Research Article

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A New Concept for Deeper Integration of Converters and Drives in Electrical Machines: Simulation and Experimental Investigations

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Abstract: This paper introduces a new concept for integrated electrical motor drives (IEMD) with the aim of minimizing the number of inverter's power switching components. The latter is switched reluctance motor (SRM) based. The control strategy is jointly designed, inspired by Flyback power supplies operating at very high frequencies. A simple case study on an 8/6 SRM has been carried out. The study enables to highlight most challenging problems that have to be overcome in future works: overvoltages during switching due to the flux leakage, and the efficiency of the magnetic material constituting the machine at high switching frequencies. This concept turns out to be an interesting basis for a very advanced integration of the switching structure within electrical machines.

Keywords: Electrical conversion, Electrical motor, Converter integration, polyphase motor.

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1 Introduction

The need for more and more compact embedded electrical applications has led to the emergence of electrical motors with integrated variable speed drives. These "smart" machines would have many advantages, both in terms of electromagnetic compatibility (EMC) and usage flexibility. They would also significantly increase the power-to-mass ratio of electric actuators. However, integrating power electronics components as close as possible to an electrical machine is not an easy task, because inside an electrical machine is a very disturbed environment: strong electric and magnetic fields can occur, temperature conditions are way beyond power electronics standards and the drives may be subjected to unusual mechanical vibrations and stress. The integration process cannot be taken any further without rethinking about the switching structure [1, 2]. An elegant and efficient solution is to use structures with fewer active components to facilitate their integration.

This is henceforth the objective of our study which proposes to use a structure inspired by a Flyback converter that transfers energy through a transformer using a single active component associated with a diode in its simplest structure [3]. In the case of an electrical machine, the rotating magnetic circuit may be seen as transformer whom various coils act as primary and/or secondary windings.

In the first part, we will describe in detail the new structure, its operating principle, and highlight potential advantages. An application example based on an 8/6 SRM has been investigated. Then, in the second and third parts, the first simulation and experimental results will be presented as this study is still in an explanatory stage. Results provide however the understanding how the functioning and suggestions for future works.

2 A New Concept for IEMD

2.1 Distributed converter and elementary switching cells

In the design that we propose to study, rather than a usual centralized power electronic conversion structure that feeds all coils via a conventional multiple-phase coupling, the conversion structure is distributed to each of the machine's coil. This distributed inverter's architecture allows the use of elementary switching cells for each coil, significantly reducing the constraints that apply to the latter. This elementary cell includes, as shown in Figure 1, two

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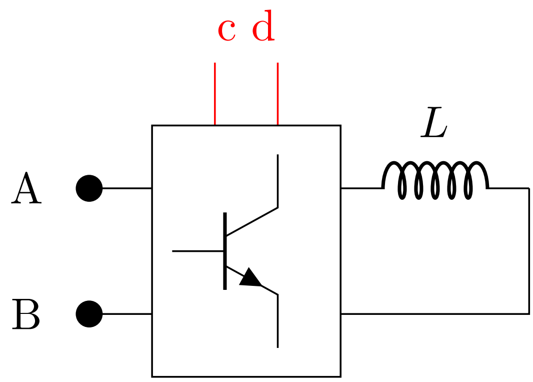


Figure 1: Elementary switching cell supplying an electrical machine's coil

terminals dedicated to energy transfer (A and B) and two terminals dedicated to cell control (c and d).

2.2 Structure and operating principle

The original principle of a Flyback converter is to transfer energy through a transformer with two steps. During the first step the electrical energy is transmitted to the magnetic circuit through a primary winding and is stored in an air gap allowing not to saturate the magnetic material. In the second step, the energy goes to the load via a secondary winding [3]. The flux continuity in the magnetic circuit is guaranteed by the switching of a controllable component at the primary and a diode at the secondary. This structure makes it possible to easily vary the power transmitted to the load and the presence of the transformer allows to have large difference between primary and secondary voltage without reducing the efficiency of the converter.

The structure of SRM is quite close to a transformer with two coils placed on two opposite stator teeth and separated by the rotor which ensures the circulation of magnetic flux between them (Figure 2). These two coils are conventionally connected in series or parallel. Nevertheless, it is possible to consider them separately as the primary and secondary of a transformer. We then obtain the new structure of integrated converter which is a *reversible Flyback converter*, whereby the role of the demagnetizing diode is performed by a current reversible MOSFET which must be controlled in a relevant manner.

The operating principle relies on two mains assumptions:

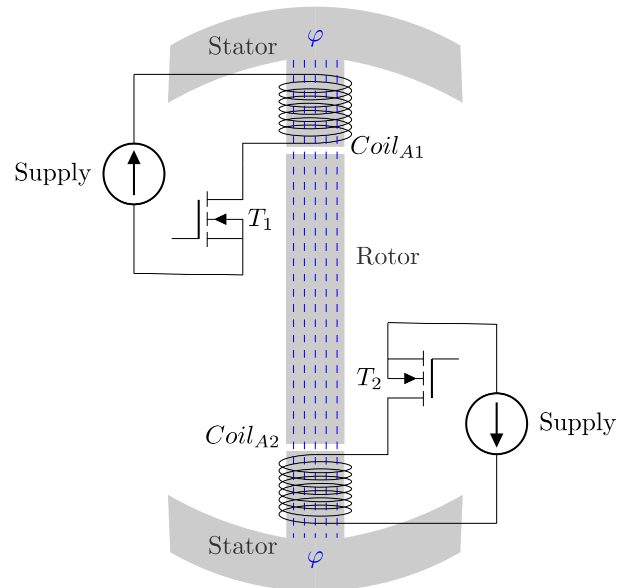


Figure 2: The new structure for integrated converter in SRM using simplest elementary switching cells in each coil.

- the magnetic coupling of the primary and secondary coils is perfect,
- there is no hysteresis phenomenon within the magnetic material.

Then, the system's functioning can be described as follows:

- In the first phase, Coil_{A1} is powered by T_1, which increases the flux linkage φ. This phase consists of magnetizing the magnetic circuit by Coil_{A1}.
- In the second phase, T_2 is activated while T_1 is being switched off. The flux φ then continues to run in the same direction, but decreases under the control of Coil_{A2}. In the Coil_{A2}, a current is induced, passing through T_2 and goes back to the supply, retrieving energy. This phase is the demagnetizing phase of the circuit by Coil_{A2} and completes a switching period.

Then come the moment when the magnetic circuit is completely demagnetized, the current in Coil_{A2} is reversed under the effect of the voltage supply. The current in Coil_{A2} increases, magnetizing the machine in the opposite direction. Phenomenon acts exactly as same as before, except that the magnetic flux through the two coils is reversed. The operating principle can also be illustrated in the following diagram (Figure 3).

In this diagram, the functioning is described for the interval between θ_u and θ_a, *i.e.* successive unaligned and aligned positions of the rotor's pole with regards to the stator's pole. While the rotor rotates an angle $\theta_a - \theta_u$, a large

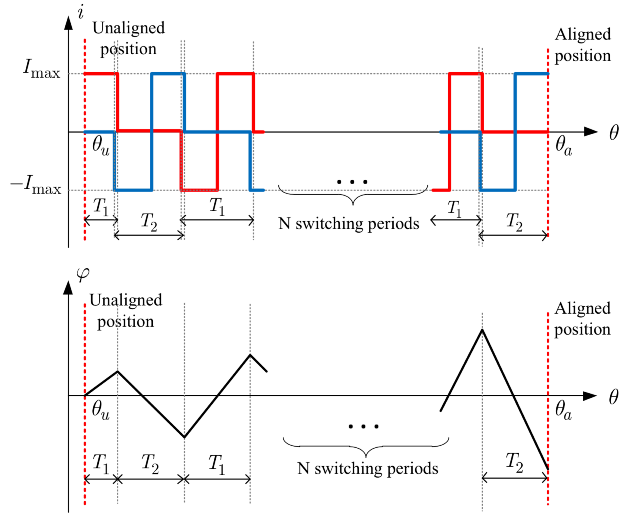


Figure 3: Functioning diagram.

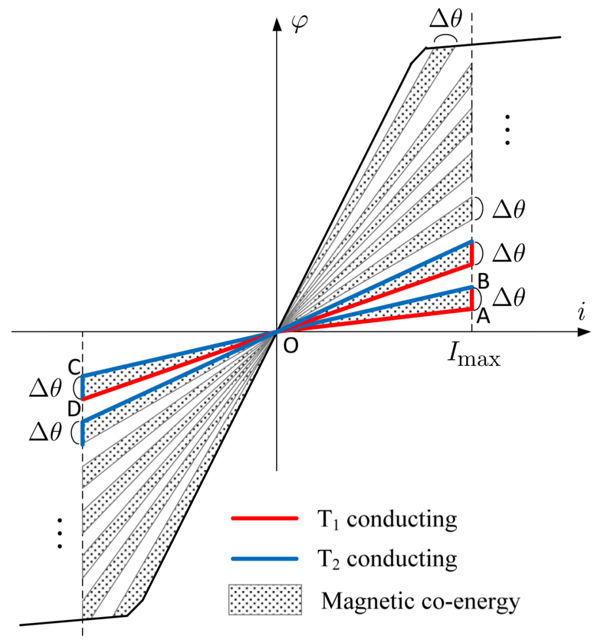


Figure 4: Principle of torque creation with this proposed converter and functioning principle.

number of switching periods should take place. As the magnetic flux through each coil reverses, switching component in series with the coil should also be capable of supporting reversed current. Otherwise, since the flux must remain continuous, T_1 and T_2 must therefore be ordered with a slight stacking of one on top of the other to ensure smooth operation of the whole system. It is noteworthy that unlike the traditional Flyback converter, during the SRM's energy conversion cycle, the magnetic flux's magnitude increases as the machine's reluctance decreases.

Now, we will discuss how electromagnetic torque can be created with regards to the proposed structure and functioning principle. In order to illustrate the torque creation principle, in Figure 4 we graphically represent the SRM's energy conversion cycle.

Knowing that electromagnetic torque is linked to the magnetic co-energy in the machine by the following expression:

$$\Gamma = \left.\frac{\partial W_{co}}{\partial \theta}\right|_{i=\text{constant}} \tag{1}$$

Whereby:
Γ: electromagnetic torque [Nm]
W_{co}: magnetic co-energy [J]
θ: rotor's position [rad]
i: phase current [A]

The created torque in this control strategy depends on the magnetic co-energy set up during one energy conversion cycle, represented by the dotted areas (Figure 4). It is noteworthy that the total surface areas of generated magnetic co-energy in this functioning principle is theoretically exactly equivalent to that of a conventional operation [4, 5].

- Firstly, T_1 conducts. The current through T_1 increases rapidly to its maximum value I_{max}, while the flux linkage φ increases rather slowly since we are still near to the unaligned position. The working point moves from the point O to the point A (Figure 4). The current through T_1 is maintained constant during a small interval during which the rotor rotates a little angle$\Delta\theta$, the working point then moves to B.
- Secondly, at the point B, T_1 is switch off. Here begins the demagnetization phase carried out by $Coil_{A2}$. The current through T_2 is negative and decreasing until the point O. At the point O, the current reverses and the flux linkage goes to the opposite direction. This is the magnetizing phase carried out by $Coil_{A2}$ until C. As the rotor rotates, the flux linkage increased from the point C to the point D.

The whole process repeats again and again, but the flux linkage's magnitude becomes stronger and stronger until the rotor reaches the aligned position. Beyond the aligned position, all T_1 and T_2 are switched off so as not to create reverse torque.

2.3 Possible advantages of the concept

Several advantages may be offered by the concept:

- The extreme simplicity of the structure allows for the integration as close as possible of switching components to the coil. On the one hand, this provides obvious advantages in terms of EMC since the wire connection between the converter and the motor is reduced to the shortest possible length. On the other hand, this allows the conversion function to be integrated deep into the electrical machine for achieving increased power density.
- This functioning principle is very distinguish to the most common SRM's functioning, because this concept exploits bidirectional phase currents and magnetic flux linkage [4, 5]. By the way, further works are pursued in order to clarify its worthy interest in terms of reducing torque ripple, vibrations, and noise.
- For the machine's isolation system (EIS), this concept may bring some interests. Unlike the configuration of coils connected in series in one phase where possible non-homogeneous overvoltage distribution may take place in different coils. In this structure, each coil is supplied independently, the voltage constraints (ex. PWM switching) applied to the isolation materials should be limited and identical for all coils.
- With this type of elementary switching cells, we can envisage the control system that does not use galvanic isolation. And there would be a single common neutral point for the power part and for the control part.

2.4 Challenges for the implementation and possible solutions

2.4.1 Overvoltage due to the leakage flux[1]

The main problem of this structure will come from leaks in the imperfect coupling between primary and secondary (first assumption). Indeed, the leakage flux cannot be demagnetized and will create significant overvoltage to the MOSFET during switching. Figure 5 explains the phenomenon [6, 7].

The more this leakage flux increases, the higher the overvoltage ΔV becomes. It is fundamental to take into account this phenomenon in this case since the rotor's rotation will significantly modify the flux distribution and hence the coupling between the primary and secondary windings.

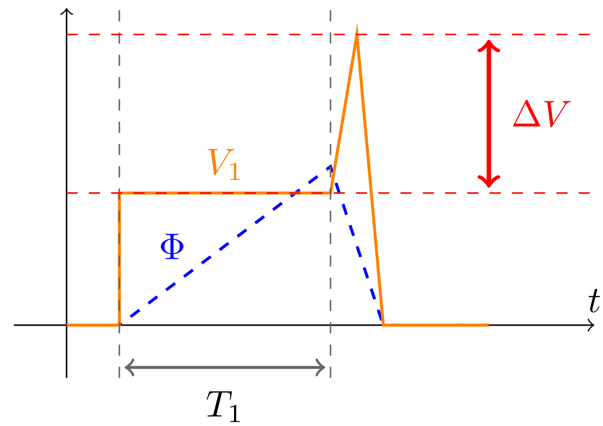


Figure 5: Switching overvoltage due to leakage flux.

Three solutions are possible to deal with this overvoltage. The first possibility is to use MOSFETs sized for supporting high voltages. The second one is to dissipate this overvoltage in a Zener diode (Figure 6a). Finally, the last one consists of using a clamp circuit (Figure 6b) [8].

2.4.2 Efficiency of magnetic material at high frequencies

In this operation, the magnetic material is magnetized and demagnetized at very high frequencies. The performance of electrical machine is directly dependant on the efficiency of the magnetic material at these high frequencies. The potential challenge will be to design the magnetic core constituted by suitable ferromagnetic or ferrite materials, capable of working efficiently at very high frequencies.

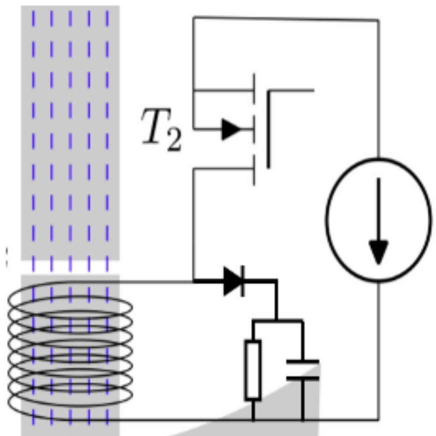
3 Case Study on Integrated Converter into an 8/6 SRM

3.1 Simulation results

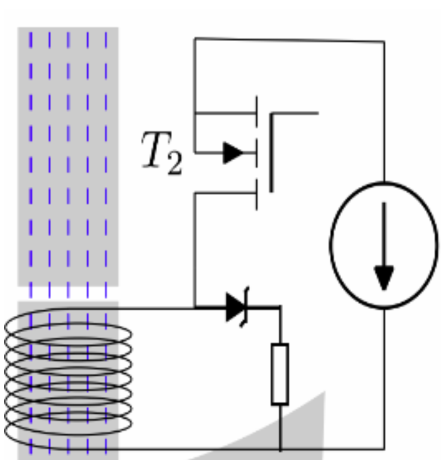
This integrated converter has been implemented into an 8/6 SRM, constituting our first case study of the new concept.

Finite elements (EF) modelling of the magnetostatics phenomenon inside the machine has been carried out in order to evaluate the magnetic coupling between coils (Figure 7). The 8/6 SRM turns out to be an 8-phase machine

1 The definition of leakage flux here is linked to the coupling of the primary and secondary windings in the Flyback converter. This is henceforth to be distinguished from the stator-rotor leakage flux.



(a)



(b)

Figure 6: The avoidance of overvoltage phenomenon by using (a) Zener diode; (b) clamp circuit.

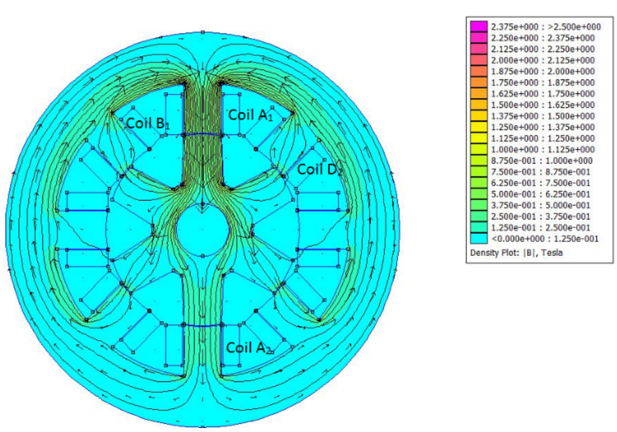


Figure 7: EF modeling of the machine showing the coupling between two opposite coils at the aligned position.

with 8 separated stator coils. The machine has the rated current of 4A and the rated voltage of 200V.

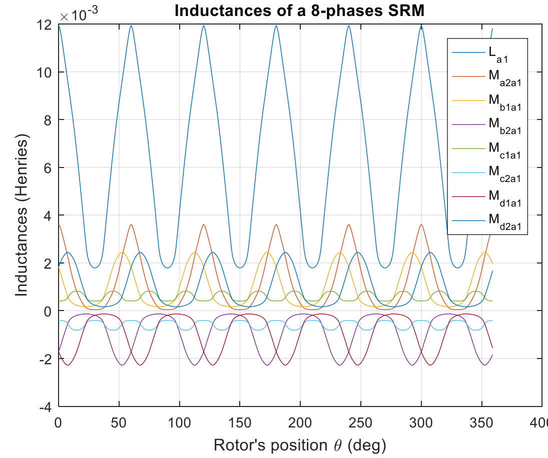


Figure 8: Self- and mutual-inductances in an 8-phase machine.

The coupling between Coil_{A1} and Coil_{A2} is represented by the mutual inductance M_{a2a1}, which is much smaller compared to the self-inductance of Coil_{A1}, L_{a1}. This implies that we should obtain very important overvoltage over switching components.

However, we may observe in the Figure 8 that, the sum of the three inductances M_{a2a1}, M_{b1a1}, and M_{d2a1} should cover almost the self-inductance L_{a1}. That suggests us the possibility to use not only Coil_{A2} but also Coil_{B1} and Coil_{D2} (Figure 7) in order to demagnetize the circuit of Coil_{A1}, which would also be possible with this structure.

3.2 Experimental investigation and results

In this part of the article, experimental results will be presented and discussed. To demonstrate the concept of reversible Flyback converter and its first challenge of overvoltage mentioned in the previous sections, the experimental tests have been carried out.

Two configurations of elementary switching cells can be considered: 1. stator mounted elementary cells; 2. rotor mounted elementary cells. In the first one, each of stator coils is connected to an elementary cell containing a MOSFET component as shown in Figure 9. That covers the idea of integrating power converter components within the machine. Then test can be done through two opposite stator coils.

In the second one which is performed in this study, two coils are manually reeled up in 65 turns; these two coils are inserted around two opposite rotor's teeth instead of the stator's teeth to create the necessary varying magnetic flux linkage, Figure 10; and one electronic active component MOSFET is used for each cell where it is connected

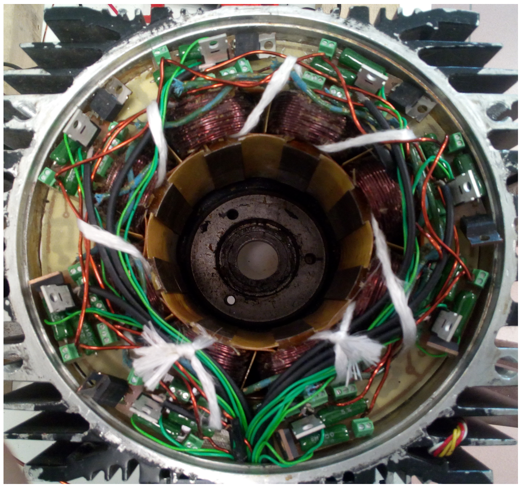
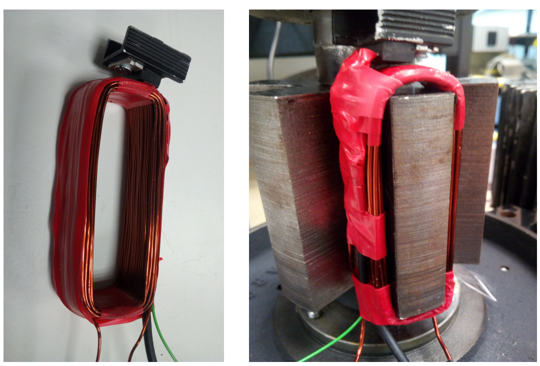
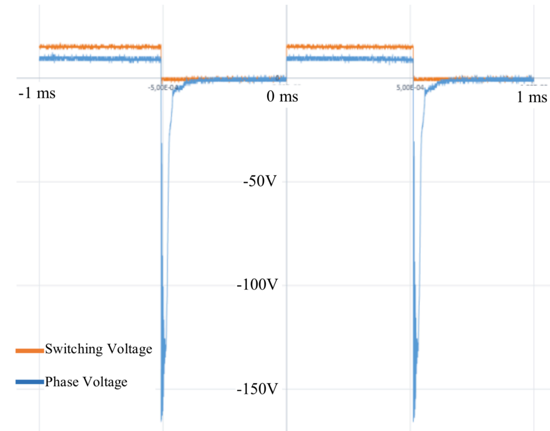


Figure 9: Electronic components integration to stator coils.

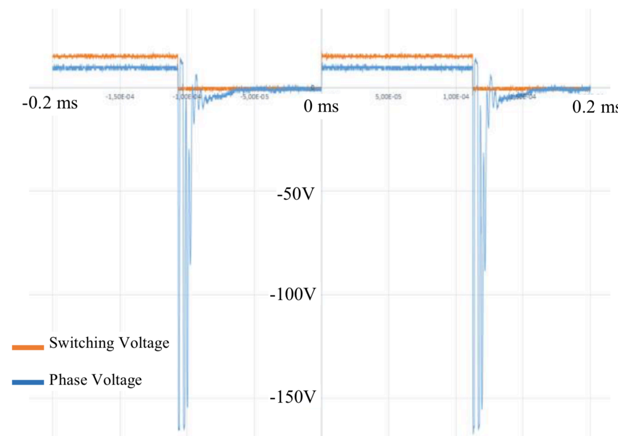


(a) (b)

Figure 10: Electronic components integration to rotor coils.



(a)



(b)

Figure 11: Overvoltage level at (a) 1 kHz, (b) 5 kHz.

directly to the ends of the coil to cover the integration idea, so that first coil will act as primary Flyback converter and the second will act as the secondary.

In the first step, the ends of primary side are connected to DC supply of 10V value, where the secondary ends are connected to a resistor of 33Ω value. The shaft is blocked against any produced torque; hence one can test the level of overvoltage that may occur.

Figure 11a-b illustrates the results of overvoltage level from two tests at two different frequency values. First one is carried out at 1 kHz and the second one at 5 kHz. Results show that the level of overvoltage is saturated and is about ten times of supply voltage. Nevertheless it is always in the tolerable limits of the used components.

Thus by using a competent sized for high voltage level, the new concept of control can be used if avoidance of overvoltage phenomenon it is guaranteed. As already mentioned, such approaches can be carried out through using Zener diode, clamp circuit or high voltage range components. Hence that opens the possibility door of further research and development to be continued. The use of active circuits is also an interesting possibility, it will nevertheless be necessary to carefully adapt the chosen method to the considered machine.

4 Conclusions & Future Works

This paper has presented a novel concept for integrated converters and drives in electrical machines. This concept has the simplest converter's structure with only one switching component per phase, enabling a deeper integration electrical motor drives for achieving lower electromagnetic emissions, and increased power densities.

The operating principle is discussed in detail showing the torque creation principle. The concept is firstly implemented into an 8/6 switched reluctance motor. Simulation and experimental investigations are carried out, considering possible difficulties in the implementation such as switching overvoltage. Further works both in the theoretical and experimental plan are being pursued so as to entirely implement the concept and specify all worthy advantages that it may offered. It is obvious that a complete thermal study will be required to implement this method in a motor. The results obtained with the first running prototype will be published soon. A more complete study of the advantages of this new concept will then be presented by comparing it with other equally promising solutions [9].

References

[1] Brown N. R., Jahns T. M., Lorenz R. D., Power converter design for an integrated modular motor drive, Conference Record of the 2007 IEEE Industry Applications Conference, 2007, pp. 1322-1328.

[2] Wang J., Li Y., Han Y., Integrated modular motor drive design with GaN power FETs, IEEE Transactions on Industry Applications, vol. 51, n° 4, 2015, pp 3198-3207.

[3] Kazimierczuk M. K., Pulse-width modulated DC-DC power converters, 2015, John Wiley & Sons.

[4] Multon B., Principe et éléments de dimensionnement des machines à réluctance variable à double saillance autopilotées, Journées de la section électrotechnique du club EEA, 1993, pp 19-25

[5] Miller T. J. E., Switched reluctance motors and their control, 1993, Magna physics publishing and clarendon press.

[6] Papanikolaou N. P., Tatakis E. C., Active voltage clamp in flyback converters operating in CCM mode under wide load variation, IEEE Transactions on industrial electronics, vol. 51, n° 3, 2004, pp 632-640.

[7] Chung S-K., Transient characteristics of high-voltage flyback transformer operating in discontinuous conduction mode, IEE Proceedings-Electric Power Applications, vol. 151, n° 5, 2004, pp 628-634.

[8] Lin B. R., Hsieh F. Y., Soft-switching zeta–flyback converter with a buck–boost type of active clamp, IEEE Transactions on Industrial Electronics, vol. 54, n° 5, 2007, pp 2813-2822.

[9] Chithrabhanu A., Vasudevan K., A Novel SRM Drive Employing a Buck-Boost Energy Recovery Stage, IEEE International Conference on Power Electronics, Drives and Energy Systems, 2018.