Concept and control of a Capacitive Boost Processor for a Permanent Magnet Synchronous Motor

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Context / Objectives

Thanks to its superior efficiency and power density [1], the Permanent Magnet Synchronous Motor (PMSM) seems to be the best option for an electric aircraft propulsion system. However, the PMSM generates a Back-EMF which amplitude is directly proportional to rotational speed, and opposes the input phase voltage. As the PMSM speed increases, there is a point where the input phase voltage is not sufficient to oppose the Back-EMF and operate the PMSM drive at maximum torque. This characteristic of a PMSM drive is in opposition with the needs of aero propulsion systems, which require operation at maximum torque and maximum speed simultaneously to optimize the power density of the PMSM (Figure 1). Solutions exist but have drawbacks on the performance of the drive (Table 1). The objective of this project was to develop a solution to use the properties of the electrical resonance in powering a PMSM drive, to potentially improve its performances. The concept of a Capacitive Boost Processor (CBP), presented herein, has been developed for this purpose (Figure 2).

Table 1. Existing strategies to increase the power density of a PMSM drive and their drawbacks

Strategy	Drawbacks
Increase the DC source voltage	+ Stress on VSI electronics [4] + Switching losses [4] + Iron losses in the PMSM [5] - Maintenance operations Safety
Boost DC-DC converter upstream of the VSI [2, 3]	+ Stress on VSI electronics [4] + Switching losses [4] + Iron losses in the PMSM [5] + DC-DC Conversion losses [2, 3]
Boost DC-DC converter upstream of the VSI and increased switching frequency [2, 3, 4]	++ Stress on VSI electronics [4] ++ Switching losses [4] + DC-DC Conversion losses [2, 3]
Boost DC-DC converter upstream of the VSI and multi-level VSI [2, 3, 4]	+ Switching losses [4] + DC-DC Conversion losses [2, 3]
Capacitor in series with PMSM phases [6]	Small (+42%) power increase [6]

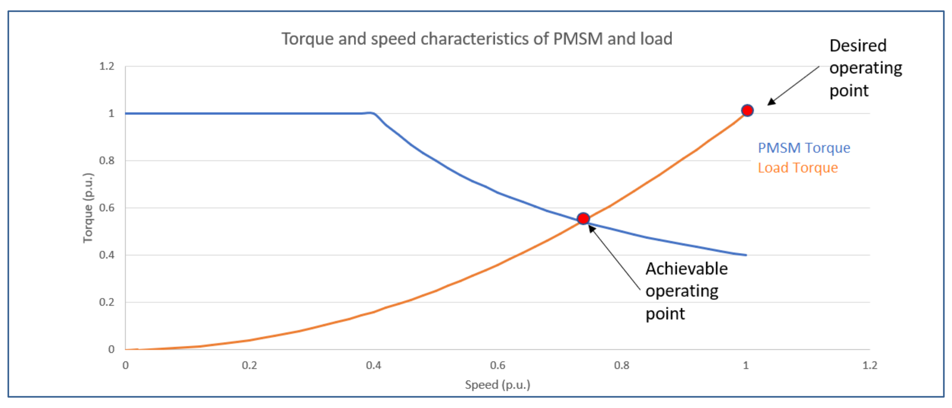

Figure 1. Typical PMSM and propeller (load) torque

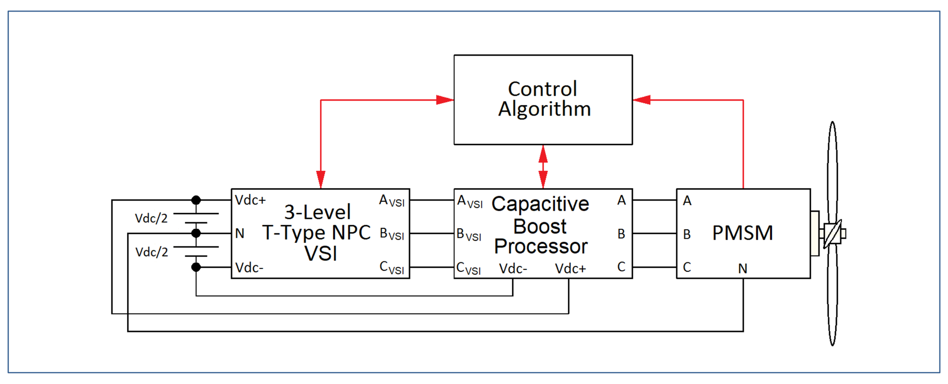

Figure 2. Proposed PMSM drive with the CBP

Concept/Topology

The concept of the Capacitive Boost Processor is to connect a pre-charged capacitor in series with each PMSM phase during operation when the DC voltage is not sufficient to achieve Maximum Torque per Amp control. This concept brings the following advantages: First, each motor phase becomes a RLC circuit with a resonant behavior that intrinsically oscillates current. Second, the CBP being between the VSI and the PMSM, the electronics of the VSI do not suffer from the increased power.

The architecture of the CBP is modular and includes four Configurable Capacitor Modules (CCM) and one Recharge Module. Each CCM can be connected to a motor phase or the Recharge Module, and can set their variable capacitor's polarity. The Recharge Module uses the dynamics of a RLC circuit to reach charged capacitor voltages above the DC source voltage. The VSI assists the discharge of the capacitors to shape a sinusoidal phase current and achieve Max Torque per Amp. The CCM's capacitances and recharge inductance are selected to match the PMSM's phase inductances and speed target. The CBP switches at low frequency and operates at almost Zero Current Switching. The system, including the losses, has been simulated using Matlab/Simulink.

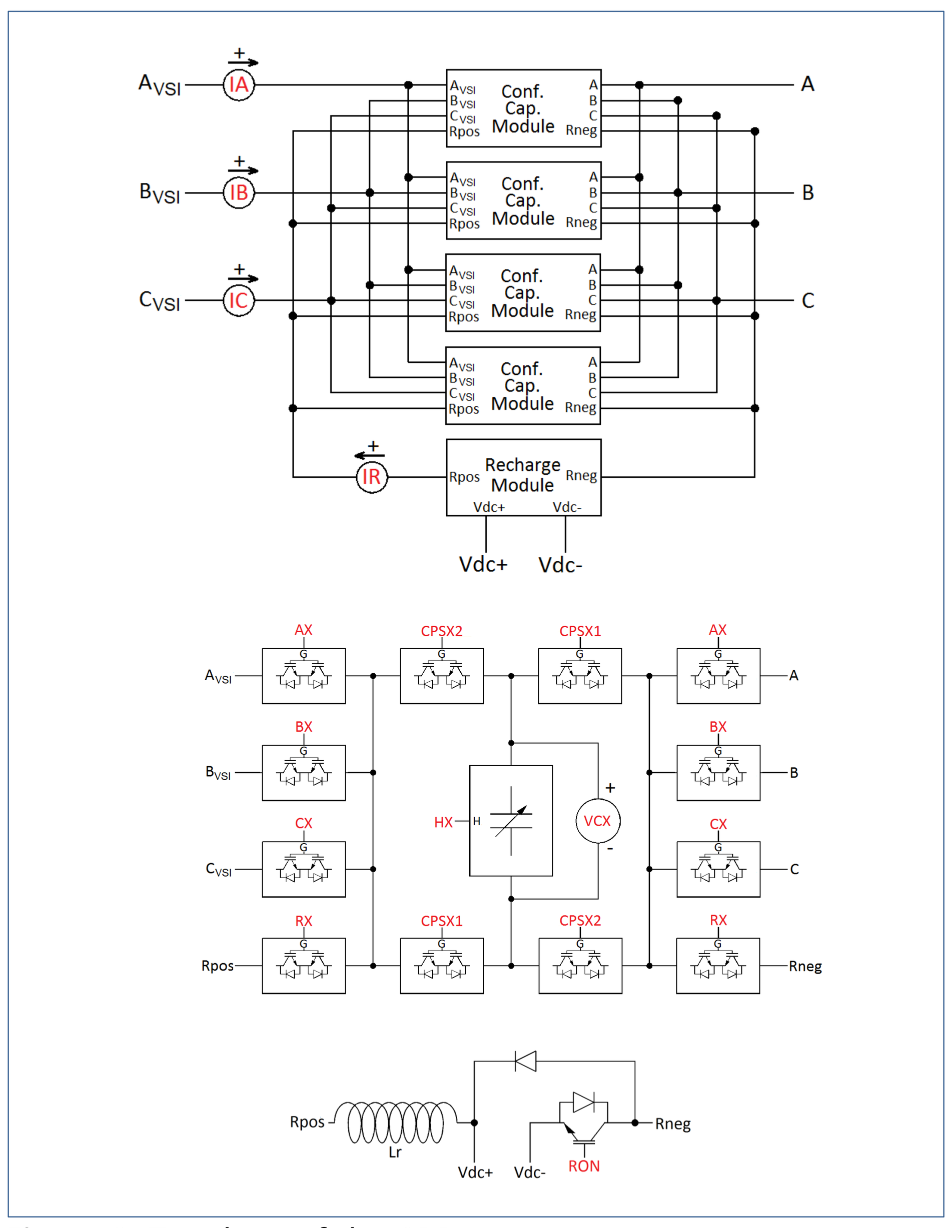

Figure 3. Topology of the CBP

Results/Conclusions

The simulation results show that the proposed drive successfully achieves steady state operation of a PMSM at 6500 rpm and 14 N.m. For the given DC link voltage, the CBP allows to increase the power of the PMSM to 325% of nominal power, while generating low phase current harmonics. The control algorithm successfully achieves Maximum Torque per Amp control, and successfully manages the switches of the CBP to pre-charge the capacitors to the target voltage and to discharge them in the motor phases.

This technology is at its early stage of development and therefore a lot of work remains to make it airworthy. The next papers will be about the safety and reliability of the system, and about a comparative performance analysis with the state of the art.

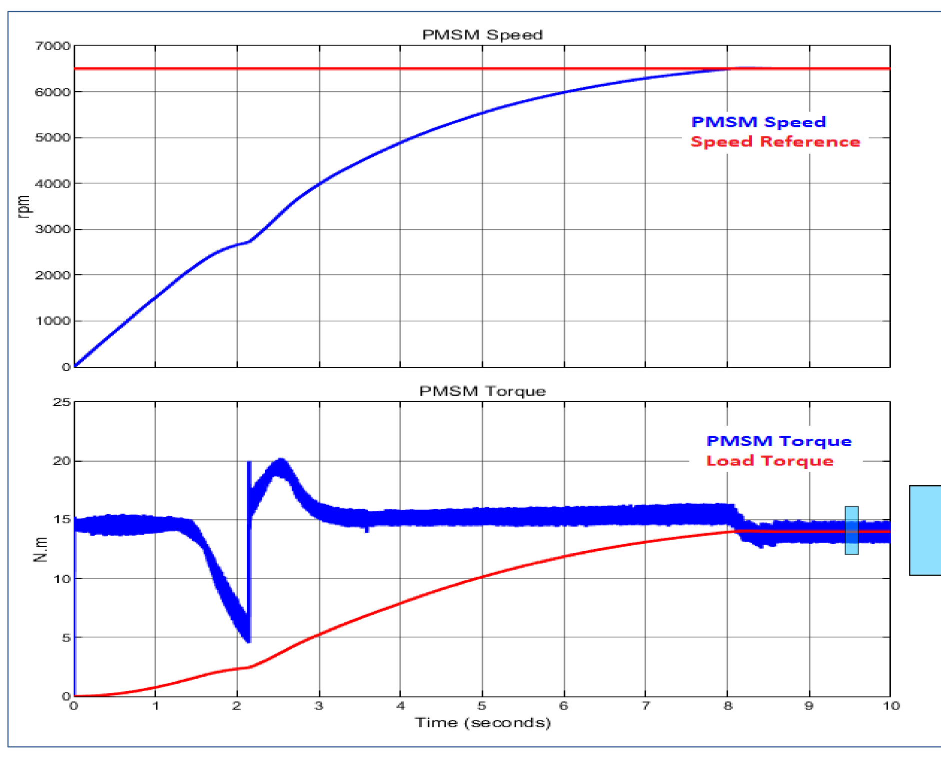

Figure 4. Propeller run-up

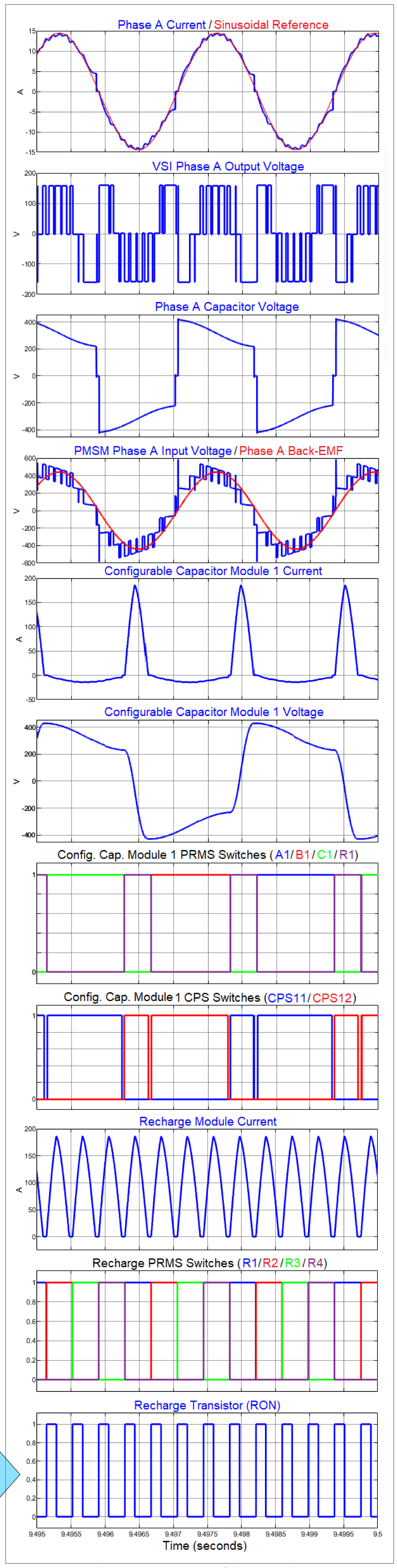

Figure 5. Steady State operation of the CBP drive at 14 N.m and 6500 rpm

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References

1. T. Finken et al, Comparison and design of different electrical machine types regarding their applicability in hybrid electrical vehicles, 18th International Conference on Electrical Machines, 2008, pp. 1-5.
2. K. Yamamoto et al, Comparison between flux weakening and PWM inverter with voltage booster for permanent magnet synchronous motor drive, Proceedings of the Power Conversion Conference-Osaka, 2002, Vol.1, pp. 161-166.
3. R. Wang et al, PMSM driving system design for electric vehicle applications based on bi-directional quasi-z-source inverter, 2018 13th IEEE Conference in Industrial Electronics and Applications (ICIEA), 2018, pp. 1733-1738.
4. D. Liang et al, Evaluation of high-speed permanent magnet synchronous machine drive with three-level and two-level inverter, 2015 IEEE International Electric Machines & Drives Conference (IEMDC), 2015, pp. 1586-1592.
5. K. Yamazaki et al, Harmonic Loss and Torque Analysis of High-Speed Induction Motors, IEEE Transactions on Industry Applications, 2012, Vol.48, pp. 933-941.
6. K. Lee et al, Power Capability Improvement of Interior Permanent Magnet Synchronous Motor Drives Using Capacitive Network, 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), 2019, pp. 2597-2602.