Extended Modulation Strategy for Wide Input Range Flying Capacitor based High Step-down LLC Resonant Converter

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***Abstract*—LLC converters operating across wide input voltage ranges tend to deviate from their optimal efficiency point, leading to a decline in overall performance. The flying capacitor based isolated resonant converter ($FCiRC$) with its frequency multiplication capability, is a viable candidate for high power density converter design. It offers a high step-down conversion from 800 V input to 48 V regulated output. Nevertheless, limiting its boundaries, the existing modulation scheme does not allow for a wide-input range operation. Addressing this shortcoming, the current work proposes three additional modulation strategies allowing the converter to operate under a wide input voltage ranging from 160 V to 960 V, delivering a regulated 48 V output. The converter maintains a stable efficiency of approximately 91 % across all modulation strategies, while preserving its key benefits—such as simplified magnetic design despite wide frequency variations across modes, and lower voltage stress on the switches. Experimental validation of the proposed modulation strategy has been presented.**

***Index Terms*—Wide voltage gain, Flying capacitor, DC-DC, LLC Resonant Converter.**

I. Introduction

Demand for renewable energy sources increasing globally, also intensifies the need for robust connecting dc-dc converters to ensure reliable and efficient operation of the system. Environmental consequences on the photovoltaic system leads to the generation of unstable output, while the load requires a steady input. This has increased the demand for a reliable wide input voltage, constant output dc-dc converter [1], fulfilling the segment requirements shown in Fig. 1. Optimal efficiency range of converter for the complete operating range is essential. LLC resonant converters have been a viable choice for an isolated dc-dc converter with improved soft-switching range, high efficiency, power density and low magnetic interference. Extending the voltage gain of these converters has been a challenge and several works have addressed this constrain, either by structural changes or modified control strategy.

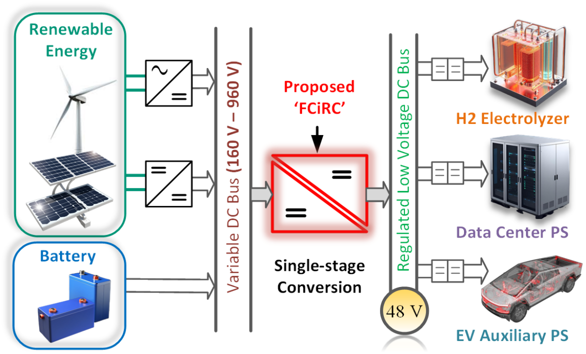

Fig. 1. Application overview of a single-stage, wide input, step-down and regulated output converter.

Parametric variation (switching frequency, phase-shift) being a prime-factor in extending the voltage gain of LLC converters, at-times it leads to deviations from the resonant point deteriorating the overall system performance. In [2], the author proposed a multi-mode operating scheme for a series-half bridge LLC topology, to extend the input voltage range. Nevertheless, the converter operates under sub-optimal conditions with varying resonant frequency under different modes. The stacked switch CLLC converter in [3], presents a hybrid control strategy for four modes of operation, thereby extending the voltage gain of the converter under a narrow frequency range. Phase-shift control with a fixed frequency also allows widening the range [4], adversely the high circulating current affects the efficiency during light load conditions. Alternatively, phase-shift control with modified dual half-bridge units on the primary-side [5], helps varying the turns ration dynamically to attain a wide voltage range. Apart from modifying the converter topology and control strategy, few works have been presented with configuration changes in the resonant tank (inclusion of notch filter [6], auxiliary bridge circuit [7], parallel inductor loop), in order to accommodate the frequency variations for achieving wide voltage gain. A dual transformer configuration [8] with variable switching frequency control, sets a wide voltage gain range but poses challenges in maintaining soft switching across the entire operating range. The drawback in such topology adaptations, is the added control complexity, bulkier hardware and associated power loss.

Leveraging the advantage of flying capacitors, [9] presents a half-bridge stacked flying capacitor based isolated resonant converter with high step-down capability. The proposed frequency multiplication strategy, plays an important role in reducing the mass of passive elements and achieving high power density. But the presented modulation strategy is applicable only for a 800 V input and 48 V output condition. Addressing this voltage range limitations of FCiRC, the current research proposes three additional modulation strategies that extend its input voltage range between 160 V and 960 V for a regulated 48 V output. Ensuring the converter's operation at a fixed resonant frequency (f_r), each of the modulation scheme establishes its own frequency multiplication factor and voltage gain, supported by two degree-of-freedom control flexibility.

II. Proposed Modulation Strategy

The flying capacitor based multilevel isolated resonant converter proposed in [9], utilizes half-bridge modules (SM_1-SM_4) in series with the flying capacitors (C_{F1} and C_{F2}) and split dc-link capacitors (C_{IN1} and C_{IN2}) distributed across the bridge modules, as shown in Fig. 2. The converter operation is rooted to the flying capacitor's charging and discharging sequence, as well as the order of utilization of the dc-link capacitors. Extending the ability of the converter for a wide-range of input and regulated output voltage without losing the resonant point, three different modulation strategy has been proposed - Mode B for 600 V input; Mode C for 400 V input; and Mode D for 200 V input (in addition to the Mode A modulation scheme for 800 V input discussed in [9]). Table I, summarizes the operating parameters for different modes of operation, established by the two degree-of-freedom control flexibility (i.e., duty-cycle (d) & switching frequency (f_{sw})).

TABLE I
FCiRC Modulation parameters.

Operating Modes	Frequency Multiplication	Phase Shift	Duty Cycle	Voltage Gain
Mode A	$f_r = 4 \cdot f_{sw}$	90°	12.5%	16:1
Mode B	$f_r = 3 \cdot f_{sw}$	120°	16.6%	12:1
Mode C	$f_r = 2 \cdot f_{sw}$	180°	25.0%	8:1
Mode D	$f_r = f_{sw}$	-NA-	50.0%	4:1

During Mode A (or Four Factor Modulation) 4 primary driving signals with a 90° phase-shift, control the switches S_1, S_2, S_7 and S_8. The corresponding modulation scheme as shown Fig 3, has 4 active states under one time-period,

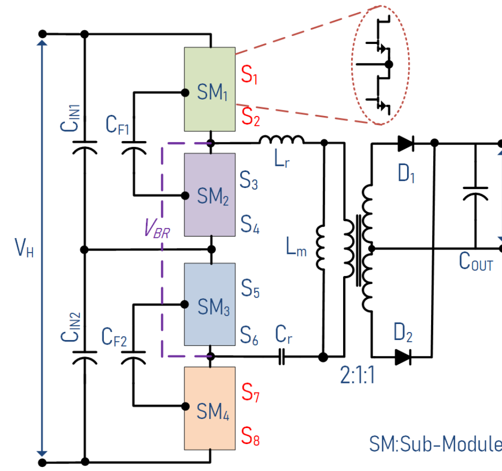

Fig. 2. Flying capacitor based resonant converter topology.

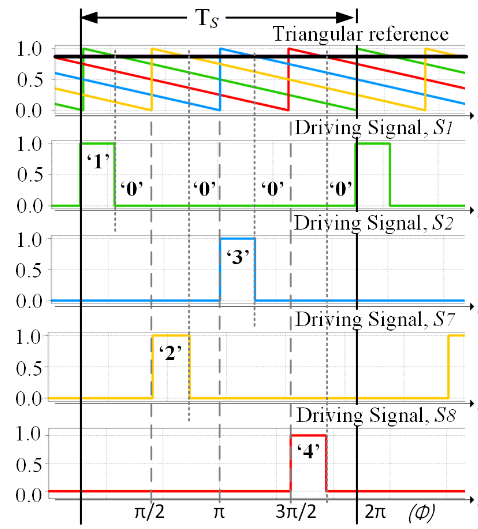

Fig. 3. Mode A of the proposed modulation strategy for 800 V input voltage.

along with a zero cycle in-between every active power cycle. The order of switching constitutes the sequence of charging and discharging cycle of the flying capacitors C_{F1} & C_{F2} respectively, as highlighted in Fig. 5(a) & (b). The switching frequency in this mode is at a factor of 4 compared to the resonant frequency. The zero cycle, is a passive operating state providing a circulating path for the reactive current in the resonant tank, indicated in Fig. 5(f). As a rule of thumb, every modulation strategy introduces a zero cycle in between each of its active power cycle. The Mode B (or Three Factor Modulation) operation replaces the individual charging cycle of the flying capacitors, by a unified C_{F1} & C_{F2} charging cycle, as shown in Fig. 5(c). With only 3 driving signals for switches S_1, S_2 and S_7, each of them are phase-shifted by 120°. Figure 4(a) illustrates the gate signal switching sequence of Mode B. In this mode, the multiplication factor of the switching frequency to the resonant frequency is reduced to a

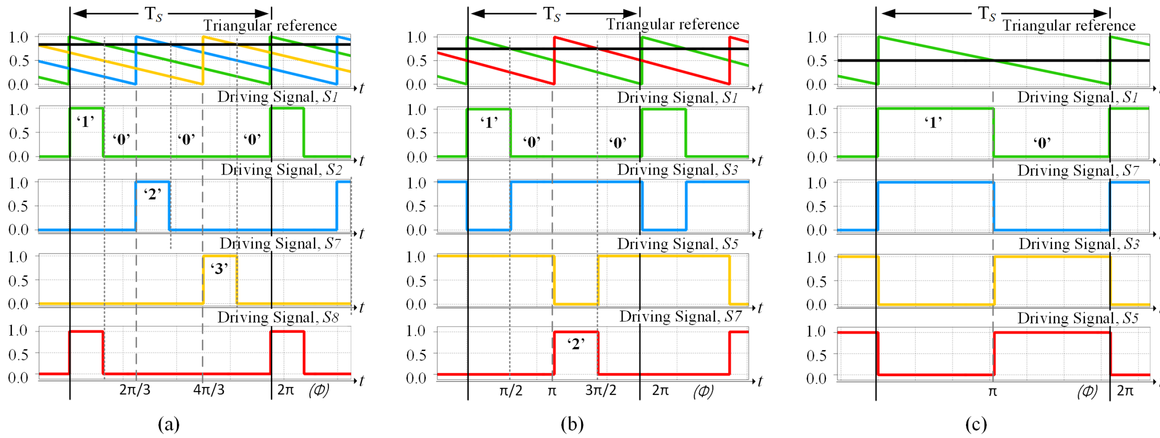

Fig. 4. Proposed modulation strategy (a) Mode B for 600 V input voltage at $f_r = 3 \cdot f_{sw}$, (b) Mode C for 400 V input voltage at $f_r = 2 \cdot f_{sw}$ and (c) Mode D for 200 V input voltage at $f_r = f_{sw}$.

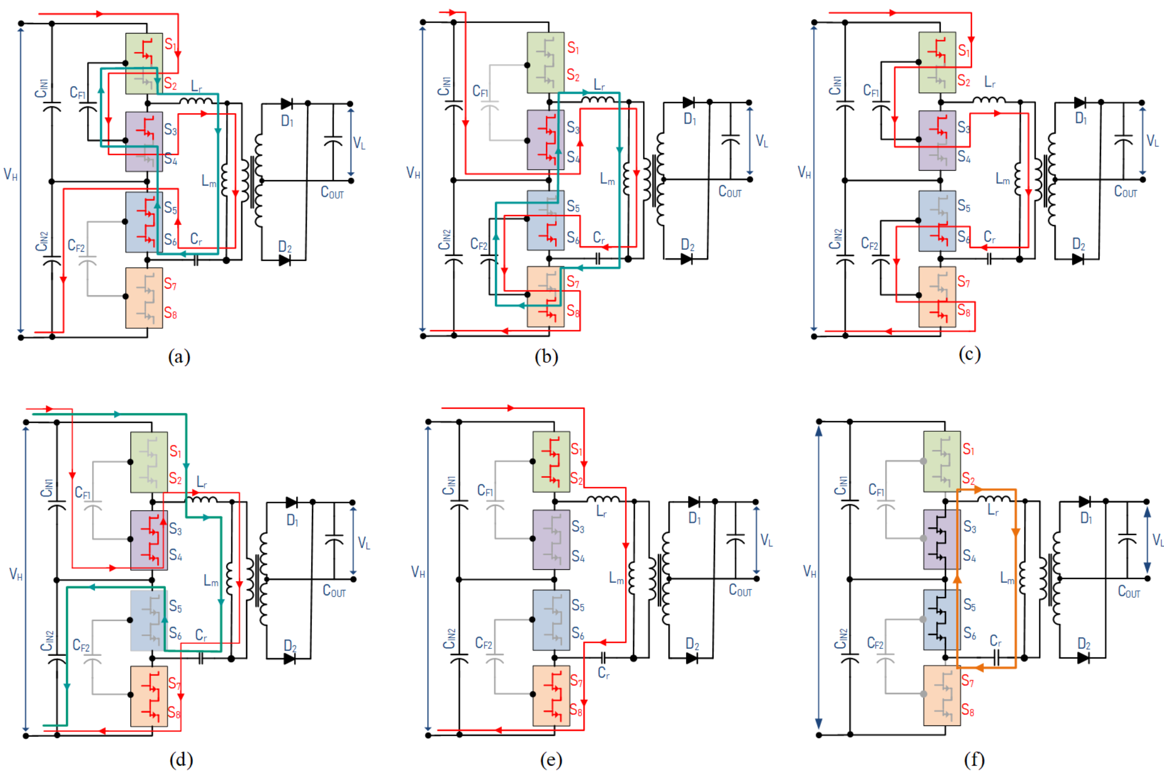

Fig. 5. Operating modes of the FCiRC (a) C_{F1} charging (red-line) and discharge (green-line) cycle; (b) C_{F2} charging (red-line) and discharge cycle (green-line); (c) C_{F1} & C_{F2} combined charging cycle; (d) C_{IN1} cycle (red-line) and C_{IN2} cycle (green-line); (e) Mode D cycle; (f) $Zero$ cycle.

factor of 3.

Mode C (or Two Factor Modulation) is proposed for a 400 V input voltage operating condition. With the flying capacitors remaining idle during this mode of operation, two new power cycles are introduced across the split dc-link capacitors C_{IN1} and C_{IN2}, as illustrated in Fig. 5(d). This mode of operation has 2 primary driving signals (180° phase-shift) for switches S_1 and S_7. Unlike the other modulation strategy, here the switches in a sub-module are fed with the same driving signal. Sub-modules SM_1 & SM_3 form one active cycle across C_{IN1} and SM_2 & SM_4 forms the succeeding power cycle across C_{IN2}, with an intermittent zero-state. The modulation strategy of Mode C is shown in Fig. 4(b). The resonant frequency is twice the switching frequency during this mode. Simplified from the other operating modes, Mode D (or Unity Factor Modulation) for a 200 V input condition, has only one primary driving signal applied to switches S_1, S_2, S_7 & S_8 and rest of the switches receiving complimentary signal (Fig. 5(b)).

Similar to Mode C, the flying capacitors C_{F1} & C_{F2} remain inactive in this mode of operation. The power cycle is formed across the combined dc-link capacitors, aided by sub-modules SM_1 & SM_4.

With a fixed frequency variation band and gain limits between 1.2 (G_{max}) & 0.8 (G_{min}), the extended input voltage range is achieved, as shown in 6. Setting the nominal operating points at inputs voltage levels of 200 V, 400 V, 600 V and 800 V, the consolidated input voltage operating range of the proposed converter is between 160 V and 960 V.

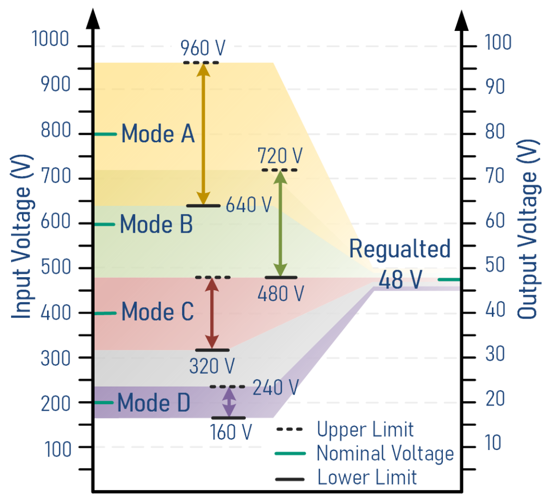

Fig. 6. Extended operating range of FCiRC under different operating modes.

III. Experimental Validation

The proposed modulation strategy has been experimentally validated on a hardware prototype based on Gallium-Nitride Switches and Integrated Planar Transformer, shown in Fig. 7. A detailed overview of the operating parameters as well as the critical component(s) parameter have been listed in Table II.

TABLE II
Converter parameters.

Parameter	Symbol	Value
Input Voltage	V_H	80 − 480 V
Output Voltage	V_L	24 V
Output Power	P_{out}	350 W
Switching Frequency	f_{sw}	17.5 − 70 kHz
Resonant Frequency	f_r	70 kHz
Magnetizing Inductance	L_m	102.68 µH
Leakage Inductance	L_r	8.50 µH
Resonant Capacitance	C_r	600 nF
Flying Capacitance	C_f	26.2 µF

The voltage ratings are scaled down by half, i.e., input voltage range of Mode A is 400 V, 300 V input for Mode B, 200 V input for Mode C and 100 V for Mode D, towards

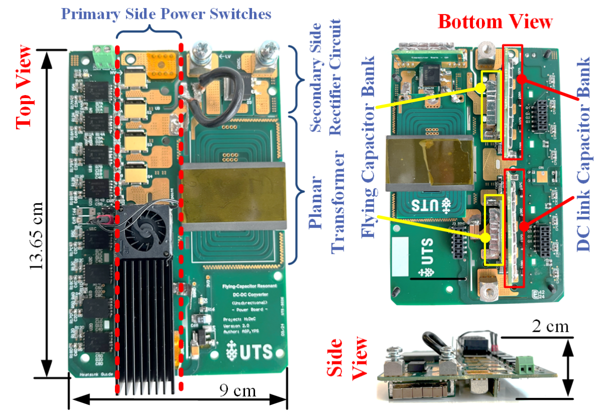

Fig. 7. Hardware prototype of the proposed resonant converter.

a regulated 24 V output. Preliminary validation tests have been performed at power rating of 350 W and a resonant frequency around 70 kHz. As proposed in the modulation strategy, the frequency multiplication effect is evident in the experimental results. This can be observed by comparing the number of pulses on the gate-signal (red) and the primary bridge output voltage (V_{BR}) (blue), across one time-period from the experimental waveform(s) shown in Fig. 8. Mode A, B and C has a frequency multiplication factor (f_r/f_{SW}) of 4, 3 and 2, respectively. Also extracted from the maximum amplitude of primary bridge output voltage waveform, are the voltage stress (V_{DS}) on individual power switches as well the charged voltage levels of the flying capacitors C_{F1} & C_{F2} and the dc-link capacitors C_{IN1} & C_{IN2} voltages. Balance in the maximum amplitude of the primary bridge output voltage, indicates uniform charging and discharging sequence of the flying capacitors. By virtue of the modulation strategy, the capacitor voltages are evidently self balanced.

During Mode A, the maximum V_{DS} is around 100 V, which is at a factor of 4 compared to the input voltage. Likewise, the voltage stress during Mode B and Mode C are being reduced by a factor of 3 and 2, respectively. The voltage stress on the switches in Mode D, remains equal to the input voltage. A uniform maximum voltage stress of 100 V is observed across all difference operating modes. This reduced voltage stress on the switches, allows the flexibility to choose low-voltage switching devices while building the hardware, thereby reducing the overall cost. The balanced sinusoidal current waveform (pink) exemplifies the converter's operation at resonant frequency, under varying switching frequency conditions. Also can be observed during each power-cycle, is the zero-voltage switching of the switches.

Due to the balance in switching frequency and number of active switches during each mode of operation, the overall loss distribution remains uniform (observed in simulations). For a 350 W input power and 24 V regulated output, a constant efficiency 91 % is measured around, for the different modes as shown in Fig. 10. The thermal measurements during mode A operation, is shown in Fig. 11. The maximum temperature

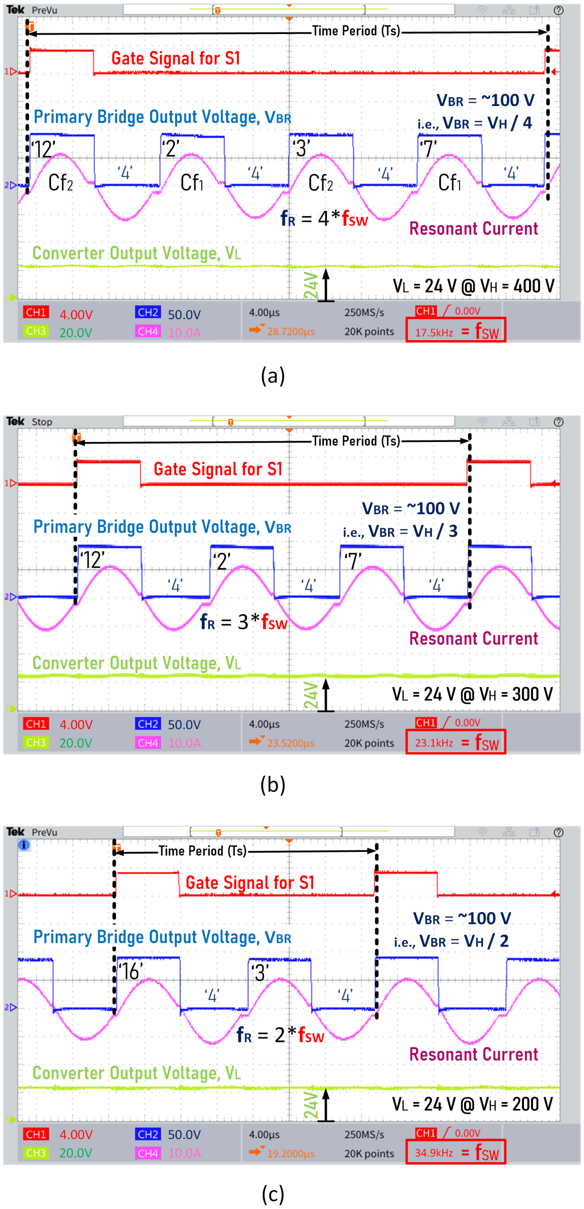

Fig. 8. Measurement results of the FCiRC for (a) Mode A (V_H = 400 V, f_{SW} = 17.5 kHz); (b) Mode B (V_H = 300 V, f_{SW} = 23.1 kHz); and (c) Mode C (V_H = 200 V, f_{SW} = 34.9 kHz) operations. Waveform description: Channel 1 (red) - Reference gate-signal; Channel 2 (blue) - Primary-bridge output voltage; Channel 3 (pink) - Resonant current and Channel 4 (green) - Output voltage.

of the switches are uniform and well below its safe operation region. This condition is repeated during other operating modes as well.

IV. Conclusion

A multi-mode modulation strategy for extending the input voltage range of a flying capacitor based isolated resonant dc-dc converter has been proposed and validated experimentally. Operating at a constant resonant frequency despite the variations in switching frequency between the modes, helps to maintain uniform loss distribution and efficiency, without compromising the performance metrics. This allows to improve the power-density of such converters. Further works are being undertaken to validate the converter at higher resonant frequency for the wide input voltage, under full load conditions.

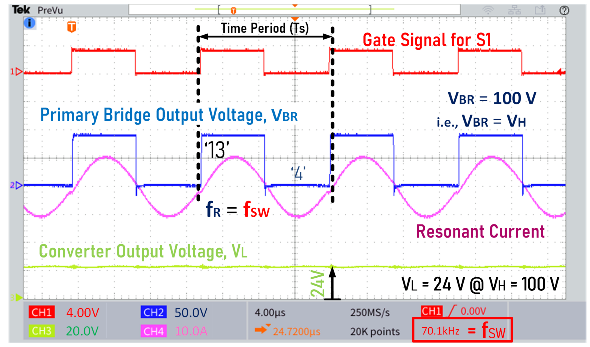

Fig. 9. Measurement results of the FCiRC for Mode D (V_H = 100 V, f_{SW} = 70.1 kHz) operations.

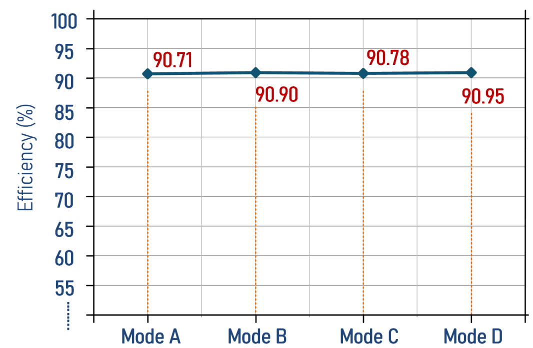

Fig. 10. Measured efficiency of the converter for all the proposed modulation strategy, at 350 W output power, well regulating the output voltage to 24 V from input voltage 100 V - 400 V.

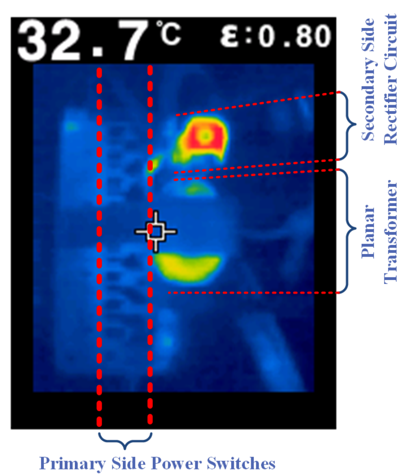

Fig. 11. Measurement thermal behavior of the converter (Mode A operation).

References

[1] Q. Cao, Z. Li, and H. Wang, “Wide voltage gain range llc dc/dc topologies: State-of-the-art,” in 2018 International Power Electronics Conference (ECCE Asia), 2018, pp. 100–107.

[2] H. Luo, C. Yao, L. Xu, and X. Wang, “A multi-mode combined control method for wide input voltage application based on series-half-bridge llc resonant converter,” in 2024 3rd International Conference on Power Systems and Electrical Technology (PSET), 2024, pp. 188–193.

[3] R. Emamalipour, S. Derakhshan, and J. Lam, “A multimode control scheme for output regulation and voltage balancing in a stacked-switch resonant converter with extended high efficiency for wide gain range applications,” IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 11, no. 2, pp. 1838–1853, 2023.

[4] Y. Shen, H. Wang, A. Al-Durra, Z. Qin and F. Blaabjerg, ”A Bidirectional Resonant DC–DC Converter Suitable for Wide Voltage Gain Range,” in IEEE Transactions on Power Electronics, vol. 33, no. 4, pp. 2957-2975, April 2018.

[5] P. Jia and M. Liu, ”A Wide Range LLC Resonant Converter Realized by an Adjustable Turns Ratio Transformer,” in IEEE Transactions on Power Electronics, vol. 40, no. 8, pp. 10396-10401, Aug. 2025.

[6] M. Chen, B. Chen, Y. Wang, P. Wang, M. Zhang and C. Che, ”A High-efficiency Resonant DC-DC Converter with Wide Voltage Gain Range,” 2022 IEEE Energy Conversion Congress and Exposition (ECCE), Detroit, MI, USA, 2022, pp. 1-6.

[7] P. Jin, J. Zhang, Y. Lu, Y. Guo, G. Lei and J. Zhu, ”Variable Frequency Isolated Bidirectional CLLC Resonant Converter With Voltage Controlled Variable Capacitors,” in IEEE Transactions on Industrial Electronics, vol. 70, no. 9, pp. 8907-8917, Sept. 2023.

[8] D. Sha, H. Zhong and D. Zhang, ”A Resonant DAB DC-DC Converter Using Dual Transformers With Wide Voltage Gain And Variable Switching Frequency,” 2020 15th IEEE Conference on Industrial Electronics and Applications (ICIEA), Kristiansand, Norway, 2020, pp. 748-752.

[9] A. Palanisamy, J. Hassan, D. Lu, R. P. Aguilera, and Y. P. Siwakoti, “A high step-down flying capacitor resonant converter with quadruple frequency at the resonant tank,” in 2024 IEEE 9th Southern Power Electronics Conference (SPEC), 2024, pp. 1–4.