

Control Strategies for High Frequency Power Electronic Converters

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Abstract—A research project targeting the control of future power electronics is discussed. The technology gap between switching frequencies and calculation time at the expected introduction of wide-bandgap semiconductor switching components is introduced. The benefits of exploiting the future switching components at their maximum frequency are explained. The necessity for a new family of control strategies to bridge the gap between calculation time and switching frequencies, and the planned research to develop this control family is given.

Index Terms—Power Electronics, Sliding mode control,

I. INTRODUCTION

Current power electronic converters for drive or grid-coupling applications use switching frequencies ranging from 5 to 20 kHz. At these frequencies, enough processing time is available between switching instants to calculate complicated algorithms, such as FOC (Field Oriented Control) or Voltage and Frequency Droop Control [1]. High-level targets such as speed or position reference following for drive applications or power factor correction and power quality conditioning for grid coupled converters are achieved within bounds in this way. If the switching frequency were to increase, these targets could be achieved within tighter bounds, optimizing the overall performance of the application.

The switching frequency in power electronic converters is at this point limited by the switching component itself. Based on silicon semiconductor technology, the components for this order of magnitude of power (1 kW–10 MW) are used at their technical maximum frequency. According to roadmaps for semiconductors [2][3], based on figures of merit, over the next years various new components will be introduced in wide bandgap semiconductor technology. Silicon-Carbide (SiC) and Gallium-Nitride (GaN) are the most promising future technologies [4][5]. The properties of these materials make it possible to produce switching components with significantly lower switching losses than with silicon technology, that switch at higher frequencies (100 kHz up to few Mhz) and can resist higher working temperatures (600 K). This will allow cooling systems to be simplified (use passive instead of active cooling) and decrease in volume. At this time, (Schottky-) diodes are commercially available, and the first JFET transistors are being introduced [6][7][8]. For switching power supplies it has been proven that they can significantly increase efficiency of the whole system, even without increasing the switching frequency. At higher switching frequencies,

the passive components in converters, but also in filters can be smaller and therefore cheaper.

The benefits of using wide-bandgap semiconductors in drive and grid coupling applications will only be realized when used at higher switching frequencies. Current control algorithms use up too much calculation time (20–50 μs) to be used at these projected frequencies. The evolution of calculation speed of the micro-controllers and sensors in the feedback of the control will not increase proportionally. By the time the new technology of switching components becomes available, the relation between calculation time and time between switching instants will have changed a few orders. Current control strategies will not be computed within a single switching period and can therefore not be used as such. Using less complex algorithms that need less computation time is possible, but will result in lower performance at the high-level targets. This would be in contrast to the current evolution towards more precise, more efficient control strategies.

The time is ripe to research a family of robust control strategies that can be calculated in limited time, yet achieve the same or more advanced high level targets of the current control strategies. The possibilities of the future wide-bandgap power electronic switching components should be fully exploited to maximize efficiency in existing applications. Current control strategies can be accelerated up to a certain level, but the possibilities are limited and insufficient [9]. An evolution towards sensorless control is favorable, because it comprises an extra time gain [10].

Even though the research project comprises the whole scope of power electronic applications, the two most applications that will receive the most attention are drives and grid coupled converters. They are the most demanding on processing time, while combining a broad set of control targets.

II. PROBLEM DESCRIPTION

Two families of control strategies for power electronic converters, applied to both drives and grid coupled converters, coexist [11][12][13]. These families differ in the way the intelligence of the control is divided over separate layers of the circuit.

The last step in controlling a converter exist of the commands to switch to the active power electronic components. This command can be given by a higher control level, that could implement PWM(Pulse Width

Modulation) or SVM(Space Vector Modulation) to achieve a certain output voltage reference, or with DTC(Direct Torque Control) or related controls like DPC(Direct Power Control), where a combination of references (flux, current, voltage,...) is translated into a certain switching order.

The first of these methods has no intelligence appointed in that last step, a certain output voltage reference can only be realized in one way by a converter, namely by controlling the duty cycle of a certain power electronic switch. The exact voltage reference is not realized at any time, but averaging over one switching period the voltage reference is achieved. The second method applies some intelligence to the last step, even though it is achieved with the same mathematical complexity. A good understanding of the system to be controlled (asynchronous motor, distribution grid,...) allows combining multiple references (flux, current, voltage, speed, power,...) into a single switching order. In the first method the voltage reference is determined by a higher level control algorithm such as FOC, which holds the complete control intelligence for that particular method. This has the consequence that this control algorithm represents a lot of processing time for the processing unit of the converter. Within each switching period the full control algorithm must be computed to pass a useful voltage reference to the sublevel.

In the second method the references are determined by simpler algorithms, which diminishes the load for the processing unit. The sublevel then combines references to determine the best switching command. The intelligence of the control is spread out over these two levels.[13]

Currently the limiting factor for increasing the switching frequency of power converters is the switching component itself. Higher switching frequencies are possible, but would increase the working temperature of the component due to increased losses and cooling problems. The lifetime and reliability of the component would decrease. In industrial converters a switching frequency of a few tens of kHz is used, few do more, because in current semiconductor technology, the losses induced by the increased switching instants will undo the advantages of increasing the switching frequency.

Due to new developments in semiconductor technology, this situation will not be sustained. Not the power electronic components, but the control will become the limiting factor. This goes for both control strategies, en for both the higher level of control is the most time consuming and therefor the limiting factor for the whole system.

III. RESEARCH TARGET

The main target of this research project is the design, documentation and application of a new family of control strategies for power electronics, apt for future high frequency power converters realizing high level control targets. The family of control strategies should be built around a common methodology. It differs only

in the application specific implementation. Examples of control strategy families are sliding mode control [14], model predictive control, optimal control, etc.

Typical for the algorithms should be the low complexity, so that they can be calculated with existing microcontroller technology within a switching period. Nonetheless they should achieve the same high level control targets as current control strategies, even for the most demanding tasks as drive and grid-coupling applications.

The desired control algorithm family uses a common design methodology and can therefor easily be used for all power converters (DC-DC converters, single and multiple phase DC-AC, AC-DC and AC-AC converters).

IV. RESEARCH STEPS

The first milestone would be identifying the most apt control technique currently available to develop, being the most promising in diminishing calculation time while achieving high-level goals. To conclude this task, a thorough research of existing control methodologies for power electronics and their implementation should be conducted, focussing on applications where current controls pose high demands on the processing hardware. A review of the current control algorithms in drive and grid coupling applications would give the opportunity to obtain insights necessary to complete this research task. Also, control of current high frequency applications such as lighting and lowpower DC-DC conversion should be investigated.

There are two important aspects to reducing the calculation time to realize the performance of existing control algorithms for high level control targets. The first one being the optimization of existing control techniques, often designed in a logical way for human thinking, but not necessarily optimized from a calculation technical point of view. So does [15] describe an optimization of computation time of an existing transformation algorithm that served as a part of an FOC algorithm, by applying a less logical but more computationally more efficient structure. This direction however is not under full research attention, the biggest improvements are expected to be in the second aspect.

The second aspect is the optimization of the distribution of control intelligence between the control levels. Instead of putting all the intelligence into one upper level, which becomes computationally heavy, there exists a tendency to spread the intelligence over different levels, that represent together a smaller computational load. The same performance will only be reached at sufficiently high switching frequencies. DTC and DPC are examples of control strategies that spread intelligence over the control levels, and attract a lot of research.

A similar discussion has been held in Artificial Intelligence, where researchers fought between making world models and complex logical machines to analyze those world models as opposed to the frequent application

of simple reflexes.[16] High level control targets could be achieved, without being literally programmed into reflexes.

For power electronics, the idea of reflexes is easily supportable, the challenge being to collect the correct combination of simple rules to form a control algorithm that achieves high level control targets. The lowest level of DTC/DPC can be understood as reflexes of this kind. This makes DTC/DPC at this stage in the research project the most promising technology to investigate further. The purest form of DTC/DPC is sliding mode control [17], where also the higher level controller is written as a set of lower level reflexes.[18]

The second milestone would be to develop this control technique to a general control methodology, with a precise mathematical description. This would increase the use of the research, because it makes the results more transferable to existing and future applications. By simulating these control algorithms the correctness of the mathematical description can be proven. The technique should also include a design methodology, so that controllers for any application can be easily constructed. By increasing the system in complexity in gradual steps, the efficiency of the research can be guaranteed. The simulations will not cover secondary effects like EMC. Since these are of little influence on the research target, this simplification is justified.

The third milestone is to realize this control technique in a drive and a grid-coupling application. The described wide-bandgap semiconductor components are not available for power ratings in the order of magnitude that the applications are. Therefore, the implementation will be made on scaled models. Two scalings need to be done to completely prove the possibility of this control methodology. The first scaling would be in frequency, using currently available converters, and limiting in software the calculation time available for control. This allows for a fast construction of a low frequency test of the high frequency control algorithm, no hardware needs to be designed. The second scaling will be in power. A converter built from existing silicon mosfets for low power and high switching frequency will be used to demonstrate the possibilities of the control methodology. Possible applications are a driving a high speed four quadrant drive of a PMSM (Permanent Magnet Synchronous Machine) and a grid-coupled four-quadrant converter feeding a three-phase load. This last milestone is both the validation of the complete research project as the first step towards developing specific control implementations. Both scaled models avoid the combination of high voltages and high frequencies, thereby limiting the EMC (Electro Magnetic Compatibility) concerns that would interfere with the experiments.

Achieving these three milestones would ensure that the design methodology and control family are functional. Once these milestones are met, adaptive optimization should be investigated. A robust control is able to realize a

stable working of the system for a broad variety of system parameters, while achieving high level control targets. The robustness of the control will be investigated both on system and control parameters. The adaptive optimization is a control on a higher level, that may be refreshed at a lower frequency than the control of the converter, and that optimizes the control for variations in the parameterspace of the control. This must happen online, without loss of control. At no time may the adaptive controller variate the controls into an unstable region. This adaptive control is necessary to ensure both robust and efficient control. In a fast control loop, the robust, non optimal and less efficient controller must realize the high level control targets, while the slow adaptive control loop changes the control system to be optimal for the controlled system.

V. BENEFITS

The wide bandgap semiconductors with their broader working conditions, especially the higher switching efficiency and the higher working temperature, make the technology interesting to apply even without the increase in switching frequency. It will at the same time reduce the necessary heat to be cooled of the switching components by being more efficient and generating less heat, as it will make the cooling system much simpler and efficient by increasing the working temperature and therefor intrinsically the cooling efficiency. Passive cooling would become a possibility, making drives silent. With the higher switching frequencies, passive components in applications, filters and power converters themselves can be made smaller. This would reduce both space requirements as material cost. Passive components are at this time an important part of these two costs. The automotive industry, especially in the hybrid branch, is looking forward to use power electronics at temperatures comparable to the engines temperatures, so that cooling circuits and requirements could be simplified.

When new high frequency converters and the techniques to control it will be available, not only will current applications run more efficiently, but new applications will see light. A market for small silent efficient and light power converters is yet to be opened.

VI. CONSIDERATIONS

Higher operating temperatures will put stress on soldering. Current solderings are not able to withstand these higher temperatures. New allows with higher melting points will have to be found. But even at the lower operating temperatures, the new semiconductors will increase overall efficiency.

Higher frequencies will increase the EMC considerations. High voltage time derivatives will increase radiation and emission of electromagnetic noise. The higher frequencies will induce wave guide effects on conductors to the application and in the converter itself. Circuit design for these power levels and frequencies will have to be investigated.

If by the time this research is completed either

the wide bandgap semiconductor technology hasn't commercialized or FPGA's made a breakthrough in advancing their processing speed, this research will not be obsolete. It will still provide the possibility to easily design control systems for any application. It will also reduce the cost of necessary calculation power.

VII. CONCLUSION

This research project will focus on bridging a future gap between computational power and control necessity at future semiconductor switching frequencies. Achieving this main target will allow all power electronic applications to achieve references within tighter bounds while being more energy and space efficient. The design of the control strategy and subsequent the testing in simulation and in scaled models will provide a family of control strategies that combine robust and adaptive control.

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