ANALYSIS AND APPLICATIONS OF TRANSFERRING POWER WITH A TRANSFORMER WITH A HIGH LEAKAGE INDUCTANCE

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ABSTRACT

Often in power electronics the construction of a transformer results in considerable leakage inductance which is undesirable. An example is when electrical power is induced from a stationary to a rotary object by means of a transformer. This requires that the primary and the secondary windings and cores be separated and hence a high leakage inductance results. A method has been investigated by the authors to induce power from a stationary to a rotary object in order to replace the permanent magnets in a Permanent Magnet Brushless Motor (PMBM) with a wound rotor [1]. This method requires a special transformer with split windings and cores which results in high leakage inductance and poor coupling. In this paper, the problems associated with using a transformer with high leakage inductance is described and analyzed. The solution to these problems is also described which can be applied in other situations where a transformer with high leakage inductance is used. Requirements of safety standards for separation of the windings of the isolation transformer and battery operated apparatus that utilize a transformer with a high primary to secondary winding turns ratio are examples of situations that the findings in this paper can be applied to minimise the effect of leakage inductance.

INTRODUCTION:

With the advances in power electronics and microprocessor control systems, variable speed motors for direct drive systems are becoming popular. At the moment three categories of the drive systems are being extensively investigated [2][3]. These drive systems are: Vector Control Induction Motor (IM) drive, Switched Reluctance Motor (SRM) drive and Permanent Magnet Brushless Motor (PMBM) drive systems. For most domestic and industrial applications these motor drive systems must be designed to satisfy some or all of the following requirements:

Required power rating

- Ability to operate in constant power region
- Wide speed range
- Bi-directional
- Low cost
- Sensorless speed and position detection, as related to reliability and low cost
- High peak to average torque capacity
- High efficiency
- Ease of torque and speed control
- Low maintenance and reliability
- Low Electromagnetic Interference (EMI)
- Small size

A new type of brushless motor is being investigated, and developed and described by the authors [1] which is potentially superior in regard to the above requirements compared with other types of motor drive systems. The stator of this motor is similar to a Permanent Magnet Brushless Motor but the permanent magnets of the rotor are replaced with a wound rotor. The power to the rotor is supplied with a specially constructed transformer with stationary primary and rotary secondary cores and windings. This transformer is driven at high frequency and hence its size is small. The rotary section of the transformer is mounted on the rotor and hence rotates as the rotor spins. The secondary winding voltage is rectified and the resultant dc voltage is connected to the rotor winding and generates the static magnetic field similar to a permanent magnet. This static magnetic field, however, can be varied to generate variable motor airgap flux densities and hence the speed and the torque of the motor can be changed.

This arrangement results in a motor which is similar to the brushed dc motors with excellent low-speed high-torque performance without the brushes and maintenance problems associated with it. The performance of the motor is expected to be better than permanent magnet motors because the airgap magnetic flux can be varied electrically[6]. The cost of the motor is expected not to exceed PMBM due to the high cost of the permanent magnets[4]. Because the airgap magnetic flux of the motor can be increased a higher peak to average torque is expected compared with a PMBM and for the same rotor size SRM. The motor drive system presented for this motor has the capability of sensorless speed and position detection and further cost improvements in system design is expected [8].

The major limitation in realisation of this motor is the power limits that can be induced from the stationary primary winding to the rotary secondary. Due to separation of the primary and secondary windings, the coupling is poor, hence and a resonant capacitor in series with the transformer is used to increase the power transferred to the secondary. With this method, the induced power can be increased many fold [1]. In the following sections, the characteristics of the transformer are analyzed and simulation results are illustrated.

THE HF TRANSFORMER:

Figure 1 illustrates the simplified schematic of the prototype circuit to induce power from the stationary primary to the rotary secondary. In this figure the model of the transformer with the impedances transferred to the primary side have been shown. The first glance at the parameters of this transformer indicates a high leakage inductance value and a low magnetisation value which opposes what is normally desirable in a transformer.

The parameters of the circuit are:

R_s = 0.5 ohm, the equivalent winding resistances transformed to primary side.
L_L = 300uH, the leakage inductance transferred to primary side.
L_m = 450 uH, the magnetisation inductance.
C= 47nF, the resonant capacitance.
f_L= 42kHz, the voltage source resonant frequency for C and LL
R_L= rotor winding resistance

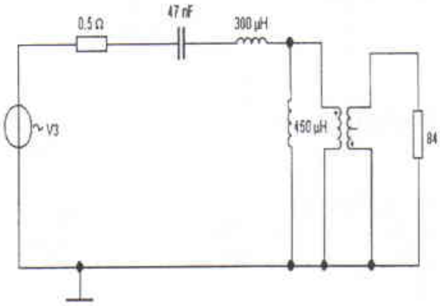

Figure 1. Simplified schematic of the prototype.

The voltage source is the fundamental voltage of a half-bridge converter which is 153V rms if the off-line filtering capacitors are large enough.
A direct off-line rectifier generates 240x√2 =340V dc voltage, if the filtering capacitors are large. The peak voltage of the fundamental harmonic for a bridge converter with 340V dc link voltage is 2/π*V_{dc}=216.5V and the rms voltage is 216.5/√2 =153V. Hence this value has been used for simulations.

Without the resonant capacitor (C short circuit), it can be proved that the maximum power that can be transferred to the load is limited and occurs when the condition of EQU-1 applies:

$$\frac{1}{R^2}+\frac{1}{L_m^2\omega^2}=\frac{1}{L_L^2\omega^2}$$

For the circuit of Figure 1 the maximum power that can be transferred with a half bridge converter is when R=106 ohms and then P=55W.

With the resonant capacitor, it can be proved that the gain of the characteristic equation of the circuit of Figure 1 is:

EQU-1

$$\left|\frac{V_o(j\omega)}{V_s(j\omega)}\right|=\frac{1}{\sqrt{\left(\frac{\frac{\omega^2}{\omega_t^2}-1}{\frac{\omega^2}{\omega_m^2}}\right)^2+\left(\frac{\frac{\omega^2}{\omega_L^2}-1}{\frac{Q\omega}{\omega_L}}\right)^2}}$$

where

$$\omega_m^2=\frac{1}{L_mC}\quad,\quad\omega_t^2=\frac{1}{(L_m+L_L)C}\quad\text{and}$$

$$Q=RC\omega_L$$

The variation of the gain of the circuit with respect to the operating frequency has been illustrated in Figure 2. It is clear from this Figure that if the operating frequency is close to ω_L when the load resistance is high (high Q), a voltage gain is associated with the circuit of Figure 1. However, for low load resistances, operating the converter at ω_t results in attenuation of the output voltage while operating at ω_L results close to unity even at Q=0.1. A conclusion to this observation is that the power inducing capacity of the circuit has increased dramatically with the insertion of the resonant capacitor. For instance for the same amount of load resistance of 106 ohms, the output power is now 220W. This value is not the optimum value. In fact, the output power can be increased if the load resistance is increased and the operating frequency is shifted toward ω_t . Figure 3 illustrates the output power verses the load resistance.

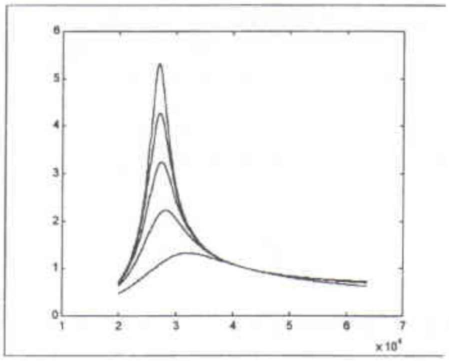

Figure 2. Output gain vs operating frequency.

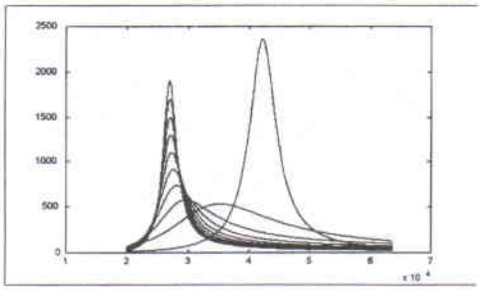

Figure 3. Output power vs load resistance.

CIRCUIT SIMULATION RESULTS:

Using a circuit simulator the circuit of Figure 1 has been simulated for ac and transient analysis. Figures 4-7 illustrate the transient response of the circuit for various Q values and operating frequencies. It can be observed that for low load resistance values, the output voltage is close to the source voltage (153V) only when the operating frequency is close to ω_L (Figures 4-5). When the load resistance is high, the output voltage is higher than the supply voltage when the operating frequency is close to ω_t (Figure 6-7). These results confirm the variation of the output power vs the load resistance which has been illustrated in Figure 3.

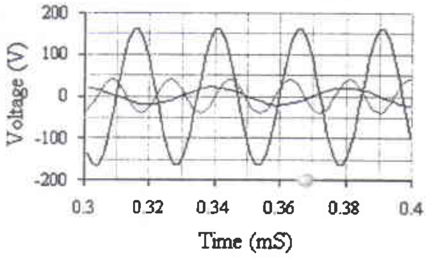

Figure 4. Transient response, Q=0.1.

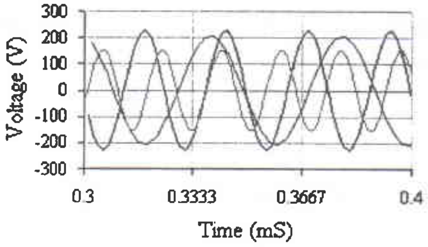

Figure 5. Transient response, Q=1.

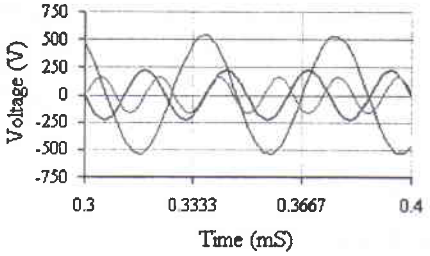

Figure 6. Transient response, Q=3.

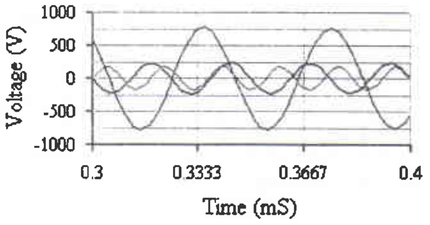

Figure 7. Transient response, Q=5.

The ac analysis of the circuit of Figure 1 is also illustrated in Figure 8 which is basically the same as the solution of the characteristic equation of Figure 1.

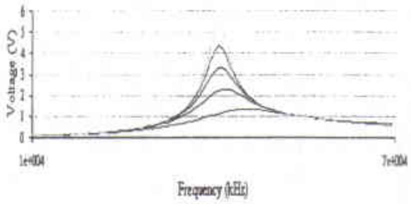

Figure 8. ac analysis for Q=1-5.

The circuit and findings presented in this paper can be applied to many situations in power electronics. One important application is in the driving battery operated lighting systems with the lamp operating at high voltage where the battery voltage can be only a few volts. In this case a transformer is required with many secondary winding turns and only a few primary winding turns. This results in a high leakage inductance of the transformer. The problem can be aggravated by the fact that safety standards for Safe Extra Low Voltage (SELV) require specific creepage and clearance distances and physical isolation between two windings. Hence less coupling between the windings results in high leakage inductance. This is a general problem in switch mode power supply systems. The problem can be solved by applying a series resonant topology taking the advantage of a limiting factor (i.e. the leakage inductance) in designing a power conversion system with little inherent limitation in power conversion levels. The main application of the method described for the reduction of the leakage inductance is when power is required to be transferred from a stationary object to a rotary object with no brushes particularly in an electrical motor or generator.

CONCLUSIONS:

In this paper a method was described to reduce the effect of the leakage inductance when transferring power with a transformer. The method utilises a series resonant converter technology and it was demonstrated that there are two important resonant frequencies ω_L and ω_t. It was demonstrated that for a given supply voltage, for low load resistance a higher power can be transferred to the secondary if the operating frequency is close to the resonant frequency of the leakage inductance and the series capacitor ω_L. ω_t is the resonant frequency of the resonant capacitor with an inductance equivalent to the addition of the magnetisation and leakage inductances. For high load resistances, operating close to ω_t results in a higher power transfer to the secondary. The method described in this paper has many applications in power electronic where electrical power is transferred by means of a transformer with high leakage inductance and low magnetisation inductance.

REFERENCES:

1. H. Mahdavian, A. Zayegh, A. Kalam; "Model of a Sensorless Position Detector for Brushless Motor". Proceedings of the 3rd Intern. Confer. on Modelling and Simulation, Oct. 1997, Melbourne, Australia, pp311-316.

2. A. G. Jack, B.C. Mecrow, and J. Haylock; " A Comparative Study of Permanent Magnet and Switch Reluctance Motors for High-Performance Fault-Tolerant Applications". IAS, V32, NO. 4, July/Aug 1996, pp889-895.

3. K. D. Jackson, M. D. McCulloch, C. F. Landy; "A Study of the Suitability of Electric Drives to the Task of Driving Conveyors". IAS 1993, pp488-495.

4. B. Chalmers, L Musaba, and D. Gosden; "Variable-Frequency Synchronous Motor Drives for Electric Vehicles". IAS, V32, NO. 4, July/Aug 1996, pp896-903.

5. K. Harmer, P. H. Mellor, D. Howe; " An Energy Efficient Brushless Drive System for a Domestic Washing Machine". Power Electronics and Variable-Speed Drives, 16-28 October 1994, Conference Publication No. 399, IEE, pp514-519.

6. Patterson, R. Spee; " The Design and Development of an Axial Flux Permanent Magnet Brushless DC Motor for Wheel Drive in a Solar Powered Vehicle". IAS V31, NO. 5, Sept/Oct 1995, pp1054-1061.

7. F. Witulski; "Introduction to Modeling of Transformers and Coupled Inductors". IEEE Transactions on Power Electronics, May 1995, v10, pp349-357.

8. Mahdavian, A. Zayegh, A. Kalam; "Model Of An Intelligent Speed And Position Detector For A Brushless Motor With Wound Rotor", Proceedings Of CCM'98, Contrib. of Cognition to Modelling, July 1998, pp13.36-13.39.