Design Calculation of Single-Phase Permanent Slip Capacitor Induction Motor Used In Washing Machine

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Abstract- In today's world, time of the people is scarce and consequently it is very valuable. So the role of washing machine is very important for domestic application because of saving time. For a very long time, efforts have been made to overcome the difficulties associated with washing clothes manually. It is painstaking, wearisome and time consuming to constantly wash bulky clothes, especially the very dirty ones. In this paper, a single phase induction motor is designed for working the operations of a domestic clothes washing machine. There are two types of motor: single phase and three phase. Among these, single phase induction motors are used in many washing machines because of their advantages. These motors are the most suitable for washing machine which often depending of their size is not an inexpensive option. To have long life of the machine, costly high quality materials are to be used. In practice electrical machines are designed to have an operating life span of 5 to 10 years with low initial cost. This paper presents single phase permanent slip capacitor induction motor applications and design calculation of single-phase, 373 W, 4 pole, 220 V, 50 Hz.

Indexed Terms- Design Calculation, Single Phase Induction Machine, Permanent Slip Capacitor Induction Motor, Washing Machine

I. INTRODUCTION

The washing machine operated by a motor, which is connected to the agitator through a unit called a transmission. The motor and transmission are near the bottom of the machine, while the agitator extends up through the middle of the machine.

Washing machine motor is a device used for driving the clothes in the washing machine and induces the machine to run at a predetermined speed. It runs with the help of the AC induction motor. It is situated on the lower body of the machine and the motor forces the belt to tumble the wash tub. The motor is responsible for the tumbling, rotating and washing of the clothes. The motor is empowered with running at a low, medium and high level based on the requirement of washing. It is also assigned with the operation of spinning and drying the clothes. The machine is installed in the washing machine in a horizontal way and it is built up with high starting torque. It offers a reliable operation and easy maintenance. It can be used in a fully automatic machine and also in the semi-automatic washing machine.

Single-Phase Motors are suitable for applications in domestic, commercial, entertainment, scientific, industrial fields, powering small type machine tools and water pumps. These motors are built with the best quality materials with outstanding performance, easy maintenance and reliable running. Single phase capacitor motors are capacitor start, permanent split capacitor and capacitor start capacitor run. These are suitable for 220 V, 50 Hz single phase ac supply. Capacitor run motors have high efficiency and power factor which is suitable for machine tools, washing machines and centrifugal pumps. This paper studied the design calculation of single phase permanent slip capacitor induction motor.

II. METHOD FOR CONTROLLING AN ELECTRIC MOTOR USED IN WASHING MACHINE

A circuit configuration in Figure 1 for driving an electric motor, in particular of a washing machine, includes power switches connected to connection terminals of the electric motor and to a voltage intermediate circuit. A driver circuit is connected to the voltage intermediate circuit and to the power switches. A control unit or a micro controller is connected to the driver circuit. The control unit generates control signals for controlling at least one rotation speed of the electric motor.

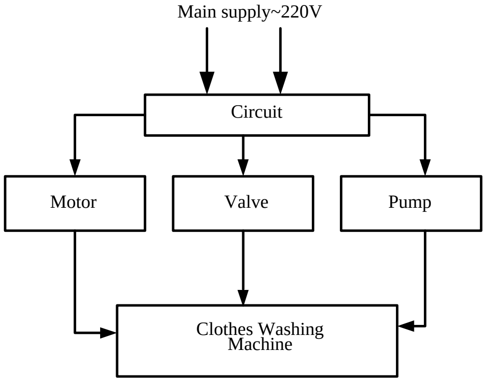

Figure 1. Block Diagram of Washing Machine

Figure 1 shows the block diagram of washing machine. The driver circuit generates short-circuit control signals for driving the power switches, which bring about a short circuit of the connection terminals connected to the power switches, independently of the control signals from the control unit. The driver circuit generates the short-circuit control signals as a function of a detection of an overvoltage of the voltage intermediate circuit over a desired voltage range. A method for controlling an electric motor is also provided.

III. PERMANENT SLIP CAPACITOR INDUCTION MOTOR

Permanent split capacitor (PSC) motors do not have a starting switch or a capacitor strictly for starting. Instead, permanent split capacitor motors have a run-type capacitor that is permanently connected in series with the start winding. This makes the start winding an auxiliary winding after the motor reaches running speed. Because the run capacitor must be designed for continuous use, it cannot provide the short-term "boost" of a starting capacitor. Therefore, starting torque of a PSC motors is low, ranging from 30 to 150 percent of rated load, which makes the motors unsuitable for hard-to-start loads. However, unlike split-phase motors, PSC motors have low starting currents, usually less than 200 percent of rated full-load current, making them excellent for applications with high cycle rates.

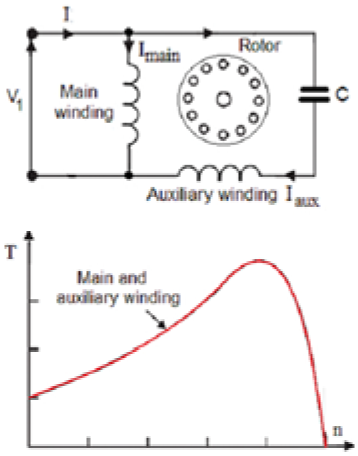

Figure 2. Permanent Slip Capacitor Induction Motor: (a) connection diagram and (b) torque-speed characteristic

Permanent split capacitor motors have several advantages: since they do not require a starting mechanism, they can be designed for easy reversing. They can also be designed for optimum efficiency and high power factors at rated load. They are considered to be the most reliable single-phase motors, primarily because a starting switch is not required. Permanent split capacitor motors have a wide variety of applications depending on the design. Examples include direct drive fans, blowers with low starting torque requirements and intermittent cycling applications such as adjusting mechanisms, valve actuators, gate operators and garage door openers, many of which also require reversing.

IV. DESIGN CALCULATION OF PERMANENT SLIP CAPACITOR INDUCTION MOTOR

A. Specification of Single-phase Induction Motor

Rated output power : 373 W
Rated voltage per phase : 220 volts
Speed : 1500 rpm
Number of pole : 4 poles
Number of phase : single-phase
Frequency : 50 Hz
Type : Permanent split capacitor

B. Main Dimension of Stator Frame

Based on the rating of the motor and giving due consideration to all the factors, following values are assumed for the design parameters involved in equation.

$$D^2L = 16.5\times C_o \frac{h.p}{r.p.m}\times K_f K_t \times 10^6 \qquad (1)$$

Output coefficient, $C_o = 0.29$ Tesla
Frequency constant, $K_f = 0.96$
Values of type constant, $K_t = 1.42$

$$D^2L = 16.5\times 0.29\frac{0.5}{1450}\times 0.96\times 1.42\times 10^6 = 2249$$

cm^3

The most favorable proportions between D_0 and L,
$L = 0.3D_0$

Therefore, $0.3\,D_o^3 = 2249$
$D_o = 19.57$

Take, $D_o = 20$ cm
L = 6 cm

The ratio of stator internal to outer diameter is
$D_i/D_o = 0.59$ (for 4 pole)

Thus, internal diameter of stator $D_i = 12$ cm
Number of stator slot = 24

C. Details of Stator Punching

Parallel-sided teeth with flat bottom slot are assumed for the present case of single phase induction motor.

(i) Slot opening
For motor with 24 slots, slot opening,
$b_{10} = 0.068 + 0.0175D_i$ cm (2)
$D_i = 6$ cm
Therefore, $b_{10} = 0.278$ cm
Depth of the tip of the slot, $h_{10} = 0.07$ (assumed)
Depth of the mouth may be assumed 1 to 1.5 times the depth of the tip. Assuming this ratio as 1.3,
Depth of the mouth, $h_{11} = 1.3 \times 0.07 = 0.09$ cm

(ii)Width of the tooth

$$b_{t1} = \frac{(1.27 + 0.035D_i)D_i}{S_1} \qquad (3)$$

= 0.77 cm

(iii) Stator core depth,

$$d_{c1} = \frac{B_t}{B_C}\times\frac{S_1\times b_{t1}}{\pi\times P} \qquad (4)$$

= 1.94 cm

(iv) Width of the slot at top section
Assuming parallel sided teeth and trapezoidal slots with flat bottom, the width of the slot at the mouth is given by,

$$b_{11} = \frac{\pi(D_i + 2(h_{10}+h_{11}))}{S_1} - b_{t1} \qquad (5)$$

= 0.77 cm

(v) Depth of the slot below the mouth,

$$h_{14} = 0.5(D_o - D_i) - (h_{10} + h_{11} + d_{c1}) \qquad (6)$$

= 1.9 cm

(vi) Width of the slot at bottom,

$$b_{13} = b_{11} + 2h_{14}\tan\alpha \qquad (7)$$

= 1.27 cm

Length of Air Gap

$$l_g = 0.013 + \frac{0.0042D_i}{\sqrt{p}} \qquad (8)$$

= 0.0382 cm

D. Design of Main Winding

The main dimensions and all other details of the stator punching have been decided above. With these details, the next step will be to design the main proper main winding for the motor.

(i)Winding factor
The type of winding used for the motor is concentric. The sinusoidal distribution of the winding reduces the harmonics in the air gap flux wave to a minimum.
The number of stator slots = 24
Thus, the number of stator slots per pole = 24/4 = 6
Number of coils per slot = 3

$$\text{Winding factor}, K_{wm} = \frac{K_{p1}T_1 + K_{p2}T_2 + K_{p3}T_3}{T_1 + T_2 + T_3} \qquad (9)$$

= 0.7988

(ii) Total flux per pole
Total flux per pole, $\phi = 0.637\,A_t\,B_t$ (10)
$= 0.637\times b_{t1}\times L_i \times$ number of teeth per pole $\times B_t$
= 2.34 m Wb

(iii) Number of turns

$$E = 4.44\, f\phi K_{wm}T_m \qquad (11)$$

Number of turns, $T = \frac{220}{4.44 \times 50 \times 0.00234 \times 0.7988}$

= 530 turns

Total conductor in main winding = 530 × 2 = 1060

Turn per pole = 530/4 = 133

(iv) Turns in various coil of winding

The number of turns in series per pole = 530/4 =133

The maximum number of main winding conductors in a slot is 59.

(v) Size of conductor

$$\text{Current in main winding, } I_1 = \frac{h.p \times 746}{\eta \times V \times \cos\varphi} \qquad (12)$$

= 4.2 A

Current density in the main winding can be assumed as 4.5 A/mm^2.

Area of main winding conductor, A_m = 4.2/4.5 = 0.93 mm^2

Diameter of bare conductor with 19 SWG wire = 1.02 mm

With enamel covering, the addition to diameter = 0.075 mm

Insulated diameter of conductor = 1.02 + 0.075 = 1.095 mm

Number of turns in series per pole = 126

(vi) Space factor

$$\text{Gross slot area} = \frac{h_{11}(b_{10} + b_{11}) + h_{14}(b_{11} + b_{13})}{2} \qquad (13)$$

= 1.98 cm^2

Space occupied by 59 strands of insulated diameter of 1.095 mm

Space occupied $= 59 \times \frac{\pi}{4} \times (1.095 \times 10^{-3})^2$ = 0.556 cm^2

$$\text{Space factor of the slot} = \frac{\text{Space occupied by insulated conductor}}{\text{Gross slot area}}$$

(14)

= 0.28

≈ 0.3

A space factor of 0.3 for the stator is quite satisfactory.

(vii) Resistance of main winding

The length of mean turn for each of the coils per pole of a concentric winding is given by,

$$L_{mt} = \frac{8.4(D_i + h_s)}{S_1} \times \text{slots spanned} + 2L \qquad (15)$$

Height of stator slot = $h_{11} + h_{14}$ = 0.09 + 1.9 = 1.99 cm

Length of mean turn of main winding,

$$L_{mtm} = \frac{l_{mt1}T_1 + L_{mt2}T_2 + L_{mt3}T_3}{T_1 + T_2 + T_3} \qquad (16)$$

= 33.98 cm

Total number of turns = 530

Resistance of main winding, $r_{1m} = \frac{\rho L_{mtm} T_m}{a_m}$ = 4.66 ohm

Copper losses in main winding = $(I_m)^2 r_{1m}$ = 82.2 watts

E. Main Dimension of Rotor

Length of air gap = 0.0382 cm

International diameter of stator = 12cm

Outer diameter of rotor, $d_r = D_i - 2l_g$ = 11.924 cm

Rotor core length = stator core length = 6 cm

Number of rotor slots should be chosen, so as to avoid cogging, cusps and to minimize noise and vibration. The best number of rotor slots thus selected will be equal to 36.

Thus, Number of rotor slot, S_2 = 36

(a) Detail of rotor punching

(i) Width of teeth

$$b_{t2} = \frac{0.95 S_1 b_{t1}}{S_2} \qquad (17)$$

= 0.54 cm

Slot opening in present case, b_{20} = 0.075 cm

Depth of the tip, h_{20} = 0.08 cm

(ii) Radius of round slot

$$r_{21} = \frac{\pi(D_r - 2h_{20}) - S_2 b_{t2}}{2(S_2 + \pi)} \qquad (18)$$

= 0.22 cm

(iii) Conductor diameter

$d_c = 2r_{21} - 0.038$= 0.402 cm

Nearest standard size is 8 SWG whose diameter, d_c = 0.406 cm

Area of rotor conductor = 13 mm^2

(iv) Rotor core depth

Rotor core depth depend may be taken approximately 95 percent of stator core depth.

Thus, rotor core depth, d_{c2} = 0.95 × 1.94 = 1.843 cm

(b) Equivalent resistance of the rotor

Equivalent resistance of the rotor referred to stator main winding is given by,

$$r'_{2m} = m(N_m)^2 K_{wm}^2 \rho \left[\frac{l_b}{A_b N_b} + \frac{0.64 D_m}{P^2 A_e} \right] \qquad (19)$$

= 6.785 ohm

Number of conductors in main winding, N_m = 1060
Winding factor for main winding, K_{wm} = 0.7998
Number of rotor bar, N_b = 36
Allowance for skewing etc = 1.0cm (assumed)
Gross core length
= 6 cm
Length of rotor bar, l_b
= 6 + 1 = 7 cm
Area of rotor bar, A_b
= 13 mm^2
Outer diameter of rotor, d_r = 11.924 cm

Based on outer diameter of rotor, mean diameter of end ring, D_m = 7 cm (assumed)

Area of end ring, $A_e = \frac{1}{\pi}\left[\frac{N_b}{P}\right] A_b$ (20)

= 37.24 mm^2

Equivalent rotor current, $I_2' = I_1 \cos \phi$ (approximately) (21)
= 4.2×0.62 = 2.604 A

Total rotor copper losses = $(I'_2)^2 \, r'_{2m}$ (22)
= $(2.604)^2 \times 6.785$ =46 watt

F. Performance Calculation

The performance and design data sheet of the motor in Table I is to be worked out at a certain slip, copper losses are to be calculated as per the given slip. To complete the design the computation of core, copper and iron losses is required.

(i) Core loss

Core losses can be calculated exactly in the same manner as for three phase induction motor.

Core loss in stator tooth;
Flux density in stator teeth, B_{t1} = 1.3 Tesla (wb/m^2)
Number of stator teeth = 24
Area of the stator tooth = 5.58 × 0.845
= 4.72 cm^2
Height of the stator teeth = 2.06 cm
Volume of all the stator teeth = 24 × 4.72 × 2.06
= 233.36 cm^3
Density of the material = 7.8 gm per cm^3
Weight of all the stator teeth = 233.36 × 7.8 × 10^{-3}
= 1.82 kg
Thus, total losses in stator teeth = 6.1 × 1.82 = 11.1Watts

Core losses in stator core;
Flux density in stator core, B_c = 1.08 Tesla (wb/m^2)
Sectional area of stator core = 10.83 cm^2
Mean diameter of stator core = 20 – 1.94 = 18.06 cm
Volume of the stator core = (π × 18.06) × 10.83
= 614.46 cm^3
Weight of stator core = 614.46 × 7.8 × 10^{-3} = 4.79 kg

Thus total losses in stator core = 4.79 × 4.1
= 19.65 watts

(ii)Surface losses
Total iron losses due to fundamental frequency flux
= 11.1 + 19.65 = 30.75 watts

Surface losses may be assumed approximately 90% of the above = 30.75 × 0.9 = 27.68 watts
Total core losses = 30.75 + 27.68 = 58.43 watts

The bearing friction and windage loss depends upon the type of bearing, load on the bearing and the peripheral speed of the bearing. For sleeve bearings the loss is about to 5 to 8% of the output.

Friction and windage loss is assumed as 5% of output
= 0.05×373=19 watts

(iii) Copper losses
Forward impedance

$$Z_f = \frac{\left(\frac{r'_{2m}}{2s} + \frac{jX_{lm}}{4}\right)\frac{jX_m}{2}}{\left(\frac{r'_{2m}}{2s} + \frac{jX_{lm}}{4}\right) + \frac{jX_m}{2}} \qquad (23)$$

Z_f =37.75+j53.36=65.37 ∠54.72

Backward impedance

$$Z_b = \frac{\left(\frac{r'_{2m}}{2(2-s)} + \frac{jX_{lm}}{4}\right)\frac{jX_m}{2}}{\left(\frac{r'_{2m}}{2(2s)} + \frac{jX_{lm}}{4}\right) + \frac{jX_m}{2}} \qquad (24)$$

Z_b = 1.591+j3.186=3.56 ∠63.46

Current drawn by the motor from the mains

$$\overline{I_1} = \frac{V}{|Z_{1m}| + (|Z_f| + |Z_b|)} \quad (25)$$

$$\overline{I_1} = 3A$$

Magnitude of current drawn by the motor from the mains is 3 A.

$$\text{Stator copper losses} = I_1^2 \, r_{1m} \quad (26)$$

$$= (3)^2(4.66) = 41.94 \text{ W}$$

$$\text{Rotor copper losses (m)} = I_1^2 \frac{r'_{2m}}{k} \quad (27)$$

$$= 38.16 \text{ W}$$

Total core loss = 58.43 W

Friction and windage loss = 19 W

$$P_{in} = P_{out} + \text{Losses} \quad (28)$$

$= P_{out}$ + (Stator copper losses + Rotor copper losses + Total core loss + Friction and windage loss)

$$= 373+58.43+41.94+38.16+19 = 530.53 \text{ W}$$

$$\text{Power factor} = \frac{P_{in}}{VI_1} = \frac{530.53}{220 \times 3} = 0.8$$

$$\text{Efficiency} = \frac{P_{out}}{P_{in}} = \frac{373}{530.53} = 0.7$$

$$\text{Full load torque} = \frac{P_{out}}{\frac{2\pi \times N_r}{60}} = 2.4565$$

Nm

Pull out torque = 5.1 Nm

Ratio = Pull out torque/Full load torque =5.1/2.5 =2.04

Which is about 200% of full load torque.

$$I_s = I_{sm} \frac{\sqrt{(R_a + R_m)^2 + \{X_{lm} + (X_{la} - X_c)\}^2}}{\sqrt{R_a^2 + (X_{la} - X_c)^2}} \quad (29)$$

$$= 14.69 \text{ A}$$

This is about 3.5 times full load current.

V. DESIGN CALCULATION RESULT OF PERMANENT SLIP CAPACITOR INDUCTION MOTOR

Table I Design Data Sheet of (373 W) Single-phase Induction Motor

Specifications	Symbol	Unit	Design value
Full load output	-	W	373
Line voltage	V	volts	220
Frequency	f	Hz	50
Number of phase	-	-	1
Number of poles	P	-	4
Speed	N_s	r.p.m	1500
Type	-	-	Permanent split capacitor
Main Dimensions			
Output coefficient	C_o	cm	0.29
Outer diameter of stator stampings	D_o	cm	20
Internal diameter of stator stampings	D_i	cm	12
Gross length of stator core	L	cm	6
Details of Stator Punchings			
Number of stator slots	S_1	-	24
Slot opening	b_{10}	cm	0.278
Depth of the tip	h_{10}	cm	0.07
Depth of the mouth	h_{11}	cm	0.09
Width of the tooth	b_{t1}	cm	0.845
Stator core depth	d_{c1}	cm	1.94
Width of the slot at the top section	b_{11}	cm	0.77
Length of air gap	l_g	cm	0.0382
Width of the slot at the bottom	b_{13}	cm	1.27
Stator Main Winding			
Windings factor	K_{wm}	-	0.7988
Flux per pole	ϕ	weber	0.00234
Number of turns	T_m	-	530
Maximum number of conductors in a slot	-	-	59
Conductor section	α_m	mm^2	0.811
Wire used for conductor	-	-	19SWG
Number of strands	-	-	1
Diameter of insulated conductor	d_i	cm	1.095
Space factor for slot	-	-	0.3
Length of mean turn	l_{mtm}	cm	33.98
Resistance of winding	r_{1m}	ohm	4.66
Copper losses of the winding	P_o	watts	82.2

Details of Rotor Punching			
Outer diameter of rotor punching	D_r	cm	11.924
Number of rotor slots	S_2	-	36
Width of the tooth	b_{t2}	cm	0.54
Slot opening	b_{20}	cm	0.075
Shape of slot	-	-	Round
Radius of round slot	r_{21}	cm	0.22
Conductor diameter	d_c	cm	0.402

Equivalent resistance of rotor	r'_{2m}	ohm	6.785
Rotor core depth	d_{c2}	cm	1.843
Performance			
Iron losses in stator teeth	-	Watts	11.1
Iron losses in stator core	-	Watts	19.65
Total iron losses due to fundamental frequency flux	-	Watts	30.75
Surface losses	-	Watts	27.68
Total core losses		Watts	58.43
Friction and windage losses		Watts	19
Slip	S	Percent	3
Current drawn by the motor from the main	I_1	Amps	2.7
Stator copper losses	-	Watts	41.94
Rotor copper losses	-	Watts	38.16
Input to the motor	-	Watts	530.53
Torque	T	Nw-m	2.45
Efficiency	η	Percent	70
Power factor	$\cos\phi$	-	0.8

VI. CONCLUSION

Motor design must be provided with a suitable controller that will be capable of starting and stopping the motor and of performing other control functions that are required for the satisfactory operation of the motor. The choice depends upon the size of motor and severity of the duty.

The first step is based on the main data and the properly assumed values of specific loadings the process of design is initiated with the determination of the main dimensions of the motor, which in turn decide the design of other parts of the motor. The second step is the design data for the various parts of the motor and then used to calculate the performance. The performance thus calculated should satisfy the service conditions the calculated performance of the designed motor must be within certain expected values.

This paper calculates the 373 W single-phase induction motor design and with starting torque section. The speed of this motor is 1500 r.p.m. The recommended approach to designing a single-phase induction motor has the dimension of the stator and rotor and the design of main winding. In this motor, the internal diameter of the stator is 12 cm and the gross core length is 6 cm. Assuming depth of tip is 0.07 cm and depth of mouth is 0.09 cm. Rotor diameter of the motor is 11.924 cm. So, the length of air-gap is 0.0382 cm. This motor is the permanent split capacitor type motor. In this design, the full-load slip is 3 %, power factor is 0.8 and full-load efficiency is 67 %, so that, this machine design can be able best performance. Therefore, this design calculation is provided for designers and electrical engineering students.

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