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Characterisation of a Ring-Wound Variable Reluctance Motor

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Abstract: - This paper discusses the measurement of static magnetic characteristics of a new winding configuration for Variable Reluctance (VR) machine. The concept of employing a double ring winding in a VR machine is investigated. This differed from the typically used single, half-pitched, salient pole winding. As a result of combining two ring windings to produce flux linkage in one-stator tooth the flux linkage is significantly increased. The magnetomotive force of the phase coil is increased as the number of turn increased. The increase in the number of turn is accommodated in the space around the stator ring. In this way, impressive forces can be expected from modestly sized VR machine. A variable inductor device was built to simulate the electromagnetic parameters of a VR machine in both single salient pole winding and double ring winding configurations. The method employed for static magnetic characteristics measurement is based on the inductance measurement in terms of flux linkage per amps.

Key-Words: - VR motor, magnetic characteristics

1 Introduction

VR motor is diagrammed in Fig. 1, is a simplified eight-pole stator and a six-pole rotor machine [1]. Torque is developed by the tendency of a magnetic circuit to adopt a configuration of minimum reluctance, to maximise the magnetic flux, Lawrenson et al [2]. This tendency translates into a rotation of the rotor so that its poles align with the stator's poles. These pole pairs are in turn energised sequentially from a dc source through electronic switches, thereby creating the rotating torque.

Variable reluctance motors have developed around the concept of short pitching each phase winding, generally around a single stator pole, Lawrenson etal [2] and Ray et al [3]. However Mecrow [4] and Liang et al [5] have proposed alternative winding configurations, which may lead to improve efficiency and performance. The concept of a fully pitched winding in VR motor was explored by Mecrow [4]. While Liang et al [5] employed both short and full pitch windings.

This paper proposes a new winding configuration for VR machines. The configuration uses the available space around the ring of the stator as an alternative to the stator winding on the salient pole. Fig 2 shows the double ring windings and the single salient pole winding otherwise known as the single or half-pitched winding. By wiring the two ring windings in series the effect is to produce the same direction of flux flow in any stator pole.

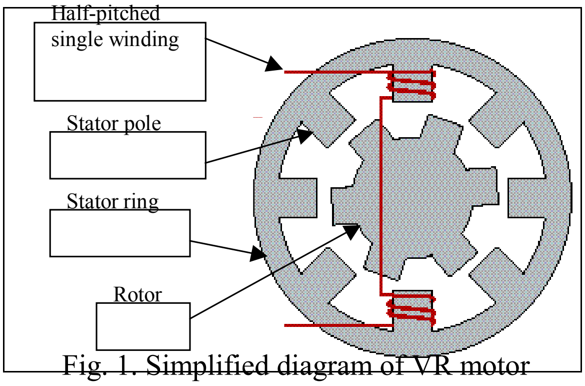

Fig. 1. Simplified diagram of VR motor

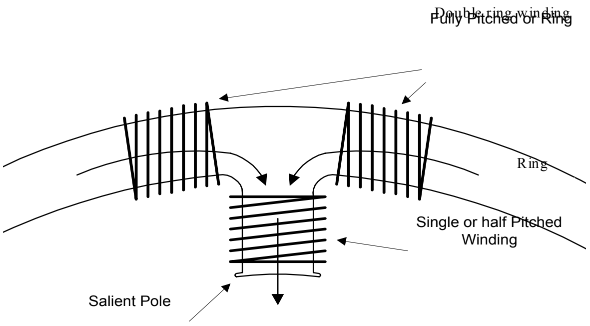

Fig. 2. Winding configurations for VR Motor

The new winding configuration allows various options for the motor designer, firstly by making use of the extra space the number of turns on the stator winding can be increased, possibly even doubled, this increases the flux linkage. Remembering that the flux linkage is the merely the product of the flux in webers and the number of turns with which the flux is linked. A second option is to retain the same number of turns but increase the diameter of the windings, this reduces the resistance of the winding as a result reduces the heat losses (i^2R) produced in the motor. This may be beneficial for smaller motors where the winding resistance can be critical due to the relatively small diameter wire used in the stator coils.

It should be noted that although the stator/rotor size would not changed in the proposed winding configuration but the motor frame size may change to accommodate the extra copper on the outer ring space.

One of the objectives for this research was to investigate the possible benefits associated by doubling the number of turns in the stator winding. It is believed that as a result of increasing the number of turns, and hence the flux linkage, the efficiency of the motor could be improved resulting in an improvement in the produced torque of the motor. To test this argument, a dummy variable inductor was constructed to simulate the action of the switched reluctance motor. The ring and salient windings were incorporated into the device so that comparisons could be made with each configuration.

The static magnetic measurement method employed measures the inductance in terms of flux linkages per amp. By taking a number of readings at different currents, a complete magnetisation characteristic for the machine winding can then be obtained.

2 Measurement Method

The method employed for the inductance measurement is a relatively simple method that can be used to measure the inductance of a machine winding or dc choke. The method applies an accurately known voltage for an accurately known time in the form of a short voltage pulse to the winding whose inductance is to be measured [6]. The resulting peak current occurring at the end of the voltage pulse is then accurately measured.

The ratio of flux linkages to the peak current is a direct measure of inductance.

The static measurements are based on the fundamental equations for an inductor:

$$V = iR + \frac{d\psi}{di} \tag{1}$$

Rearranging to give:

$$\psi = \int_0^T (V - iR)dt \tag{2}$$

Where V is the applied voltage across the inductor and iR is the resistive voltage drop across the resistance of the winding. By controlling the pulse duration, T, the flux linkage, Ψ will be controlled.

The inductance L is obtained as the ratio of the flux linkage Ψ to the peak current I creating it, assuming zero initial conduction, ie:

$$L = \frac{\psi}{I} \tag{3}$$

From equations (2) and (3), the inductance can be expressed as:

$$L = \frac{(V - iR)T}{I} \tag{4}$$

The resulting equation (4) for inductance now simply becomes the applied voltage less the resistive voltage drop across the windings, multiplied by the pulse time duration, divided by the peak current. Since the current increases almost linearly over time, so (iR) can be replaced by (IR/2). In this way there would be no need for continuous current measurement and the peak current value is sufficient to accomplish the inductance measurement. This makes the final equation to be:

$$L = \frac{(V - \frac{IR}{2})T}{I} \tag{5}$$

By using short high voltage pulses, the effects of the winding resistance are substantially reduced since the great majority of the applied voltage pulse appears across the inductive element of the winding. The benefit of using a high voltage for inductance measurement, perhaps even higher than normally appearing, is illustrated in Fig. 3. This shows how the same peak current gives rise to a smaller percentage volt drop in the winding resistance for a higher voltage pulse. If the potential drop across the winding is much smaller in comparison to the volt drop across the inductor then it can be largely neglected and the measurement of the inductance will be a very close approximation to the real value. It is perhaps safer to include the winding resistance into the calculations for the inductance, however by using a high amplitude short duration pulse the significance of the winding resistance becomes less important which reduces the need for exceptional accuracy in the measurement of its value.

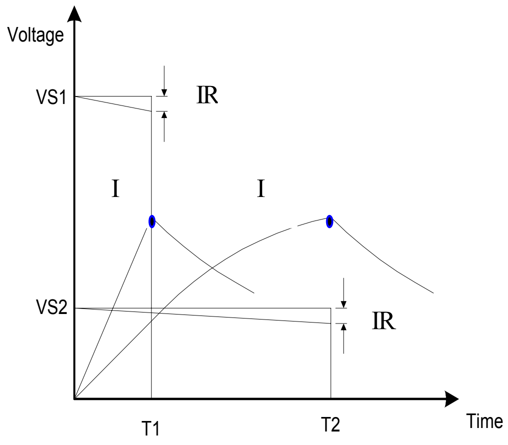

Fig. 3. Illustrating the advantage of a short high voltage pulse VS1 T1 over a long voltage pulse VS2 T2.

The higher voltage pulse also produces a more linear current increase. This is very important in the calculations for the inductance as these rely heavily on the assumption that the current rises linearly. If the current is not linear over the duration of the voltage pulse then the calculation of the inductance will not be accurate. In this scenario a mathematical model for the value of the current would have to be written for the integral to approximate its value over the duration of the pulse. Therefore to keep the inductance-measuring model simple it is advantageous to have a high amplitude short duration voltage pulse.

By applying the voltage pulses at a low repetition frequency, the heating effect of the consequent current can be minimised even though the value of the current is sufficient to cause the appreciable saturation which may be typical of normal operation. This prevents the windings from being subjected to excessive heating and the possibility of them being damaged or even burning out altogether.

The basic measurement circuitry arrangement is illustrated in Fig. 4. The voltage pulse is initially generated from a digital signal processor (DSP), here the width and time base of the pulse can be set and adjusted freely by software alterations. The MOSFET receives the voltage pulse from the digital signal processor's output port via the AND gate. The AND gate is there for the purposes of current protection. The remaining input of the AND gate dictates the conditional state for the voltage pulse to transfer through to the gate of the MOSFET.

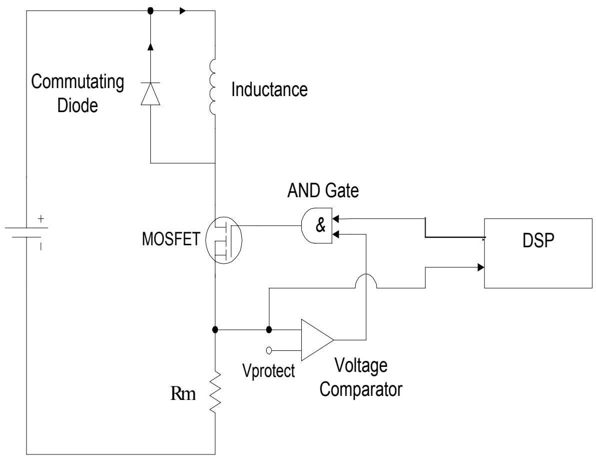

Fig. 4. Basic schematic of inductance measurement circuit.

When the voltage pulse is applied and current is conducted through the MOSFET from source to drain there is a volt drop across the current measurement resistor (Rm) which is proportional to the current flowing through the inductor to be measured. The potential drop across the measurement resistor is fed to a voltage comparator for current protection and to a peak detector circuit for measuring the peak currents developed in the winding. The voltage comparator circuit provides current overload protection for the windings of the inductor under test and the power switching devices. The peak detector circuit captures the peak voltage developed across the current measurement resistor and holds this voltage for a period of time sufficient enough for the digital signal processor to be able to sample it.

3 Testing Rig

A variable test inductor was designed and built to simulate a VR machine winding. The test inductor is equipped with three winding one for the single half-pitched winding configuration and the other two are for the double ring-winding configuration.

3.1 Construction Components

- Soft iron core ‘E’ laminations – Contain a high magnetic permeability characteristic. In their original state the E shaped laminations fit together to form a centre tapped transformer. The centre finger of the laminations was cut to accommodate the adjustable centre lamination to make the inductor variable, refer Fig. 5.

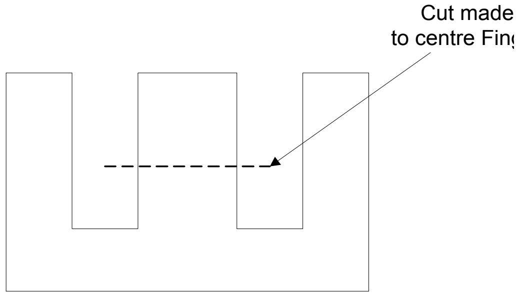

Fig. 5. Original 'E' Lamination Cut To New Shape.

- Centre lamination – Consists of 42 separate laminations stacked together. The centre lamination provides the link in the magnetic path for both single and double winding configurations (refer Fig. 6) and is made of iron with a high magnetic permeability. Each individual lamination was cut and drilled to size so the centre lamination could slide up and down freely between the 'E' laminations.
- Windings – 50 turns of copper wire around a plastic bobbin frame for each winding.
- Positional Arms & horizontal member – The positional arms extend out from the Aluminium frame and hold the centre lamination in a horizontal position. The horizontal member assists in keeping the centre lamination in the same horizontal position during testing.
- Rulers – positioned at both ends of the horizontal member. The rulers are used to ascertain the correct height of the centre laminations.

The centre laminations of the test inductor travels down to a point of being completely in-line with the 'E' laminations and then slightly past this point. To construct a complete inductance profile the centre lamination needs this travel. There is no need to go much further beyond the in-line position as the inductance profile is a mirror image of the descending profile.

3.2 Winding Configurations

The variable Test inductor has two modes of operation; these are the single winding and double winding modes, as illustrated in Fig. 6. In the single winding mode a current is applied to the centre winding. The current produced in the winding generates a magnetic field, the direction of this magnetic field is determined by the direction of the current in the winding.

The magnetic field produced from the windings is then induced into the soft-iron laminations and travels along a path (see the lines of magnetic flux) from the North to South Pole to complete the circuit. The lines of magnetic flux separate and half travel around one side of the E lamination, whilst the other half travel around the other side.

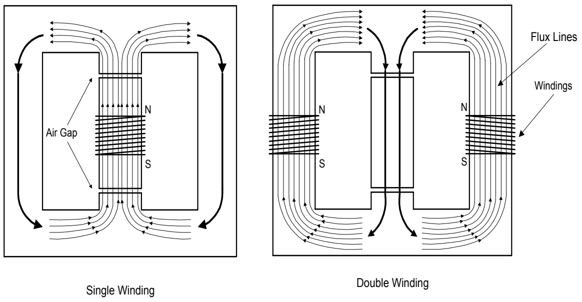

Fig. 6. Test Inductor Configurations.

For the double winding, the coils are wired in series and the same current is passed through both coils. The windings are wound in a manner such that the magnetic field created is in the same direction for both windings. As a result the magnetic flux lines circulate around the E laminations and merge into the centre lamination.

By configuring the inductor in this way the magnetic paths were the same for both the single winding and the double winding configurations. This made it possible to model the effect of increasing the number of pole windings from one to two in the variable reluctance motor. It was important the magnetic path remained the same regardless of the single or double winding configuration, just as it would be for the magnetic field travelling from the field pole to the rotor in the variable reluctance motor.

3.3 Variable Inductance

The inductor is made variable by the movement of the centre lamination in either single winding or double winding mode of operation. For maximum inductance the centre lamination lies directly in line with the centre finger of the 'E' lamination. When the centre lamination is elevated and therefore moved further away from the E lamination, the path of the magnetic flux is increased and the inductance is reduced, as illustrated in Fig. 7.

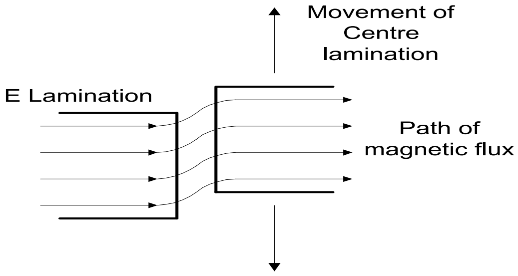

Fig. 7. Flux Path Profile.

The result of measuring and recording the inductance of the winding while the centre lamination (rotor) moves builds up an inductive profile for the motor. An example of an inductive profile can be observed in Fig. 8. It can be seen the inductance is smallest when the stator and the rotor are as far apart as they can possibly be. The inductance begins to increase as the stator and rotor move closer in-line with each other. The inductance then begins to tapper off again and reaches a maximum value when the stator and rotor are directly in line with one another.

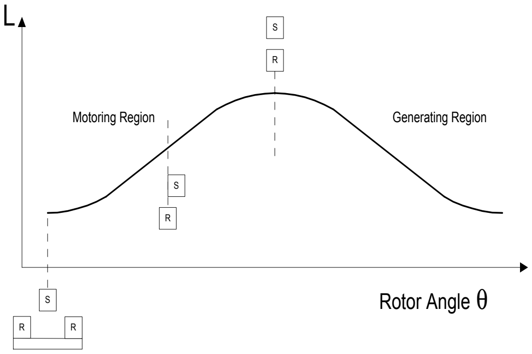

Fig. 8. Winding Inductance as a Function of Rotor Position.

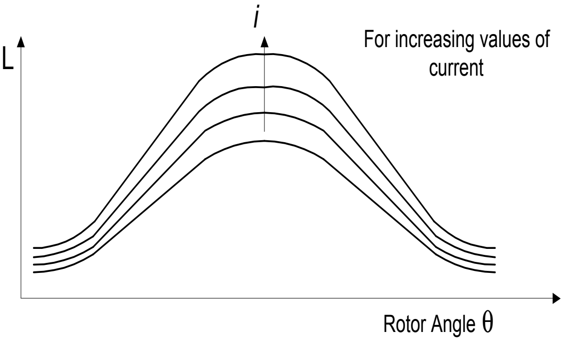

Fig. 9. Inductance Profiles for Increasing Values of Winding Current.

The inductance profile can also be plotted for varying levels of current in the winding as this also has a significant influence on the inductance. An example of the inductance profile at all rotor angles for increasing levels of current can be seen in Fig. 9. The inductance profiles show that the inductance increases with larger currents flowing in the stator winding.

4 Experimental Results

The test inductor was tested in single and double winding configurations and for each configuration 29.7 volts was supplied to its windings. The procedure for measuring the inductance followed the same steps for all measurements to ensure consistency and reliability of the results.

The inductance was measured for different positions of the centre lamination in the test inductor. The vertical position of the centre laminations simulated the changing angle of rotor with respect to stator in a typical variable reluctance motor. The lamination was moved in a descending fashion from the highest vertical position down to its lowest position in steps of 2.5mm, where every downward move of the centre lamination moved it more in line with the outer 'E' laminations. Each end of the horizontal guide member was checked at every measurement to guarantee the armature was at its correct height.

To build up an inductance profile for the test inductor, the inductance was measured with the same current flowing in the windings for all positions of the centre lamination. As the magnetic flux path changed with different positions of the centre lamination, the duration of the voltage pulse was adjusted accordingly to produce the same peak current through the windings.

The inductance measurements were conducted at winding currents of 1, 1.33, 1.67, 2.22, and 2.78

Amps. This was thought to be a sufficiently good range of winding currents for a useful comparison of the inductance profiles for the test inductor. Due to the magnetic saturation of the laminations in the test inductor the peak current was limited to 2.78A. The results of the testing can be seen in Fig. 10 for both the single and double winding configurations. The major difference in the winding configuration experimental tests was that for the same peak current to be developed in the stator windings, the voltage pulse was required to be of longer duration for the doubly wound ring configuration. In other words that the inductance (or flux linkage) for double ring winding configuration was greater than that of the traditional single half-pitched winding configurations for the same current..

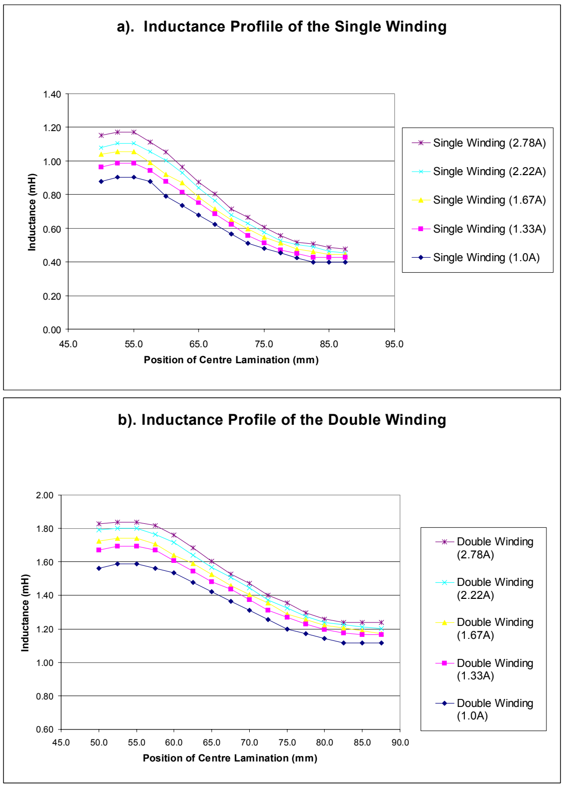

Fig. 10. Inductance profile for both single and double windings.

5 Conclusion

A new double winding configuration for VR machines has been proposed. This is differed from the typically single half-pitched winding. The proposed configuration is based on two winding around the stator ring to produce flux linkage in anyone of the stator poles. A practical variable test inductor was constructed to simulate both single and double winding VR machine.

The static magnetic characteristics for both configurations were obtained using a practical test circuit. The static measurements are based on the inductance measurement in terms of flux linkage and amp. The experimental results demonstrated that an increase in the flux linkage of around 80% for the new winding was obtained for the same value of current. It is the belief of the authors of this paper that this would lead to a substantial increase of the produced torque for the same stator/rotor size machine. However future torque evaluation on a double rewound commercial VR machine is needed for verifications.

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