TORQUE PER AMPERE ENHANCEMENT OF A THREE-PHASE INDUCTION MOTOR BY MEANS OF A CAPACITIVE AUXILIARY WINDING

Mbika Muteba and Dan Valentin Nicolae

University of Johannesburg, Department of Electrical and Electronic Engineering Technology, Johannesburg, South Africa

ABSTRACT

This paper presents the use of a capacitive three-phase auxiliary winding to enhance the torque per ampere of a three-phase Squirrel Cage Induction Motor (SCIM) for electric traction, which generally requires high torque density, a high power factor and high efficiency. The three-phase auxiliary winding is only magnetically coupled to the stator's main winding. A conventional 5.5-kW, 50-Hz, and 4-pole three-phase SCIM is modified to accommodate main and auxiliary windings in the stator slots. The practical results evidenced that on no-load the torque per ampere is ± 5 times higher with the presence of a capacitive auxiliary winding that utilizes 80 μF per phase.

I. INTRODUCTION

Three-phase induction motors comprise a vast majority of electric motors made in large sizes and mostly used in variable speed drives because of their simplicity, robustness and lower cost compared to Permanent Magnet Synchronous Machines [1]. Therefore, the SCIM is always a strong contender among traction motors in Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs). Generally, a SCIM requires reactive power for operation. Thus, its power factor is inherently poor, and it is worse especially when starting and running with light loads [2]. In EVs or HEVs, the traction motor operates with a motor drive for variable speed/torque control as well as regenerative breaking. The power factor of SCIM is also poor when operating with a power electronics converter. The enhancement of the power factor of the induction machine requires a means of reactive power compensation. Several techniques have been suggested to achieve this, including synchronous compensation, fixed capacitors, fixed capacitor with switched inductor, solid-state power factor controller, and switched capacitors [1, 2, 3, 4, 5, 6].

In recent years, the use of an auxiliary winding, which is magnetically coupled to the main winding, has been widely proposed to address the problems associated with complexity and the high cost of the synchronous compensation technique [2]. It also addresses the issue of voltage regeneration and over voltages, and a very high current inrush during starting in techniques that incorporate directly the connection of capacitors [9, 10, 11, 12]. The use of auxiliary winding also addresses the problem with techniques that incorporate controlled switches in the stator winding, which is the generation of large harmonic current in the machine and line. In [9] a static switched capacitor with an auxiliary three-phase stator winding, which is only magnetically coupled to the stator's main winding, was explored for improving the starting and operating power factor of a three-phase SCIM. The use of single phase auxiliary winding, which is only magnetically coupled to the stator's main winding and controlled by an active power filter to enhance the power factor of a three-phase SCIM, is presented in [11]. In [10] and [12], the improvement of power factor of a three-phase SCIM by power electronics static switches to control a capacitive single-phase auxiliary winding is suggested. Recently, the effect of capacitive auxiliary winding on a three-phase SCIM performance behavior has been reported [2]. In the latter, from both simulation and experimental results, it was reported that the capacitive auxiliary winding had enhanced the power factor and also had a significant impact on the efficiency and torque. As mentioned, there are different techniques that provide reactive compensation of a three-phase SCIM through an auxiliary winding. Although the power factor is proven to be greatly improved for different loading conditions, the effects on the torque and efficiency have been reported with insufficient measured data to support the simulation and analytical results. Furthermore, no analysis has been reported on the optimal auxiliary reactive compensation required to enhance the torque per ampere of the SCIM when used as a traction motor in EVs or HEVs. Table 1 gives the motor specifications, ratings and parameters.

TABLE I. MOTOR SPECIFICATIONS, RATINGS AND PARAMETERS

Description	Values
Output power (kW)	5.5
Rated current main and auxiliary winding (A)	12 & 3.18
Rated line-to-line voltage main or auxiliary winding (V)	380-V
Rated frequency (Hz)	50
based speed (RPM)	1500
Number of pole pairs	2
Number of stator slots	36
Number of rotor bars	42
Number of turns per phase main winding or auxiliary winding	108
Stator resistance main and auxiliary winding (Ω)	0.555 & 1.9
Magnetizing reactance main and auxiliary winding (Ω)	53.79 & 63.52
Stator leakage reactance main and auxiliary winding (Ω)	1.62 & 8.39
Core loss resistance main and auxiliary winding (Ω)	106.4 & 581.8
Rotor resistance (Ω)	1.01

III. ANALYSIS OF RESULTS

The experimental setting comprises of the three-phase SCIM coupled to a MAGTROL torque transducer and a WB 115 Series Eddy-Current Powder Dynamometer current brake. The brake cooling is provided by a water circulation system, which passes inside the stator to dissipate heat generated by the braking power. A MAGTROL DSP6001 high speed programmable dynamometer controller is used to provide the desired mechanical load. Fig. 1 shows the experimental setup rig photo, while Fig. 2 illustrates the power factor, efficiency and load current as function of load torque for different capacitance values.

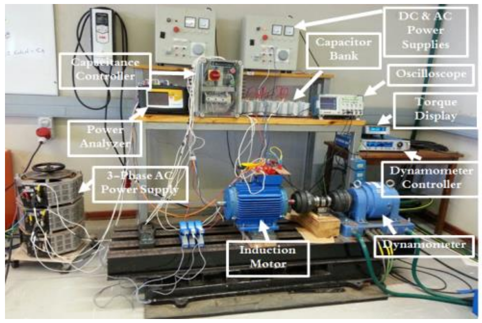

Fig. 1. experimental setup rig photo

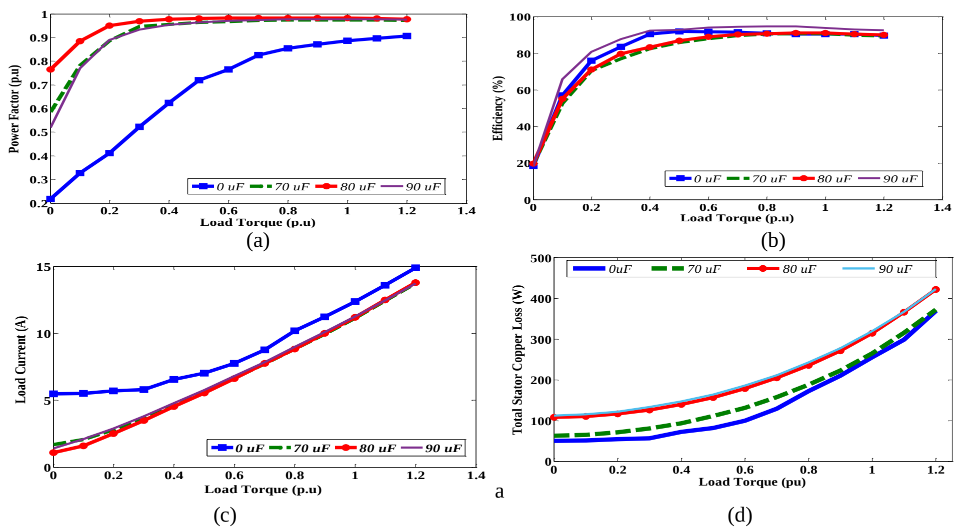

Fig. 2. Measured performance indexes as function of load torque, (a) Power factor (b) efficiency , (c) load current, (d) total stator copper loss

Observing from the experimental results in Fig. 2 , it is clear that under no-load condition, the injection of excitation current into the auxiliary winding, using 70 μF , 80 μF and 90 μF capacitors, significantly improves the power factor from 0.217 lagging to about 0.585, 0.765 and 0.52 lagging, respectively. The use of 80 μF capacitors gives optimal power factor improvent throughout the loading cycle, reaching a power factor of 0.983 lagging at rated load torque. The presence of capacitors in the auxiliary winding circuit significantly improves the torque per ampere of a three-phase 5.5-kW SCIM as shown in Fig. 2. (c). It is obsrved that on no-load the line current which is mainly magnetizing is reduced from

5.47 A for 0 μF down to 1.69 A, 1.09 and 1.41 A for 70 μF , 80 μF and 90 μF respectively. From the same measured results, it is noted at the load torque of 0.3 p.u, the line current is reduced from 5.81 A for 0 μF down to 3.64 A, 3.5 A and 3.8 A for 70 μF, 80 μF and 90 μF respectively. Fig. 3 shows the instantaneous load and excitation currents (auxiliary winding) behaviors for different load torques and capacitance values. From the FFT results, it is noted that the presence of capacitive auxiliary winding significantly affects the current magnitudes of the lower harmonic orders in both main and auxiliary windings. The auxiliary current profile exhibits a high magnitude of 3rd harmonic order at low load torque.

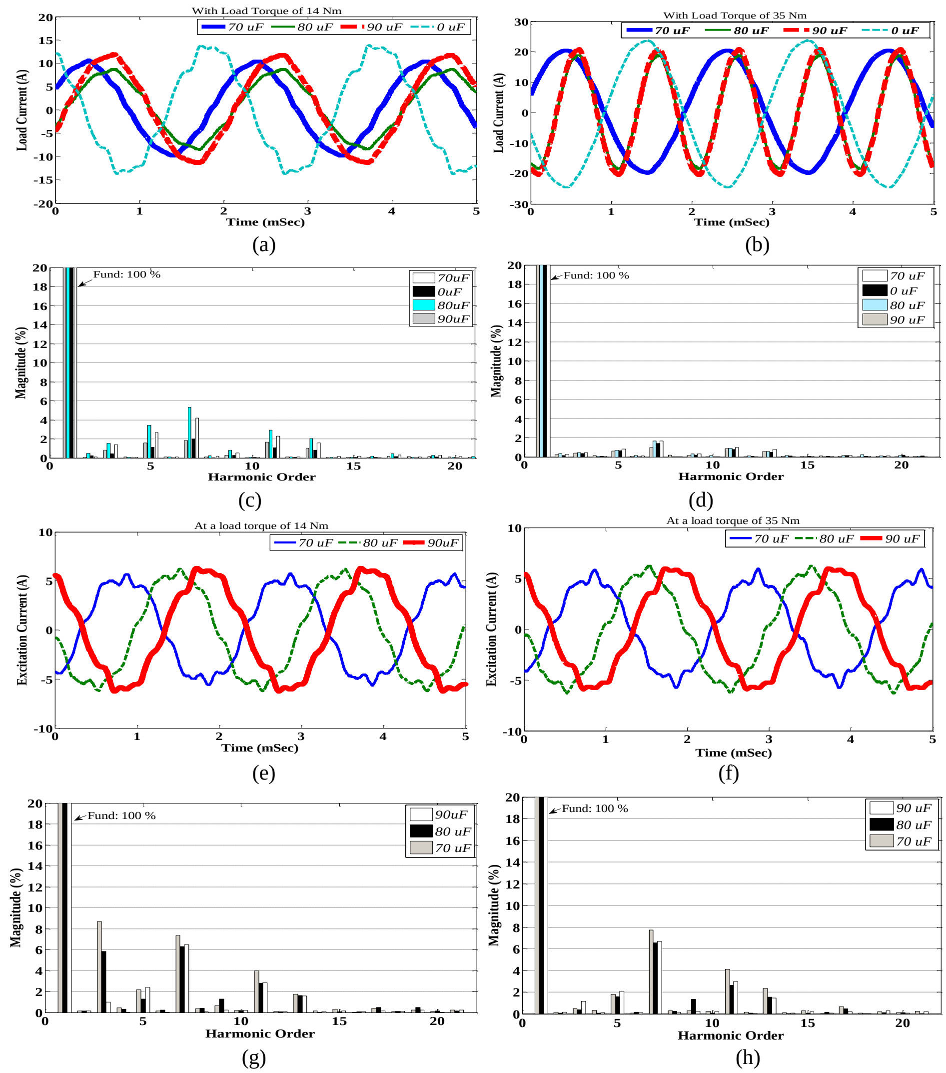

Fig. 3. Measured instantaneous current profiles, (a) load current at 14 Nm, (b) load current at 35 Nm, (c) FFT of the load current at 14 Nm, (d) FFT of the load current at 35 Nm, (e) auxiliary current at 14 Nm, (f) auxiliary current at 35 Nm, (g) FFT of the auxiliary current at 14 Nm, (h) FFT of auxiliary current at 35 Nm

IV. CONCLUSION

In this paper, a capacitive auxiliary winding as a means of torque per ampere enhancement in a squirrel cage induction motor, which is intended for use as a traction motor in EVs and HEVs, has been analyzed. From the experimental results, it was clear that the injection of capacitive current into the auxiliary winding had not only improved the motor's power factor, but had also tremendously enhanced the torque per ampere. As noticed from the measured results, it is possible to have, at the same time, better power factor, enhanced torque per ampere and good efficiency through a wide range of loading operation using an optimal single capacitance value. A detailed analysis of the results, including Finite Element Analysis results, will be provided in the final paper. Future work will cover the effect of the airgap length on the power factor, torque per ampere and efficiency of the squirrel cage induction motor with auxiliary capacitive winding. Future analysis will include, but is not limited to, the motor's performance to fit in driving pattern that satisfies torque, power and speed characteristics for EVs and HEVs.

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