Phase-Shift Control Strategy for Voltage Balancing in Three-Phase Flying Capacitor LLC Converters for Solid-State Transformer Applications

This study investigates flying capacitor voltage control in a three-level, three-phase LLC converter for solid-state transformer (SST) applications. As the power level of SSTs increases, three-phase, three-level topologies become essential to ensure high power density and efficiency. These topologies allow the use of low-voltage devices with improved performance for blocking high voltages while increasing the DC link voltage. This reduces the number of cascaded modules, easing the load on the central controller and simplifying the distributed control network, especially for high-voltage, medium-grid applications. Previous research has compared the neutral-point (NP) voltage balancing of series half-bridge (SHB) and diode-neutral-clamped (DNPC) converters. The DNPC-based LLC uses two additional diodes to regulate NP voltage, adjusting the net current during each half-cycle to charge or discharge the NP voltage. However, this results in asymmetry in the resonant current waveform, leading to asymmetric excitation voltage and a DC offset in the magnetizing current, which can cause hard switching under high-frequency conditions. In contrast, the SHB LLC converter demonstrates superior NP voltage balancing. By using phase shift modulation, a small phase shift from lead to lag adjusts the NP voltage while maintaining resonant current waveform symmetry, ensuring zero-voltage switching (ZVS). Although the SHB has better NP balancing, it lacks full-bridge operation, limiting its use in high power SSTs module.

The flying capacitor is proposed as a candidate for the SST isolated module using a three-level topology. Operation relies on maintaining the capacitor voltage at half of the DC link voltage. However, current loop mismatches or gate pulse delays can cause the capacitor voltage to deviate from this target. Even small mismatches (e.g., 5 ns), common in high-frequency applications, can lead to full depletion or full charging of the flying capacitor, resulting in uneven voltage distribution across switches, which can damage the system. Thus, precise control of the flying capacitor voltage is crucial.

Phase shift control, used in half-bridge configurations, modulates the gate pulse signals to force free-wheeling states. This introduces a new current path through the flying capacitor during the phase shift period as shown in Fig.1. The direction of current flow is controlled by the phase shift (lead or lag), while the phase shift duration controls how much charge is added or depleted from the capacitor, regulating its voltage.

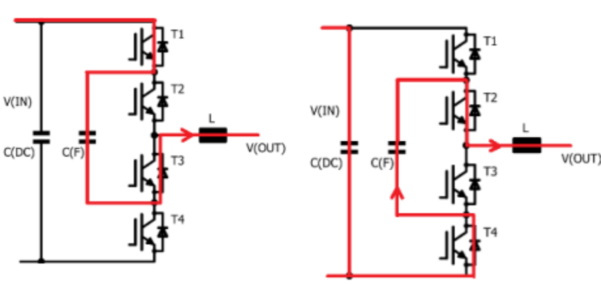

Fig. 1. Free-wheeling modes

In a full-bridge configuration, two capacitors must be managed, each potentially having different voltage states (lower, higher, or half of the DC link voltage). To maintain balanced excitation of the resonant tank, decoupling between the two capacitors is necessary. In a three-phase system, phase balance issues arise. Applying phase shift control across all three phases requires centralized control of the flying capacitors, ensuring each capacitor maintains its voltage despite phase shifts.

This issue has not been fully addressed in prior research on full-bridge flying capacitor LLCs or three-level flying capacitor LLCs. This paper extends the concept of phase shift control to these topologies, incorporating modifications to address voltage regulation challenges. The proposed solution ensures stable capacitor voltage operation even when capacitors operate at different voltage states, while maintaining balanced excitation in the resonant tank.