DESIGN CONSIDERATIONS IN AN INDIRECTLY COUPLED MULTILEVEL MOTOR CONTROLLER

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Abstract

Permanent magnet (PM) motors utilising ironless stator structures have been incorporated into a wide variety of applications where high efficiency and stringent torque control are required. With recent developments in magnetic materials, improved design strategies, and power outputs of up to 40kW, PM motors have become an attractive candidate for traction drives in electric and hybrid electric vehicles. However, due to their large air gaps and ironless stators these motors can have inductances as low as 2μH, imposing increased requirements on the converter to minimise current ripple. Multilevel converters with n cells can effectively increase the motor inductance by a factor of n^2 and are an excellent approach to minimise the motor ripple current. Furthermore by indirectly coupling the outputs of each cell, improvements in converter input and cell ripple current can also be realised. This paper examines the issues in designing a high current indirectly coupled multilevel motor controller for an ironless BLDC traction drive and highlights the limitations of the common ladder core structure.

1. INTRODUCTION

Recent trends in permanent magnet motor design for electric and hybrid electric vehicle applications incorporate the use of an ironless stator structure to reduce hysteresis and eddy current losses as well as motor size and weight [1, 2]. This leads to motors with very low inductance (<10μH). In addition PM motors also tend to be designed with an intentionally large air gap to increase copper volumes, which results in a further decrease in motor inductance.

In a conventional single-cell motor controller as shown in the circuit of figure 1 the maximum ripple current always occurs at a duty of 50% and is given by,

$$\frac{\Delta i_o}{2}(\max) = \frac{V_{dc}}{8 f_{sw}(L_{converter} + L_{motor})} \quad (1)$$

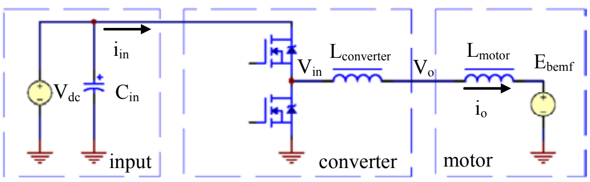


Figure 1 - Equivalent circuit for active phase in a BLDC motor controller.

The only method available to reduce current ripple in such a converter is to place a large inductance $L_{converter}$ in series with the stator windings.

One alternative approach is to introduce a multilevel dc bus as described in [3]. Since current ripple is proportional to the difference between the dc bus voltage and back EMF, controlling the dc bus level can lead to a reduction in ripple by a factor equal to the number of cells in the dc link. This approach however requires twice the silicon rated to the full load current of the converter and hence is not an ideal solution.

A more sensible technique involves utilising a parallel interleaved multilevel converter as shown in the circuit of figure 2. Here the silicon in each cell is only rated to 1/n of the total output current and hence the total silicon in the converter is the same as the single-cell converter shown in figure 1. In addition the maximum output ripple current of an n-cell converter occurs at a duty of (50/n)% and is given by (2) showing an n^2 improvement in the utilisation of the existing motor inductance.

$$\frac{\Delta i_o}{2}(\max) = \frac{V_{dc}}{8 f_{sw}(n^2 L_{converter} + n^2 L_{motor})} \quad (2)$$

The inductors L_1 to L_n in figure 2 can be left uncoupled. However, this would lead to large ripple currents in each cell of the converter with a corresponding increase in the converter input ripple current. By introducing indirect coupling, that is a negative mutual inductance between the inductors, it is possible to reduce the cell ripple current and in turn reduce the converter input ripple current.

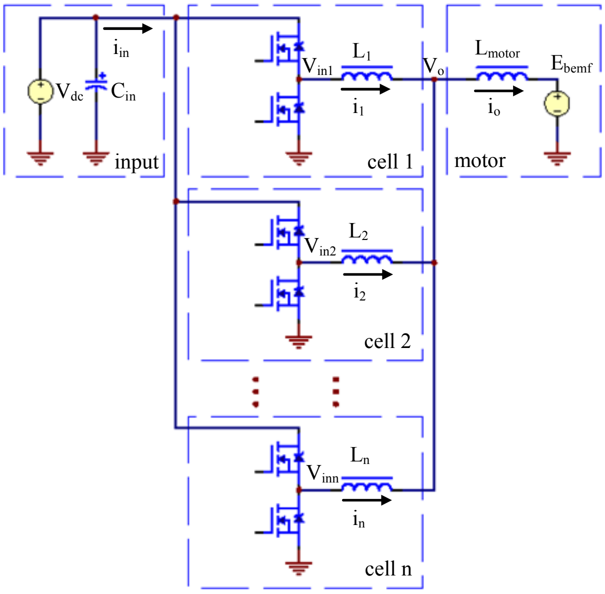


Figure 2 - Equivalent circuit for active phase in an n-cell BLDC motor controller. The modulation in each cell lags the preceding cell by a phase of $2\pi/n$ radians.

2. INDIRECTLY COUPLED INDUCTORS

Recent research has established the benefits indirectly coupled converters have in terms of cell and input ripple currents over uncoupled converters. In turn the indirectly coupled inductor has already found applications in voltage regulator modules (VRMs) for microprocessors and automotive dc-dc converters [4, 5, 6, 7].

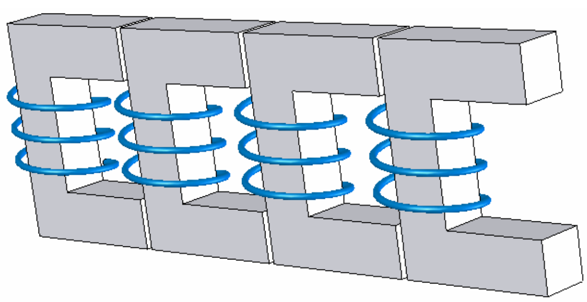


Figure 3 - Indirectly coupled ladder core structure.

The operation of the indirectly coupled inductor is quite complex and is best introduced with practical structures. Initially used for multi-interphase transformers, the ladder core, depicted here in figure 3, has recently been introduced as an indirectly coupled inductor for multilevel converter applications [4, 5, 8].

The dc flux path in a four-cell ladder core is shown in figure 4. Due to the orientation of the windings, the only dc flux in the rungs of the ladder is a result of the leakage inductance of the system. The dc flux in the core sections linking the rungs is near zero.

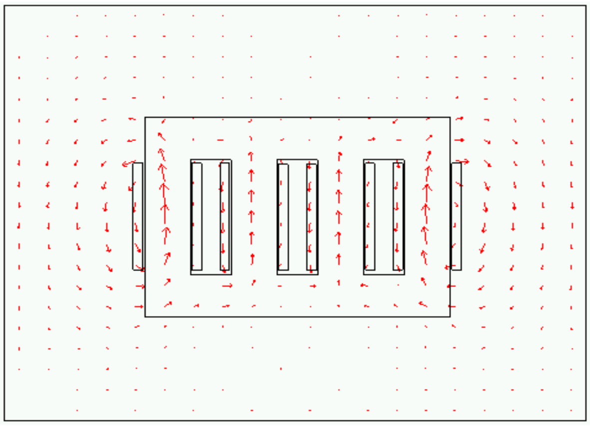


Figure 4 - DC flux path in a 4-cell ladder core.

Starting with the coupled inductor equation it can be shown that the output inductance of an indirectly coupled inductor is simply the parallel combination of the leakages.

$$\begin{pmatrix} V_{L1} \\ V_{L2} \\ V_{L3} \\ V_{L4} \end{pmatrix} = \begin{pmatrix} L_1 & -M_{12} & -M_{13} & -M_{14} \\ -M_{21} & L_2 & -M_{23} & -M_{24} \\ -M_{31} & -M_{32} & L_3 & -M_{34} \\ -M_{41} & -M_{42} & -M_{43} & L_4 \end{pmatrix} \begin{pmatrix} \dot{i}_1 \\ \dot{i}_2 \\ \dot{i}_3 \\ \dot{i}_4 \end{pmatrix} \quad (3)$$

$$\begin{aligned} V_{L1} &= L_1\dot{i}_1 - M_{12}\dot{i}_2 - M_{13}\dot{i}_3 - M_{14}\dot{i}_4 \\ V_{L2} &= -M_{21}\dot{i}_1 + L_2\dot{i}_2 - M_{23}\dot{i}_3 - M_{24}\dot{i}_4 \\ V_{L3} &= -M_{31}\dot{i}_1 - M_{32}\dot{i}_2 + L_3\dot{i}_3 - M_{34}\dot{i}_4 \\ V_{L4} &= -M_{41}\dot{i}_1 - M_{42}\dot{i}_2 - M_{43}\dot{i}_3 + L_4\dot{i}_4 \end{aligned}$$

$$\sum_{h=1}^{4} V_{Lh} = \left(L_1 - \left(M_{21} + M_{31} + M_{41}\right)\right)\dot{i}_1 + \left(L_2 - \left(M_{12} + M_{32} + M_{42}\right)\right)\dot{i}_2 + \left(L_3 - \left(M_{13} + M_{23} + M_{43}\right)\right)\dot{i}_3 + \left(L_4 - \left(M_{14} + M_{24} + M_{34}\right)\right)\dot{i}_4$$

$$\sum_{h=1}^{4} V_{Lh} = \left(L_1 - M_{11}\right)\dot{i}_1 + \left(L_2 - M_{22}\right)\dot{i}_2 + \left(L_3 - M_{33}\right)\dot{i}_3 + \left(L_4 - M_{44}\right)\dot{i}_4$$

Assuming each cell in the parallel converter has an equal leakage inductance of $L_e = L_i - M_{ii}$, then

$$\sum_{h=1}^{4} V_{Lh} = L_e \dot{i}_1 + L_e \dot{i}_2 + L_e \dot{i}_3 + L_e \dot{i}_4$$

$$\sum_{h=1}^{4} V_{Lh} = L_e\left(\dot{i}_1 + \dot{i}_2 + \dot{i}_3 + \dot{i}_4\right) = L_e \dot{i}_o$$

$$\sum_{h=1}^{4} V_{in_h} - 4V_o = L_e \dot{i}_o$$

$$\overline{V_{in}} - V_o = \frac{L_e}{4} \dot{i}_o$$

It can be easily shown that the above derivation holds true for any number of cells. The equivalent output inductance of an n-cell indirectly coupled inductor can thus be written as,

$$L_{eq} = \frac{L_e}{n} \tag{4}$$

Given (4) and (2) the maximum ripple current for an n-cell parallel interleaved indirectly coupled converter can now be written as,

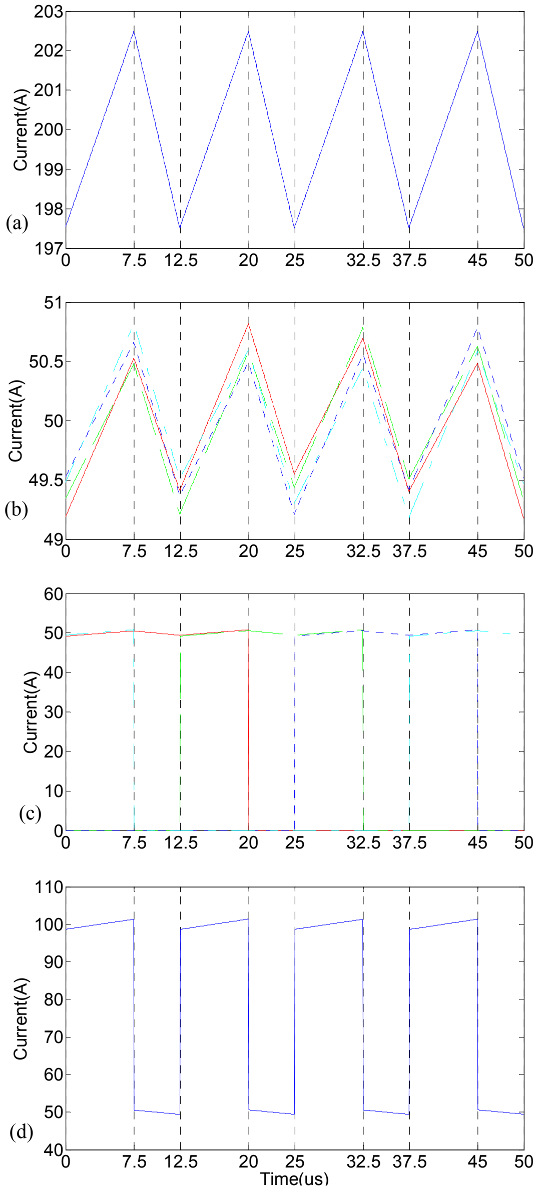
$$\frac{\Delta i_o}{2}(\max) = \frac{V_{dc}}{8 f_{sw}(nL_e + n^2 L_{motor})} \tag{5}$$

Equations for cell and input ripple currents are not so easily derived. In the simplest case the ladder core can be viewed as a multi-interphase transformer with zero leakage. The indirect coupling between phases induces near equal ac ripple currents to flow in each winding. So for a given output current ripple, an indirectly coupled inductor such as the ladder core can theoretically reduce the cell ripple currents to nearly 1/n times the output ripple.

To determine cell ripple currents for practical structures with non-zero leakage inductances and unequal mutual inductances it is easiest to solve the coupled inductor equation with the known leakages and mutuals. This is presented here in figure 5 for an indirectly coupled multilevel motor controller operating at 42V, 200A, and 40% duty. The leakage and self mutual inductances are shown in table 1.

	Level 1	Level 2	Level 3	Level 4
Leakage	17µ	17µ	17µ	17µ
Self Mutual	942µ	1160µ	1160µ	942µ

Table 1 – Values for L_i and M_{ii} in 4-cell ladder core.



Conv.	on	off	on	off	on	off	on	off
Cell	on				off			

Figure 5 - Steady state current waveforms of a 4-cell indirectly coupled ladder system operating at 42V, 50A per phase, 40% duty, 20kHz switching frequency, U67/27/14-3C81 cores in series with 2µH motor inductance. The current waveforms are (a) converter output current, (b) cell output current, (c) cell input current, and (d) converter input current.

3. PREDICTING LEAKAGE INDUCTANCE

In the applications presented in [4, 5, 6, 7] there is no series output inductance available and hence the output ripple is determined solely by the parallel combination of the indirectly coupled inductors' leakages. The goal in these applications is understandably to find a blend of minimised output, cell, and input ripple current induced by the indirectly coupled inductors.

In [5] an additional leakage plate is added to the ladder core to reduce the reluctance path of the leakage flux and in turn reduce output current ripple. Since the mutual inductances in the ladder core are much greater than the leakage this has little effect on the coupling coefficient and hence minimal reduction in cell ripple.

In [6] and [7] a new matrix integrated magnetic (MIM) core is introduced to achieve the indirect coupling. The structure being a minor derivation of the ladder core works on the same principles but incorporates a central core section to reduce the leakage reluctance.

It is important to understand the goal in designing an indirectly coupled multilevel motor controller for currents up to 200A is somewhat different to those in the above applications. Here we are supplied with a small motor leakage inductance of less than 10uH. Rather than introduce leakage into the multilevel indirectly coupled inductor the aim is to instead maximise the effect of the existing motor inductance. As previously suggested, an n-cell converter will introduce an n^2 improvement in the utilisation of the existing motor inductance.

In contrast to the VRMs and automotive dc-dc converter an indirectly coupled multilevel motor controller with an output current of up to 200A requires a minimization of leakage inductance.

A reluctance model for the ladder core structure is introduced in [4] and is repeated here for convenience in figure 6.

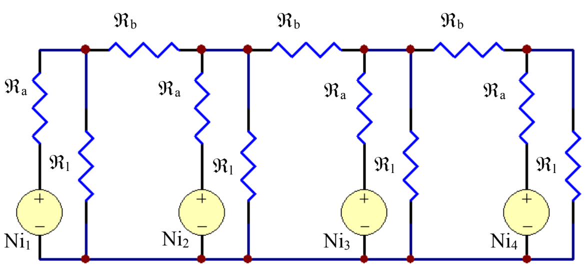


Figure 6 - Reluctance model for ladder core structure [4]

Although figure 6 is a simplified model and does not account for leakage on a turn-to-turn basis, it is apparent that any dc currents will induce a corresponding dc leakage flux to flow. The flux path for this leakage is through the rungs in the ladder core ($\Re_a$) before returning through any available air path ($\Re_l$). This can better be understood by examining the four-cell ladder core in figure 4.

The magnitude of the dc leakage flux is given by,

$$\Phi_{adc} = \frac{NI_{dc}}{\Re_a + \Re_l} \tag{6}$$

In a practical indirectly coupled magnetic structure such as the ladder core it is this leakage flux that is dictating the size of the cores. For a multilevel motor controller application with an existing output series inductance the design aim then becomes to keep the core sizes as small as possible to avoid introducing unnecessary leakage. A method for predicting the leakage inductance in the ladder core is therefore essential in the design process of such a converter.

The utilisation of finite element analysis to predict flux in the ladder rungs due to leakage is a quick and simple task with Femlab. An estimation of a 3-D simulation can quickly be realised from 2-D simulations in the front and end views. According to superposition, the total dc leakage flux in the core can be estimated as the sum of leakage flux in these two perpendicular cross sections.

The first analysis shown in figure 7, performed on the front view of a four-cell ladder core weighing 340g, allows an evaluation of flux in the ladder rungs caused by leakage only in this plane.

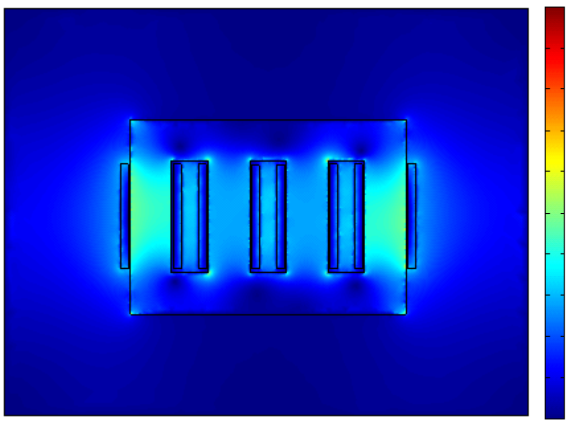


Figure 7 - Front view of finite element analysis performed on ladder core operating at 50A dc per phase, with 12 turns of 3mm diameter copper on U67/27/14-3C81 cores. (Scale ranges from 0 to 70mT)

The results indicate greater flux densities in the outside rungs of the ladder core than the inner rungs. This is to be expected with much lower reluctance paths for leakage flux in the outer air regions. According to the scale in figure 7 the flux density in the inner rungs due to leakage in this plane is approximately 25mT while the flux density in the outer rungs is approximately 35mT.

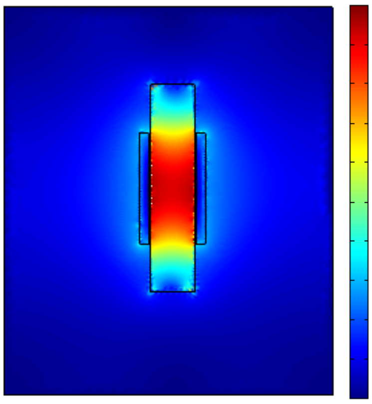


Figure 8 - End view of finite element analysis performed on ladder core operating at 50A dc per phase, with 12 turns of 3mm diameter copper on U67/27/14-3C81 cores. (Scale ranges from 0 to 70mT)

Since the 2-D Femlab analysis in figure 7 does not include any flux induced by leakage into or out of the page, it is necessary to perform a simulation at 90 degrees to this plane. The finite element analysis of the end view of the four-level ladder is presented in figure 8. The result here implies the majority of dc flux in the rungs of the ladder is induced by leakage flux in this plane. The flux densities in each rung due to leakage in this plane are all the same and according to the scale in figure 8 have a value of approximately 65mT.

The total predicted flux density due to leakage in a four-cell ladder core operating at 50A dc per phase with 12 turns of 3mm diameter copper on U67/27/14-3C81 cores is therefore 90mT in the inner rungs and a maximum of 100mT in the outer rungs.

Since the arrangement of the windings on separate rungs in the ladder is imperative to the operation of the indirectly coupled inductor there is little control in reducing this leakage. While methods such as loosely winding the phases around the core and interleaving adjacent windings in the ladder windows may theoretically reduce the flux density in the rungs by up to a quarter, under practical conditions the core will most likely still approach saturation.

Any difference in dc load sharing between the converter cells will also introduce large dc flux in both the rungs of the ladder and linking sections. This would further suggest a firm requirement for leakage to be minimized.

Utilising larger U100/76/50 cores or introducing more cells would reduce the flux density well below saturation. However, the expense of introducing such heavy weights of ferrite into the converter would suggest this solution is unsuitable for BLDC traction drives for electric and hybrid electric vehicles where mass should always be kept to a minimum.

The results of the finite element analysis indicate the use of the ladder core and derivative structures as suspected, are limited by the dc leakage flux induced by large dc currents. While this may not be a problem for applications such as voltage regulator modules and automotive dc-dc converters where the desired ratio of dc current to leakage inductance is much lower, an alternative technique must be incorporated in high current PM motor controllers such as those for electric and hybrid electric vehicle traction drives.

4. MULTI-INTERPHASE TRANSFORMERS

One technique capable of significantly reducing leakage and more suited to high current multilevel motor controller applications is to use two-cell inter-phase transformers (2-IPTs) in a whiffletree or cyclic cascade configuration as shown in figure 9. In [8], a total of four such configurations, each having different characteristics in terms of volume, weight, and complexity, have been verified as having the same functionality as the multilevel ladder core.

The configuration in [8] most advantageous in terms of number of 2-IPTs and total per unit rating is the whiffletree structure. However, it is only possible to use this structure for converters with powers of two cells. The cyclic cascade on the other hand is well suited to modularisation and still performs well in terms of total per unit VA rating and number of2-IPTs.

The major advantage of using 2-IPTs to indirectly couple phases in a multilevel motor controller is the capability to interleave the windings on each core. This technique, commonly used in winding transformers would reduce leakage inductance to an absolute minimum and in turn significantly reduce the mass of ferrite required.

With almost zero leakage, the load sharing specification of the converter would then determine the sizing of the cores. Any imbalance in dc MMF in the 2-IPTs would cause a dc flux to flow through the core. However, with tight interleaving, a core with an air gap or reduced turns could effectively be used to increase the handling capability of these unbalanced dc load currents, while still maintaining low cell ripples.

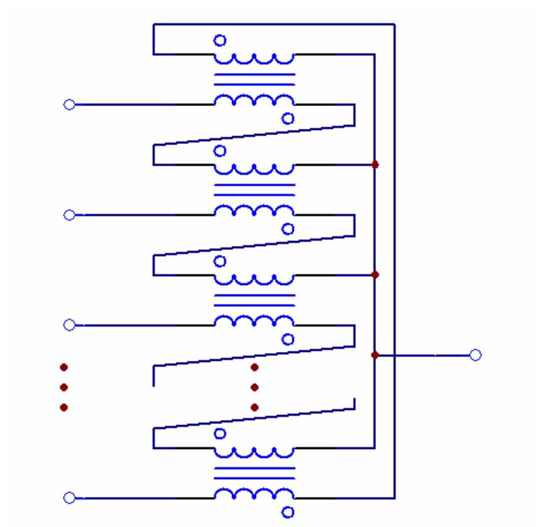


Figure 9 – The cyclic cascade configuration using 2-IPTs is a good alternative to the ladder core [8].

5. CONCLUSION

The primary consideration in designing a motor controller for an ironless PM motor is to maximize the utilisation of the very low stator inductance. A multilevel motor controller introduces an n^2 improvement in the utilisation of the existing motor inductance over the conventional single cell motor controller. Furthermore, an indirectly coupled system has additional advantages in terms of cell and input ripple current.

The common ladder core, while successfully used for VRMs for microprocessors, is not a practical solution for high current PM motor controllers. The dictation of core size by leakage flux leads to a requirement for an unnecessarily large mass of ferrite to avoid saturation.

By using two-cell inter-phase transformers in a cyclic cascade or whiffletree it is possible to significantly reduce leakage flux and in turn reduce the required mass of ferrite. With these configurations and a maximised coupling coefficient, the size of the core is now predominantly determined by any imbalance in dc load sharing of the cells and can be controlled by introducing an air-gap or by reducing turns. In addition, with leakage minimised, the cell ripple current approaches the limit of 1/n of the total output ripple.

By using 2-IPTs to achieve multilevel indirect coupling magnetic component integration is sacrificed. However, in multilevel motor controller applications modularisation can be viewed as an asset as it allows for simple modification of the controller for different current ratings.

6. REFERENCES

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