A Permanent Magnet Synchronous Machine with Motor and Generator Functionalities in Single Stator Core

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***Abstract*- This paper introduces design and analysis performed for a dual winding electric machine that operates both motor and generator mode. The proposed structure could be a considerable choice for multitasking operation and fault tolerant applications. Motor and generator windings of the electric machine are located on the same stator core. Windings are concentrated type so that electrical and magnetic isolation is maintained. With the proposed technique, simultaneous motoring and generating operations can be implemented in the single housing of electric machine. This structure provides low volume, low mass and low inertia for industrial applications. It also provides economical benefit compared to using separate motor and generator. Design considerations of the proposed electric machine are outlined in the paper. Also a comparison between distributed winding topology and concentrated winding topologies is performed. Finally experimental results are discussed.**

***Index Terms*— Permanent Magnet Synchronous Machine (PMSM), Motor-Generator (MG) operation, Concentrated Winding, Magnetic Decoupling, Dual Winding Electric Machine, Fault Tolerant Operation, Hybrid Electrical Vehicle Applications.**

I. INTRODUCTION

Popularity of PMSMs in academic studies and industrial applications are recently increasing. This arises from the compact structure, high efficiency, high power density and high torque density features of PMSM. For studies conducted up to 2000s, rotor structure modifications were the major area of the research [1,2]. Designing the surface mounted and embedded magnet rotor structures were the options under investigation [3].

In 2000s, stator core modifications were under investigation [4.5]. Concentrated winding technique has been widely investigated due to advantages such as higher torque and power density, lower end winding volume, fault tolerant capability etc. [6,7]. Several alternative techniques for winding location can be exercised. These techniques are mainly for elimination of higher back EMF harmonics and minimization of torque ripple [8,9]. By modifying stator slot geometry, torque ripple and cogging torque minimization can also be achieved [10,11,12].

Dual winding machines are a group of electric machines which may enable volume, weight and cost reduction in applications where space constraints exist. A class of Permanent Magnet Synchronous Machines (PMSM) has quite compatible structures where two winding sets may exist in the stator without interfering each other [13]. Yet simultaneous motor/motor or motor/generator operations are possible due to independent winding sets.

This paper presents a dual-winding machine structure in an effort to find out the best winding configuration with magnetic isolation so that a proper multitasking is performed. The goal of multitasking is to have simultaneous motor and generator operation of the electric machine. Furthermore, electric machine should be able to operate motor only and generator only operation as needed. [14,15].

II. PROPOSED MG MACHINE STRUCTURE

Concentrated winding coils are wound around single stator tooth as shown in fig. 1.

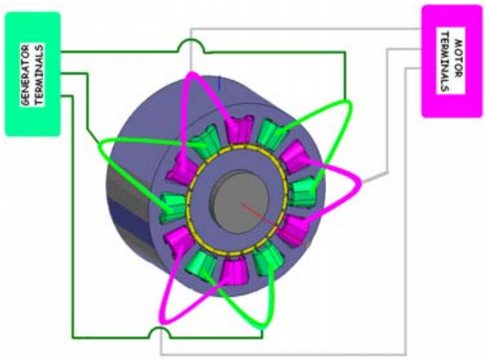

Figure 1. Connection diagram of concentrated single layer dual winding machine

Motivation for concentrated winding is to provide magnetic isolation between two sets of stator winding. It can be shown that each concentrated coil around any stator tooth has an independent magnetic circuit [8] and it does not interfere magnetically with any other coils around the stator. For this proposed dual winding electrical machine, coils are wound around single stator tooth as shown in fig. 1 and one slot is occupied solely by one coil side.

Transient Finite Element Analysis with Maxwell 2D was performed to show how concentrated winding approach is effective in decoupling two winding sets magnetically. Generator winding current magnitude is varied to observe how motor operation is influenced by generator winding current variation. In fig.2, note that higher amplitude of the generator phase currents do not show appreciable increase or decrease in the motor average torque output.

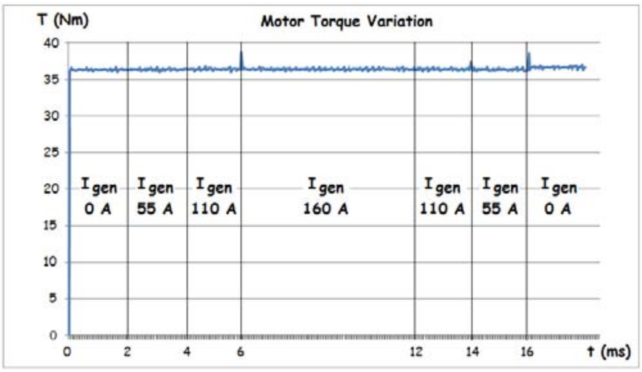

Figure 2. Motor torque variation for different load levels of the concentrated single layer dual generator winding (n=1500 rpm).

In another test, motor current magnitude is varied to see its influence on generator output voltage. In fig. 3, it can be seen that any increase or decrease in the motor current does not cause any increase or decrease in the generator back Electromotive Force (EMF). This proves that motor winding current has no effect on the generator winding magnetic circuit. Accordingly generator winding back EMF as an indicator of generator output voltage is constant regardless of motor loading.

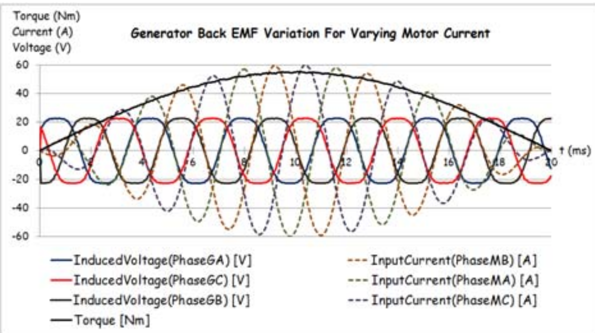

Figure 3. Generator back EMF variation for varying motor current (n=1500 rpm).

Flux distribution of the proposed electric machine was also obtained by finite element analysis. The purpose of this study is to show the behavior of the machine under various loading conditions. One important point which should be clarified is how flux lines are distributed and whether or not there is any coupling between winding sets. Figure 4 and figure 5 show flux distribution for medium and heavy load levels, respectively. The analysis show no coupling exists at medium load level. This is an anticipated result and it should be the same at the rated load level. However at heavy load level, magnetic saturation influences magnetic flux paths and hence some degree of cross coupling is observed as shown in Figure 5.

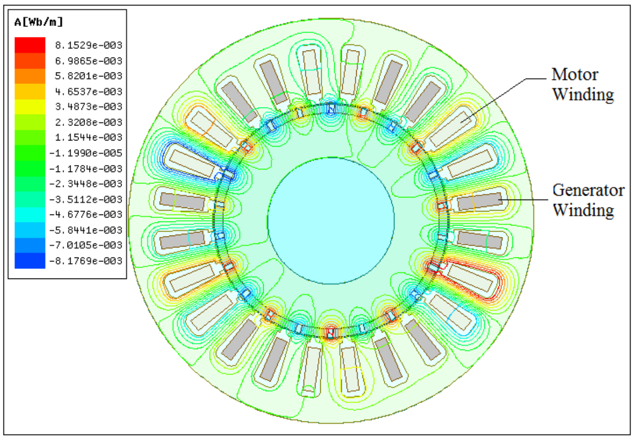

Figure 4 Flux distribution for medium load level (I_{motor}=20 A (rms), $I_{generator}$=100 A (rms)).

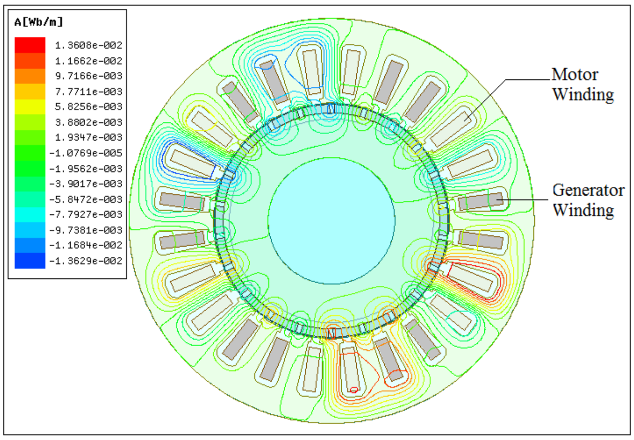

Figure 5 Flux distribution for heavy load level (I_{motor}=80 A (rms), $I_{generator}$=500 A (rms)).

III. COMPARISON WITH CONVENTIONAL APPROACHES

MG machine is compared with its alternative where two separate machines are used. Comparison consists of two phases. These phases are; physical feature comparison and electric and magnetic feature comparison of the machines. General geometrical and electrical parameters of MG machine are given in Table I and Table II, respectively. The same tables also show the data for the motor and generator which are designed with single set of winding as conventional approach.

Calculating the volumes and masses of the machines from their given geometrical parameters, DWPMSM's total volume is 6558,17 cm^3 whereas single motor and single generator's total volume is 8222,14 cm^3, respectively. Similarly DWPMSM has lower mass comparing to the total weight of classical motor and generator. When total volume and weight numbers are taken into the account, dual winding structure has significant advantage.

In addition all of above advantages, some volume, weight and cost savings also arise when we consider reduced number of position sensor, end bells and bearings. Reduction in these auxiliary but essential elements of the machine yields significant amount of space saving.

TABLE I. PHYSICAL PARAMETERS OF DIFFERENT PMSM

STATOR DATA	MOTOR	DWPMS(MG)	GENERATOR
Number of Slots	24	24	24
Outer Dia.(mm)	215	240	218
Inner Dia. (mm)	123	140	122
Total Length (mm)*	111.12	144.96	112.19
Len. of Core (mm)	89.5	120	90
Type of Steel	M1924G	M1924G	M1924G
Slot Area (mm^2)	357.7	396.3	361.39
Slot Fill Factor (%)	52.72	56.26	61.02
ROTOR DATA			
Thicknes of Mag.(mm)	5	5	5
Type of Magnet	NdFe30	NdFe30	NdFe30
Total Net Weight(kg)	19.16	32.68	20.17

*Includes end winding

TABLE II. ELECTRICAL PARAMETERS OF DIFFERENT PMSMS'

NO LOAD DATA	MOTOR	DWPMSM	DWPMSG	GEN.
St.Teeth Flux Density	1.27	1.28	1.43	1.42
St.Yoke Flux Density	0.46	0.44	0.43	0.42
THD of Ind.Voltage (%)	--------	--------	0.68	0.16
FULL LOAD DATA				
Max.Line Voltage(V)	155.75	156.11	36.65	36.53
RMS Ph. Current (A)	34.83	34.93	137.28	134.25
Efficiency (%)	93.54	92.85	90.48	92.34
Power Angle (degree)	--------	--------	40.98	40.0102
Torque Angle (degree)	25.73	26	--------	--------
Iron-Core Loss (W)	116.48	190.98	231.19	147.7
Arm Copper Loss (W)	143.21	116.01	84.527	101.05
Total Loss (W)	413.96	461.53	315.72	248.75

IV. EXPERIMENTAL RESULTS

An experimental setup was built to test performance of the proposed electric machine. Fig.6 shows the setup of the experimental system. Dual winding PMSM is driven by a squirrel cage induction motor. Four-quadrant adjustable speed drive system controls induction machine so that both motoring and generating operation would become possible. A rotary torque sensor between induction motor and DWPMSM measures torque level dynamically.

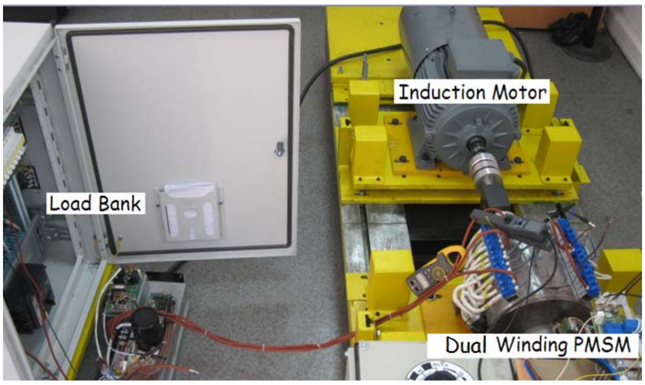

Fig 6. Experimental set up for DWPMSM

Magnetic Coupling Performance of Dual Winding Machine

To show magnetic decoupling between motor and generator windings, dual winding PMSM is driven with induction motor at 750rpm shaft speed with no load on generator. Recorded motor back EMF waveform is shown in figure 7. In the next step, generator is loaded with balanced wye connected resistive load where each phase has 250W power consumption. The recorded motor back EMF waveform is shown in figure 7.

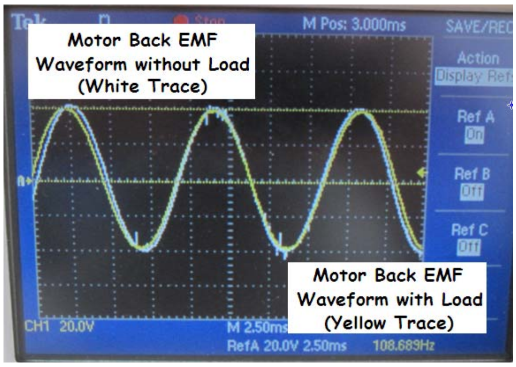

Fig 7. Motor Back EMF waveform

There is no difference between no load operation back EMF waveform and loaded operation back EMF waveform of the motor winding. The test shows that there is no magnetic coupling between motor and generator winding sets.

Motor/Generator (MG) Operation for Dual Winding Machine

In this mode of operation, motor side of dual winding machine is the only prime mover in the system as shown in figure 8. The mechanical output power generated by DWPMSM is partly used by generator side of dual winding machine and remaining mechanical power is supplied to induction machine which operates as generator. Induction machine ultimately feeds that power to utility through four-quadrant adjustable speed driver.

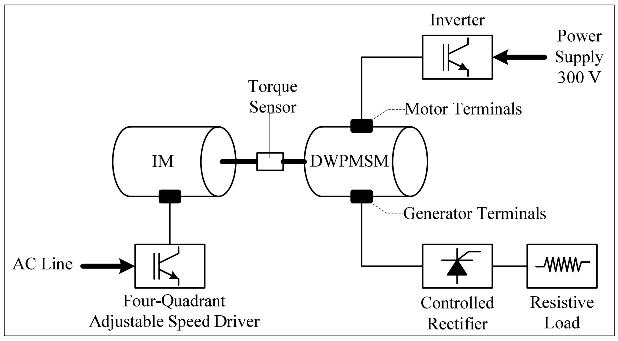

Fig 8. Block diagram of experimental setup

Although several operating points are recorded throughout operating range of the motor and generator windings, one representative sample operating point waveforms are shown here.

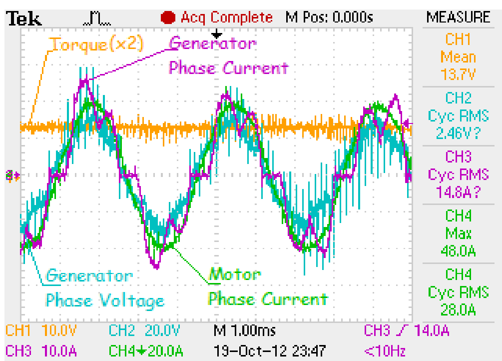

Fig 9. Motor /Generator operation (n=1500 rpm / 13.7 V-40A DC)

Figure 9 shows that the proposed electric machine has the capability of simultaneous operation both motor and generator in single stator core. Experimentally obtained efficiency numbers are given in Table III. Experimental and simulated FEA torque waveforms can be seen at Fig 10.

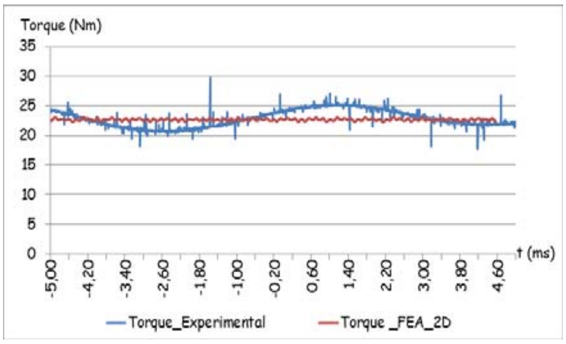

Fig.10 Comparing of Experimental and FEA torque waveforms (22.82Nm load torque)

TABLE III. MOTOR-GENERATOR OPERATION AT 1500 RPM

Shaft Torque (Nm)	**4,7**	**18,2**	**23**
Motor Input Power (W)	2912,5	4368,1	5832,46
Mechanical Output Power (W)	737,9	2857,4	2307,9
Generator Output Power (W)	2033,2	1136,6	3152,4
Total Output Power (W)	2771,1	3994	5356,8
Machine Efficiency (%)	**95,14**	**96,8**	**93,9**

V. CONCLUSIONS

A PM Synchronous Machine based dual winding electric machine is comparatively presented in the paper. Independent operation capability of the machine is presented by both finite element analysis and experimental work. Full paper will include further topics about dual winding machine such as winding structure details, further efficiency numbers from experimental work, torque ripple comparison and etc.

ACKNOWLEDGMENT

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