left[(R_S + R_B) + j(X_S + X_B - X_C)\right] + I'_{B2(2)}\left[R_M/\sqrt{(2-S)} + JXM/\sqrt{(2-S)}\right] \quad (3)$$

$$E'_{B2(2)} = I'_{B2(2)}\left[(R_S + R_B) + j(X_S + X_B - X_C)\right] + I'_{B2(1)}\left[R_M/\sqrt{(2-S)} + JXM/\sqrt{(2-S)}\right] \quad (4)$$

From (1)-(4), the rotor currents may be found as:

$$I'_{F2(1)} = \frac{1}{2}\left[\frac{E'_{F2(1)} + E'_{F2(2)}}{(R_S + R_F) + j(X_S + X_F - X_C) + 2(R_M / S + JXM / S)} + \frac{E'_{F2(1)} - E'_{F2(2)}}{(R_S + R_F) + j(X_S + X_F - X_C)}\right] \quad (5)$$

$$I'_{F2(2)} = \frac{1}{2}\left[\frac{E'_{F2(1)} + E'_{F2(2)}}{(R_S + R_F) + j(X_S + X_F - X_C) + 2(R_M / S + JXM / S)} + \frac{E'_{F2(2)} - E'_{F2(1)}}{(R_S + R_F) + j(X_S + X_F - X_C)}\right] \quad (6)$$

$$I'_{B2(1)} = \frac{1}{2}\left[\frac{E'_{B2(1)} + E'_{B2(2)}}{(R_S + R_B) + j(X_S + X_B - X_C) + 2(R_M /(2-S) + JXM / \sqrt{(2-S)})} + \frac{E'_{B2(1)} - E'_{B2(2)}}{(R_S + R_B) + j(X_S + X_B - X_C)}\right] \quad (7)$$

$$I'_{B2(2)} = \frac{1}{2}\left[\frac{E'_{B2(1)} + E'_{B2(2)}}{(R_S + R_B) + j(X_S + X_B - X_C) + 2(R_M /(2-S) + JXM / \sqrt{(2-S)})} + \frac{E'_{B2(2)} - E'_{B2(1)}}{(R_S + R_B) + j(X_S + X_B - X_C)}\right] \quad (8)$$

Considering the first motor as a reference, we obtain:

$$E'_{F2(1)} = E'_2,\ E'_{F2(2)} = E'_2 e^{j\Delta\alpha},\ S = S_1$$

and

$$\Delta\alpha = \alpha_1 - \alpha_2$$

If the second motor is considered as a reference motor, then:

$$E'_{F2(2)} = E'_2,\ E'_{F2(1)} = E'_2 e^{j\Delta\alpha},\ S = S_2$$

and

$$\Delta\alpha = \alpha_2 - \alpha_1$$

Since the calculations of both motors are identical, calculations for only one motor will be performed.

The electromagnetic torque, of the forward and backward sequences of the first motor, may be found as follows [18-19]:

$$T_{F(1)} = \frac{E'^2_2}{2\omega_o}\left[I'_{F2(1)} + \dot{I}'_{F2(1)}\right] \quad (9)$$

$$T_{B(1)} = \frac{E'^2_2}{2\omega_o}\left[I'_{B2(1)} + \dot{I}'_{B2(1)}\right] \quad (10)$$

where $\omega_0$ is the idle mode angular speed in rad/s.

Considering the rotor current $I'_{F2(1)}$ and its conjugate $\dot{I}'_{F2(1)}$, the torque represented by (9) and (10) becomes:

$$T_{F(1)} = \frac{E'^2_2}{2\omega_o}\left[\left(\frac{(R_S + R_F)(1-\cos\Delta\alpha)}{(R_S + R_F)^2 + (X_S + X_F - X_C)^2} + \frac{\left(R_S + R_F + \frac{2R_M}{\sqrt{S}}\right)(1+\cos\Delta\alpha)}{\left(R_S + R_F + \frac{2R_M}{\sqrt{S}}\right)^2 + \left(X_S + X_F + 2X_M/\sqrt{S} - X_C\right)^2}\right) + \left(\frac{\left(X_S + X_F + 2X_M/\sqrt{S} - X_C\right)\sin\Delta\alpha}{\left(R_S + R_F + \frac{2R_M}{\sqrt{S}}\right)^2 + \left(X_S + X_F + 2X_M/\sqrt{S} - X_C\right)^2} - \frac{(X_S + X_F - X_C)\sin\Delta\alpha}{(R_S + R_F)^2 + (X_S + X_F - X_C)^2}\right)\right] \quad (11)$$

$$T_{B(1)} = \frac{E'^2_2}{2\omega_o}\left[\left(\frac{(R_S + R_B)(1-\cos\Delta\alpha)}{(R_S + R_B)^2 + (X_S + X_B - X_C)^2} + \frac{\left(R_S + R_B + \frac{2R_M}{\sqrt{2-S}}\right)(1+\cos\Delta\alpha)}{\left(R_S + R_B + \frac{2R_M}{\sqrt{2-S}}\right)^2 + \left(X_S + X_F + 2X_M/\sqrt{2-S} - X_C\right)^2}\right) + \left(\frac{\left(X_S + X_B + 2X_M/\sqrt{2-S} - X_C\right)\sin\Delta\alpha}{\left(R_S + R_B + \frac{2R_M}{\sqrt{2-S}}\right)^2 + \left(X_S + X_B + 2X_M/\sqrt{2-S} - X_C\right)^2} - \frac{(X_1 + X_F - X_C)\sin\Delta\alpha}{(R_S + R_B)^2 + (X_S + X_B - X_C)^2}\right)\right] \quad (12)$$

And the total torque of the first motor becomes:

$$T_{(1)} = T_{F(1)} - T_{B(1)} \qquad (13)$$

The second motor torque can be determined similarly as:

$$T_{(2)} = T_{F(2)} - T_{B(2)} \qquad (14)$$

The main effect of $X_c$ and $R_M$ on the system behavior can be found using the following factors:

$$K_m=R_M/R_2 \text{ and } K_c=X_c/R_M$$

Factors $K_m$ and $K_c$, used for the adjustment of the synchronization capability of the system, are not variables that can be controlled during the system operation. They are constants. But changing their values, in this paper, is aiming at determining their impact on the synchronization capability and recovery time at various load conditions. Therefore, the synchronization system will be tested at different values of these factors in order to find their optimum values.

Thus, to design a synchronization system having the desired synchronization capability and recovery time at the possible maximum difference in the motors loads, the system will be simulated at different values of factors $K_m$ and $K_c$. Then, once the optimum values of these factors are determined, the dimensions and the parameters of *RL*-element can be calculated [11].

## 3 Results and Analysis

The proposed synchronization system has been simulated to analyze the effect of the capacitance in the stator circuit and *RL*-element in the common rotor circuit. Based on this analysis, the optimum values of the factors $K_m$ and $K_c$ will be chosen for certain conditions of operation of the synchronization system.

In this work, MATLAB/Simulink is used to model and simulate the characteristics of CSSPIM. Two identical CSSPIMs with slip-ring rotors are used. The ratings of these motors are: 2.2 hp, 1430 rpm, 50 Hz, 4 Poles, 220 V, and $C_{st}$=200 µF.

Fig.4 shows the speeds of both motors of the system without *RL*-element. This figure shows three different cases: first, when both motors are operating with equal loads; second, when one motor is loaded more than the other one by 40%; and third, when one motor is loaded more than the other one by 140%. It is clear from Fig.4 that the greater the loads difference is, the greater the difference in the motor speeds is. Thus, the system needs more efficient synchronization system when the difference in loads is great.

Fig.5 illustrates three speed curves of the motors of the same system, but with *RL*-element. These curves are when the difference in loads is 40% and $K_c$=9 with rated $C_{st}$, while $K_m$= 0.4, 0.6, and 0.7 respectively. From this figure, it is noticed that the system goes into synchronism. Also, it is clear that as factor $K_m$ increases, the recovery time decreases. Fig.5 also shows that the difference of speeds during starting still unaffected and it needs sufficient recovery time, which is undesired in applications with frequent starting of the motors. To solve this problem, factor $K_c$ is decreased, since decreasing its value increases the starting torque of the motor and, consequently, the recovery time will decrease.

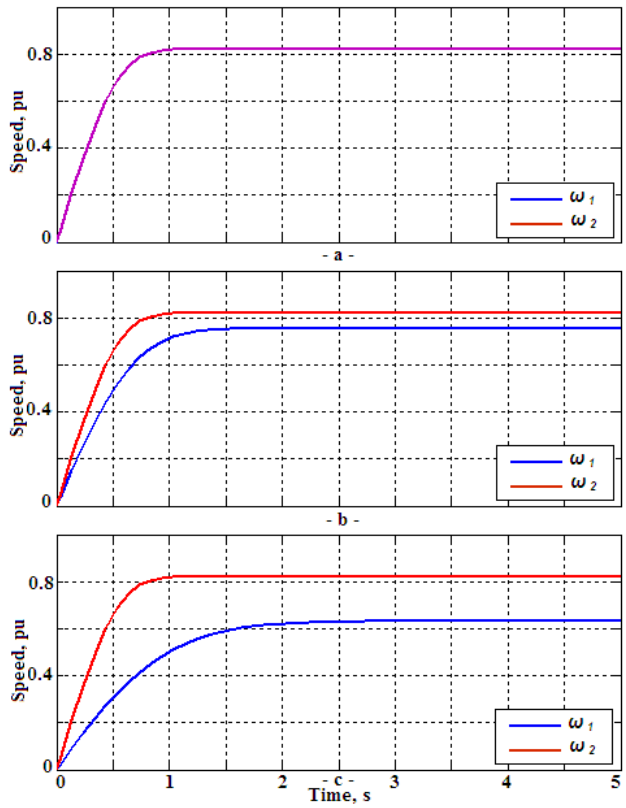


Fig.4 Speed of the motors: *a*) $L_1$=$L_2$, *b*) $L_1$=1.4$L_2$, *c*) $L_1$=2.4$L_2$

The factor $K_m$= 0.7 is quiet enough to achieve the required synchronization when the loads are different by 40%. Fig.6 presents the system performance at larger difference in motor loads. The system was tested when the difference of loads is greater than 40%. Fig.6 shows that some oscillations may appear at larger values of load difference. However, the system goes into synchronism and both of the motors will run, after an acceptable recovery time, with equal speeds but lower than the rated. The oscillations here appear because of the strong effect of *RL*-element. In this case, just after the appearance of this big difference in loads, the mostly loaded motor will rapidly slow down and the lightly loaded motor will rapidly speed up. Because of the system inertia, the motors will continue changing their speeds even after the equality causing some oscillations. After 2-3 cycles of oscillations, the system goes into synchronism within an acceptable recovery time as shown in Fig.6c.

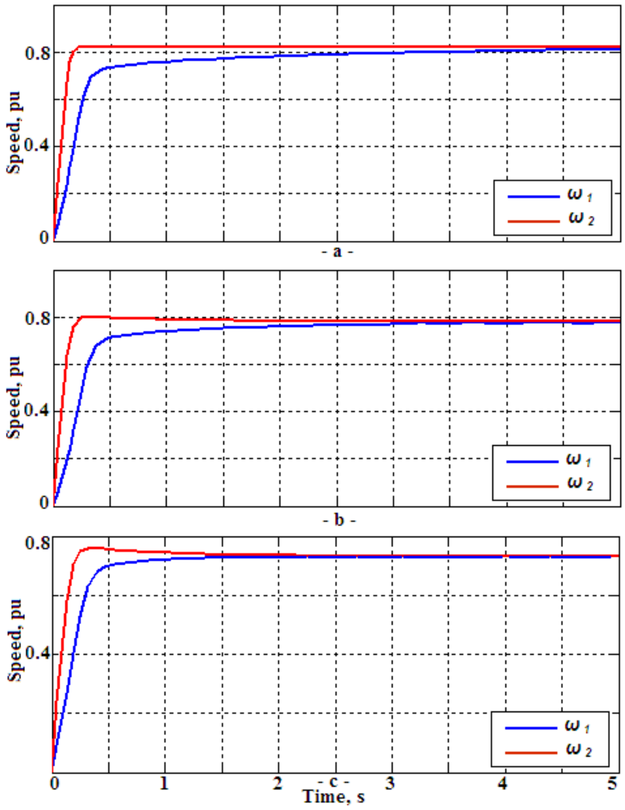


Fig.5 Speed of the motors when $L_1$=1.4$L_2$ and $K_c$=9, *a*) $K_m$= 0.4, *b*) $K_m$= 0.6, *c*) $K_m$= 0.7

Fig.7 shows speed curves of the motors with the same value of $K_m$= 0.7, load difference of 40% and with different values of $K_c$. From Fig.7, it is noticed that as factor $K_c$ decreases, the recovery time reduces. The recovery time is reduced by one third when $K_c$ is decreased from 9 to 7.

From the simulation results, it is obvious that by choosing the suitable *RL*-element parameters (factor $K_m$), the required synchronization capability may be achieved for a given maximum possible loads difference of the system motors. And by choosing the optimum value of factor $K_c$, the difference of motors speeds during starting and the recovery time can be reduced.

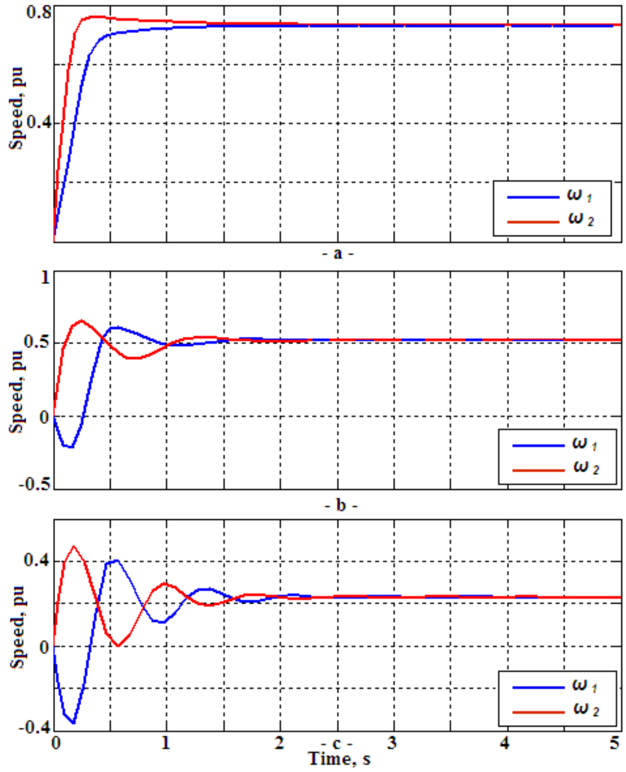


Fig.6 Speed of the motors when $K_c$= 9 and $K_m$= 0.7, *a*) $L_1$=1.4$L_2$, *b*) $L_1$=1.8$L_2$, *c*) $L_1$=2.4$L_2$

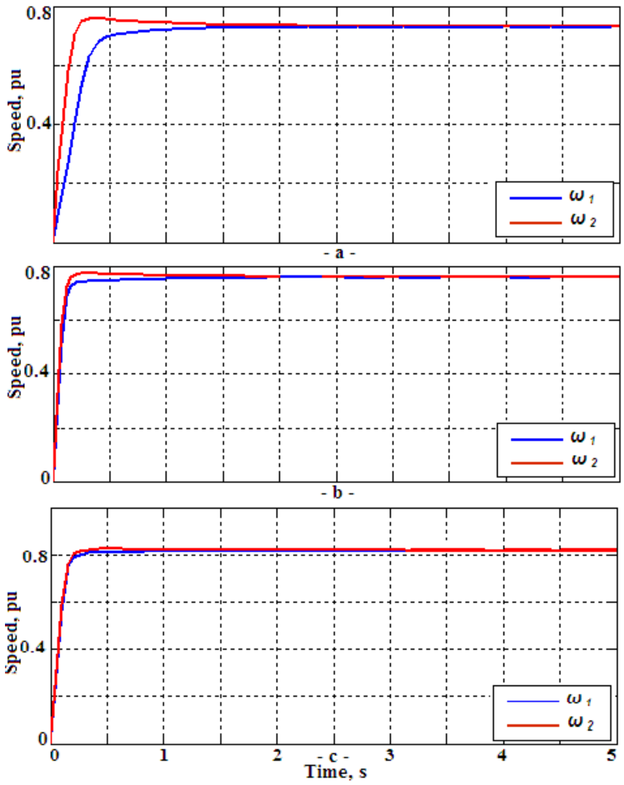


Fig.7 Speed of the motors when $K_m$= 0.7 and $L_1$=1.4$L_2$, *a*) $K_c$= 9, *b*) $K_c$= 7, *c*) $K_c$= 6

## 4 Conclusion

Speed synchronization system of multiple capacitor-start single-phase induction motors can be achieved by using the traditional electromagnetic shaft synchronization system. The maximum limit of the synchronization capability and the recovery time of the system may be achieved by selecting the stator and rotor parameters (adjusting $K_c$ and $K_m$ factors). Increasing factor $K_m$ improves the system performance and reduces the drawback in terms of synchronization capability, while decreasing factor $K_c$ decreases the recovery time by developing larger starting torque. On the other hand, the main disadvantage of the proposed system is the reduction of the system efficiency which is associated with the slip-ring rotors and *RL*-element.

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