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A CASE STUDY ON ANALYSIS OF CAPACITOR FAILURE IN PERMANENT SPLIT CAPACITOR RUN SINGLE PHASE INDUCTION MOTOR IN LOW SLIP REGION

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***Abstract*— This paper presents a case study on capacitor failure analysis in Permanent-Split Capacitor-Run Single-Phase Induction Motor (PSCRSPIM) in low slip region. It emphasizes the motor performance in low slip region and detailed analysis carried out for Capacitor voltage and current variation with respect to slip. Motor Equivalent circuit parameters are extracted from dc test, no-load test and locked-rotor test. MATLAB simulations are carried out. Theoretical and experimental results are plotted. The premature failure of capacitor faced by PSCRSPIM users is answered at the end of the Paper. Contrary to the general concept that overloaded machine will fail; the paper is addressing the failure of lightly loaded machines.**

***Keywords*— AC machines, PSCRSPIM, low slip, equivalent circuits, parameter estimation, parameter extraction capacitor voltage, current.**

Nomenclature—

F, θ, ωt	MMF, space angle, time angle
F_f, F_b	Rotating MMF in space angle direction, Rotating MMF in opposite direction
N_m	Effective number of turns of the stator winding.
I_{max}	Maximum current flowing through the stator
P_{LR}, I_{LR}, V_{LR}	Locked rotor power, current, and voltage
R_{LR}, X_{LR}, Z_{LR}	Locked rotor resistance, reactance, and impedance.
R_{sm}, R_{sa}	DC resistance of the main and auxiliary winding
R_s, X_s	Stator resistance and reactance
R_r, X_r	Rotor resistance and reactance
P_{NL}, I_{NL}, V_{NL}	No-load power, current, and voltage
X_{sm}, X_{mm}	Main winding reactance and magnetizing reactance
P, f	Number of poles and frequency (in hertz).
S	Slip
S_f, S_b	Forward slip (S) and backward slip (2-S)
Z_{fa}, Z_{ba}	Effective impedance of forward and backward branch of auxiliary winding
Z_{sa}	Auxiliary winding impedance
X_{sa}	Auxiliary winding reactance
C, X_c	capacitance, reactance of non-ideal capacitor

$V_m,\ V_a$	Line voltage applied to main and auxiliary winding
I_m, I_a	Current in main and auxiliary winding, when both windings are in operation
V_{cthe}, V_{cexp}	Theoretically computed Voltage across capacitor, Experimental result of Voltage across capacitor
I_{cthe}, I_{cexp}	Theoretically computed Current through capacitor, Experimental result of current through capacitor

I. INTRODUCTION

Single Phase Induction Machines form the work-horse of various fractional power domestic and agricultural applications such as employed in fans, refrigerators, mixers, vacuum cleaners, washing machines, kitchen appliances, etc. They are often designed to be simple, rugged and low-cost. A majority of single-phase induction machines are PSCRSPIM. These machines have two-stator windings in space and time quadrature [1]. Although SPIMs are simpler in construction as compared to their three-phase counterparts, their analysis happens to be more complex. IEEE Standards 114–1982 [1] and 114–2001 [2, 3] are available for testing SPIM; however, these do not provide the method for extracting the parameters of PSCRSPIM [4, 5]. Conventionally, the parameters of SPIM are extracted using no-load and locked-rotor test results. However, except for capacitor-run motor, these tests are made with the auxiliary winding kept open. In capacitor-run motor, auxiliary winding parameters also contribute in these test results even though the rest of the procedure, to find the main and auxiliary winding parameters, remains the same as that of plain SPIM [6-8]. In three possible equivalent circuits of SPIM have been developed for parameter estimation, and an empirical technique has been used for the presented alternative models; wherein, the rotor resistance is varied as a function of slip to improved electrical and mechanical performance predictions [9,10]. In this work, the experimental test results from dc, no-load, and locked-rotor tests, exclusively required for the development of equivalent circuit of PSCRSPIM. The rotor circuits for the forward rotating field (S) and backward rotating field (2-S) are used for calculating forward branch impedance and reverse branch impedance [11]. Slip variation in forward branch impedance and reverse branch impedance and total auxiliary winding impedance calculations are obtained. Detailed analysis carried out on capacitor performance with variation of slip [12-15]. Failure reasons are addressed in PSCRSPIM at low slip. This paper is organized as follows: A case study of PSCRSPIM, based on double-revolving-field theory followed by parameter extraction for stator and rotor of the motor using dc, no-load, and locked-rotor tests, has been discussed for a case study in Section II. Section III describes the MATLAB simulation studies are carried out using obtained parameters. Section IV describes the validation of theoretical and experimental results complete equivalent circuit of PSCRSPIM. Section V concludes the work along with future directions.

II. ANALYSIS AND PSCRSPIM PARAMETERS ESTIMATION

In PSCRSPIM, the two windings are placed in the stator with their axis displaced 90 electrical degrees in space. The impedances of the two circuits are such that the currents in the main and the auxiliary windings are phase-shifted from each other. The motor is equivalent to an unbalanced two-phase motor. However, the result is a rotating stator field that can produce the starting torque. The two windings can be properly designed to make the motor behave as a balanced two-phase motor.

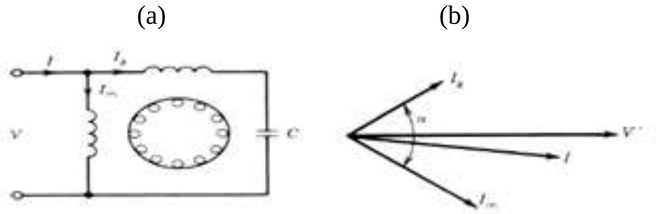

Fig. 1. (a) PSCRSPIM Circuit (b) Vector Diagram

$$F(\theta, t) = N_m I_{max} \cos\theta \cos\omega t \tag{1}$$

$$= \frac{N_m I_{max}}{2}\cos(\omega t - \theta) + \frac{N_m I_{max}}{2}\cos(\omega t + \theta)$$

$$= F_f + F_b \tag{2}$$

In PSCRSPIM, as shown in Fig. 1, the capacitor is connected in series with the auxiliary winding is not cut out after starting and is left in the circuit all the time.

To find out the performance analysis of PSCRSPIM in low slip region, equivalent circuit parameters are derived from DC test, no-load and locked-rotor tests. From which, Magnetizing reactance, Stator and rotor leakage reactance and stator referred rotor winding resistance can be computed from no-load and locked-rotor test data.

DC Test –

In this test, dc voltage is applied across the stator winding, after removing the capacitor, and the dc current is then measured. Stator winding dc resistance Rs thus can be computed. The main winding resistance Rsm and auxiliary winding resistance Rsa are proposed to be measured separately by applying dc voltage across individual winding and measuring the dc current of each, after removing the capacitor.

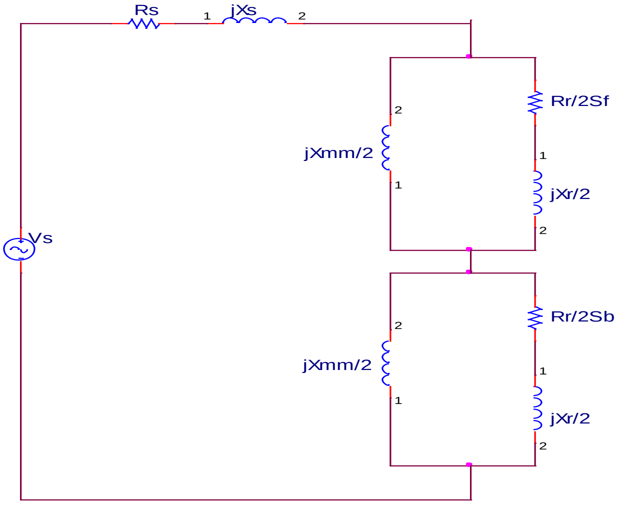

Fig. 2. Equivalent Circuit of PSCRSP Induction Motor

No-load Test -

In no-load test, rated voltage V_{NL} is applied, and current I_{NL} and power P_{NL} are measured at no load. Since the no-load slip is small, the rotor resistance of forward branch is assumed to be infinite. The resistance associated with backward rotating field is small enough so that magnetizing current may be neglected from Fig.2, which results in the equivalent circuit of Fig. 3.

$$P_{NL} = I_{NL}^2 R_{NL} \tag{3}$$

$$Z_{NL} = \frac{V_{NL}}{I_{NL}} \tag{4}$$

$$R_{NL} = \frac{P_{NL}}{I_{NL}^2} \tag{5}$$

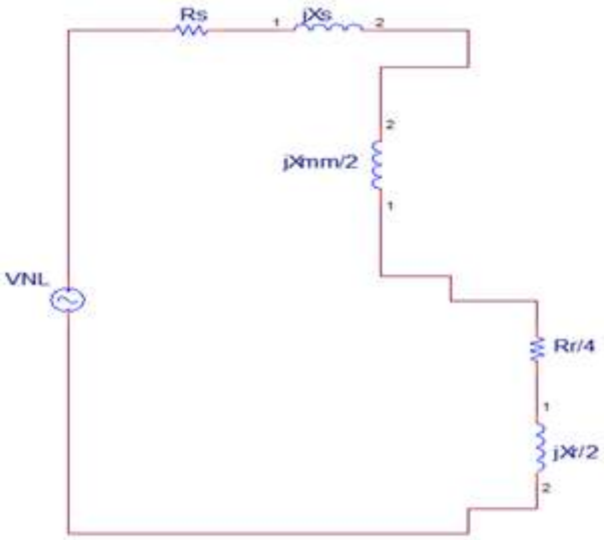

Fig. 3. Equivalent Circuit of PSCRSP Induction Motor at No-Load

Locked Rotor Test –

In locked-rotor test, the rotor is held at standstill while exciting both the windings with locked-rotor voltage V_{LR} such that the locked-rotor line current I_{LR} equals the rated current. Since the slip at standstill is unity, the rotor circuit impedance is much smaller than the magnetizing reactance. Therefore, the magnetizing reactance may be eliminated from the equivalent circuit as in Fig. 4.

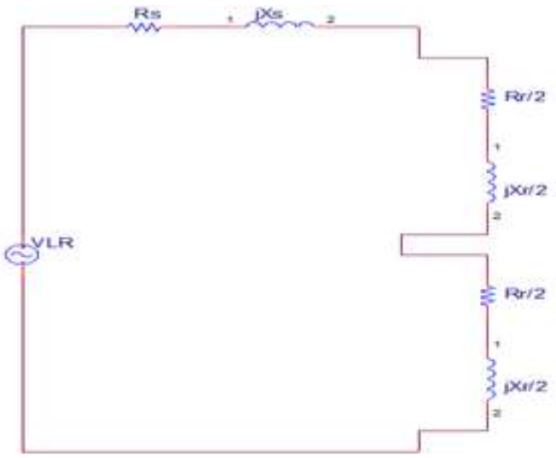

Fig. 4. Equivalent Circuit of PSCRSP Induction Motor with locked rotor

The locked-rotor resistance R_{LR} is computed as

$$R_{LR} = \frac{P_{LR}}{I_{LR}^2} \tag{6}$$

The locked rotor impedance is given by

$$Z_{LR} = \frac{V_{LR}}{I_{LR}} \tag{7}$$

Locked-rotor reactance is computed as

$$X_{LR} = \sqrt{Z_{LR}^2 - R_{LR}^2} \tag{8}$$

Rotor winding resistance Rr is then computed as

$$R_r = R_{LR} - R_S \tag{9}$$

The stator main, auxiliary and rotor leakage reactance are considered to be equal and can be obtained from Fig. 5 as

$$X_s = X_{sm} = X_{sa} = X_r = \frac{X_{LR}}{2} \tag{10}$$

The magnetizing reactance X_{mm} can be computed from no load and blocked rotor test as

$$Z_{NL} = \sqrt{R_{NL}^2 + (0.5X_{mm} + X_s + 0.5X_r)^2} \tag{11}$$

This case study aims towards the voltage variation across the capacitor with respect to slip. Hence, the voltage across the capacitor from Fig.5 can be found out from equivalent circuit of auxiliary winding of PSCR motor. The voltage across the capacitor can be find out as

$$V_C = I_C X_C \tag{12}$$

I_C can be find out as $\frac{V_a}{Z_{sa}}$

Where, $Z_{sa} = R_{sa} + j(X_{sa} - X_c) + 0.5Z_{fa} + 0.5Z_{ba}$ (13)

$$Z_{fa} = R_{fa} + jX_{fa}$$

$$= \left(\frac{R_r}{s_f} + jX_r\right) in\ parallel\ with\ jX_{mm} \quad (14)$$

$$R_{fa} = \left(\frac{X_{mm}^2}{X_{22}}\right)\frac{1}{SQ_2 + \frac{1}{SQ_2}} \quad (15)$$

$$X_{22} = X_r + X_m \quad (16)$$

$$Q_2 = \frac{X_{22}}{R_2} \quad (17)$$

$$X_{fa} = \frac{X_r X_{mm}}{X_{22}} + \frac{R_{fa}}{SQ_2} \quad (18)$$

$$Z_{ba} = R_{ba} + jX_{ba}$$

$$= \left(\frac{R_r}{s_b} + jX_r\right) in\ parallel\ with\ jX_{mm} (19)$$

$$R_{ba} = \left(\frac{R_r}{2-S}\right)\left(\frac{X_{mm}}{X_{22}}\right)^2 \quad (20)$$

$$X_{ba} = \frac{X_r X_{mm}}{X_{22}} + \frac{R_b}{(2-S)Q_2} \quad (21)$$

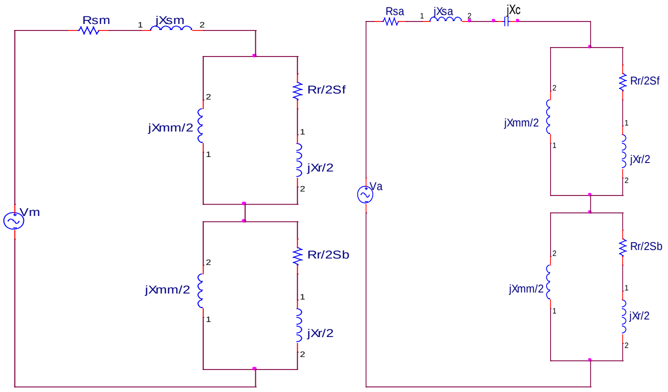

Fig 5. Equivalent circuit of Main winding and Auxiliary winding of PSCRSP induction motor

Experimental Measurement-

An experiment is carried out for PSCRSPIM 0.5 HP, 240 V AC, 1.9A, 50Hz, 1400 rpm, 18" sweep air circulator fan with 8 microfarads, 450V AC capacitor.

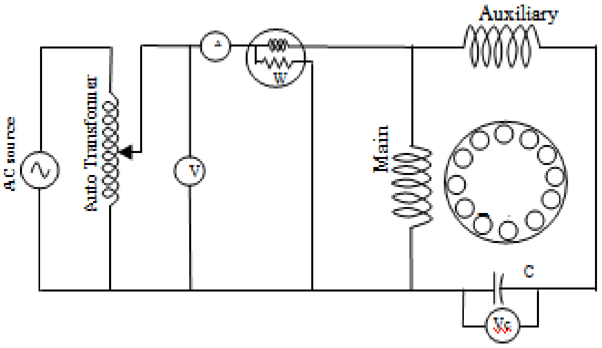

Fig. 6. Experimental setup for No-load & Loacked Rotor test

No load test results:

$$V_{NL} = 240\ V, I_{NL} = 0.56\ A, P_{NL} = 120\ W$$

Locked rotor test results:

$$V_{LR} = 117.5\ V, I_{LR} = 1.9\ A, P_{LR} = 180\ W$$

From the above equations, the estimated parameters will be

Table -1. 0.5 HP, 240 V AC, 1.9A, 50Hz, 1400 rpm PSCRSPIM parameters

Parameters	**Resistance / Reactance in Ω**
R_s	16.76
X_s	18.24
R_{sm}	25.2
X_{sm}	18.24
R_{sa}	50.1
X_{sa}	18.24
R_r	33.37
X_r	18.24
X_{mm}	331

III.MATLAB SIMULATION MODEL & RESULTS

With the above parameters, for 0.5 HP, 240 V AC, 1.9A, 50Hz, 1400 rpm MATLAB simulations are carried out and slip varied from 0.01 and 0.05. Fig.7 depicts the MATLAB simulink model. Results are plotted for slip 0.01 and 0.05. From Fig. 8, it is observed that at S=0.01, capacitor voltage found to be 443V AC and From Fig.9, it is observed that at S=0.05, capacitor voltage found to be 362 VAC. At low slip values capacitor voltage is nearer to capacitor rated voltage.

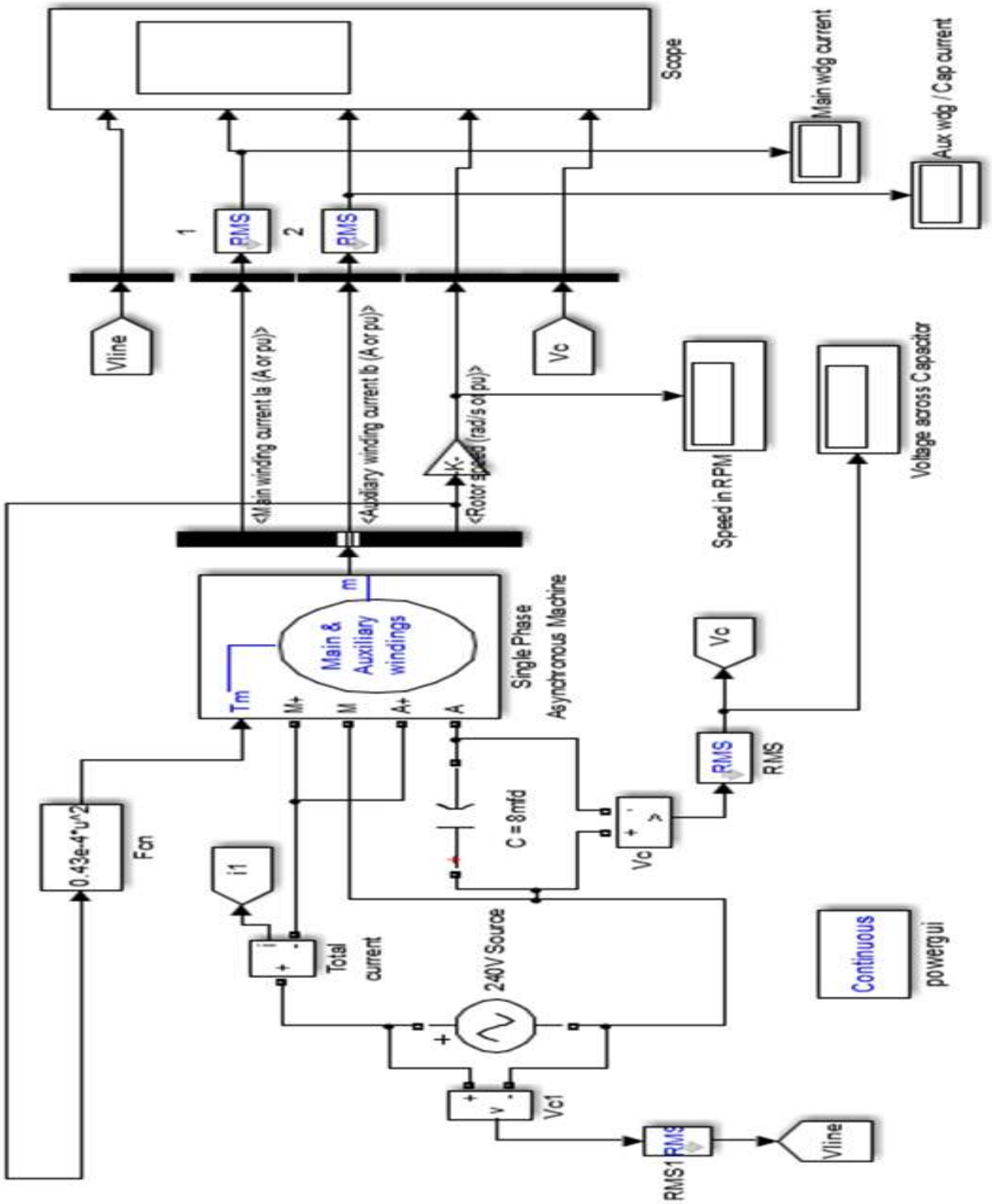

Fig. 7. MATLAB Simulink model for 0.5 HP, 240 V AC, 1.9A, 50Hz, 1400 rpm PSCRSPIM

Simulation results:

For Slip = 0.01 (low slip or lightly loaded)

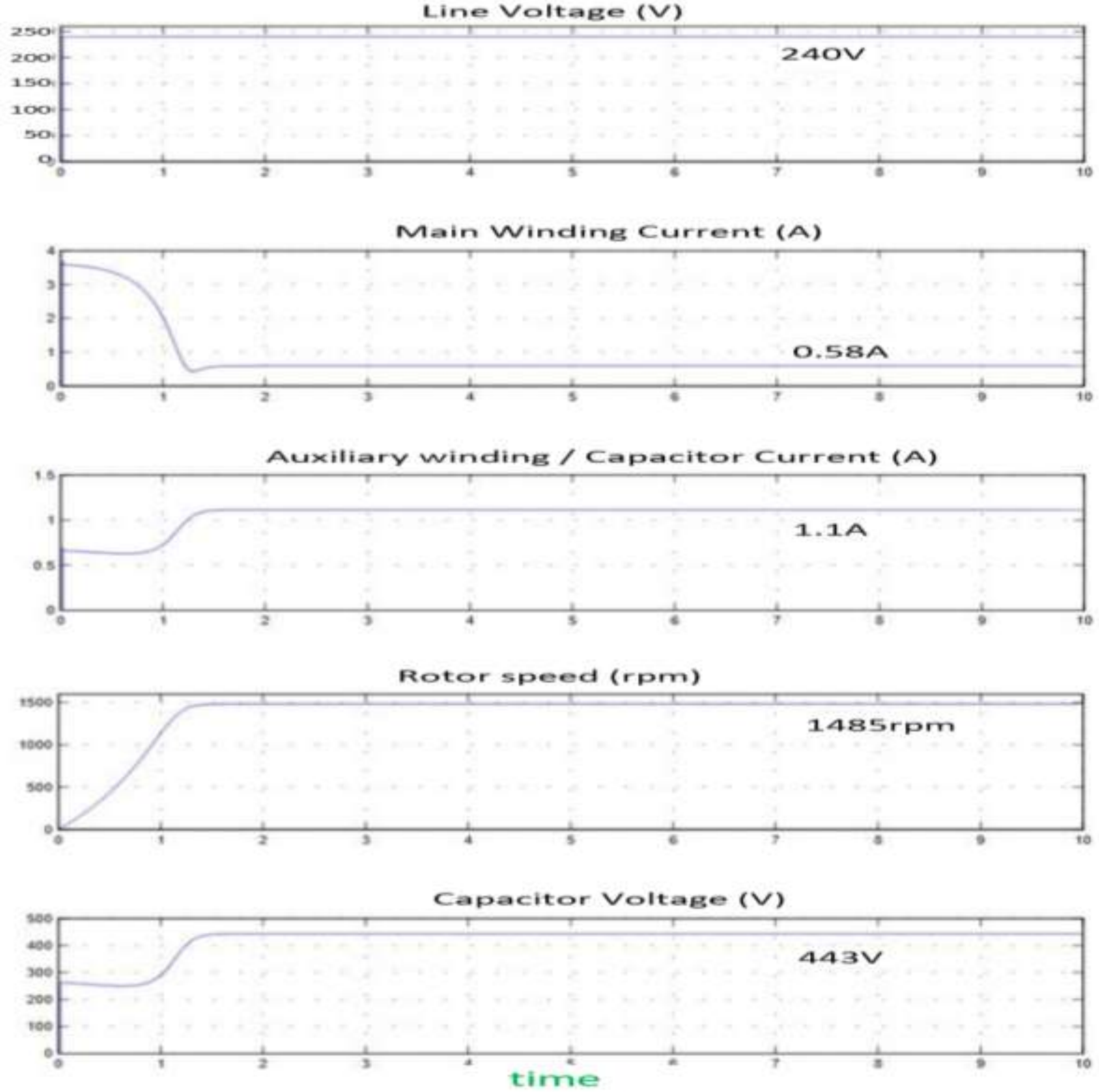

Fig 8. Simulation results for slip = 0.01

For Slip = 0.05(high slip or heavily Loaded

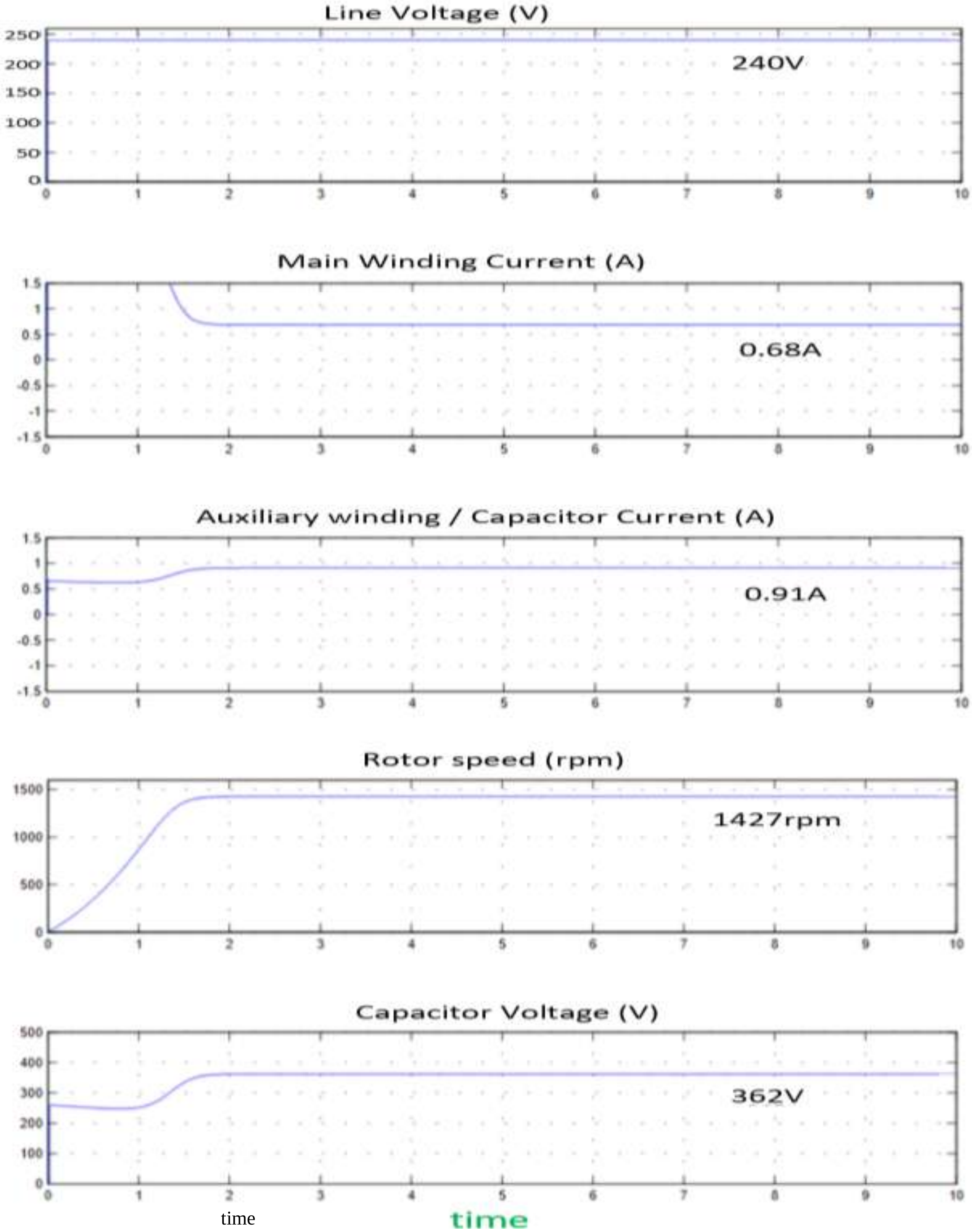

Fig 9. Simulation results for slip 0.05

IV. THEORETICAL AND EXPERIMENTAL RESULTS VALIDATION

Fig. 10 and 11 shows the theoretical calculation for forward branch impedance and reverse with variation of slip. With variation of slip from 0.01 to 0.05, forward branch impedance is decreasing and reverse branch impedance is almost constant. Fig. 12 and 13 shows the theoretical and experimental results for capacitor voltage and current. This is due to at low slip region, forward branch impedance is more, with addition of capacitive reactance overall impedance will come down there by auxiliary winding current increases. This results more capacitor current and leading in nature with respect to voltage at low slip. Hence capacitor voltage increases. As slip increases, forward branch impedance dominates capacitive reactance, hence overall impedance is more and capacitor current decreases. Theoretical, experimental and MATLAB simulation studies are matching.

Table-II. Theoretical and experimental results for capacitor voltage and current with variation of slip

S.No	Slip	Voltage across capacitor in Volts		Current through Capacitor in Amps	
		$V_{cthe.}$	$V_{cexp.}$	$I_{cthe.}$	$I_{cexp.}$
1	0.01	443	437	1.05	1.09
2	0.02	416	420	1.01	1.04
3	0.03	398	404	0.98	0.99
4	0.04	380	386	0.91	0.93
5	0.05	356	362	0.88	0.89

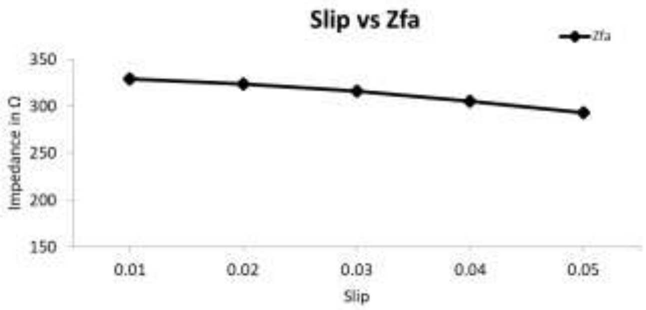

Fig.10. Slip vs forward branch impedance

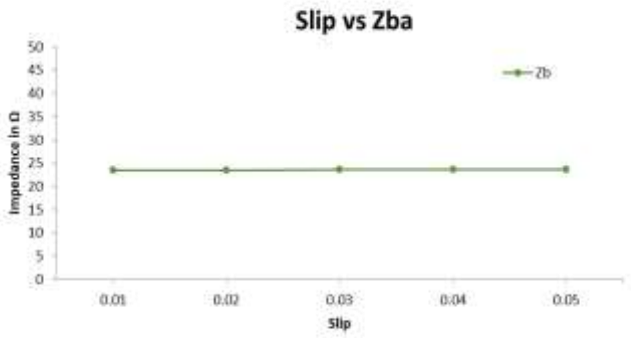

Fig.11. Slip vs Reverse branch impedance

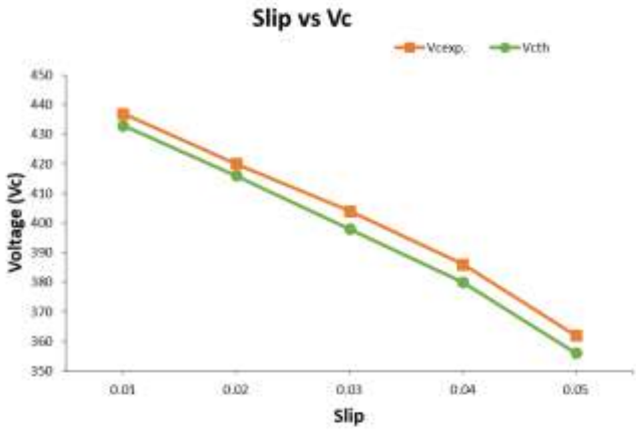

Fig.12. Slip vs Voltage across the capacitor theoretical and practical results

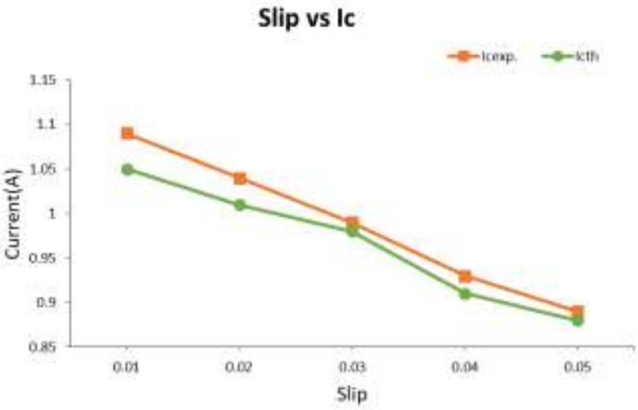

Fig.13. Slip vs Current through the capacitor theoretical and practical results

V. CONCLUSION

From the above analysis, it can be concluded that; a PSCRSPIM running under lightly loaded condition (low slip) will draw more current through the aux winding &capacitor and hence leads to failure of capacitor. In Air Circulators fans scenario, there is a tendency for the manufacturers for using same power rated motor for two/three size sweep fan leaves for economical production reasons. 400mm and 600 mm sweep fans using same rated motor which is designed for 600mm. The motor with 400mm leaves now experience lightly loaded condition and eventually fail prematurely. In general fans scenario converting specific material of earlier leaves to lightly loaded aluminum or plastic ones thus reducing the load on the original motor. Though, apparently one may assume saving with the above improvement, but the motor will fail prematurely due to capacitor failure under lightweight materials. The capacitor values shall be suitably re-assessed for PSCRSPIM in case of any changes in the load conditions especially lightly loaded conditions. This paper suggests a single phase motor to be run always with designed load. Improper design of air circulator leaves, appliances load may lead to damage of SPIM. The case study reveals that during the capacitor failures of PSCRSPIM, the load on the PSCR single phase induction motor has to be certainly looked into.

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