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TEST RESULTS ON SYNCHRONOUS RELUCTANCE MACHINE WITH AUXILLIARY WINDING FOR LEADING REACTIVE POWER INJECTION

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ABSTRACT
This paper reports the performance of Synchronous reluctance machine with a conventional rotor structure and a 3-phase auxiliary winding for leading reactive power injection. The machine was built, tested and their measured performance compared to that of a conventional machine of the same dimension and size. It is shown that the modified machine has a saliency ratio clearly influenced by the capacitor. Experimental results of this machine configuration corroborated *theoretical analysis and showed that the torque as well as the power factor performance is better compared to conventional reluctance.*

KEY WORDS
Performance improvement, Synchronous Reluctance Machine, Capacitance Injection.

1. Introduction

Synchronous reluctance motor is one of the oldest types of electric motors, and has since attracted the significant research effort of investigators to improve its performance [1] – [7]. The synchronous reluctance motor is a singly salient machine in which the rotor is constructed to employ the principle of reluctance torque to produce electromechanical power. The stator is typically wound in an identical manner to that of an induction machine while the rotor is constructed with different configurations varying over the simple salient, flux barrier, axially laminated and segmental type [1, 4, 6, 8]. In evolving these rotor configurations, the objective has consistently been that of obtaining a rugged and simple construction of motor having a high torque density, efficiency and power factor [8]. To achieve these goals, focus has been to maximise the saliency ratios (X_d/X_q) and X_d-X_q, and these has consistently followed a geometrical approach.

In [5], the use of a balanced 3-Φ auxiliary winding connected to a balanced capacitor for leading reactive power injection so as to improve the performance of synchronous reluctance was discussed and theoretically established. It used the field theory approach and coupled circuit method to develop equations which demonstrate an improved power factor and torque. The conceptual diagram of the machine is as shown in Fig. 1.

This paper therefore aimed to present an experimental investigation of a synchronous reluctance machine with an auxiliary winding for leading reactive power injection. It is meant to verify the validity of the theoretical analysis presented in [5].

The synchronous reluctance machine used in this experimental investigation has a standard frame DZ112M 4.0 kW, 4-pole induction motor stator. The stator winding was rewound to have two sets of single layer full pitch stator windings. The auxiliary winding was however wound using wires of thinner diameter so that the stator slot will be able to accommodate the two set of windings. The rotor is of the simple salient type. The particular machine used in this validation experiment is a cage reluctance synchronous motor.

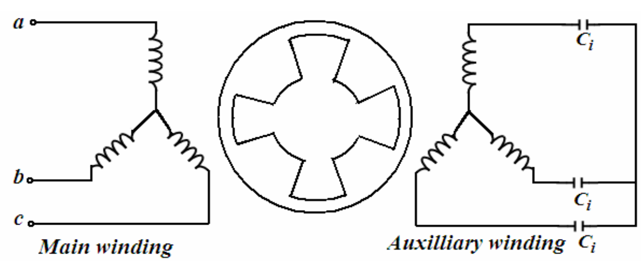

Figure 1. Synchronous Reluctance machine with Auxiliary winding and Capacitance injection

2. Motor Parameter Measurements

A simplified block diagram of the test set up is shown in Fig. 2. The set up consist basically of a balanced three phase supply, a variable dc power source, a Tektronix 4925, digital phosphorous DPO4079 oscilloscope, a fluke 1735 power logger, a synchronous reluctance motor adapted from a squirrel cage induction motor and a dc machine operated in the generator mode to load the motor.

A no-load test was carried out on the experimental machine to determine it's per phase total reactance X_d. The machine was fed with a 50Hz sinusoidal source, and the total per phase reactance X_q was obtained using the pull-out torque test highlighted by Honsinger [3]. The stator resistances were measured using the dc test. The variations of the measured values of direct axis reactance (X_d) obtained at 1500rpm and quadrature axis reactance (X_q) obtained at a very large angle possible were plotted against the applied phase voltage are presented in Fig. 3. It is easily observed from the curves that measured X_d is considerably influenced by the level of saturation, whereas X_q is only slightly influenced.

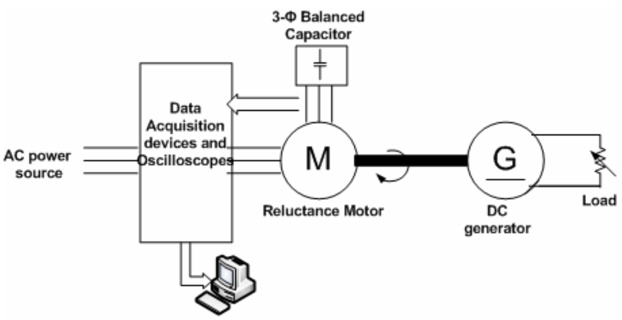

Figure 2. Simplified block diagram of test set up

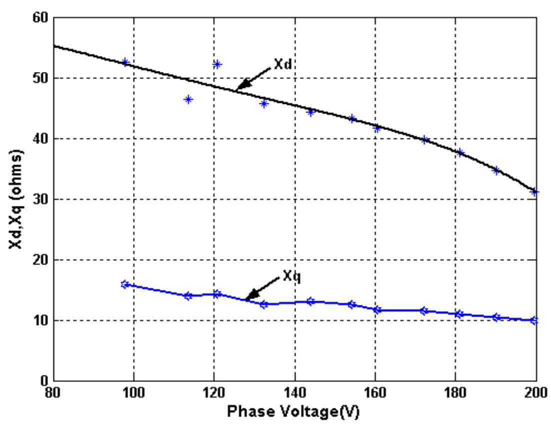

Figure 3. Variation of measured X_d, X_q with phase voltage for the uncompensated machine

3. Variation of motor parameters with Capacitance

The per phase equivalent circuit of the machine configuration that is the subject of this paper as previously developed [5] is shown in Fig. 4.

When balanced static capacitors were connected across the auxiliary winding as shown in Fig. 4, the sensitive parameters of the machine that actually describe its power capability were again evaluated. Graphical representations of the variation of the measured d-axis reactance (X_d), q-axis reactance (X_q) and the saliency ratio (λ) of the machine with the capacitance are shown respectively in Figs. 5, 6, and 7. It is observed that while X_d obviously increases with the size of capacitance injected, X_q was only slightly reduced. Thus, the saliency ratio (λ) as well as (X_d-X_q) increases. An increase of the saliency ratio obviously demonstrates an improvement in the torque capability of the machine [1], [6], [8].

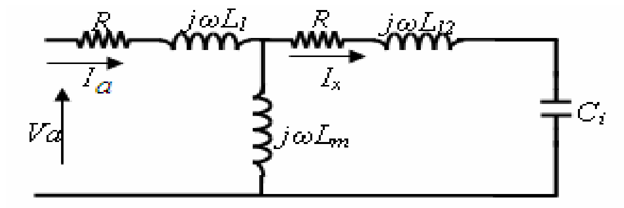

Figure 4. Per phase equivalent circuit of the machine configuration

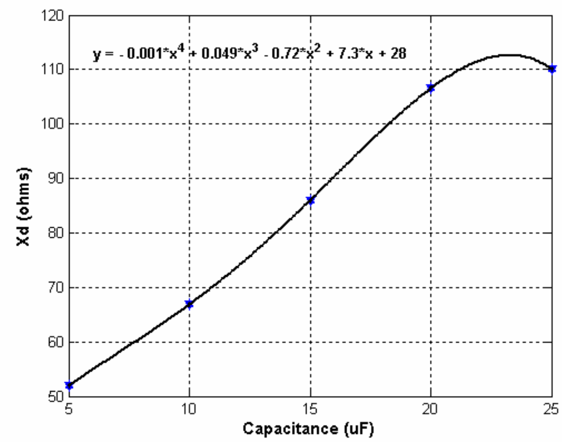

Figure 5. Variation of measured X_d with the Capacitance injected

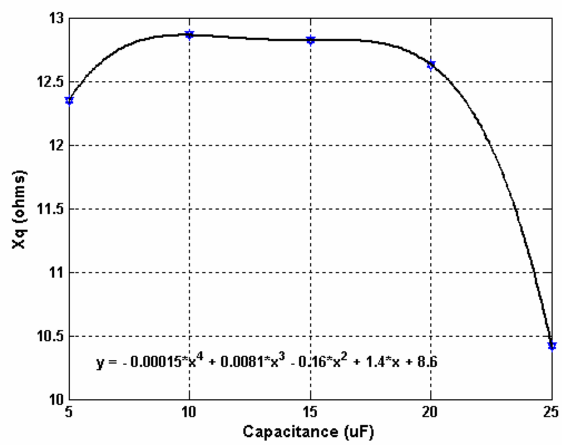

Figure 6. Variation of measured X_q with the Capacitance injected

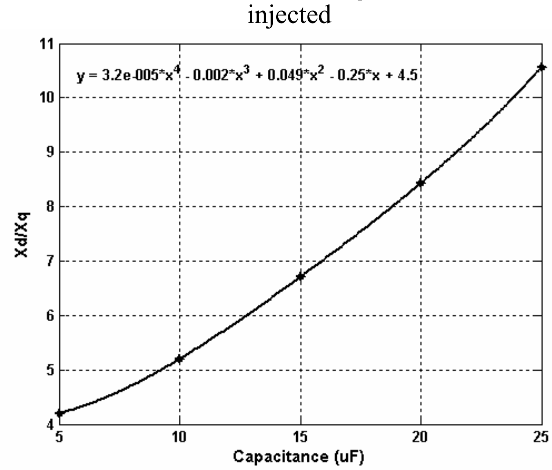

Figure 7. Variation of measured saliency ratio with the Capacitance injected

The relationship between the measured parameters (X_d, X_q, and λ) of the machine and the capacitance injected into the machine is fit with a fourth order polynomial equation written as:

$$\lambda = 3.2e^{-005}C^4 - 0.002C^3 + 0.049C^2 - 0.25C + 4.5 \qquad (1)$$

$$X_d = -0.001C^4 + 0.049C^3 - 0.72C^2 + 7.3C + 28 \qquad (2)$$

$$X_q = -0.00015C^4 + 0.0081C^3 - 0.16C^2 + 1.4C + 8.6 \qquad (3)$$

where C represent the size of the capacitance injected. Thus, for a typical capacitance value the possible power capability of the machine can invariably be determined. However, it is necessary to know that, the size of capacitance that can be injected via the auxiliary winding at any point in time will have a limit imposed possibly by the current carrying capability of the auxiliary winding. In this experimental work it was observed that going beyond a capacitance value of 25uF will endanger the auxiliary winding. Furthermore, it has been demonstrated in [5] that for a typical machine an appropriate size of capacitor that will that will properly compensate both the power factor and torque of the machine over a wide range of load angles can be determined.

Table 1
Specifications for the Machine

Phase voltage	150V
Frequency	50 Hz
Poles	4
Direct axis reactance	43.41Ω
Quadracture axis reactance	12.60Ω
Main winding resistance	4.766Ω
Auxiliary winding resistance	18.76Ω
No of slots	36
Number of turns per coil	45

4. Steady state Performance

In order to avoid the excessive saturation of the machine at high voltage, load tests were performed on the experimental machine at 150V phase voltage. Fig. 8 and 9 illustrate the variation of the measured power factor as well as the torque as a function of load angle. For all the chosen capacitance value over the range of load angle obtainable before pull out, the measured results of Fig. 8 show that the machine with an auxiliary winding for reactive power compensation presents a better power factor.

Similarly, as a follow up to the fact that the saliency ratio of the machine improves with the capacitance injection, it is evidently seen in Fig. 9 that particularly beyond the load angle of 15°, the torque capability of the machine with the configuration been discussed is better. As an illustration, at a load angle of 25°, and with a capacitance of 25uF injected, the torque capability of the machine was improved from its initial value of 8.8N.m to 10.42N.m. This represents about 18.18% torque improvement at that capacitance

A 3D contour plot showing the variation of the torque as function of load angle and capacitance is shown in Figure 10.

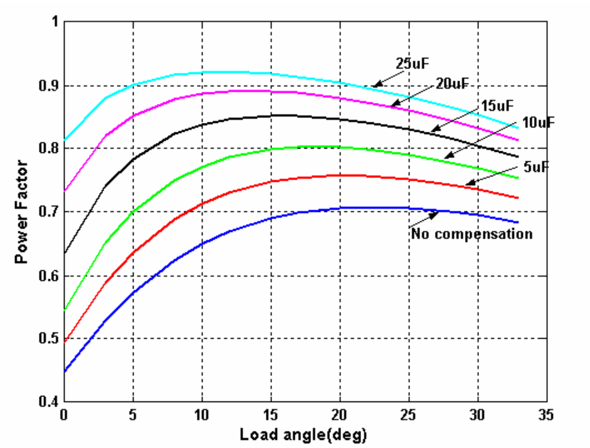

Figure 8. Variation of power factor with load angle at different capacitance

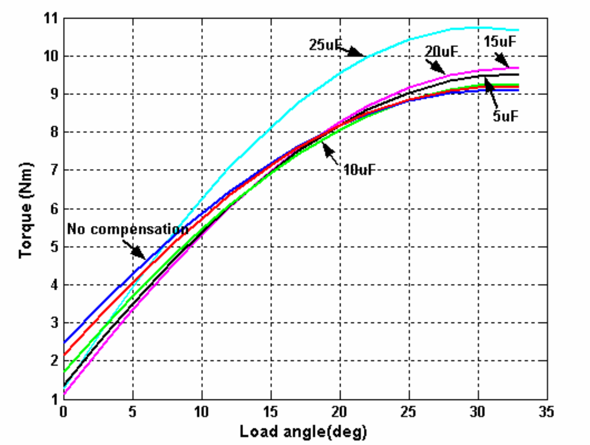

Figure 9. Variation of Torque with load angle at different capacitance

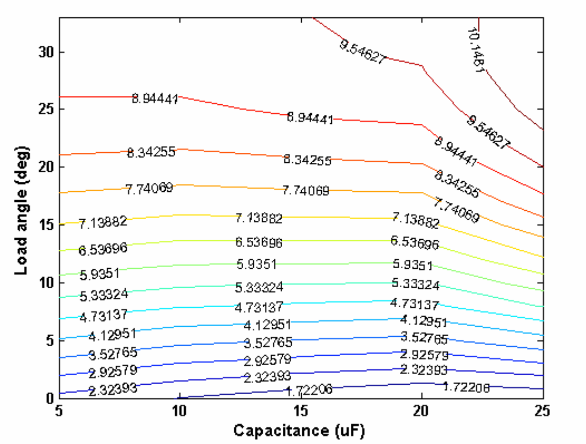

Figure 10. Contour plot of the torque as a function of load angle and capacitance

Figs. 11 and 12 show the no-load current and voltage waveforms for an uncompensated test machine and the one with 20μF compensation respectively. The current waveforms have obvious harmonics, which may be primarily adduced to the nature of the rotor of the machine that is used for these experimental tests. As indicated in table 2, the harmonic content of the current waveform of the uncompensated machine is 21%, as against the 29% of the compensated machine. It is further seen in this table that with increased loading, which is the natural operational situation of the machine, the harmonic content of the compensated machine is much improved than the ordinary. This indicate that the injection of the capacitor also improve the current harmonic in the machine, particularly under loading condition.

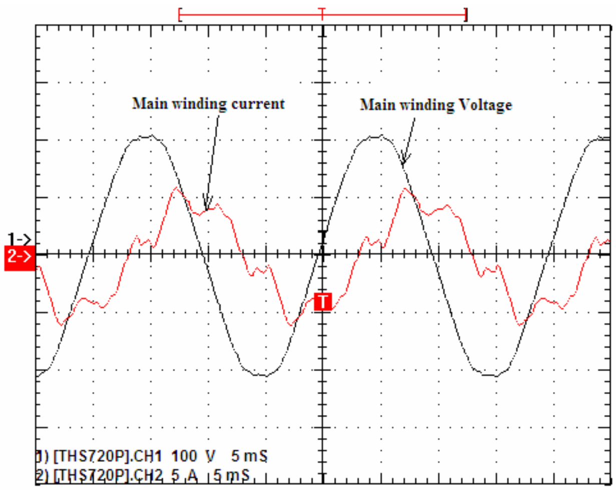

Figure 11. Waveforms of main winding voltage and current of the machine without capacitance and on no-load

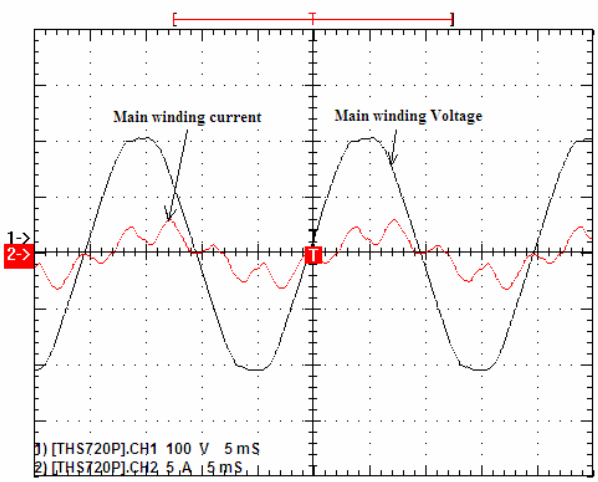

Figure 12. Waveforms of main winding voltage and current of the machine with 20μF capacitance on no-load

The power factor compensation situation is also made obvious from the waveforms of Fig. 11-13, by comparing the zero crossing of the current and voltage for the machine with and without compensation. It is also easily observed from Fig. 13 and 14 that the auxiliary winding is unitly coupled to the main winding.

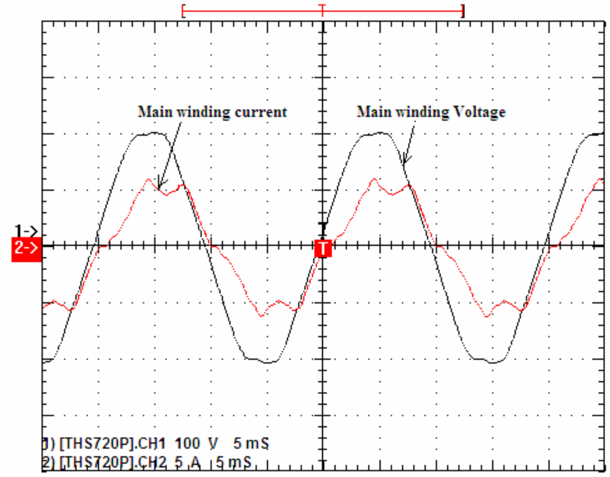

Figure 13. Waveforms of main winding voltage and current of the machine with 20μF capacitance under load condition

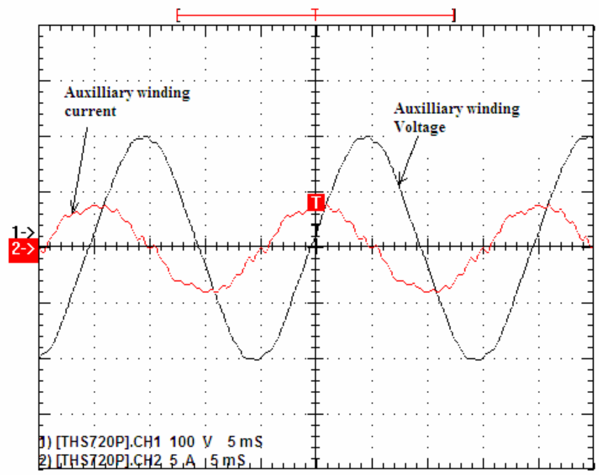

Figure 14. Waveforms of auxiliary winding voltage and current of the machine with 20μF capacitance under load condition

4. Dynamic Performance

The starting characteristic as well as the load change response of the machine was measured. The dynamic test was done with a high inertia coupled to the shaft of the motor, and the motor supplied with a sinusoidal supply at 50Hz. The starting characteristics of the machine with and without compensation as captured using a Tektronix oscilloscope are respectively shown in Fig. 15 and 16. A quick view at these two figures illustrate that the machine with the capacitance attached to the auxiliary winding settles faster than the other one. This goes on to demonstrate that the capacitance in the auxiliary winding also assist in the synchronisation of the machine.

The response of the machine to a sudden change in load is as displayed in Fig. 17. A load torque of 9.5Nm was switched in with the machine compensated using a 20uF capacitor. It is seen from the expanded portion of the oscilloscope display that the harmonic content of the current waveform as well as the power factor of the machine was improved

Table 2
Comparative total harmonic distortion (THD) of the machine

Load Angle (deg)	THD (%)		Difference (%)
	Machine without Capacitance	Machine with 20uF capacitance	
0	22.7	25.3	-2.6
3	21.2	21.4	-0.2
5	20.3	17.5	2.8
8	19.6	14.2	5.4
10	17.7	12.6	5.1
12	17.0	11.7	5.3
15	15.6	10.8	4.8
17	14.7	10.4	4.3
20	13.7	10.2	3.5
22	13.0	9.8	3.2
25	11.9	9.2	2.7

5. Conclusion

In this paper, a synchronous reluctance machine with an auxiliary winding for leading reactive power injection has been built and tested. Both steady state and dynamic characteristics were presented, explaining the impact of this configuration on the power factor, torque capability, synchronization and the harmonic characteristics of the machine. The measured parameters and performance characteristics obtained from the experiments corroborate the theoretical analysis and claims presented in an earlier article [5]. It is experimentally shown in this paper that:

1. The saliency ratio of the machine discussed here can be improved by the injection of leading reactive power. For this typical situation, a fourth order polynomial equation was used to express the relationship between the saliency ratio and capacitance injected.
2. The modified machine operates at a better power factor as high as 0.95, when compared to the uncompensated machine.
3. For machine of the same dimension, at different load angles, particularly beyond 15° for this typical case, the modified machine delivers a higher torque than the uncompensated machine.
4. The capacitor introduced in the auxiliary winding assist the synchronisation of the machine.
5. The current harmonic content of the modified machine is much better particularly under loading condition.

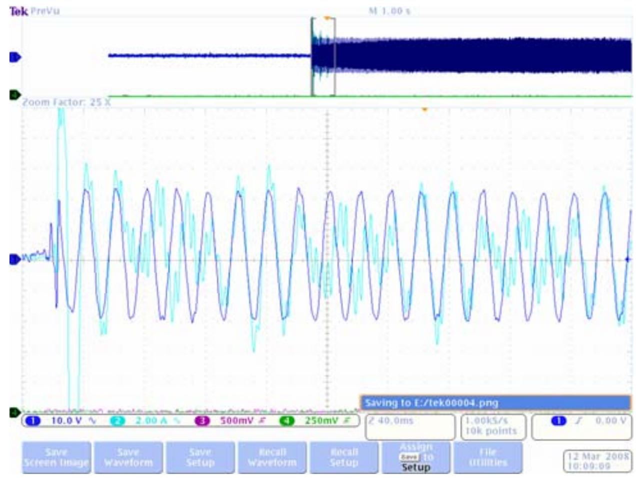

Figure 15. Starting characteristic of the compensated machine

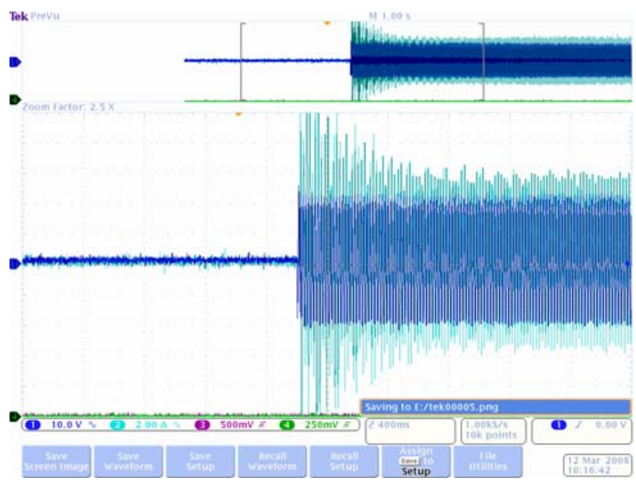

Figure 16. Starting characteristic of the uncompensated machine

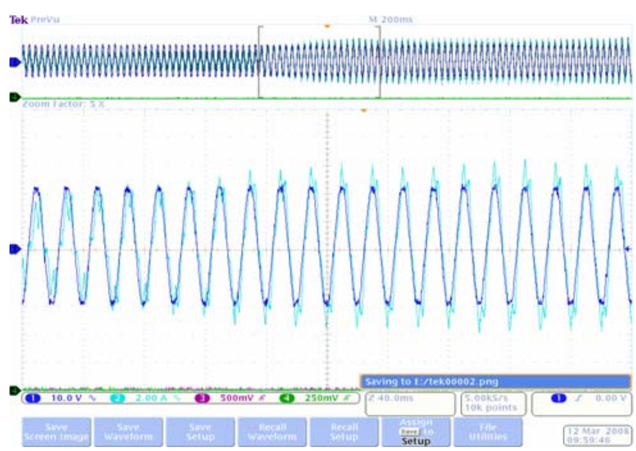

Figure 17. Response of the machine to sudden load change to 9.5Nm

With the known advantages and application area of synchronous reluctance machine, the configuration experimentally investigated in this paper should find acceptability particularly with better rotor design options.

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