



Split-phase motor running as capacitor starts motor and as capacitor run motor

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Abstract

In this paper, the input parameters of a single phase split-phase induction motor is taken to investigate and to study the output performance characteristics of capacitor start and capacitor run induction motor. The value of these input parameters are used in the design characteristics of capacitor run and capacitor start motor with each motor connected to rated or standard capacitor in series with auxiliary winding or starting winding respectively for the normal operational condition. The magnitude of capacitor that will develop maximum torque in capacitor start motor and capacitor run motor are investigated and determined by simulation. Each of these capacitors is connected to the auxiliary winding of split-phase motor thereby transforming it into capacitor start or capacitor run motor. The starting current and starting torque of the split-phase motor (SPM), capacitor run motor (CRM) and capacitor star motor (CSM) are compared for their suitability in their operational performance and applications.

Keywords

Auxiliary winding; Capacitor start motor; Capacitor run motor; Maximum torque; Split-phase motor; Standard capacitor; Starting current; Starting torque

Introduction

The split-phase motor has both main winding and auxiliary winding and these windings are displaced by 90 electrical degree [1, 2]. Single phase capacitor motor can be used for driving pumps, lower power fans, refrigerators, drills, washing machines and compressors [3, 4]. The split-phase induction motor is investigated through MATLAB normal running operation and at maximum torque by the addition of appropriate value of resistance connected to the starting winding. The input parameters of the single phase split-phase induction motor is used as input data to capacitor start-motor and capacitor run motor which are further investigated to run at maximum torque respectively through the gradual addition of the value of capacitor until motor (capacitor start and capacitor run) develop maximum torque. The starting current and the starting torque of each motor is investigated by simulation. The effect of the starting current and the starting torque of the split-phase motor, capacitor-start motor and the capacitor-run motor through the characteristics are displayed by MATLAB. The study of these performance characteristics enable one to know the areas of applications of each motor. The study of the single phase motors which are low power factor machines becomes necessary because of their applications in domestic, commercial and industrial purposes. In [5], there was investigation on an effective model of single phase induction motor with an adjustable switching capacitor. For purpose of understanding, the winding diagrams are drawn for two single phase motors with different number of slots. In [6], capacitors are varied based on torque developed in order to determine the capacitor motor's maximum efficiency. Researchers such as Mahdi Alshamasin also investigated the optimal performance of single phase capacitor run induction motor [7]. The capacitor versus efficiency of permanent split capacitor (PSC) is also investigated by MATLAB and determined in [8]. Single phase motors are not self-starting because they do not produce rotating magnetic field. Single phase motors are classified as single phase induction motors (resistant-start or split-phase, capacitor start, capacitor run and shaded pole), single phase synchronous motors (reluctance and hysteresis motor) and single phase series or universal motor [9]. The induction motor type of motors have squirrel cage rotors and a single phase distributed stator winding. Using double revolving theory [10], when the rotor is at standstill and the stator winding is connected to single phase ac power supply, a pulsating magnetomotive force (mmf) and a pulsating magnetic flux Φ_s is established in the axis of the stator winding. This flux induces current in the rotor circuit by transformer action which

results in the production of the pulsating magnetic flux Φ_r along axis of the stator flux Φ_s . According to Lenz's law, the two fluxes oppose each other. The angle between these fluxes is zero and no starting torque will be developed. When the rotor is in running conditions either by spinning the rotor or by using auxiliary circuit, the motor can develop torque. A pulsating field is equivalent to the combination of two rotating magnetic fields of half the magnitude but which is rotating at the same synchronous speed in opposite directions. Some characteristics of single phase induction motors are investigated in [11]. The pulsating produces no torque but produces a humming effect and makes the motor noisier than poly-phase motors. The effect of this pulsating torque can be minimized by using elastic mounting or rubber pads.

The aim of this research is to study the starting current and starting torque of the capacitor start motor and capacitor run motor at the value of capacitor that is connected each to their auxiliary winding to develop maximum torque using the input parameters of the split-phase motor. We want to establish the advantage of one motor over the others. Motor running at low starting current at maximum torque will be suitable for any applications.

Material and method

The input data of a single phase split-phase induction motor are collected from laboratory for the purpose of investigation. This is achieved by using the data through the mathematical expressions for the purpose of simulation in order to obtain the desired result. The input parameters are given in Table 1.

Table 1. Input parameters

Symbol	Quantity	Input values
$V_m=V_a$	Input phase voltage to main and auxiliary winding	120V
R_{1m}	Main winding resistance	1.6Ω
X_{1m}	Main winding reactance	2.5Ω
R_{1a}	Auxiliary winding resistance	2.5Ω
X_{1a}	Auxiliary winding reactance	2.5Ω
$R_{2'}$	Auxiliary resistance referred to main winding	1Ω
$X_{2'}$	Auxiliary reactance referred to main winding	1.6Ω
X_{mag}	Magnetisation reactance	42Ω
f	Frequency	50Hz
C_1	Capacitor for capacitor start motor	$300\mu F$
C_2	Capacitor for capacitor run motor	$30\mu F$

Algorithm

Algorithm is or are series of steps taken in order to obtain desired results of any problem. First SPM, CRM and CSM characteristics are investigated on normal operations. SPM input data are later transformed to the design characteristics of capacitor run and capacitor start motor. The magnitude of capacitor that develop maximum torque in capacitor start motor and capacitor run motor are investigated and determined by simulation.

Stator winding diagrams

The winding techniques of a single phase motor are shown in both Figure 1 and 2. These are not results but illustrations. The winding diagrams of single phase motors are made up of 16 and 24 slots respectively with each of 4 poles shown in Figure 1 and 2.

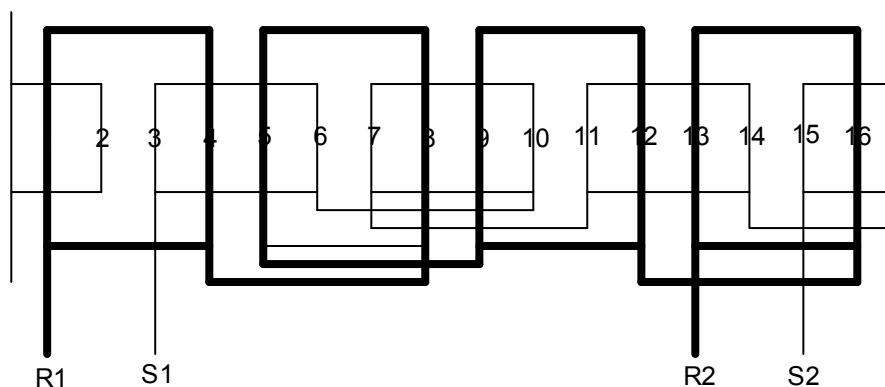


Figure 1. Single phase winding with 16 slots and 4 poles

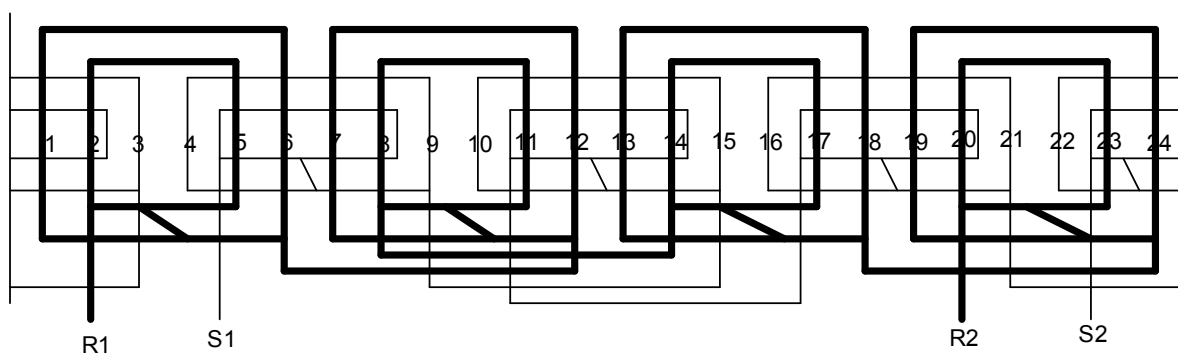


Figure 2. Single phase winding with 24 slots and 4 poles

Split-phase circuit diagram

The circuit diagram of a split-phase motor is shown in Figure 3.

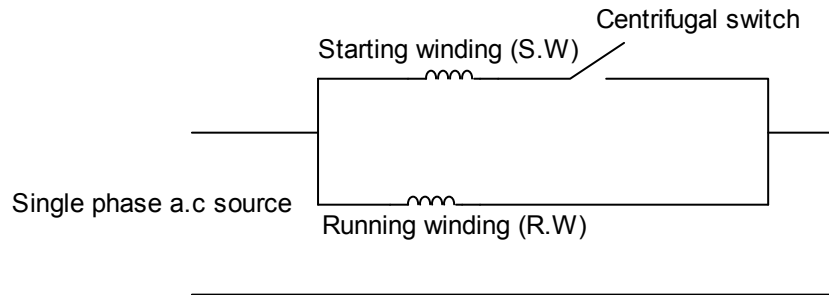


Figure 3. Split-phase motor

The running winding has large size of wire with low resistance and high inductive reactance, as a result, the current of the running winding lags behind the voltage to approximately 90° electrical degrees while the starting winding has low wire gauge or low wire size with high resistance and low inductive reactance, and due to low wire size, the high starting current known as the locked rotor current can cause motor to overheat resulting in the failure of the starting winding.

The current of the starting winding leads the current of the running winding by approximately 30° electrical degrees as shown in Figure 4.

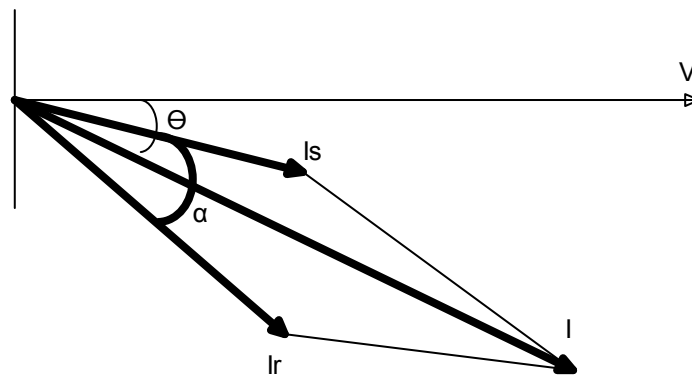


Figure 4. Vector diagram of split phase motor

The torque developed by this motor is directly proportional to the size of an angle between the running and starting winding currents.

The direction of rotation of the motor is normally reversed by interchanging the leads of the starting winding.

The speed regulation of the motor varies from 2 to 5% between no-load and the full-load and the motor moves with constant speed like three phase induction motor.

Split phase motor is used as fans, washing machines and in domestic refrigerators. In refrigerators, relay coils are used instead of centrifugal switches.

Main and Auxiliary circuit at standstill and running condition

The Equivalent circuit of split phase motor at standstill condition is shown in Figure 5.

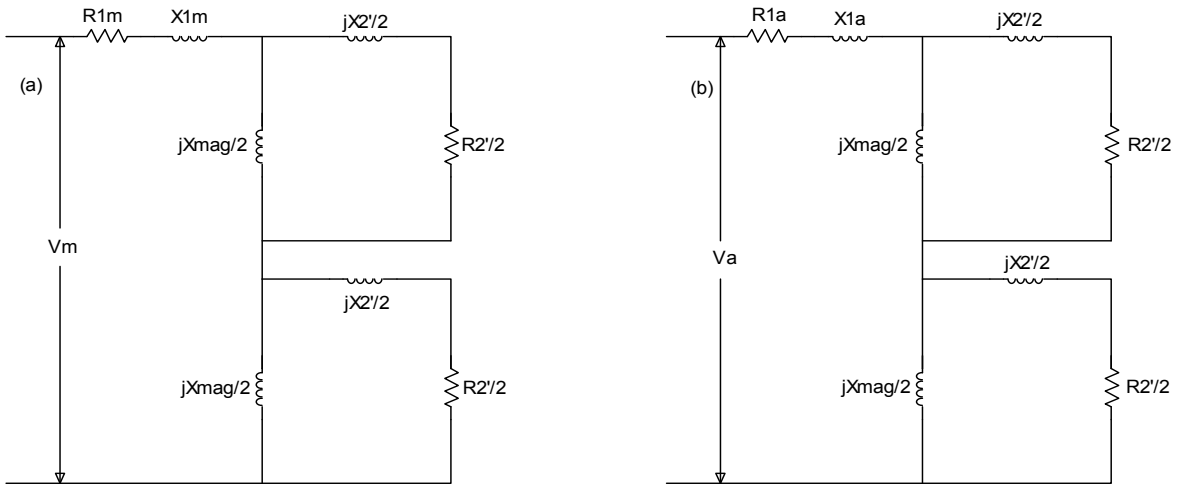


Figure 5. Equivalent circuit of split-phase motor at standstill condition

Figure 5 left is the Equivalent circuit of the main winding at standstill while Figure 5 right is the Equivalent circuit of the starting or auxiliary winding at standstill condition.

Figure 6 shows the Equivalent circuit of the main winding of split phase motor at running condition.

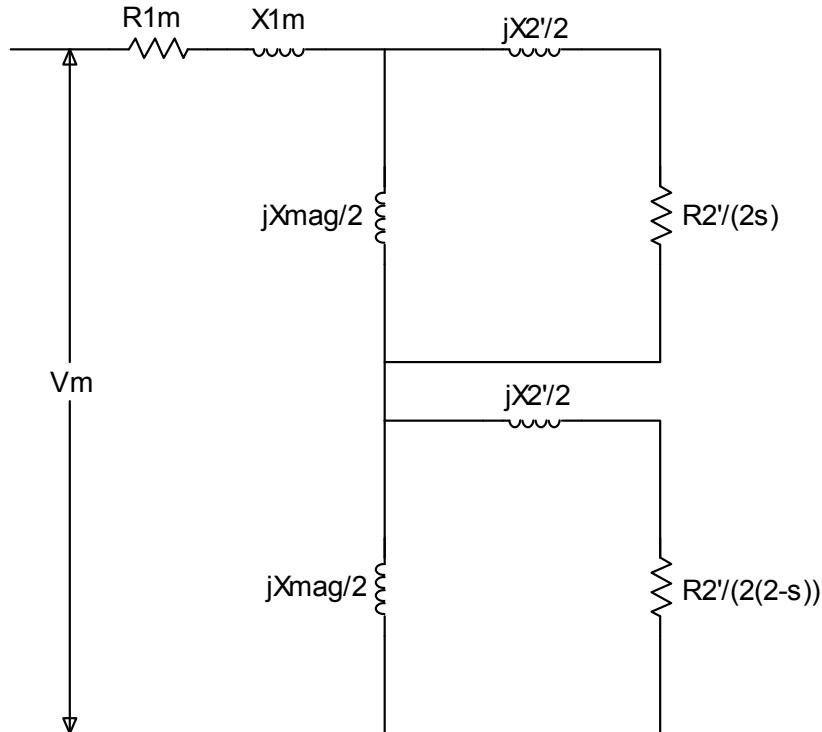


Figure 6. Equivalent circuit of Split phase motor at running condition

Capacitor star motor

The circuit diagram of capacitor start motor is shown in Figure 7, a capacitor is connected in series with the starting winding (larger wire size than the split phase motor) in order to provide higher the starting torque than that obtained from split phase motor and also to limits the starting surge current to a value lower than that of the split phase motor.

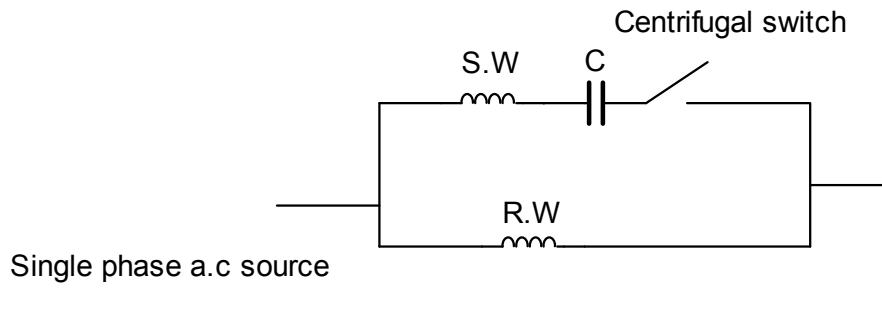


Figure 7. Capacitor start

The capacitor does not improve the power factor of the motor but improve the starting torque. The starting torque depends on the angle between the starting current and the running winding and this angle is larger in a capacitor start, induction run motor than in a split phase motor, and a high starting torque is obtained with low starting current. Figure 7 is the vector diagram of a capacitor start, induction run motor.

The motor is used where a strong starting torque is needed such as in the compressors, vacuum pumps, high pressure water pumps and oil burners. The vector diagram of capacitor start motor is shown in Figure 8.

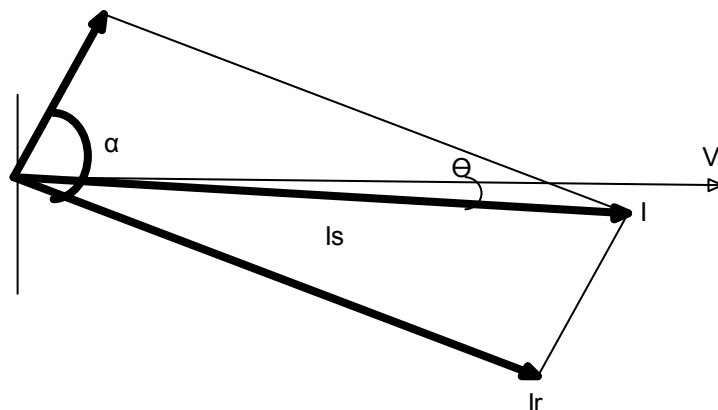


Figure 8. Vector diagram of capacitor start, induction run motor

Figure 9 shows the Equivalent circuit of capacitor start motor at standstill condition. Figure 9(a) is the main winding circuit at standstill condition while figure 9(b) is the auxiliary winding circuit at standstill condition. At standstill condition, the slip is zero.

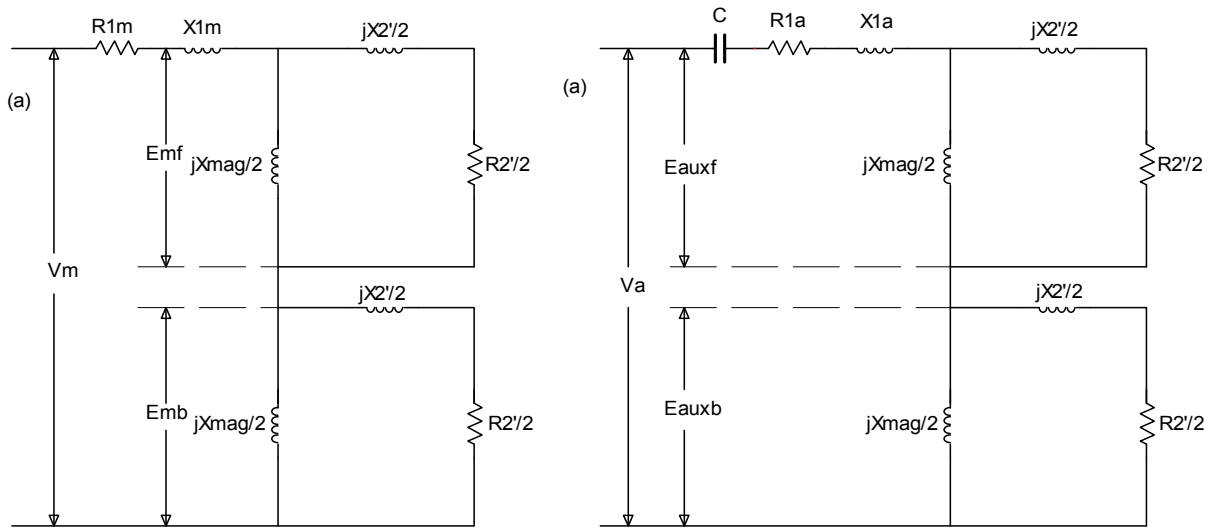


Figure 9. Equivalent circuit of capacitor start motor at standstill condition

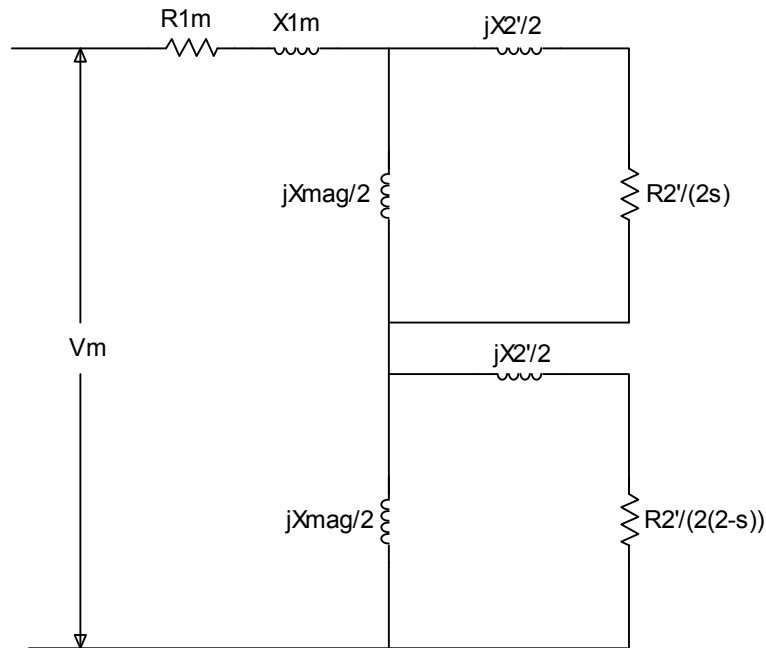


Figure 10. Equivalent circuit of main winding of capacitor start motor at running condition

The Equivalent circuit of the main winding of capacitor start motor at running condition is shown in Figure 10. At forward rotating field, the slip is indicated as s and when the field rotates backward, the slip is indicated as $(2-s)$.

Capacitor run motor

In Figure 11, a capacitor is connected in series with the starting winding which is not disconnected by any switch when the speed rises up to 75% but remain in circuit during the

starting and running operation.

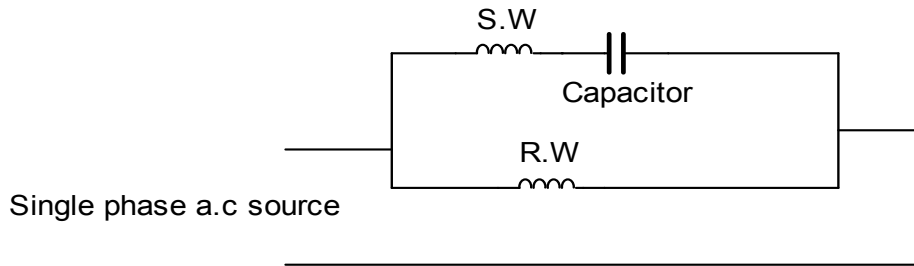


Figure11. Capacitor start, capacitor run motor with one capacitor

This type of motor is quiet in operation and it is used in oil burners, fans, wood working and metal working machines.

Capacitor start, capacitor run motor with two capacitors

The capacitor start, capacitor run motor with two capacitors has a high starting torque with good speed regulation and a power factor of nearly 100 per cent at the rated load.

This type of motor is used as fans, compressors and in refrigerator units. The circuit diagram is shown in Figure 12. Figure 13 shows the Equivalent circuit of capacitor run induction motor at standstill condition.

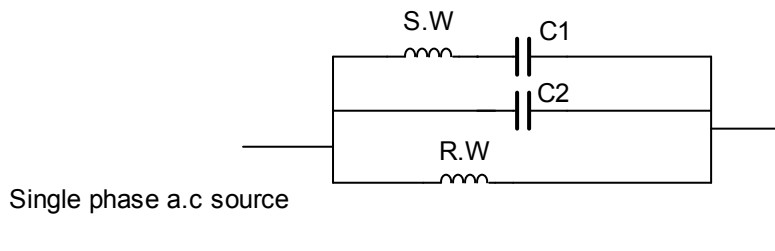


Figure12. Capacitor start, capacitor run motor with two capacitors

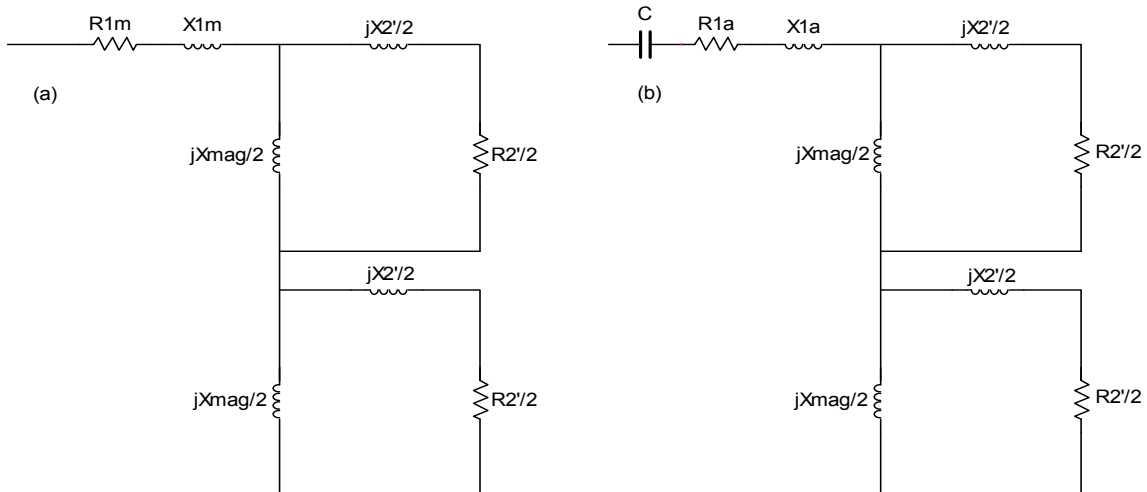


Figure 13. Equivalent circuit of a capacitor run induction motor at standstill condition

Figure 13(a) is the Equivalent circuit of the main winding of the capacitor run motor while Figure 13(b) shows the Equivalent circuit of the auxiliary winding of the capacitor run motor. The Equivalent circuit of capacitor run induction motor at running condition is shown in Figure 14.

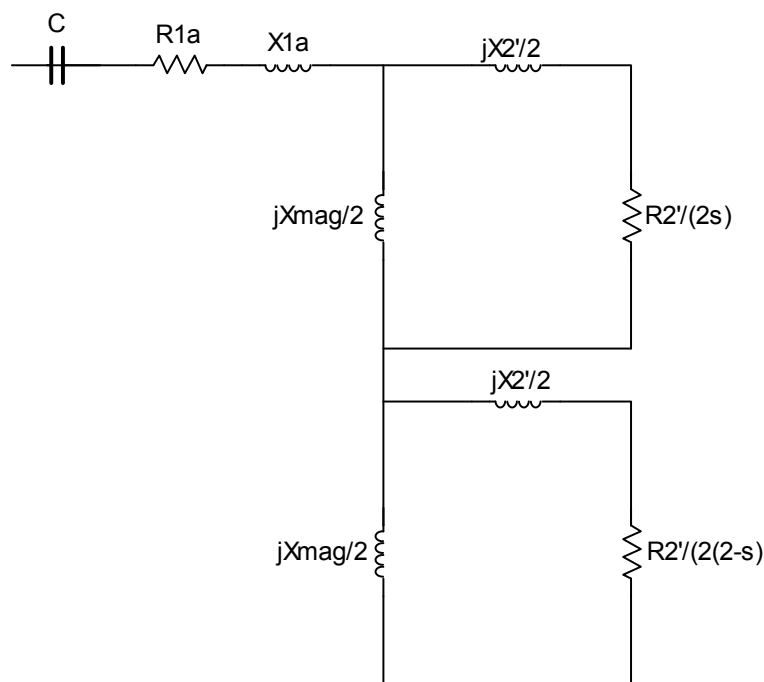


Figure 14. Equivalent circuits of a capacitor run induction motor at running condition

Mathematical analysis at no-load and full load

At no-load

The leakage impedance of the main and auxiliary winding is given by:

$$Z_{1m} = R_{1m} + jX_{1m} \tag{1}$$

The leakage impedance of the auxiliary winding is given by:

$$Z_{1a} = R_{1a} + jX_{1a} \tag{2}$$

The ration of the number of turns of the auxiliary winding to the number of turns of the main windings is given by:

$$a = \frac{N_a}{N_m} \tag{3}$$

The value of the external capacitor to be inserted in series with the auxiliary winding to obtain maximum starting torque is given by:

$$C = \frac{10^6}{2\pi f \left(X_a + \frac{R_a R_m}{|Z_m + X_m|} \right)} \tag{4}$$

The capacitive reactance is given by:

$$X_c = \frac{10^6}{2\pi f C} \quad (5)$$

The capacitance impedance connected in series with the auxiliary winding is given by:

$$Z_c = -jX_c \quad (6)$$

The input voltage is the same across the main and auxiliary winding of the motor and this is given by:

$$V_m \angle 0^\circ = V_a \angle 0^\circ \quad (7)$$

The forward impedance at no-load is given by:

$$Z_{ff} = \left(\frac{(0.5R_2' + j0.5X_2')j0.5X_{mag}}{0.5R_2' + j0.5X_2' + j0.5X_{mag}} \right) \quad (8)$$

The backward resistance is equal to forward resistance of the motor at starting and this is expressed by:

$$R_{bb} = R_{ff} = \frac{|Z_m| - R_{1m}}{2} \quad (9)$$

The impedance of the main winding is given by:

$$Z_m = R_{1m} + X_{1m} + 2 \left(\frac{(0.5R_2' + j0.5X_2')j0.5X_{mag}}{0.5R_2' + j0.5X_2' + j0.5X_{mag}} \right) \quad (10)$$

The impedance of the auxiliary winding of split phase motor is given by:

$$Z_a = R_{1a} + jX_{1a} + 2 \left(\frac{(0.5R_2' + j0.5X_2')j0.5X_{mag}}{0.5R_2' + j0.5X_2' + j0.5X_{mag}} \right) \quad (11)$$

For capacitor start motor and capacitor run motor, the impedance of the auxiliary winding is given by:

$$Z_a = R_{1a} + j(X_{1a} - X_c) + 2 \left(\frac{(0.5R_2' + j0.5X_2')j0.5X_{mag}}{0.5R_2' + j0.5X_2' + j0.5X_{mag}} \right) \quad (12)$$

The main winding current for split phase and capacitor start motor is given by:

$$I_{m(sp)} = \frac{V_m \angle 0^\circ}{Z_m} \quad (13)$$

The auxiliary current of a capacitor run motor is given by:

$$I_a = \frac{V_a \angle 0^\circ}{(Z_a - jX_c + a^2(Z_{ff} + Z_{bb}))} \quad (14)$$

The main current of the capacitor run motor is given by:

$$I_{m(cr)} = \frac{V_m \angle 0^\circ}{Z_{1m} + Z_{ff} + Z_{bb}}, \text{ where } Z_{ff} = Z_{bb} \quad (15)$$

The auxiliary current of split phase and capacitor start motor is given by:

$$I_a = \frac{V_a \angle 0^\circ}{Z_a} \quad (16)$$

The starting current of single phase motor

$$I_{st} = I_m + I_a \quad (17)$$

The starting torque developed by the motor is given by:

$$T_{st} = \frac{2|I_m||I_a|(R_{ff} + R_{bb})\sin(\theta_a - \theta_m)}{2\pi N_s / f} = K I_a I_m \sin \alpha \quad (18)$$

where $K = \frac{2(R_f - R_b)}{2\pi N_s / f}$ and $\alpha = \theta_a - \theta_m$

At full load slip

The forward impedance at full load slip:

$$Z_f = R_f + jX_f = \frac{(0.5R_2' / s + j0.5X_2')j0.5X_{mag}}{0.5R_2' / s + j0.5X_2' + j0.5X_{mag}} \quad (19)$$

The backward impedance at full load slip:

$$Z_b = R_b + jX_b = \frac{(0.5R_2' / (2-s) + j0.5X_2')j0.5X_{mag}}{0.5R_2' / (2-s) + j0.5X_2' + j0.5X_{mag}} \quad (20)$$

The input Impedance of single phase motor is given as:

$$Z_{in} = Z_f + Z_b + R_{1m} + jX_{1m} \quad (21)$$

The input current of the motor running on full load:

$$I_{in} = \frac{V_m \angle 0^\circ}{Z_{in} \angle \phi} \quad (22)$$

The torque developed at rated speed is given by:

$$T_{rs} = \frac{I_{in}^2 \times (R_f - R_b)}{2\pi N_s / f} \quad (23)$$

The input power to the motor is:

$$P_{in} = V_m \angle 0^\circ \times I_{in} \times \cos \phi \quad (24)$$

The sum of the torque developed at rated speed and the starting torque is given by:

$$T = \frac{I_{in}^2 \times (R_f - R_b) + 2a |I_m| |I_a| (R_{ff} + R_{bb}) \sin(\theta_a - \theta_m)}{2\pi N / f} = K I_a I_m \sin \alpha \quad (25)$$

Results and discussion

Table 2 shows the value of various capacitors inserted in the starting (auxiliary) winding of a capacitor run motor (CRM) to develop the respective value of torque during the normal operation of the motor.

Table 2. Capacitor and Torque values of CRM

Capacitor (μF)	400	500	525	550	600	620	625	630
T (N-m)	6.56	8.6	8.95	9.22	9.54	9.58	9.58	9.57
Capacitor (μF)	640	650	700	725	750	775	800	
T(N-m)	9.58	9.57	9.39	9.24	9.06	8.87	8.67	

In Table 3, the torques developed by each capacitor start motor at various capacitor is shown at its normal operation.

Table 3. Capacitor and Torque values of CSM

Capacitor (μF)	600	625	650	700	725	750	775	790	800
T (N-m)	9.32	9.62	9.82	10.2	10.3	10.35	10.37	10.36	10.34
Capacitor (μF)	825	850	875	900	925	950	1000	1500	
T (N-m)	10.29	10.2	10.1	9.97	9.81	9.66	9.3	5.86	

Table 4 shows the starting current and the starting torque of CRM, SPM and CSM when the input data of SPM is used as input parameters for CRM and CSM with the connection of capacitors whose values are 30 and 300 microfarad to the starting winding of CRM and CSM respectively.

Table 4. Starting current and starting Torque of CRM, SPM and CSM

Motor types	CRM	SPM	CSM
Tst (N-m)	0.19	0.96	4.14
Ist (A)	24.59	47.66	41.32

CRM has both the lowest starting current and the lowest starting torque compared with CSM and SPM.

In Table 5, CRM developed the lowest starting current and highest starting torque at maximum torque using various capacitors in CRM and CSM and investigated by MATLAB to produce maximum torque.

Table 5. Starting current and starting Torque of CRM, SPM and CSM at maximum Torque

Motor types	CRM	SPM	CSM
Tst (N-m)	10.36	2.04	9.58
Ist (A)	34.84	38.14	58.61

The Torque versus speed characteristics of SPM and CSM are shown in Figure 15. It is cleared that the starting torque of CSM is more than the starting torque of SPM. Any of the motors can be applicable depending on the starting torque of a load.

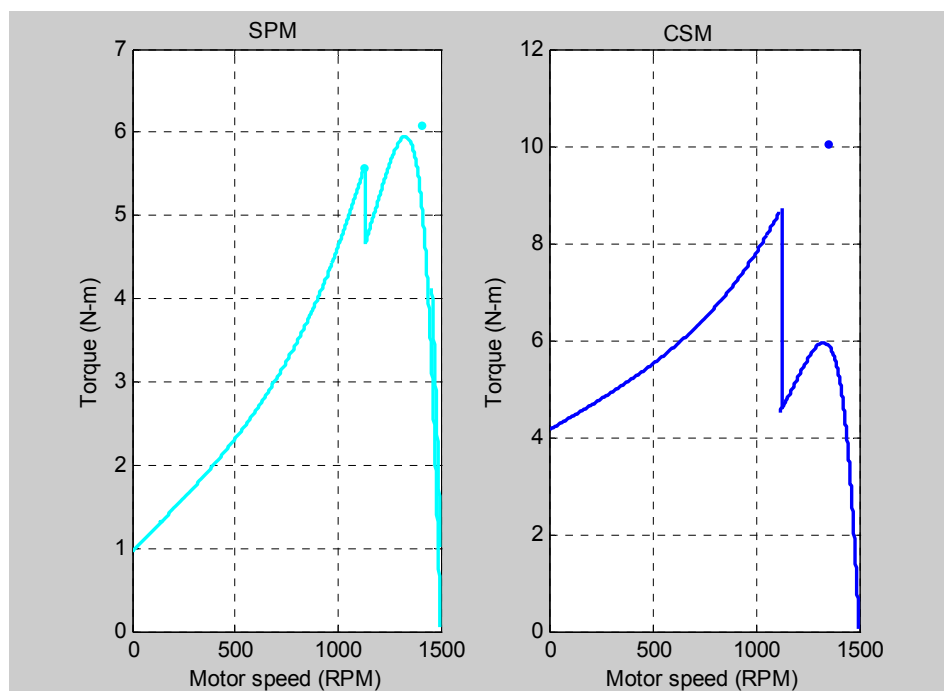


Figure 15. Torque versus motor speed characteristic of SPM and CSM

Figure 16 shows the Torque versus motor speed of SPM and CRM. SPM has a higher starting torque. The Torque versus motor speed characteristics of CSM and CRM are shown in Figure 17. The starting torque of CSM is higher than the starting torque of CRM. The Torque versus capacitor characteristics of a capacitor run motor and a capacitor start motor under investigation by MATLAB is shown in Figure 18. This it is to determine the value of capacitor connected in series with the starting winding of CRM and CSM each that will develop maximum torque in each motor. At point of intersection of the K, both motor develop

the same torque with the same magnitude of the capacitor.

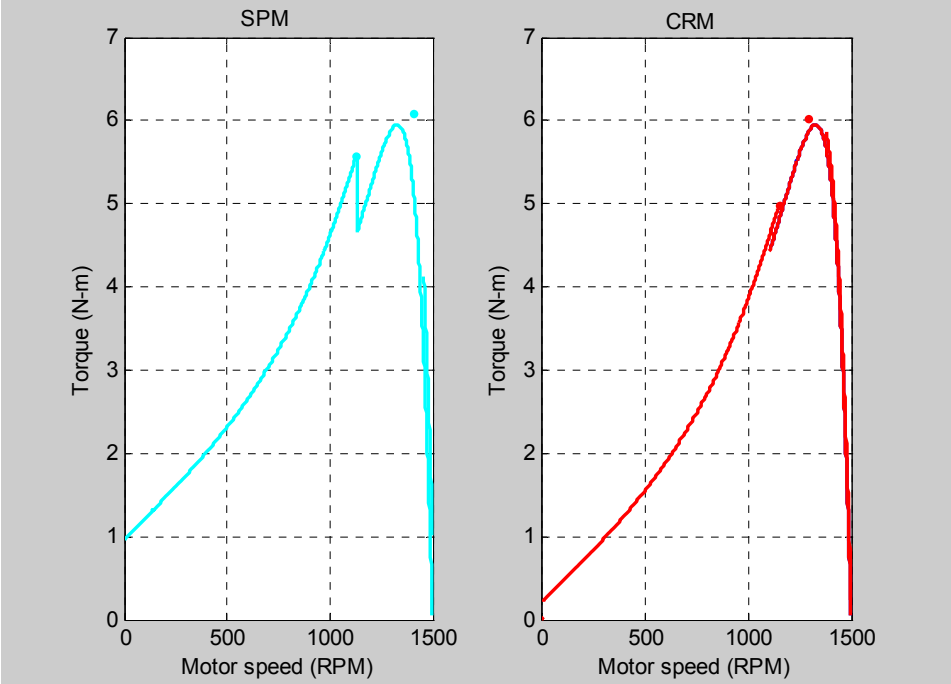


Figure 16. Torque versus speed characteristic of SPM and CRM

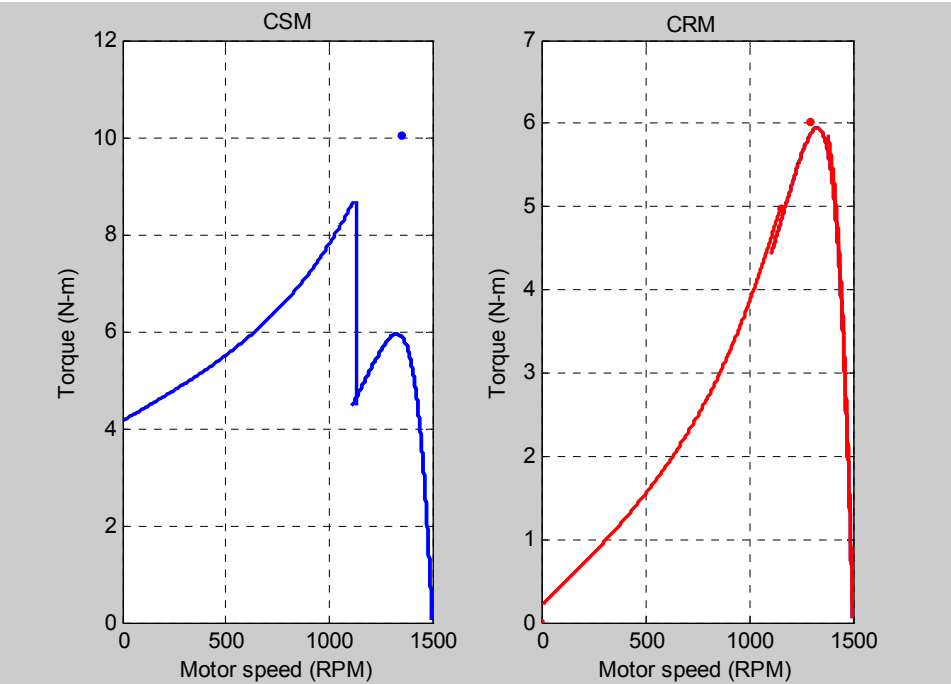


Figure 17. Torque versus motor speed characteristic of CSM and CRM

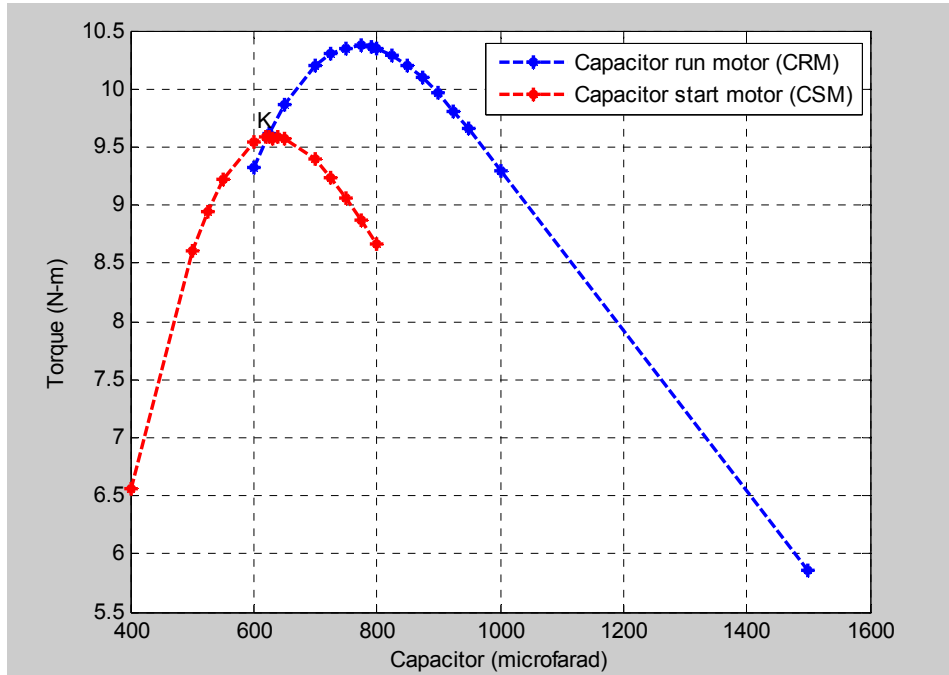


Figure 18. Torque versus capacitor characteristic

Figure 19 shows the Torque versus motor speed characteristics of CRM, CSM and SPM of each of them is operating at maximum torque in the absence of the centrifugal switch.

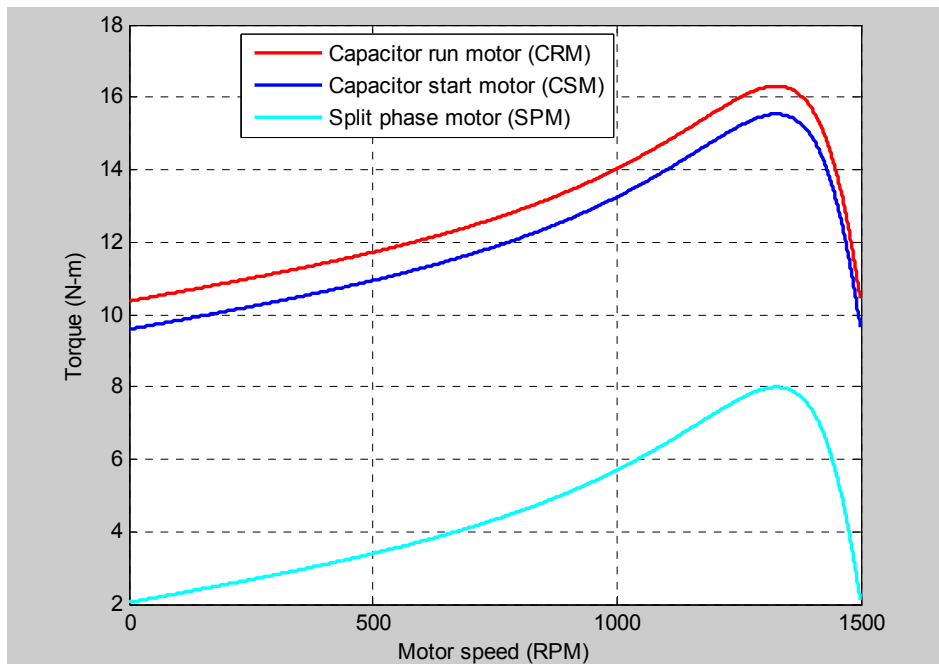


Figure 19. Torque versus motor speed characteristic of CRM, CSM and SPM

The CRM has the highest starting torque and followed by the CSM. SPM has the least starting torque. All these are subject to the initial given input data from SPM used as input data for the operating conditions for CRM and CSM. When the value of 300 microfarad

capacitor is connected on each of CRM and CSM, the Torque versus motor speed characteristic is shown in Figure 20. The Torque versus motor speed characteristics of each motor is shown in Figure 21.

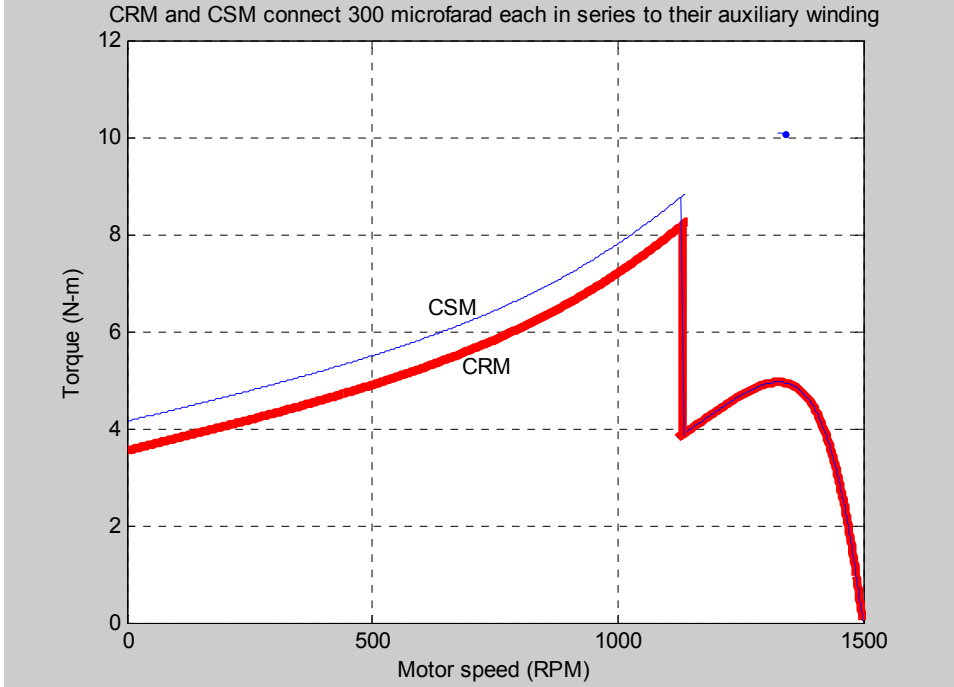


Figure 20. Torque versus motor speed characteristic of CSM and CRM with $C=300\mu F$ each

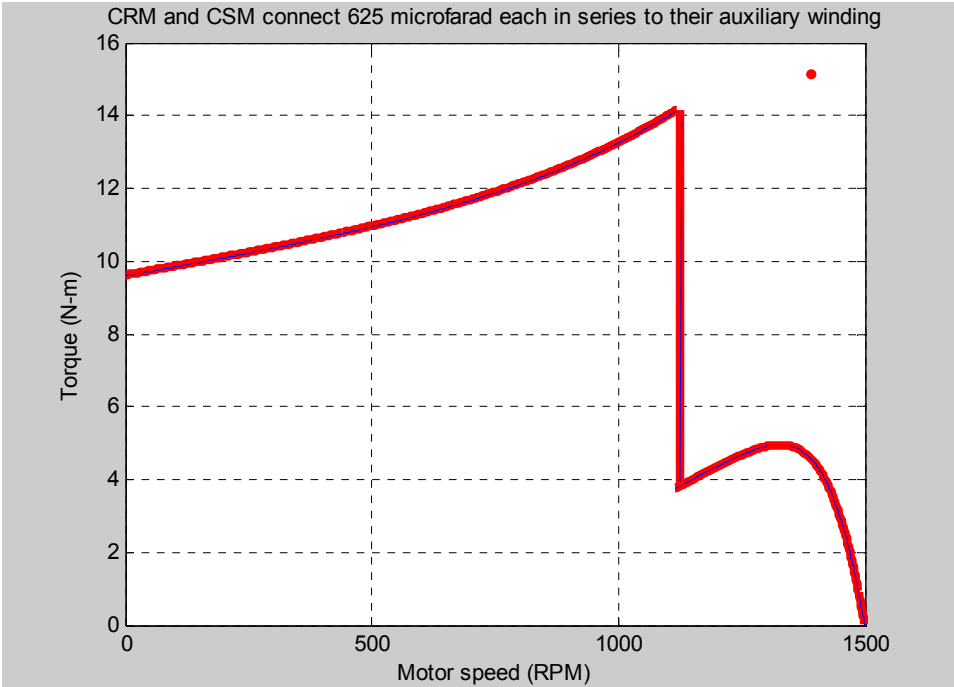


Figure 21. Torque versus motor speed characteristic of CRM and CSM with $C=625\mu F$ each

For Figure 20 the capacitor start motor has a higher starting torque than the capacitor run motor. Any of the motors can be applied depending on the area each is needed. There is

further investigation by MATLAB simulation as value of the capacitor connected each in series with the starting winding of CRM and CSM is increased from 300 microfarad to 625 microfarad capacitor. At this value of capacitor, each motor develops the same starting torque.

The value of capacitor needed for CRM to develop the highest torque is 800 microfarad. This value is now connected each in series with their starting winding and the torque produced by each is shown in Figure 22.

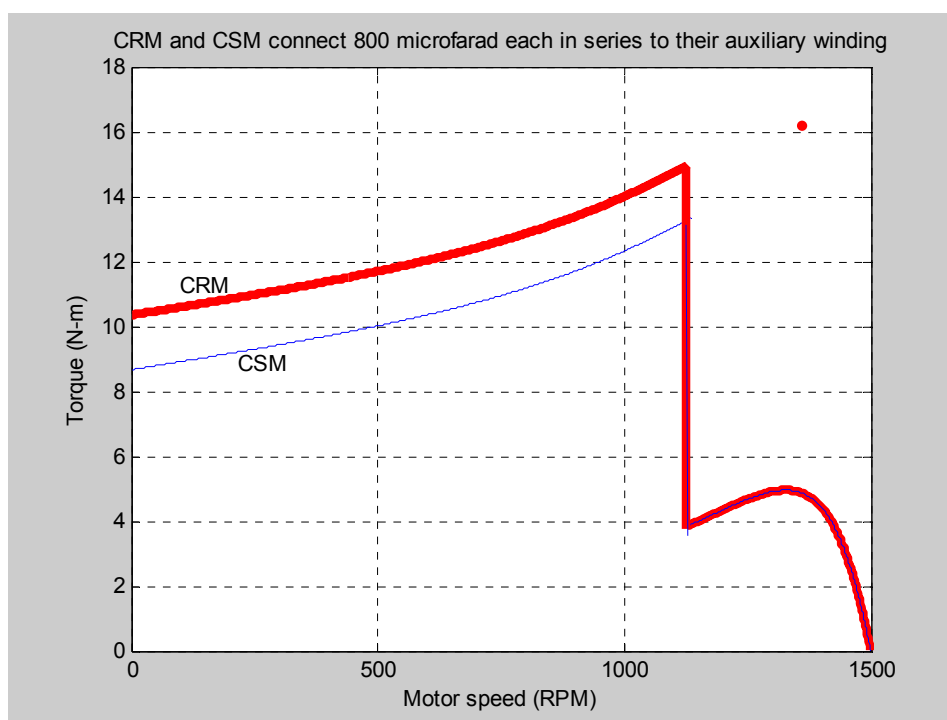


Figure 22. Torque versus motor speed characteristic of CRM and CSM with $C=800\mu F$ each

It is obvious that CRM produces the higher starting torque than the CSM. The starting current versus the starting torque characteristics of CRM, SPM and CSM are shown in Figure 23. If each motor is to operate in normal (N) torque or serves as original input data, the starting current is indicated as N, and as each motor has to be operated at maximum (M) torque, their starting current are indicated each by M.

Figure 23 shows the starting current and the starting torque of each motor in a bar form for further illustration. The advantages of CRM over the CSM and SPM at the value of 800 microfarads, is its ability to develop the highest starting torque and lowest starting current. This is desirable for high starting torque load. The same wire size for each motor cannot be used as each has variable starting current which is a limitation that will be further investigated in our next research.

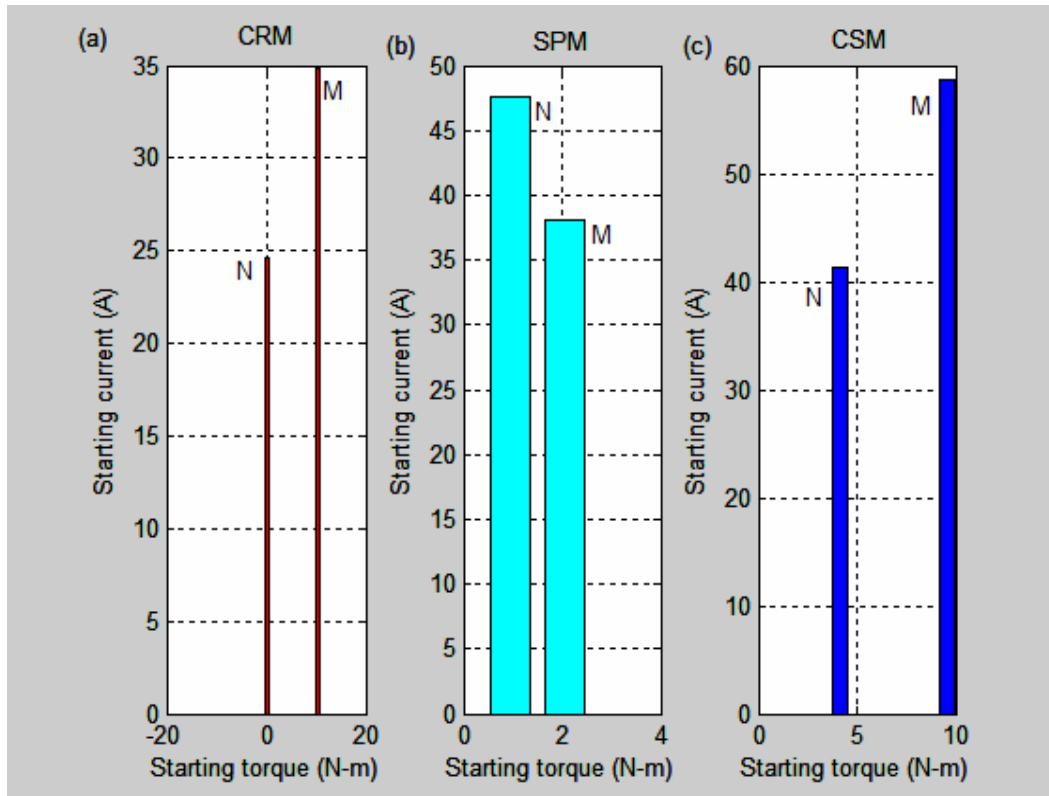


Figure 23. Starting current versus starting torque characteristic of CRM, SPM and CSM

Conclusions

The maximum capacitor that makes each of the motor to develop maximum torque is determined. Investigation of input parameters of each motor through MATLAB simulations shows that CRM develops the highest starting torque and lowest starting current.

Motor with higher starting current prevents longer life span, causes heat losses and lamination breakdown, thereby decreasing its efficiency and should not be desirable

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