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Balanced Capacitor Self Excited Braking Of A Polyphase Induction Motor.

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ABSTRACT. *This work presents balanced capacitor self excited braking of a polyphase induction motor. Analytic expressions have been developed to determine the boundaries of speed and capacitance at which self excitation occurs in a three phase induction motor as a function of the machine parameters. Various factors which influence the braking performance of a given motor are examined. Balanced capacitor self excited braking of an induction motor depends on the self excitation process. Provided that a residual magnetism exists, the machine will self-excite, thus producing a counter torque which eventually brakes the machine. A model of this braking scheme has been built with MATLAB/SIMULINK R2013b software and a test three phase induction motor is simulated using the model. Various simulation results were obtained in order to examine the effects of terminal capacitance, load torque and control resistance. Highlights of this study on a test machine shows that using 1500µF capacitor without control resistance, the speed range for self excitation was 1780-400 RPM, while the range fell to 1780-1550 RPM when a series control resistance of 500Ω is connected to each capacitor. However, in the former case, the current transient of 5000A occurred upon initiation of self excitation, while for the latter case, the transient current is about 300A with the load torque being the same. Also without a control resistance, the transient voltage across the 1500µF capacitor is 1100V while it is only 4V with a series control resistance of 500Ω per phase. It has also been found that the use of large capacitors causes excessive voltage and current transients, while small capacitors are not suitable for low speeds.*

KEY WORDS- *Self-excitation, Braking, Induction motor, residual magnetism, MATLAB, SIMULINK.*

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I. INTRODUCTION

Induction motors are used mainly in industrial manufacturing and processing systems due to their characteristic robustness, ruggedness and low cost. Braking in an induction motor depends mainly on the principle of producing a counter torque to oppose the motoring torque in order to bring it to a full stop or slow down its speed. Braking is very important in industrial processes in order to ensure the safety of operating personnel and equipment. Generally, there are two categories of braking applied in braking induction motors in industries, which are electrical and mechanical braking methods. Electrical braking can further be classified as plugging, Ac dynamic, D.C dynamic and capacitor self excited braking.

D.C dynamic braking is widely used to brake the squirrel cage induction motor [1]. It involves the connection of a D.C source across any two of the stator terminals with the other terminal kept open while the main supply is switched off [2]. Since the rotating shaft's kinetic energy is to be dissipated, the additional D.C energy is indeed a waste, and gives rise to the problem of overheating in certain industrial application requiring frequent stops. Another major disadvantage of D.C dynamic braking is that it fails when there is general power failure, and hence requires an external D.C source or an auxiliary braking technique, should the safety of operating personnel and equipment be guaranteed [1].

Plugging in an induction motor involves the process of phase sequence reversal of the the supply to a motor by interchanging any of the two stator supply leads in order to produce a reversal torque that will brake the motor [3]. Plugging is usually applied only in smaller induction machines due to some problems it suffers when applied to large induction motors. One of the disadvantages of plugging is that large currents are drawn from the supply, which are usually above the starting current of the motors and raises the problem of damage to motor windings as well as huge power loss [3]. Another downside of plugging is that the machine tends rotate at the reverse direction if the power supply is not switched off when the speed reaches zero.

When two or all of the three stator terminals are short-circuited after switching off the main supply, magnetic braking is achieved [1,2]. After the supply is cut off, the residual magnetic flux of the rotor rotating due to inertia induces currents in the short-circuit. These induced currents oppose the motion of the motor according to Lenz's law.

Capacitor or capacitor reactor braking has been suggested in [4] as an alternative to D.C dynamic braking. This involves the connection of capacitor across any two of the stator terminals when the main supply is disconnected with the other terminal left open. However, this braking technique suffers from a low braking torque.

A multi-stage braking scheme which combines capacitor and magnetic braking has been analyzed in [1]. In this scheme, the capacitor braking method is first applied at high speed while the magnetic braking is applied at low speed. The effect of saturation of the leakage flux has been taken into account by expressing the leakage flux into two components the saturable and the non saturable parts. It has been found out that saturation effects tend to increase the magnitude of capacitor required for achieving self excitation.

Balanced capacitor self excited braking of an induction motor is achieved by connecting a balanced set of uncharged capacitors across each of the stator terminals while the main supply has been disconnected. A steady state analysis of this braking scheme has been attempted in [3,5,6], where a number of assumptions were made to solve a fifth order polynomial in terms of the magnetizing reactance. An estimation of the braking time has been made in [3]. Balanced capacitor self excitation braking depends mainly on the principle of self excitation. This is made possible since an induction motor can operate as a generator, by connecting capacitors across the stator terminals, which accept the leading current from the induction generator operation. Braking is achieved by conversion of the kinetic energy into electrical energy. Provided residual magnetism is present, there is always the possibility that self excitation will occur.

II. STEADY STATE BRAKING ANALYSIS

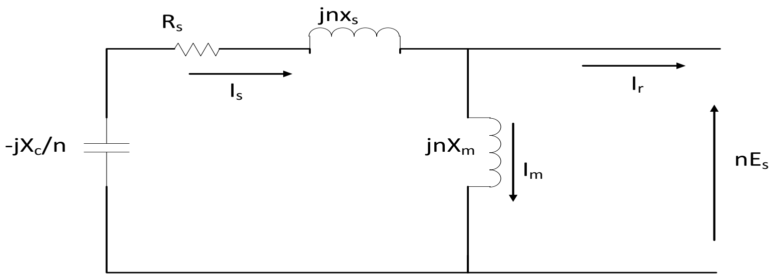
The conditions necessary for self excitation are governed by saturation of the main flux paths, which in the steady state is regarded as a variation of the magnetizing reactance. For self excitation to occur, the value of the capacitive reactance connected across the stator terminals must have a reactance less than the critical slope of the magnetization curve at the supply frequency. Upon self excitation, the speed of the motor falls, leading to a fall in frequency. As a result, the magnetizing reactance, which has an inverse relationship with the frequency, increases until it reaches the critical slope of the magnetization curve. When this happens, self excitation ceases and the machine is brought to rest under the influence of friction and load torque.

For a steady state analysis of a three phase induction motor under balanced capacitor self excitation braking, the normal motoring conventions will be applied, though the machine generating electrodynamically speaking. The following table results from a comparison between normal motor operation and balanced capacitor self excited braking operation.

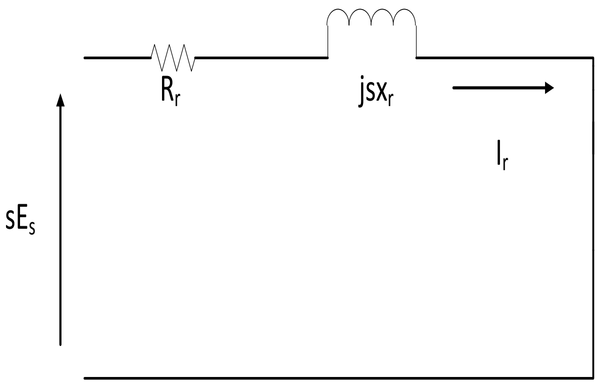
Table 1. Comparison between normal motoring operation and capacitor self excited braking condition.

	Normal motor operation	Braking condition
Stator frequency (Hz)	f	Nf
Synchronous speed(r.p.s)	f/p	nf/p
Slip speed (r.p.s)		
Rotor speed (r.p.s)	sf/p	sf/p
Slip frequency (Hz)	(1-s)f/p	vf/p = (n-s)f/p
	Sf	sf

The circuit used for the analysis is shown in figure 1



(a)
Frequency is nf



(b) frequency is sf

Figure 1. Steady state circuit diagram for balanced capacitor self excited braking of a three phase motor. The stator frequency is nf = (v+s)f.

E_s is the stator induced e.m.f by a current I_m at a frequency 'f' in Hz. X_c is the capacitor's reactance. Figures 1 (a) and (b) are embodied as shown in figure 2 using voltage scaling factor.

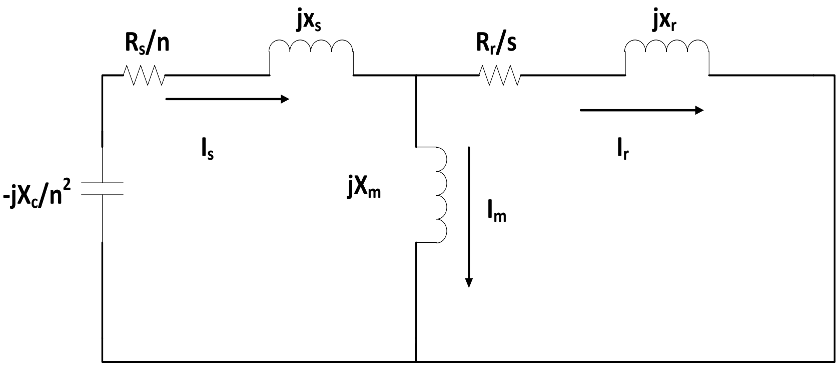


Figure 2.Simplified equivalent steady state circuit. Frequency = f Hz.

Hancock [5] has reported detailed analysis of figure 2. Applying Kirchhoff's Voltage Law (KVL) to the two loops of figure 2:

$$I_s[R_s/n + j(x_s + X_m - X_c/n^2)] - jI_rX_m = 0 \quad (1.).$$

$$I_r[R_r/s + j(x_r + X_m) - jI_sX_m = 0 \quad (2).$$

From equation (2)

$$I_s = I_r[R_r/s + j(x_r + X_m)]/jX_m \quad (3).$$

Substituting equation (3) into (1) and separating into real and imaginary parts we have:

$$R_rR_s/ns - X_rX_s + X_rX_c/n^2 - X_m^2 + j[(X_s - X_c/n^2)R_r/s + X_rR_s/n] = 0 \quad (4.)$$

Equating the real and imaginary parts to zero and solving simultaneously;

$$(X_rR_s + R_sX_m^2)s^2 + (v + s)R_rX_m^2 s + R_sR_r^2 = 0 \quad (5.)$$

solving this as a quadratic equation in s, we obtain two values of the slip as follows;

$$s_1 = -R_rR_s/vX_m^2 \quad (6.)$$

$$s_2 = -vR_rX_m^2/(R_rX_m - X_rR_s) \quad (7.)$$

The corresponding values of n are obtained using equation (8)

$$n = v + s \quad (8)$$

That is,

$$n_1 = v - R_rR_s/vX_m^2 \quad (9.).$$

$$n_2 = v - vR_rX_m^2/(R_rX_m - X_rR_s) \quad (10).$$

Approximately;

$$n_2 \approx vX_r^2R_s/(X_r^2R_s + X_m^2R_r) \quad (11.)$$

It is noteworthy that the values of slip are negative, confirming the fact that the machine is generating electrodynamically speaking.

From equations (1),(2),(6),and (9), we obtain:

$V^4X_m{}^5 + (x_sv^4 - v^2X_c)X_m{}^4 - (2v^2R_rR_s + Rsv^2)X_m{}^3 - (2x_sv^2R_sR_r + x_rR_s{}^2v^2)X_m{}^2 + R_s{}^3R_rX_m + x_rR_sR_r = 0$ (12)

This is a fifth order polynomial in terms of the magnetizing reactance. The significance of equation (12) lies on the fact that self excitation is essentially a variation of the magnetizing reactance.Thesolution of this equation gives the fractional speed at which self excitation occurs as a function of the magnetizing reactance and the capacitive reactance. Neglecting the third and lower powers of X_m, we obtain

$v^4X_m{}^5 + (X_sv^2 - v^2X_c)X_m{}^4 = 0$ (13)

and

$X_m = X_c/v^2 - x_s$ (14)

or $X_s = X_c/v^2$ (15)

where $X_s = X_m + x_s$ (16)

Thus, $v = (X_c/x_s)^{1/2}$ (17)

Next, substituting the the next set of values, that is s_2 and n_2 into equation and neglecting the third and lower powers of X_m we have:

$X_m \cong [v^2R_s{}^2(4x_rx_s + 3x_r{}^2) - 4X_cR_sx_r(R_r + R_s)]/ [X_c(R_r + R_s)^2 - v^2R_s{}^2(x_r + x_s)]$ (18)

Simplifying further,

$X_m = [v^2(4x_s + 3x_r)/X_c - 4(1 + R_r/R_s)]/[(1 + R_r/R_s)^2 - v^2(x_r + x_s)/X_c]$ (19)

To consider the practical limits, it is clear that X_m and$x_r$must be positive. This implies that the numerator and denominator of equation (19) must either be both positive or negative.

For the numerator to be positive,

$v^2(4x_s + 3x_r)/X_c - 4(1 + R_r/R_s) > 0$ (20)

viz, $v > \sqrt{\{[4(1 + R_r/R_s)X_c]/(4x_s + 3x_r)\}}$ (21)

and for the denominator,

$(1 + R_r/R_s)^2 > v^2(x_r + x_s) / X_c$ (22)

i.e, $v < \sqrt{[(1 + R_r/R_s)^2X_c/(x_r + x_s)]}$ (23)

Now in general, $4/(4x_s + 3x_r) < (1 + R_r/R_s)/(x_r + x_s)$ so that equation (22) and (23) are compatible. Thus the condition where both the numerator and the denominator are negative is therefore, incompatible. Assuming that $x_r = x_s$, and Rr = R_s, then the lower limit of v will be $1.07(X_c/x_s)^{1/2}$ while the upper limit of v is $1.41(X_c/x_s)^{1/2}$. This range of speed is too narrow and when the value of x_s is substituted into the equations (21) and (23) for the lower and upper limits of v, it will be found out that a very large capacitance is needed to bring about a small decrease in speed of the motor. Therefore, s_2 and n_2 are not useful for predicting effective and efficient braking, since the total braking time will tend to be very large, which is an unwanted situation.

The values s_1 and n_1, and $X_m = (X_c/v^2) + x_s$will correspond to a more efficient and effective braking condition, since the braking time will tend to be smaller in this case.

III. SIMULATION RESULTS

The machine with parameters in table 2 was simulated using MATLAB/Simulink R2013b and the results of the simulation shpw good agreement with predicted results.

Table 2. Machine parameters for simulation

Parameter	Value
Number of phases	3
Number of poles, p	4
Frequency(Hz)	60
Rated Speed(Rpm/Rps)	1780/186.40
Nominal Power (Hp/Kw)	50/37.3
$X_{lr}' = X_{ls}$ (Ω)	0.33
R_r' (Ω)	0.06
R_s (Ω)	0.1
X_m (Ω)	11.46
Moment of Inertia J(Kgm^2)	0.4
Friction constant,B (NmS/rad)	0.02187

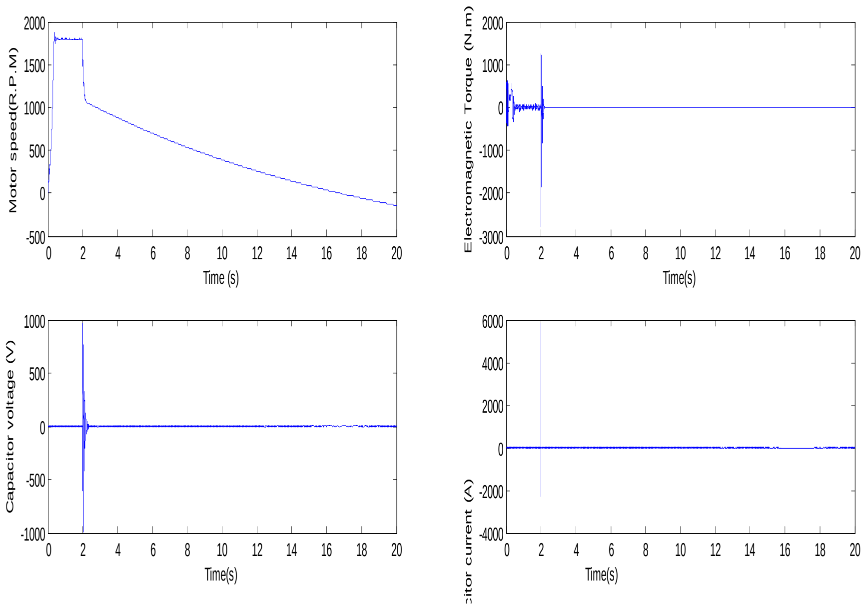


Figure 3.Braking performance for 1000µF terminal capacitor per phase and no control resistance.

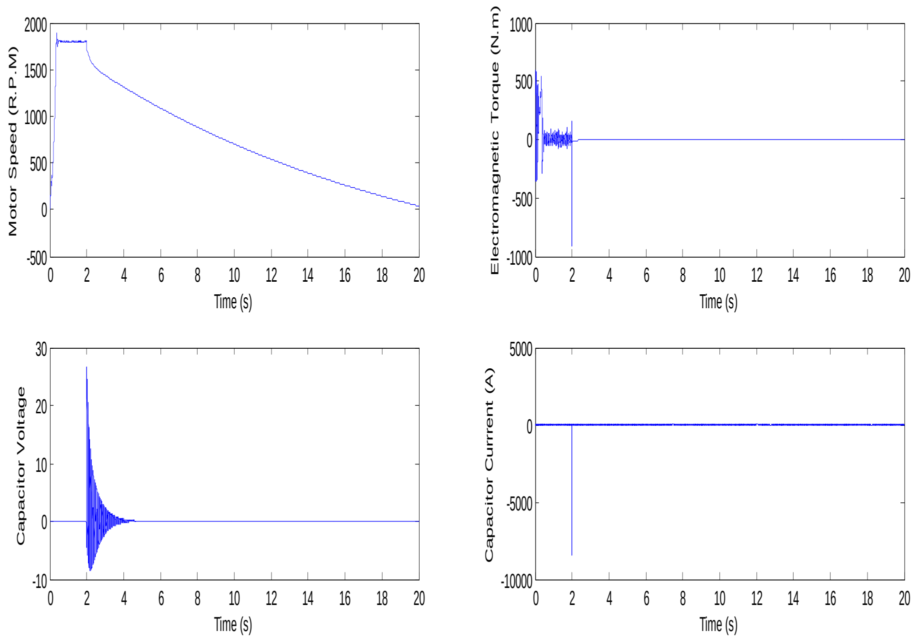


Figure 4. Braking performance using 1000µF and 100Ω control resistance.

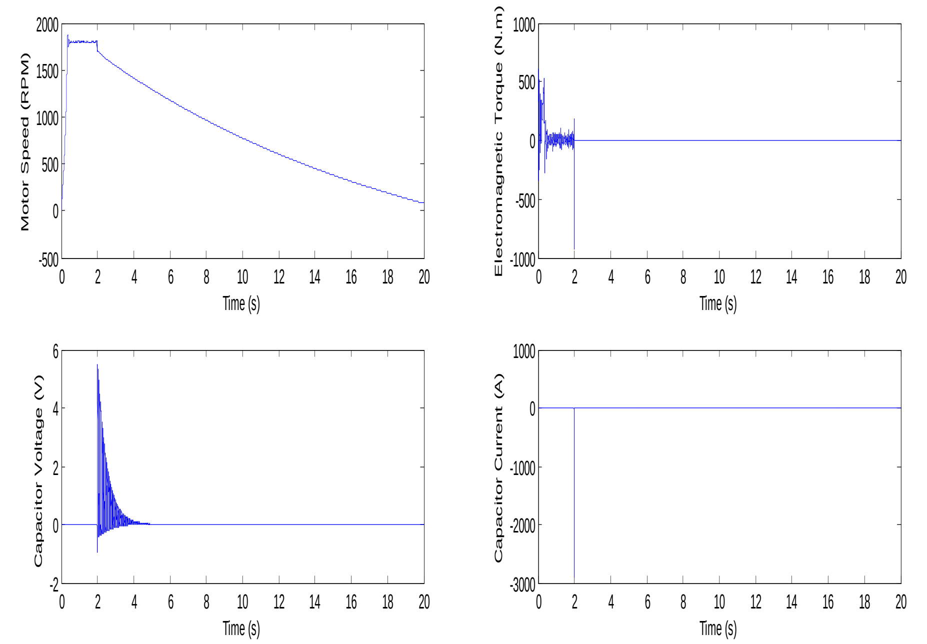


Figure 5.Braking performance with 500 Ω series control resistance and a1000μF capacitor.

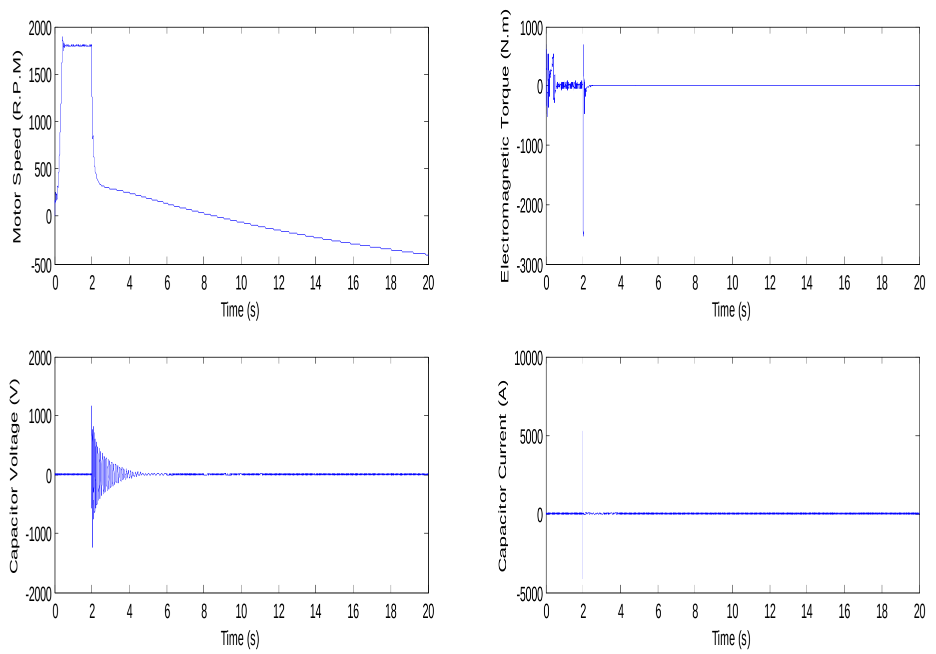


Figure 6.Braking performance for 1500μF terminal capacitor per phase and no control resistance.

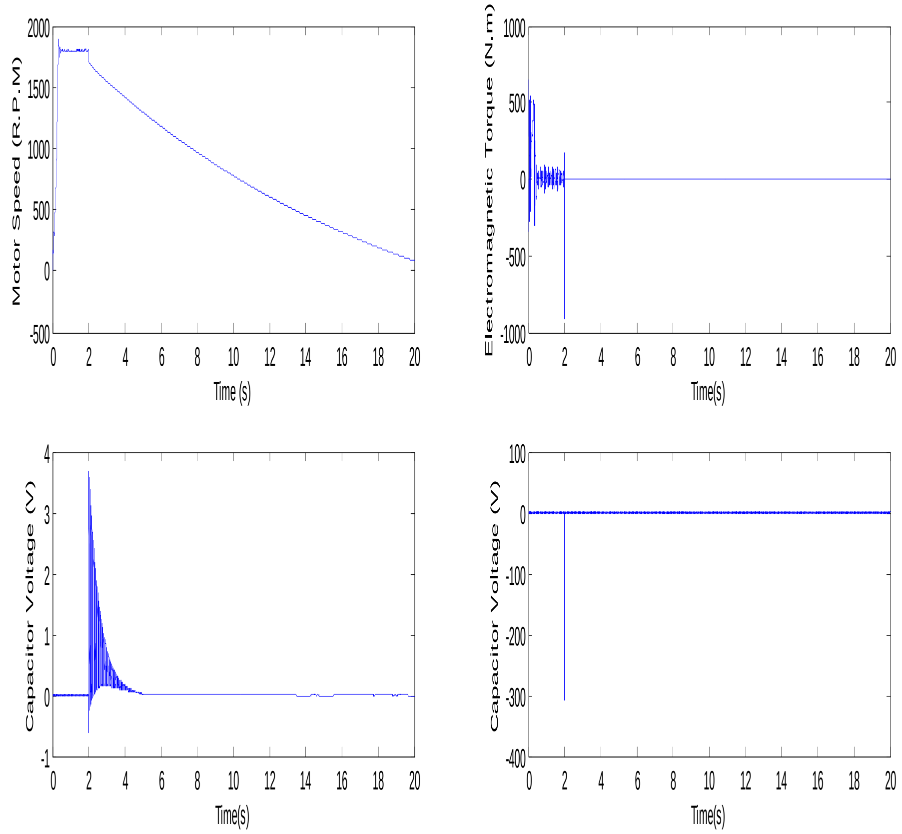


Figure 7.Braking performance for 1500µF terminal capacitor per phase and a series 500Ω control resistance.

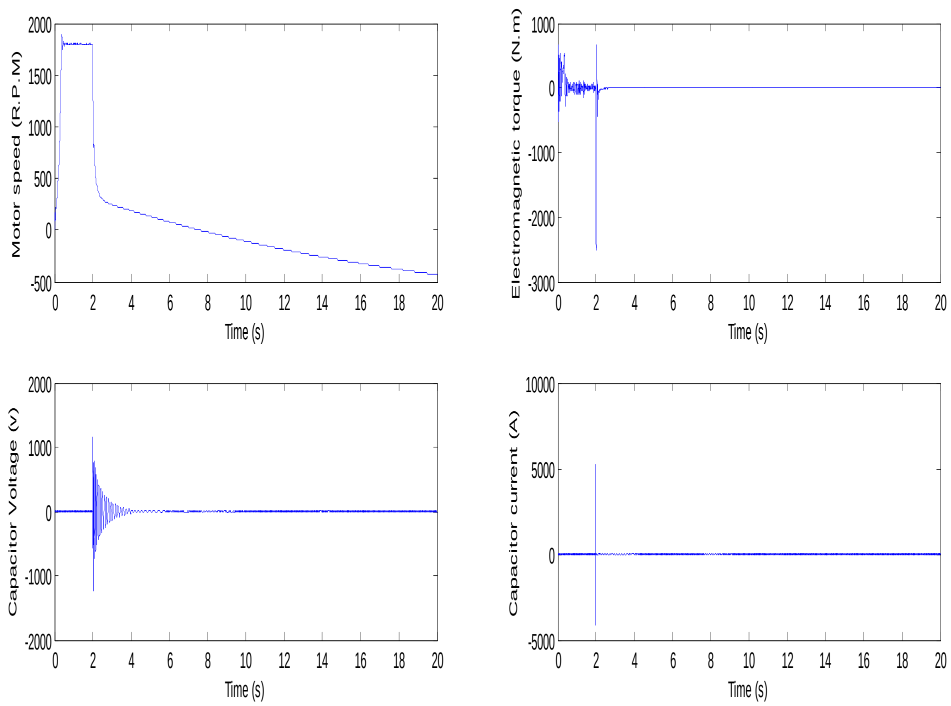


Figure 8.Braking performance for 1500µF terminal capacitor per phase and a parallel 500Ω control resistance.

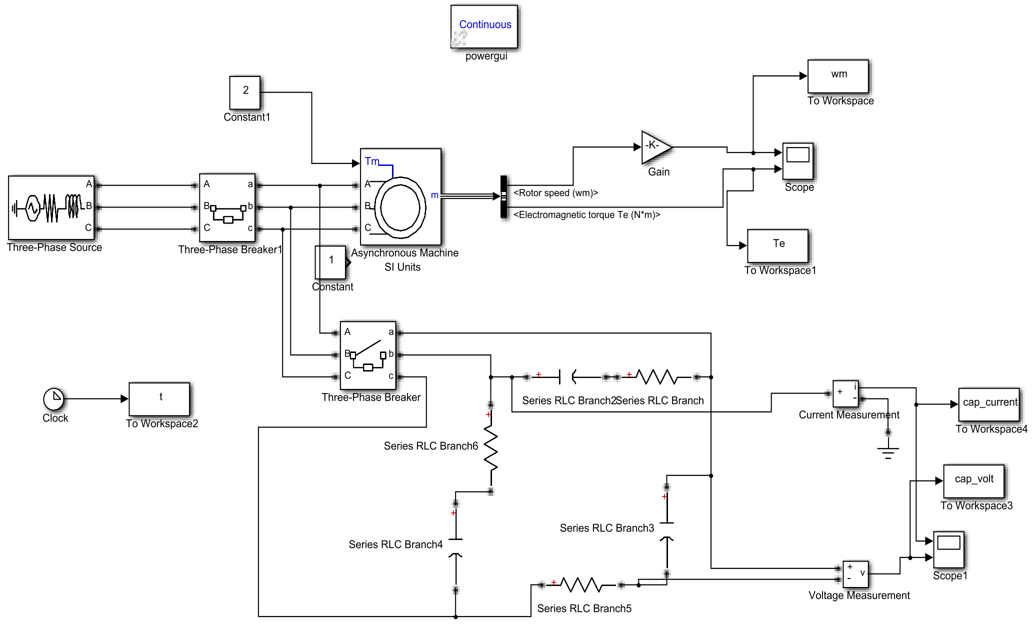


Figure 9. Simulink Model for balanced capacitor self excited braking of an induction motor

IV. DISCUSSIONS.

Balanced capacitor self excited braking of a polyphase induction motor has been analyzed as an efficient braking scheme. The most effective braking is achieved with a given value of terminal capacitance at higher speeds; therefore this braking scheme is more efficient at high speeds. In order to mitigate the high voltage and current transients usually associated with high value of capacitors, which can cause damage to the machine, an optimum value of series resistance is connected. High values of capacitance are not very suitable because they cause very high voltage and current transients that can damage the machine's windings.

Comparing the steady state analysis with the simulation results, it is obvious that there is a reasonable correlation between analytic and simulation results for the test three phase induction motor.

From figures 3 to 8, where a constant load torque was applied to the machine and different combinations of capacitor and series control reactance were used for each simulation, it is clear that the electromagnetic torque remains the same throughout the cases when no control resistance was used. Without the use of a control resistance, the speeds range at which self excitation occurred was greater, and hence, total braking time was smaller, but the problem is that there is high transient current at the initiation of self excitation, which is larger than the starting current as obvious from figure 3. Also there is a high transient voltage across the capacitor (and hence stator windings), which is higher than the rated voltage as evident from figures 3 and 6. These high voltage and current transients can cause serious damage to the machine, and hence the need for a mitigating element.

In order to solve the problems observed from balanced capacitor self excited braking without control resistance, series resistance of suitable magnitude is connected to each capacitor. As is obvious from figures 4, 5, and 7 when a control resistance is used, the high voltage and current transients in the rotor and stator circuits are reduced to harmless values. However, the use of control resistance suffers the problem of decreasing the speed range at which self excitation occurs and hence increases the total braking time. Therefore, to solve this problem, an optimum value of control resistance is used in order to strike a balance between reduction of voltage and current transients and reducing the total braking time.

Comparing figures 6and 8, where the same load torque and terminal capacitance were used, except that no control resistance was used in the former case, while a parallel resistance of 500Ω was used in the latter case, it is obvious that the characteristics (graphs) are the same. This refutes the claim in [2] that parallel control resistance enhances braking performance as it neither reduced the braking time nor reduced the high current and voltage transients.

V. CONCLUSIONS

Balanced capacitor self excited braking of a polyphase induction motor has been shown to be an effective method of braking an induction motor. The simulation results show a good correlation with predicted results. It is obvious from the simulations that an optimum value of control resistance and terminal capacitance produce the best braking performance. This braking method has been shown to be more effective at higher speeds. Control resistances, when connected in series improve the braking performance by reducing the high voltage and current transients generated upon the initiation of self excitation, but reduce the speed range over which self excitation occurs. From figures 6 and 8, it is obvious that series control resistance is superior to parallel control resistance in terms of current and voltage transient reduction.

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