An Efficient and Compact Single-Stage High-Frequency-Link Medium Voltage AC to DC Converter

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***Abstract*—High frequency (HF) link medium voltage AC (MVAC) to low voltage DC (LVDC) converters are attractive as they do not use expensive and heavy line frequency transformers. They find a wide range of essential applications, including solid-state transformers, grid integration of renewables storage, fast charging of electric vehicles, etc. This paper presents a new topology and modulation strategy for HF link MVAC to LVDC converter that supports bi-directional power flow at any power factor at high power quality. It achieves high efficiency due to the low frequency and soft-switching of power devices. The proposed solution uses multi-level architecture in each cascaded module and a quad-active bridge configuration to combine DC-side bridges in all three phases resulting in a significant reduction in the number of devices. The single-stage architecture avoids the electrolytic DC link capacitor present in each module of the conventional multi-stage solution that experiences a second harmonic ripple and improves reliability and power density. The proposed solution is verified through simulation and experiment.**

***Index Terms*—Medium voltage AC, High-frequency-link, Dual active bridge, Quad active bridge, EV fast charging**

I. Introduction

Medium voltage AC (few kV to tens of kV) to low voltage DC (few hundreds of volts) power converters have a wide range of applications such as solid-state transformers [1], large scale PV integration [2], and electric vehicle fast-charging [3], etc. The conventional approach uses a low-frequency transformer to step down the voltage and use an active front-end rectifier followed by an isolated DC-DC converter. This approach has a bulky transformer, which increases the weight and cost of the system.

In a high-frequency link approach where no line frequency transformer is used, an isolated DC-DC converter followed by a single-phase AC-DC converter is used as a primary module. AC ports are cascaded, and the DC ports are parallel connected of multiple such modules to realize the MVAC to DC converter [4]. This topology, however, has a large device count. The DC side H-bridges of each module can be combined using a multi-winding transformer to reduce device count. In [1], three such units are combined in a single phase through a four winding transformer to obtain a quad active bridge (QAB) architecture. The DC side units from three different phases are combined to form the QAB architecture in [5], a paper that uses multilevel structure in the AC side of a module to reduce the number of modules in a phase. Multi-stage power conversion topologies discussed above have hard-switched AC-DC converter, which reduces the efficiency and limits increase in switching frequency to reduce the size of the AC side filter components. Due to single-phase AC-DC conversion in each module, the intermediate capacitor voltage experiences a second harmonic ripple. This requires a large electrolytic capacitor, which reduces both the overall system's reliability and power density.

Single-stage single-phase AC-DC high-frequency link converters can be used as a primary module, and this will obviate the use of intermediate electrolytic capacitance. A rectifier type AC-DC module is used in [2] that supports unidirectional power flow at unity power factor. In [6], a similar architecture is used. However, a multi-winding transformer is used to combine DC side bridges in the same phase. A cycloconverter type single-stage AC-DC unit is used in [7] that uses AC switches, and a multi winding transformer similar to [6] and can support bi-directional power. Here switches are hard-switched.

This paper presents a novel single-stage MVAC to LVDC converter and a modulation strategy with the following advantages:

1) Bi-directional power flow at any power factor.
2) A multilevel architecture is used in each module's AC side to reduce the number of modules (by half) cascaded in each phase.
3) Line frequency switching of the AC side bridge and soft-switching of the rest of the converter ensures high efficiency.
4) The three-phases DC side bridges are combined to eliminate the possibility of a second harmonic ripple even in the converter's DC port. It also helps to reduce the device count.
5) No complex AC switches and multi-winding transformers are used.

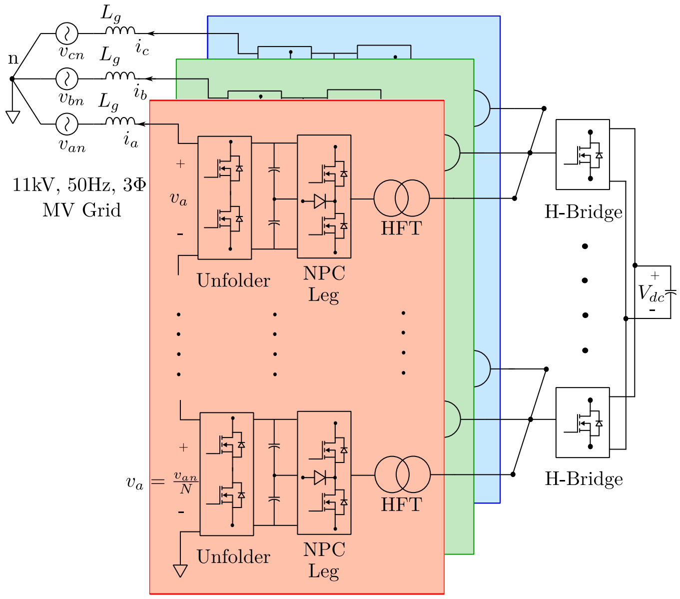


Fig. 1: Single stage MVAC to LVDC converter

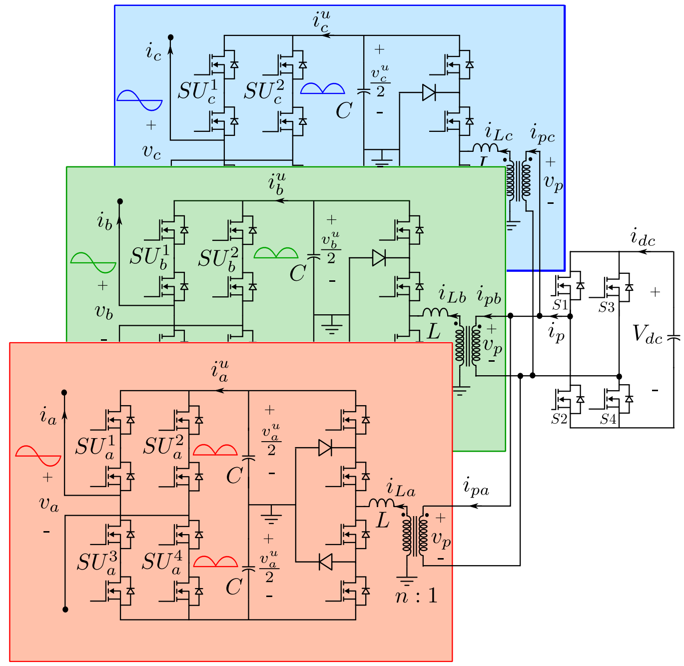


Fig. 2: One module of proposed topology

Since high-frequency transformers are used, no intermediate electrolytic DC capacitors are employed, lossless switching is ensured, and the number of modules and devices are reduced, the proposed converter results in a highly efficient, compact, and reliable solution.

The rest of the paper is organized as follows. Section II provides the detailed analysis of the converter and its modulation strategy. Section III presents the simulation and experimental results. Section IV concludes the paper.

II. Analysis of proposed converter

In this section, the proposed converter topology and its modulation strategy are discussed. The proposed converter is shown in Fig.1 and 2 which support bidirectional power flow at all power factors from medium voltage three-phase AC to low voltage DC port. It is a dual-active bridge-based topology that has a multilevel neutral point clamped (NPC) structure to accommodate higher voltage per module without increasing switch count compared to the full-bridge structure. Each phase of MVAC grid is connected to multiple series-connected unfolders to produce rectified AC at the input of each NPC leg. The capacitors are used to split the voltage and supply switching frequency current, and it doesn't filter line-frequency ripple. Filter inductors connected to the grid side ensure that switching frequency components are not injected into the grid current. Individual NPC leg is connected to one side of the high-frequency transformer, primary of three transformers from three phases are paralleled and connected to an H bridge in DC side to have constant instantaneous (averaged over a switching cycle) power flow to DC side. If each device in the AC side unit can block V voltage, the peak voltage across the NPC leg can be $2V$. As the un-folder H-bridge switches at line frequency, at the zero crossings of the phase voltage, two devices can be easily series connected to realize one switch.

A. Modulation of line frequency unfolder

Line frequency unfolders present in each phase rectify the input sinusoidal voltage to feed the dual active bridge, and it supports bidirectional power flow. There are N unfolder modules connected in series per phase. In each leg, two mosfets are connected in series to make the voltage rating of the module double the switch voltage rating. Note an equivalent multi-stage configuration as in [4]; the interlink capacitor will experience a second harmonic ripple and hence will be electrolytic.

$$v_{kn} = V_p \sin(\omega t + \Phi_k) \tag{1}$$

$$i_k = I_P \sin(\omega t + \Phi_k - \theta) \tag{2}$$

Consider the k^{th} phase voltage v_{kn} given in (1), where $k \in \{a, b, c\}$, $\Phi_a = 0$, $\Phi_b = -2\pi/3$ and $\Phi_c = 2\pi/3$. N unfolders are connected in series and each unfolder in k^{th} phase has an input voltage of $v_k = V_p \sin(\omega t + \Phi_k)/N$. The series connected unfolders carry the phase current i_k, given in (2), where θ is the power factor angle. If the $L_g - C$ filter is properly designed current i_k can be assumed to be free of switching frequency ripple.

B. Modulation of Dual active bridge

The proposed converter supports bidirectional power flow at any power factor drawing ripple-free pure sinusoidal current from the grid. In every module, the DC side is connected to the H bridge, which is connected to three high-frequency transformers, as given in Fig.2. Secondary of these three

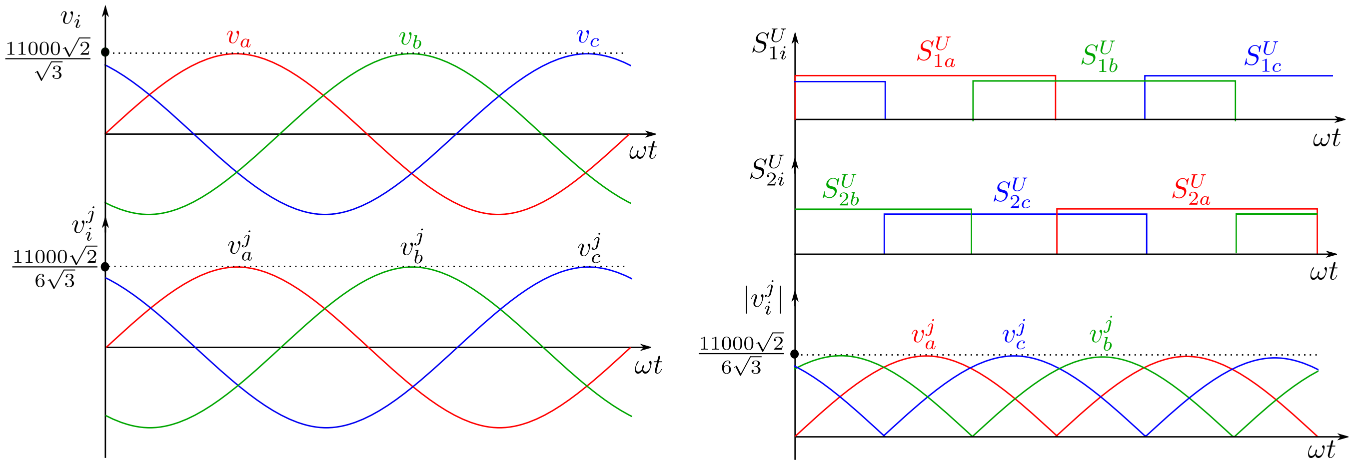


Fig. 3: Modulation of line frequency unfolder

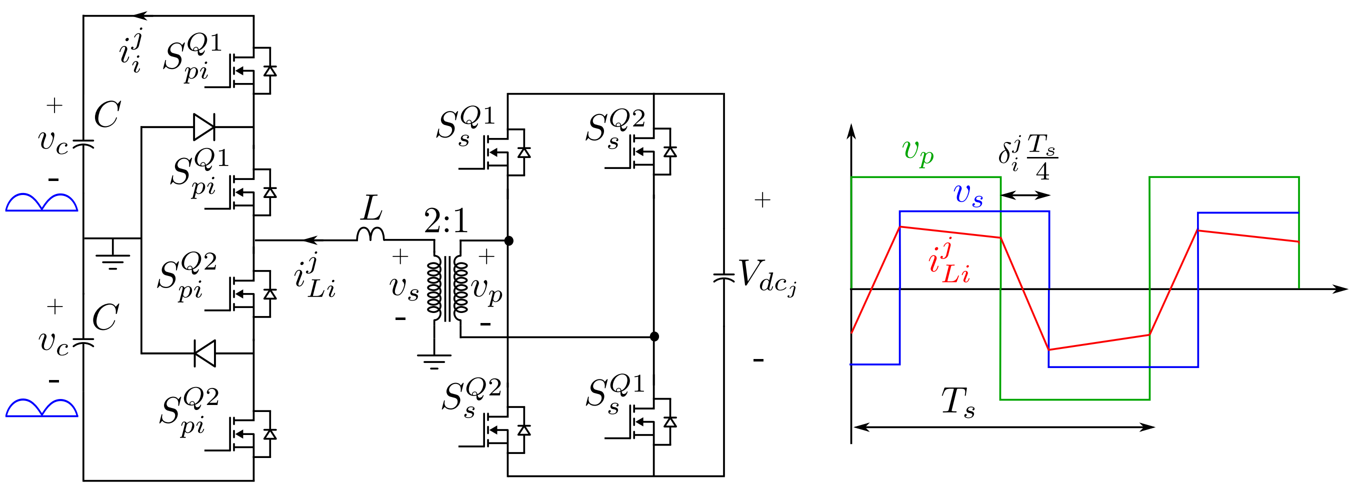


Fig. 4: HFT waveform of a module in quad active bridge

transformers are connected to NPC legs of three phases to have constant power flow per module. From the given reference power to be injected to the grid (P active and Q reactive power), amplitude and phase of the line current per-phase with respect to the phase voltage can be found as in (4). Given the measured phase voltage and reference power commands, it is possible to generate the reference line current waveform through a closed-loop controller.

$$P = \frac{3V_P I_P \cos(\theta)}{2}, \ Q = \frac{3V_P I_P \sin(\theta)}{2} \tag{3}$$

$$I_P = \frac{\sqrt{P^2 + Q^2}}{1.5V_P}, \ \theta = \tan^{-1}\left(\frac{Q}{P}\right) \tag{4}$$

The DC side H-bridge is modulated to apply a square wave voltage of amplitude V_{dc} and frequency $f_s = 1/T_s$. The NPC leg of k^{th} phase is also modulated in square wave-mode at f_s and applied voltage is at a phase-shift δ_k, Fig.4. L is the value of the series inductance and n is the transformer turns ratio. The average of the DC side current over the switching cycle (T_s) that enters the un-folder is shown as i_k^u in Fig.2. Equation (6), relates δ_k to i_k^u. Given the un-folder modulation based on the direction of the phase voltage, line current i_k is related to i_k^u through equation (5). Equation (6) being a quadratic equation, there are two solutions for δ_k, the solution less than one is selected which is the stable phase shift.

$$i_k^u(t) = \text{Sgn}(v_{kn}(t)) * i_k(t) \tag{5}$$

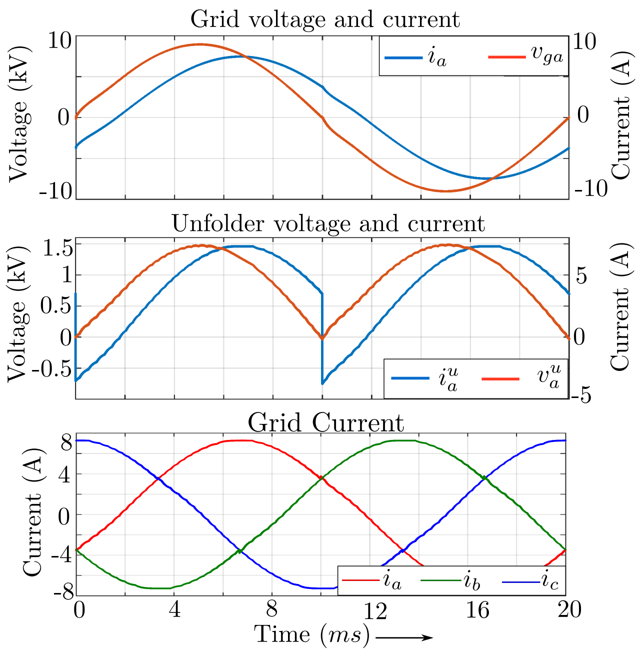
$$i_k^u = \frac{nV_{dc}\delta_k(2 - \delta_k)}{8Lf_s} \tag{6}$$

$$\delta_k = 1 - \sqrt{1 - \frac{i_k^u 8Lf_s}{vV_{dc}}} \tag{7}$$

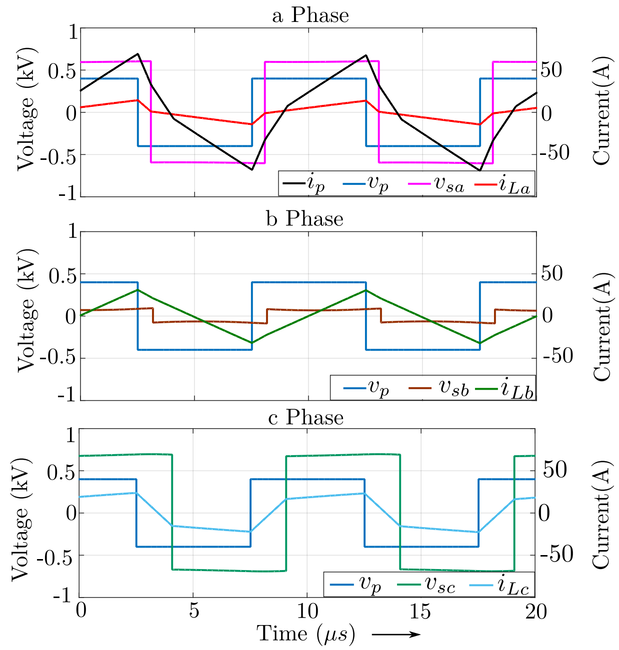
The analysis is done neglecting the line frequency current drawn by the capacitor, which is negligible. However, that can be compensated within the DAB in closed-loop operation by estimating the current drawn by the capacitor. So once i_k (through closed-loop) and i_k^u is known (5), δ_k can be found

TABLE I: Parameters for simulation

Rated power, P_o [kVA]	Switching frequency f_s [kHz]	L [μH]	Turns ratio [n]	L_g [μH]	C [μF]	DC bus voltage [V]	Grid voltage [kV]	f_0 [Hz]	Power factor [cos(θ)]
100	100	60	2:1	5	2	400	11	50	0.866(lag)



(a) Waveforms over a line cycle



(b) Waveforms over a switching cycle

Fig. 5: Simulation results

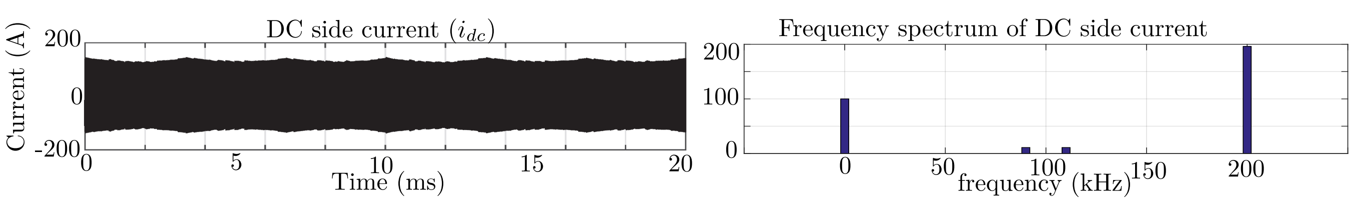


Fig. 6: DC side current per module and its frequency spectrum

using (7). It can be inferred from the representative current waveform Fig.4, that direction of the current at each switching instant will ensure soft-switching [8]. This completes the discussion on modulation strategy.

III. Simulation and experimental Results

The proposed converter with the suggested modulation strategy is simulated in MATLAB Simulink. The important parameters for simulation are given in Table I (L_g, C, L, n, f_s, Grid voltage line-line RMS, f_0, V_{dc}). It is assumed that each device in AC side of each module can block 800V (the typical voltage rating of SiC MOSFET is 1200V). This implies the number of modules in each phase $N = [11000 * \sqrt{2}/(\sqrt{3}*2*800)]+1 = 6$. The converter is modulated to transfer 100kVA at a leading power factor of 0.866. Fig. 5a shows the important simulated waveforms of a-phase over a line cycle. The line current has a peak of 7.4A and a phase shift of 30 degrees, and v_a has a peak of 1500V. This confirms the operation of the proposed converter. Fig 5b shows important waveforms in a module over a switching cycle at an instant when the A-phase voltage has a phase angle of 36^o. Fig 6 shows DC side current waveform (i_{dc} in Fig 2) in a module and its spectrum, which clearly indicates absence of second harmonic.

Experiments are carried out at a lower power of 1.3kW per phase at unity power factor. The AC input voltage is 400V L-L RMS at 50Hz and the DC bus voltage is 400V. The transformer has a turns ratio of 1.5:1 and a series inductance of 50μH. Fig 7 shows the experimental set-up that uses SiC MOSFETs (SCT3060 AL) controlled with Zynq control platform. Isolated gate driver (ADUM4135) is used for generation of gating pulses for the mosfets from PWM signals of Zynq control card. The converter is operated at a switching frequency of 75 kHz. Fig 9 shows that line voltage

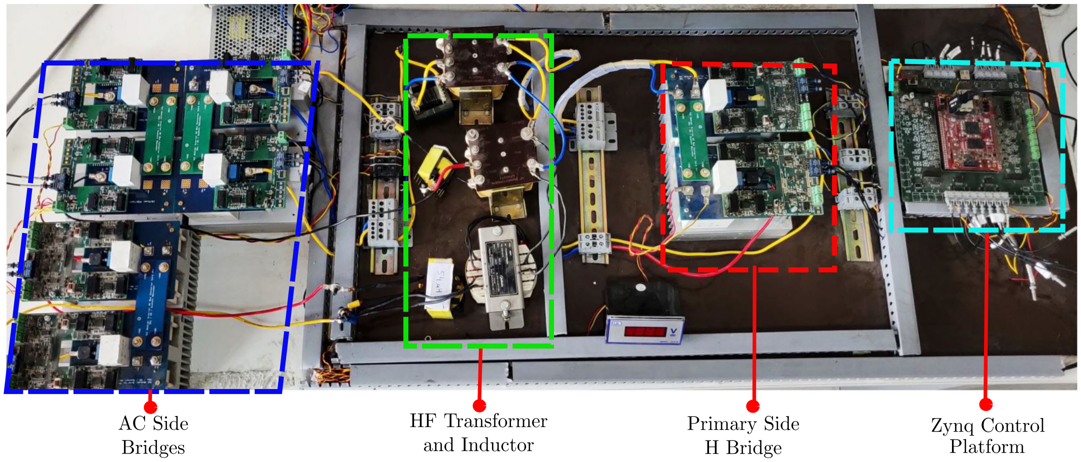


Fig. 7: Experimental Set-up

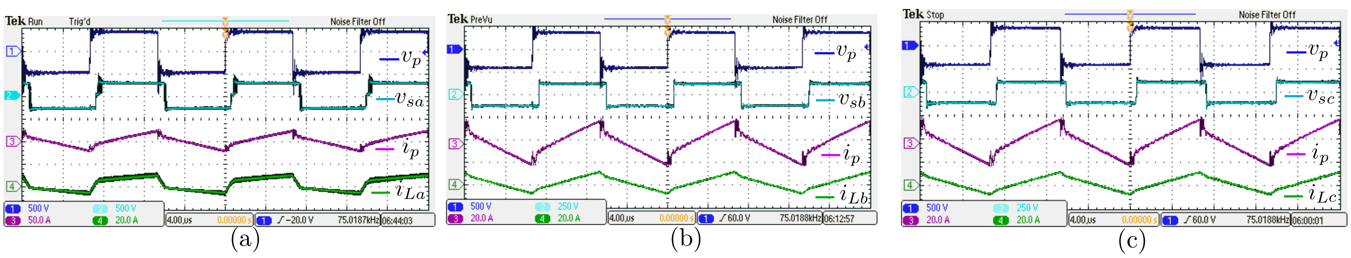


Fig. 8: Voltage and current waveforms over a switching cycle in high frequency transformer

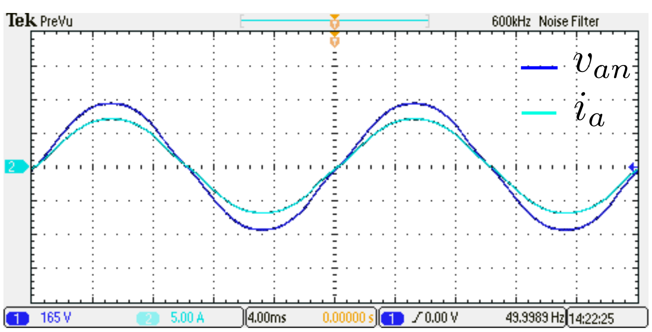


Fig. 9: AC side waveforms over a line cycle

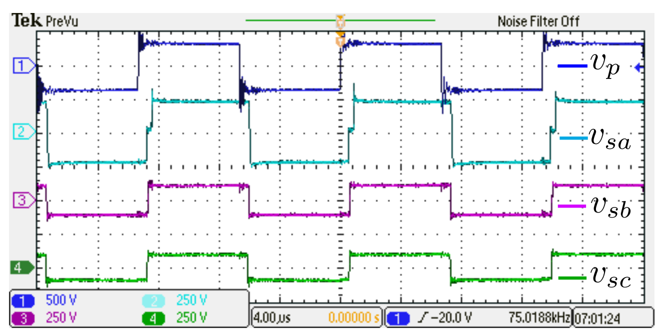


Fig. 11: HF transformer voltage waveforms in a module

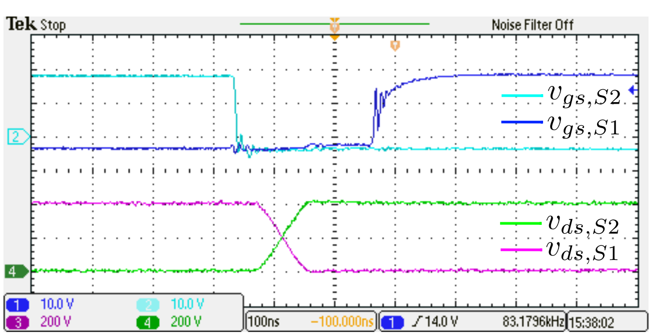


Fig. 10: Verification of soft-switching

and current waveform, while Fig 11 shows the module voltage waveforms over a switching cycle. From the figure it can be seen that the three secondary transformer voltages are phase shifted from the primary voltage (v_p) by different amount. Fig 10 shows waveforms corresponding to a leg of the DC side bridge. Linear change in drain source voltage during the dead time in gate source voltage confirms soft-switching. Fig 8 shows primary voltage (v_p), secondary voltage of three phases (v_{sa}, v_{sb} and v_{sc}), series inductor current in three phases (i_{La}, and i_{Lb}) and primary current (i_p).

IV. Conclusion

This paper presents a new isolated MVAC to LVDC that employs high-frequency transformers and supports bidirectional power flow at any power factor. Suggested multi-level configuration in each module reduces the number of cascaded units in each phase by half. The proposed quad-active-bridge configuration once again helps to reduce the number of devices. Such a configuration also results in no second harmonic ripple, even at each module's DC port. The modulation strategy ensures either line frequency switching or soft-switching of all the devices leading to high efficiency and the possibility of increasing the switching frequency for further reduction of filter sizes. The proposed topology is described, and a brief account of the modulation strategy is presented. Given simulation and experimental results, verify the suggested operation and the advantages. With lower device count, loss-less switching, no electrolytic capacitance, no AC switches, and no multi-winding transformers (challenging to fabricate), the presented converter can become a promising solution for SST renewable integration and fast charging of EVs.

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