Control of Interleaved Voltage Source Converters for Marine Applications

By

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Abstract

As marine vessels incorporate high power communication, tracking, entertainment, weapon, and airplane launch systems, the total power demand on the ship increases drastically. Traditional marine power systems cannot easily handle these increases in power demand due to the segregation of the ship's propulsion system from the ship service distribution system. In order to meet these increasing power demands, a fully-integrated electrical power system is required. However, adopting such a power system relies on systems and components not traditionally used in marine power distribution systems. Furthermore, marine power systems have unique challenges including stringent volume and weight restrictions and an increased need for redundancy that result from operating in the harsh marine environment while away from land and vendor supply chains. On top of these hardware and operational requirements, marine vessels typically have power quality and electromagnetic interference (EMI) requirements that exceed those of land-based industries.

In order to minimize the impact on the marine shipbuilding industry while making strides towards a fully-integrated electric ship, current marine vessels have begun making incremental changes to individual power distribution system components. One of the first of these incremental changes has been the incorporation of power electronics for the main propulsion motor drive. For this application, current marine vessels rely on industry proven load-commutated and cyclo-converter drives. However, these drives suffer from poor power quality which can result in motor torque pulsations and increased motor heating. To minimize these effects, large output filters are normally required, increasing overall system volume and weight. A second incremental step was the replacement of motor-generator sets with power electronic converters for development of the ac and dc ship service buses. This resulted in reduced maintenance cycles while also improving the system dynamic performance. Despite these incremental changes, the associated volume, weight, and efficiency of the power electronic components can be further improved.

This thesis addresses the power quality limitations and resulting volume/weight penalties associated with current power electronic converters used in marine applications. Interleaving, in which parallel voltage source converters are operated with phase-shifted gate control signals, is applied to increase performance of these systems while also minimizing the overall volume and weight of the power electronic components. Asymmetric interleaving, a generalized interleaving approach, will be introduced as a method to optimize several system level objectives including minimizing EMI filter component size, minimizing input and output total harmonic voltage and current distortion, and increasing system stability by minimizing harmonic frequency components that excite system resonances typically found on marine

power systems.

The parallel interconnection of interleaved modules is normally made with interphase transformers, vice multiple separate inductors, due to their ability to minimize the inter-module circulating current and reduce overall system volume and weight. However, the selection of interphase transformers over separate inductors will change the impedance between the parallel phase legs, which in turn changes the system EMI emissions. In order to investigate the effects of the interphase transformer impedance on the system EMI, this thesis develops a high frequency equivalent circuit model of the interphase transformer. It will be shown that a series resonance between the leakage inductance and parasitic capacitance creates a peaking in the dc input differential mode EMI emissions that needs to be considered in the selection of the optimal interleaving angle. Furthermore, in order to determine the optimal interleaving angle, this thesis uses a genetic-based algorithm modified for specific application to interleaving problems, thus avoiding the drawbacks of iterative, exhaustive search techniques used in previous works.

In order to maximize the benefits of the optimal asymmetric interleaving methods presented, practical implementation issues including dc-link voltage ripple, converter dead-time, and pulse width modulation (PWM) sampling effects are investigated for their effects on the harmonic cancellation property of interleaving. It will be shown that the harmonic cancellation property of interleaving is preserved in the presence of dc-link voltage ripple and converter dead-time, and when combined with known compensation methods, can be neglected when developing optimal interleaving strategies. However, when the device switching frequency is only several times larger than the output fundamental frequency, such as in high power motor drives and inverters, the PWM sampling effects can have a significant impact on the input and output harmonic spectra, reducing the benefits of interleaving. Common methods to compensate for sampling effects require either additional software or hardware implementations and impact the control loop dynamics. This thesis proposes asymmetric interleaving as an additional degree of freedom that can be used to compensate for sampling effects, thus reducing the implementation issues and control loop impacts of current methods.