Synchronous Braking of Electrical Working Shaft System

Akayleh A Saqer

Electrical Engineering Department, Faculty of Engineering
Tafila Technical University
Tafila66110, Jordan
E-mail: akayleh_em@yahoo.com

***Abstract* - In this paper a new control approach for a synchronous capability and recovery time of electrical working shaft system is developed and presented well. The proposed control strategy is to give maximum synchronous capability, minimum recovery time and speed synchronization at start-up and dynamic braking processes. Effective roles of series connected additional resistor, inductor and capacitor elements on the synchronous capability and recovery time of the system are studied. The simulation is carried out using Matlab/Simulink; and simulated results also confirm the validity of the proposed approach.**

Keywords - Synchronous capability; Recovery time; dynamic braking; Qualty factor, Electrical working shaft.

I. INTRODUCTION

Synchronous systems are widely employed to connect two or more non-mechanical connected induction motors; it is mainly used for adjusting the speed synchronization at different loads. The most popular of traditional synchronization system is a system of synchronization with auxiliary machines, synchronization systems with electrical working shaft and synchronization systems with electromagnetic systems operating shaft [3,7,11]. The new proposed electrical working shaft consists of two identical three phase wound rotor induction motors connected together to the same alternating current supply with common additional resister, inductor and capacitor elements connected series in the rotor circuit Fig.1.

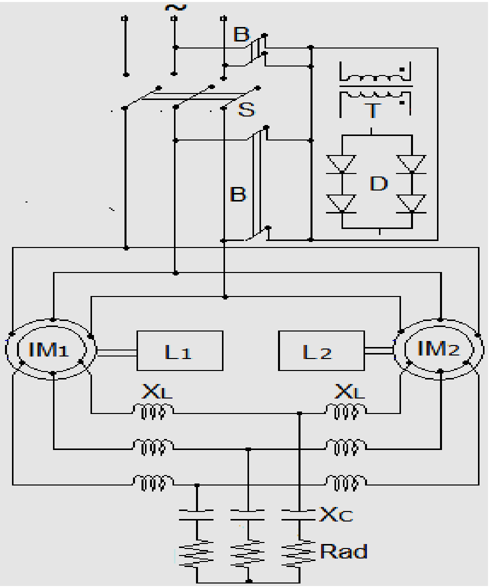

Figure.1 Electrical working shaft system.

Applications of electrical working shaft system as a speed synchronization control system can be found in paper machines, offset printing, textiles and differential drives [1,9,17].All multiple non connected mechanisms systems require synchronous rotation at start-up [2,8,10]. As a rule they requires also synchronous braking, therefore it is necessary to develop and to explore methods of braking to avoid the different angular position that allows smooth running at every start-up process. Synchronous braking as synchronous start-up should have difference braking torques proportional to located loads, determining and controlling these torques can be set changing additional parameters [5,13].In this paper a new compound design of electrical working shaft system will be investigated and controlled at start-up and braking stages based on traditional start-up of electrical working shaft system and dynamic braking techniques.

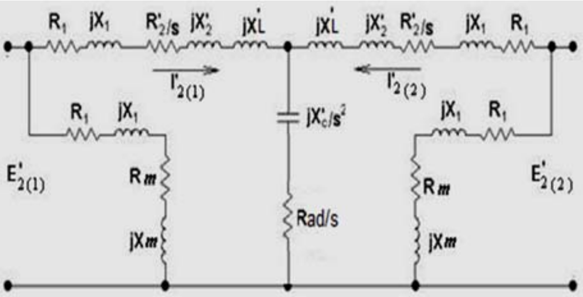

Figure 2: Simplified equivalent circuit of the system.

II. EQUIVALENT CIRCUIT

The simplified equivalent circuit for the electrical working shaft at dynamic braking is shown in Fig.2.

Where:
R_1, X_1: Stator resistance and inductive reactance.

R_2,X_2: Rotor resistance and inductive reactance.
Rc, Xm: magnetization circuit parameters.
$E_{2\,(1)}$,$E_{2(2)}$: Rotor phase voltage.
$I_{2\,(1)}$,$I_{2(2)}$: Rotor currents.
Rad: Additional resistance.
X_L, X_C: Additional inductive and capacitive reactance.
S: Slip.

A Difference of loads causes difference of phase angles between the stator and rotor windings (α_1, α_2), therefore it is possible to represent the difference in loads by the differences in phase shift. When the loads become equal, the phase shifts will be equal too ($\alpha_1 = \alpha_2$) and ($\Delta\alpha = 0$) [3]. Using equivalent circuit Fig.2, the rotor currents can be found from as:

$$I'_{2(1)} = \frac{I_o X_\mu}{2}\left[\frac{(1-\ell^{\Delta\alpha})}{\left(\frac{R'_2}{S_1}\right)^2 + J\left(X_K + X_\mu + X'_L\right)^2} + \frac{(1+\ell^{\Delta\alpha})}{\left(\frac{R'_2 + R'_{ad}}{S_1}\right)^2 + J\left(X_K + X_\mu + X'_L - \frac{2X'_C}{S_1{}^2}\right)^2}\right] \tag{1}$$

$$I'_{2(2)} = \frac{I_o X_\mu}{2}\left[\frac{(1-\ell^{-\Delta\alpha})}{\left(\frac{R'_2}{S_2}\right)^2 + J\left(X_K + X_\mu + X'_L\right)^2} + \frac{(1+\ell^{-\Delta\alpha})}{\left(\frac{R'_2 + R'_{ad}}{S_2}\right)^2 + J\left(X_K + X_\mu + X'_L - \frac{2X'_C}{S_2{}^2}\right)^2}\right] \tag{2}$$

Where: I_o - magnetization current. , $X_K = X_1 + X_2$.

If the first motor is determined as a master motor of the system so ($E'_{2(1)} = I_o X_\mu$), ($E'_{2(2)} = I_o X_\mu e^{j\Delta\alpha}$), ($S_1 = S_b = \omega / \omega_o$) and ($\Delta\alpha = \alpha_1 - \alpha_2$). If the second motor is determined as a master motor of the system so ($E'_{2(2)} = I_o X_\mu$),($E'_{2(1)} = I_o X_\mu e^{j\Delta\alpha}$),($S_2 = S_b = \omega / \omega_o$) and ($\Delta\alpha = \alpha_2 - \alpha_1$), then, the first and the second motor torques at dynamic braking mode can be determined as [6,14].

$$T_1 = \frac{2.91\, I'^2_{2(1)} (R'_2 + 2R'_{ad})}{\omega_o S_1} \tag{3}$$

$$T_2 = \frac{2.91\, I'^2_{2(2)} (R'_2 + 2R'_{ad})}{\omega_o S_2} \tag{4}$$

Where: ω_o - no load speed, S_b - Slip at dynamic braking.

Adding (1,2) to (3,4) then after some transformations the torque equations at dynamic braking will become:

$$T_{1(2)} = \frac{1.46 I_o{}^2 X_\mu{}^2}{\omega_o}\left[\left(\frac{\left(\frac{R'_2}{S_b}\right)(1-\cos\Delta\alpha)}{\left(\frac{R'_2}{S_b}\right)^2 + \left(X_K + X_\mu + X'_L\right)^2} + \frac{\left(\frac{R'_2 + 2R'_{ad}}{S_b}\right)(1+\cos\Delta\alpha)}{\left(\frac{R'_2 + 2R'_{ad}}{S_b}\right)^2 + \left(X_K + X_\mu + X'_L - \frac{2X'_C}{S_b{}^2}\right)^2}\right) \pm \left(\frac{\left(X_K + X_\mu + X'_L - \frac{2X'_C}{S_2{}^2}\right)}{\left(\frac{R'_2 + 2R'_{ad}}{S_b}\right)^2 + \left(X_K + X_\mu + X'_L - \frac{2X'_C}{S_b{}^2}\right)^2} - \frac{\left(X_K + X_\mu + X'_L\right)}{\left(\frac{R_2'}{S_b}\right)^2 + \left(X_K + X_\mu + X'_L\right)^2}\right)\sin\Delta\alpha\right] \tag{5}$$

Consider S_R as a resonante slip, Q_F as a qualty factor and Tr as a resonante torque, the final value of torque equations at dynamic braking will be:

$$T_{1(2)} = T_R \frac{S_b}{S_R}\left[\left(\frac{(1-\cos\Delta\alpha)}{K\left(1+\frac{Q_F{}^2}{2}(\frac{S_b}{S_R})^2\right)} + \frac{(1+\cos\Delta\alpha)}{\left(1+Q_F{}^2(\frac{S_b}{S_R}-\frac{S_R}{S_b})^2\right)}\right) \mp \left(\frac{\left(1-(\frac{S_b}{S_R})^2\right)\sin\Delta\alpha}{K\left(1+\frac{Q_F{}^2}{K}(\frac{S_b}{S_R})^2\right)} + \frac{\sin\Delta\alpha}{\left(1+Q_F{}^2(\frac{S_b}{S_R}-\frac{S_R}{S_b})^2\right)}\right)\right]$$

where:

$$S_R = \sqrt{\frac{2X_C}{X_K + X_\mu + X_L'}}, \quad Q_F = \frac{\sqrt{2X_C'(X_K + X_\mu + X_L')}}{R_2' + 2R_{ad}'}$$

$$Tr = \frac{1.46 I^2 X_\mu{}^2 S_r}{\omega_o\left(R_2' + 2R_{ad}'\right)}, \qquad K = \frac{R_2'}{\left(R_2' + 2R_{ad}'\right)}$$

III. SYSTEM MODELING

The block diagram of the system developed in Matlab/Simulink is shown in Fig. 3 [12,13],where the main equivalent circuit equations, dynamic torque equations, angular speed, and angular positions equations are represented. This model consists of two blocks each of them has a specific function.

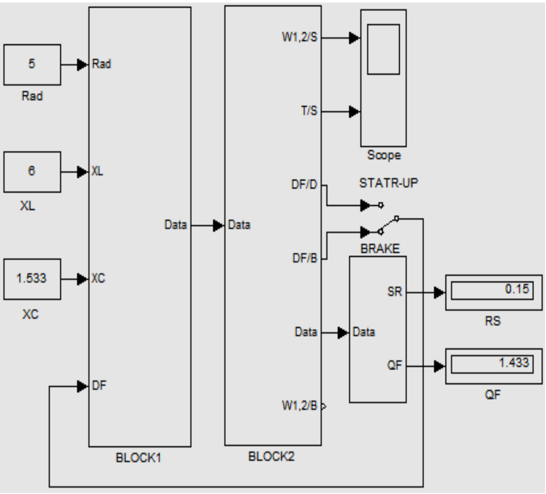

Figure 3: System block diagram

Block1 consists of different basic data, such as induction motors parameters:1.5kw, 50Hz, 4Pole, Vph=220v, Io=3.56 A, ,Xμ= 118Ω,R1=4.25 Ω ,R_2=4.26 Ω,X_1=4.82 Ω,X_2=7.425 Ω ,additional parameters in rotor common circuit:, R_{ad},X_L X_C and feedback signals:Δα,S_1,S_2 [2,5].The main equations block (2) consists of four blocks which are contains the mathematical equations that are responsible for dynamic torque calculation of the motors correction elements responsible for the synchronization process between the motors. Using the dynamic torque, angular speed, position phase shift and slip equations and relationships as a feedback signals which goes back to the block of data though one of start-up or brake modes. Using the above model synchronous capability and recovery time of the system at start-up and dynamic braking are calculated at different S_R and, Q_F values.

IV. OPERATION AND TEST

The proposed mathematical model represents a start-up and a braking synchronization of electrical working shaft system by adjusting additional parameters in the common rotor circuit. This will be accomplished according to required synchronous capability and recovery time. The proposed model can operate in the following modes:

A. *Start-Up Mode*

Start-up mode has been investigated in [3], the system only works with the additional resistor, which plays an important role in determining the required synchronous capability and recovery time of the system. It has been tested with different loads and additional resistors. At the first moment of start-up, the electromotive force induced in both motor coils is moved towards the additional element in the common rotor circuit. At equal loads the electromotive forces will be equal in magnitude and opposite in direction, therefore the motors will operate with the same speeds as separately induction motors. If the system works with different loads, the electromotive forces will not be equal in magnitude and direction, This will produce excess energy in the common rotor circuit, this energy leads to increase in speed of the highest load motor and decrease in speed of the lowest load motor until the equality of both motors speeds is reached as shown in Fig.4A. Figure.4B shows that increasing the additional resistor (Rad*) leads to low efficiency and some mechanical vibrations that occurs during start-up [3].

A proposed equitable solution to these problems is to automatically adjusting the resistance according to the required synchronous capability or difference in loads.

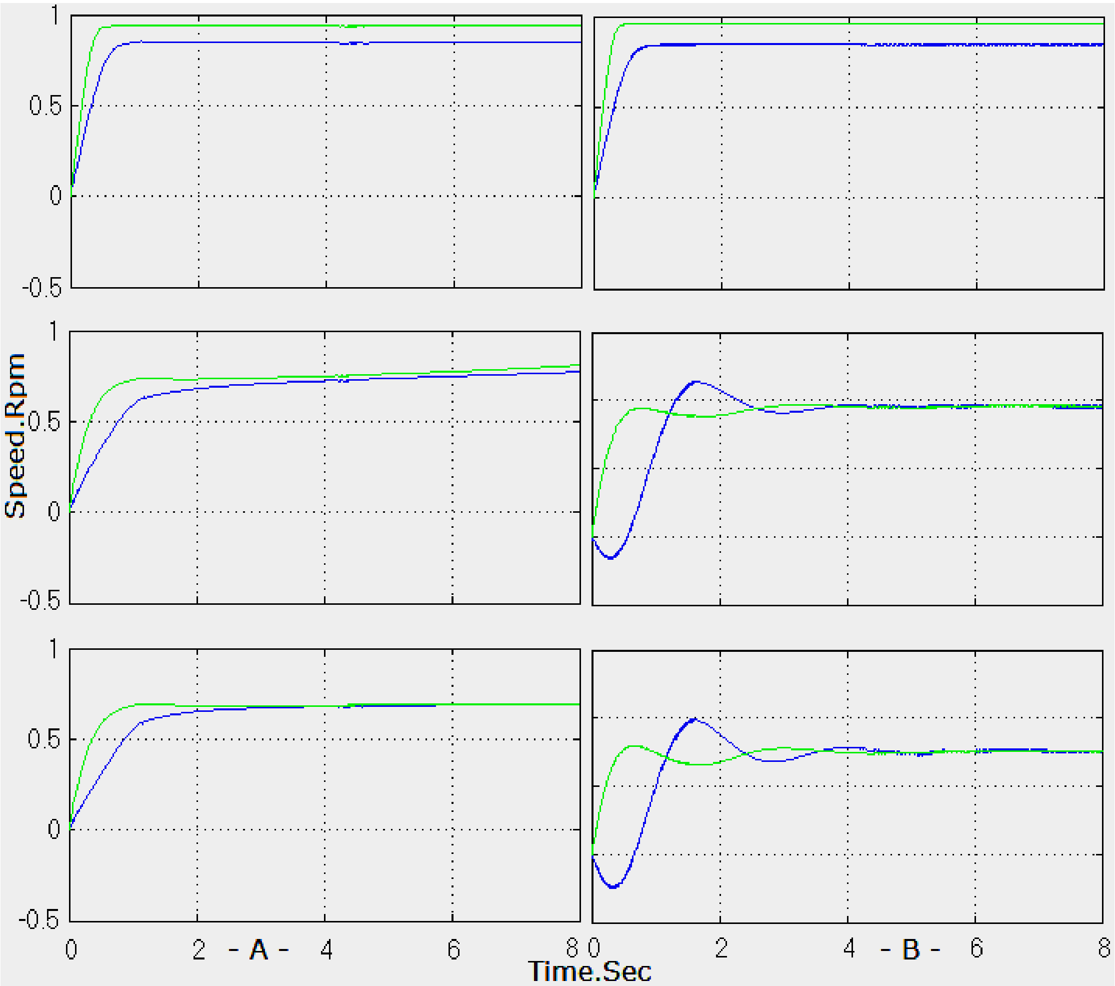

Figure 4: Speed response at start-up mode. A- L1=2L2, Rad*=0/1/1.2 , B- L1=3L2, Rad*=0/3/3.4.

B. *Braking Mode*

The actual difficulty in the dynamic braking modulation is the relationship between the stator (constant) and the rotor (rotating) fields [4,18]. In this mode, the system consists of additional resistor, inductor and capacitor elements. Figure. 5A shows the effect of resonant slip (Sr) on the dynamic torque at constant quality factor (Qf = 2.4). It also shows that an increase in (Sr) leads to an increase in the resonant torque (Tr) and in the real effective zone of dynamic torque, which leads too to an increase in synchronous capability and a decrease in recovery time of the system. At a constant resonant slip (Sr=0.1) Fig. 5B shows the effect of the quality factor on the dynamic torque. It shows that an increase in (Qf) leads to a reduction in the resonant torque (Tr) and to a reduction in the real effective zone of dynamic torque. This leads to a decrease in synchronous capability and an increase in recovery time of the system.

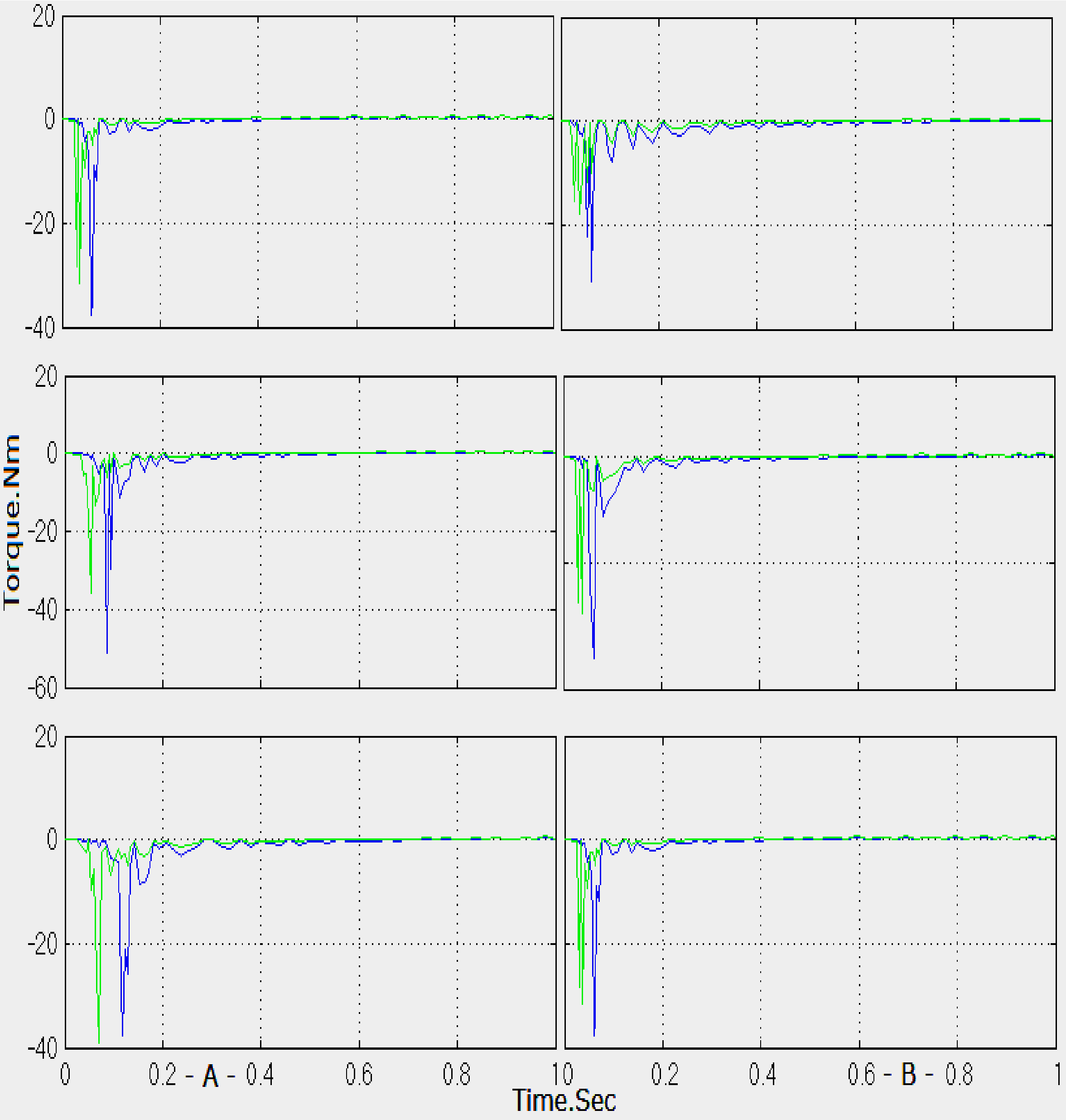

Figure 5: Torque response at braking mode. A- Qf=2.4, Sr=0.1/0.15/0.2, B- Sr=0.1, Qf=1.2/ 1.8/2.4.

C. *Full Mode*

The full time mode represents the full work period of the system from start-up to a full braking at different values of Sr, Qf. Figure.6A shows the effect of the resonant slip (Sr) on the speed response at constant qualty factor (Qf=3). It shows that increasing (Sr) leads to increasing synchronous capability and decreasing recovery time. At (Sr>0.2) it shows the increasing in both synchronous capability and recovery time.

The relationship between the quality factor and the speed response at constant resonant slip (Sr=0.1) shows that an increase (Qf) leads to a decrease in synchronous capability and an increase in recovery time. At (Qf> 2.4) the synchronous capability will be very small and the system does not have a coordinated braking as shown in Fig. 6B.

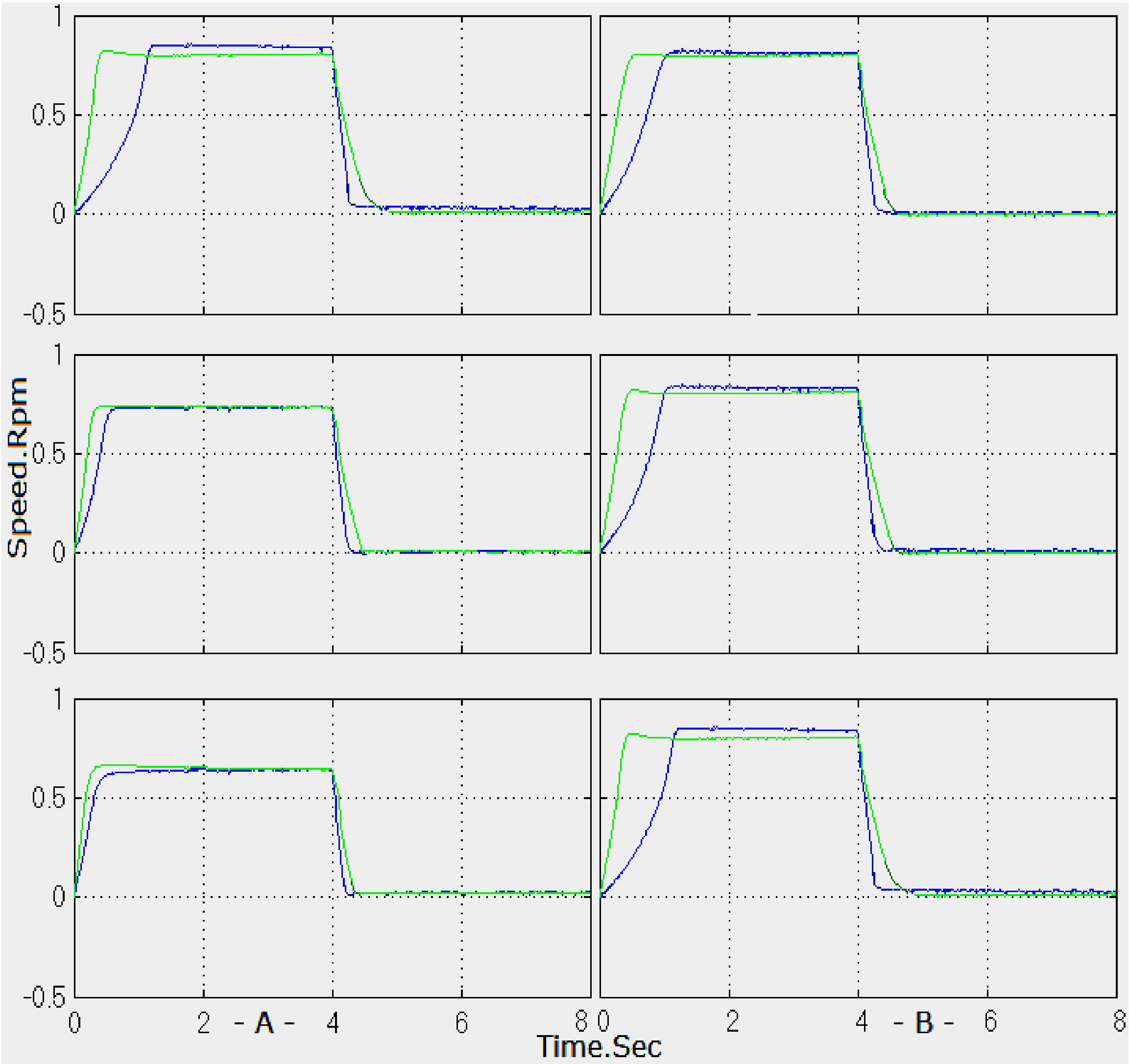

Figure 6: Speed response at full mode. A- Qf=3.0, Sr=0.1/0.15/0.2 , B- Sr=0.1, Qf=1.8/ 2.4/3.0.

Finally to work with smooth and perfect synchronous - torque capability and recovery time at start-up and dynamic braking we need the following sequence:

- Select additional resistor to give required synchronous capability.
- Select resonant slip to give required synchronous braking torque.

VI. CONCLUSION

The new proposed module creates enough synchronous braking torque that leads to smoothing start-up with minimum vibrations, depending on the difference loads we can select the values of resonant slip and quality factor that gives the required synchronous capability and recovery time. Increasing the quality factor value leads to some residual non synchronous speed which is clearly shown at the end of braking process. Also decreasing the quality factor value leads to increase in the capacitor element volume. Therefore this method is not recommended for systems with high difference in loads. For our case expedient zone of resonant slip and quality factor should be considered between 0.1>Sr<0.2 and 1.5>Of<2.4.

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