An Isolated Composite Resonant Multilevel Converter with Partial Power Voltage Regulation for Telecom Application

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***Abstract*— In this paper, an new converter that includes isolated composite resonant multilevel converter (ICRMC) that uses composite converter concept and partial power voltage regulator (PPVR) has been proposed for telecommunication application. The proposed converter can achieve high efficiency at nominal operating point since it takes minimum effort to regulate the output voltage at this point. A comparative study shows that with the proposed two operation modes of ICRMC, the proposed converter has the best capability to maintain lowest total semiconductor power stress among the existing state of the art solutions when the input voltage varies from 36V to 60V. Furthermore, zero current switching (ZCS) can be always achieved on the switching devices in ICRMC under different operating points. A 600W converter has been simulated to validate the theoretical analysis. The estimated peak efficiency can be as high as 97.65%. Fully debugged prototype and experimental results are provided in this paper.**

***Keywords*— Telecom, ZCS, Resonant, Partial Power Voltage Regulation, DC-DC converter**

I. Introduction

Over the years, the number of telecommunication and data center power delivery systems are growing rapidly. As a result, total power consumption of these systems is also significantly increased during the past years. In order to reduce energy waste, the efficiency improvement of these power systems becomes very important. Therefore, new architecture level topology called intermediate-bus architecture (IBA) becomes more and more popular since 1990s [1]. And the advantages of IBA relies on intermediate-bus converter (IBC) a lot. The functions of IBC is to generate an intermediate-bus voltage from higher voltage such as 48V and provide electrical isolation. Hence, the performance of IBC becomes a vital part of the power delivery systems' success. It's worth mentioning that although power system architectures with higher voltage level DC bus like 380V are claimed to be more efficient than that with 48V DC bus and they will become the trend of future datacenters [2]–[5], the systems with 48V is still the most common architectures in the world right now.

A lot of novel dc-dc converters have been proposed during the past years. In [6], a very high efficiency switched-capacitor DC-DC converter has been proposed for data center application. Although this converter has low power stress on semiconductors, it cannot meet the requirement that IBC in telecom system needs isolation [7]. And, its voltage conversion ratio is fixed. Therefore, in order to use this converter in telecom application, an isolation stage with voltage regulation capability is needed, either before or after the converter. However, using the additional stage is not an ideal solution because it leads to additional power consumption. In [8], a MultiTrack architecture has been proposed for application that needs wide range voltage conversion ratio and isolation. This architecture uses switched-inductor concept to achieve the voltage regulation function and switched-capacitor concept to balance the capacitor voltage in the circuit. Besides, although there are many resonant converters that are proposed during the past years [9]–[11], these converters does not use partial power processing concept in the design. In [7], sigma converter that uses partial power processing concept has been proposed, with this concept, one can achieve very high efficiency and power density. Other than the converters' architecture level improvements, optimization on magnetic components also helps increase the performance of IBC. For example, optimized matrix transformer design in [12]–[14] help the converters to achieve very high efficiency and density.

This paper proposed an isolated composite resonant multilevel converter with partial power voltage regulator. In order to achieve high density and efficiency, the proposed converter that utilizes partial power processing concept from [7] and keep the good features from [6]. In the proposed converter, the partial power voltage regulator allows the proposed converter have capability to regulate the output voltage. In order to show the advantages of the proposed converter, a comparison study of the novel DC-DC converter has been performed. As a result, the proposed converter has the lowest total semiconductor power stress and lowest semiconductor loss among the compared converters.

This paper is organized as follows: The second section will demonstrate the topology of the proposed circuit as well as its operation modes under different input voltage. The third section states the advantages of the proposed circuit in terms of total semiconductor power stress. Furthermore, detailed power loss analysis and power loss breakdown are performed to show that the proposed converter has the lowest semiconductor power loss. Section IV shows the simulated results and estimated efficiency. Simulation and experimental results are provided in Section IV. At last, section V concludes the proposed design.

II. Circuit Configuration and Oprtaing Principle

Intermediate bus architecture is widely used in data center and telecommunication power system. For telecom application, the IBC accomplishes two functions, which are provides electrical isolation and converts intermediate bus voltage to a lower voltage, such as from 48V to 12V. For data center application, the IBC only takes care of voltage conversion, isolation is not a mandatory requirement nowadays [15]. This paper proposed an IBC that is suitable for telecom applications. In this section, circuit configuration as well as operating principle will be introduced.

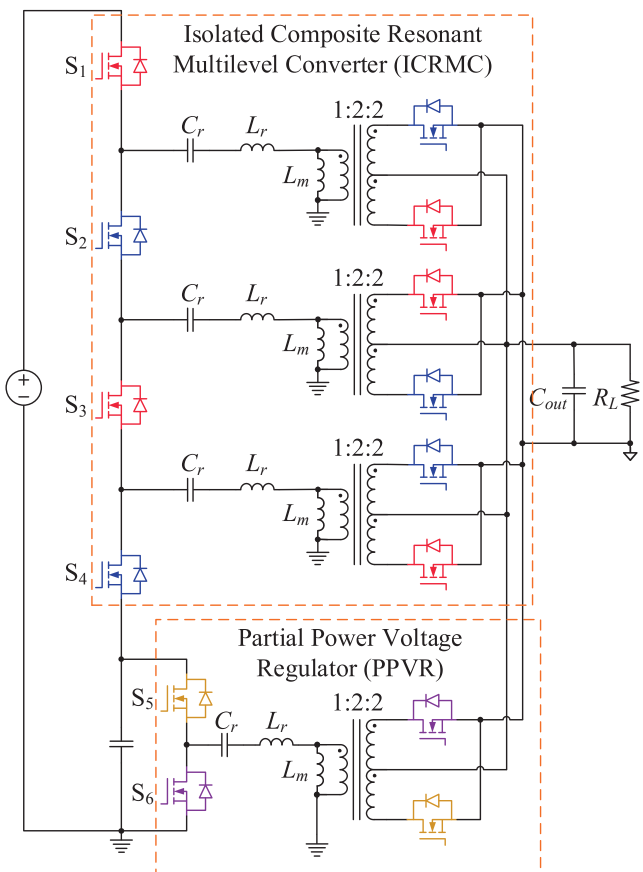


Fig.1 Structure of the proposed converter

A. Circuit Configuration

The structure of the proposed converter is shown in Fig.1. For a converter with N:1 voltage conversion ratio, its primary side has N+2 switching devices and secondary side has 2N devices. Fig.1 shows the proposed converter with 4:1 conversion ratio. In the proposed converter, the primary side circuit contains two parts. The first part has four floating MOSFETs and three resonant branches. This part of circuit has relatively fixed conversion ratio, which is 3:1. When the switch S_2 operates at bypassing mode, 2:1 conversion ratio can be achieved. More details will be mentioned in the following paper. The second part of the circuit is the partial power voltage regulator. Unlike the first part circuit, the circuit structure of this part is very flexible. It could be any isolated circuit that is capable of performing continuous and fine voltage regulation. This paper uses LLC resonant converter as an example. The secondary side of the proposed circuit has N synchronous rectifier that is composed by 2N MOSFETs. In summary, the ICRMC and PPVR in the proposed converter accomplish rough voltage regulation (3:1 / 2:1) and fine voltage regulation (continuous conversion ratio), respectively. And the secondary side circuit accomplishes current and voltage rectification function.

B. Circuit Operation Under Different Input Voltage

In order to meet the high efficiency requirement as well as make sure the converter can operate when input voltage ranges from 36V to 60V, two operation modes has been proposed for ICRMC. Note that the highest gain of PPVR is assumed to be 1. The power processed by the isolated composite resonant multilevel converter and differential power processing module can be calculated using (1) and (2), respectively. Here P_{total} means the total power processed by the proposed converter.

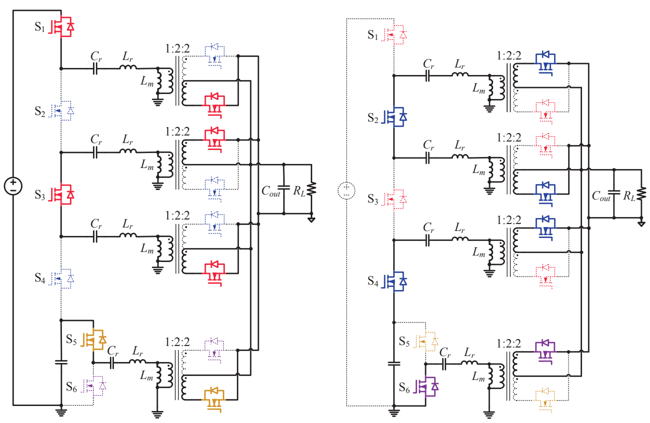
$$P_{ICRMC} = \frac{1 - V_{C1}}{V_{in}} * P_{total} \tag{1}$$

$$P_{DPP} = P_{total} - P_{ICRMC} \tag{2}$$

By using the proposed two operation modes, the proposed converter uses less effort to regulate the output voltage than that without the proposed control method.

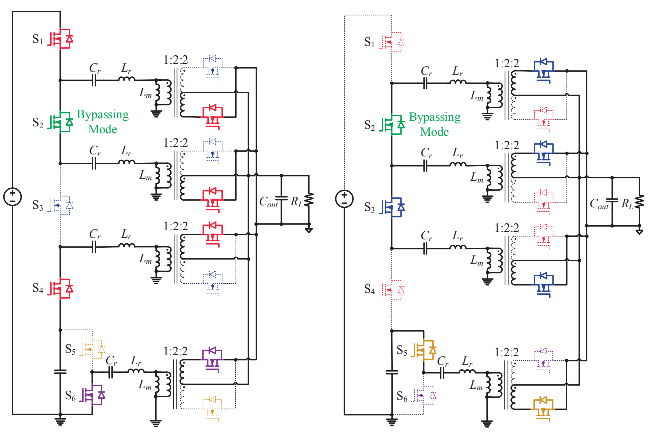
- Unregulated mode: When $V_{in} \geq 48V$, the ICRMC operates in unregulated mode. The voltage conversion ratio of this circuit is 3:1. This means the DC voltage across this module is constantly 36V. Thus, the DC voltage across PPVR will be (V_{in}-36V). For the circumstance that V_{in} ranges from 48V to 60V, the maximum voltage of the devices in PPVR is 24V. The equivalent circuits of this operation mode is shown in Fig.2(a) and Fig.2 (b).
- Bypassing mode: When $V_{in} < 48V$, the ICRMC operates in bypassing mode, which means switch S_2 is always turned on. In this mode, the voltage conversion ratio is 2:1 instead of 3:1. The DC voltage across the ICRMC is 24V. And this means the DC voltage across capacitor C_1 is (V_{in}-24V). Also, the maximum voltage of the devices in PPVR is 24V when the input ranges from 36V to 48V. The equivalent circuits of this operation mode is shown in Fig.3(a) and Fig.3(b).

Assume the PPVR uses LLC resonant converter, and all the L_r and C_r in the circuit are identical. Thus, there is no doubt that the switching devices in PPVR can achieve soft-switching. Besides, the ICRMC also processes soft-switching capability. In the case that $V_{in} \geq 48V$, when switching frequency of all switching devices in the ICRMC is very close to or matches the resonant frequency of the resonant tanks and is within the ZCS



(a) Equivalent circuit of state 1 (b) Equivalent circuit of state 2

Fig.2 Operating states when $V_{in} \geq 48V$



(a) Equivalent circuit of state 1 (b) Equivalent circuit of state 2

Fig.3 Operating states when $V_{in} < 48V$

operation region of the LLC resonant tanks, ZCS operation of the ICRMC has been achieved. Similarly, in the case that $V_{in} < 48V$, all of the switches in ICRMC still achieve ZCS except the switch operates in bypassing mode. The resonant frequency of the resonant tank can be calculated using (3).

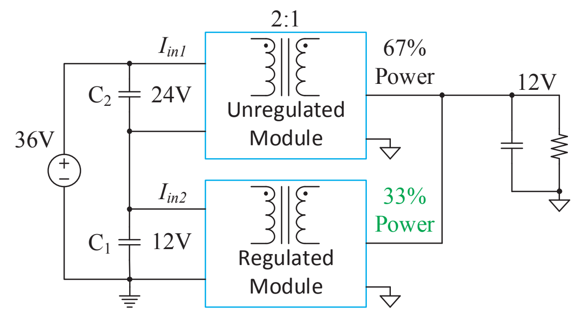
$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{3}$$

It is worth mentioning that when the input voltage is not 36V or 48V, the PPVR achieves buck function. As a result, zero voltage switching is achieved instead of zero current switching regarding the devices in PPVR.

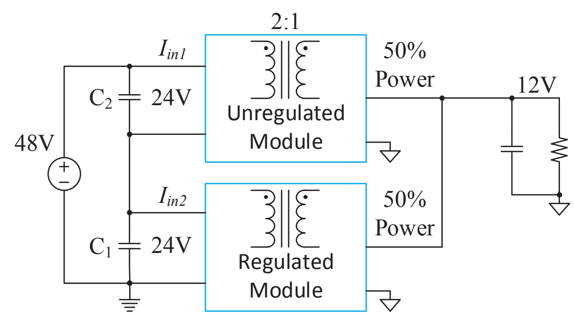
III. Comparison Between Different Solutions

A. Advantage of the Proposed Converter

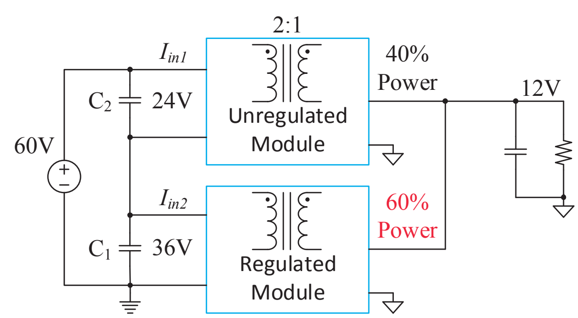
One state of the art architecture for telecom application is shown in Fig.4. Similarly, this structure has two parts, unregulated module and regulated module. When applying this architecture to dc-dc power conversation application that needs high voltage gain, its highly efficient unregulated module can process more than 90% of total power. And the less efficient regulated module only processes very minimum amount of power (e.g. less than 10%). However, for 48/12V application whose input voltage ranges from 36V to 60V, the regulated module will need to process up to 60% of the total power. Thus, the benefit of this architecture is not obvious anymore. The proposed converter, on the other hand, utilizes composite converter concept and replace the traditional unregulated module with ICRMC. The new topology shown in Fig.6 can reduce the power need to be processed by regulated module and reduce converter's total semiconductor power stress. This means less power loss on switching devices.



(a)Input voltage is 36V



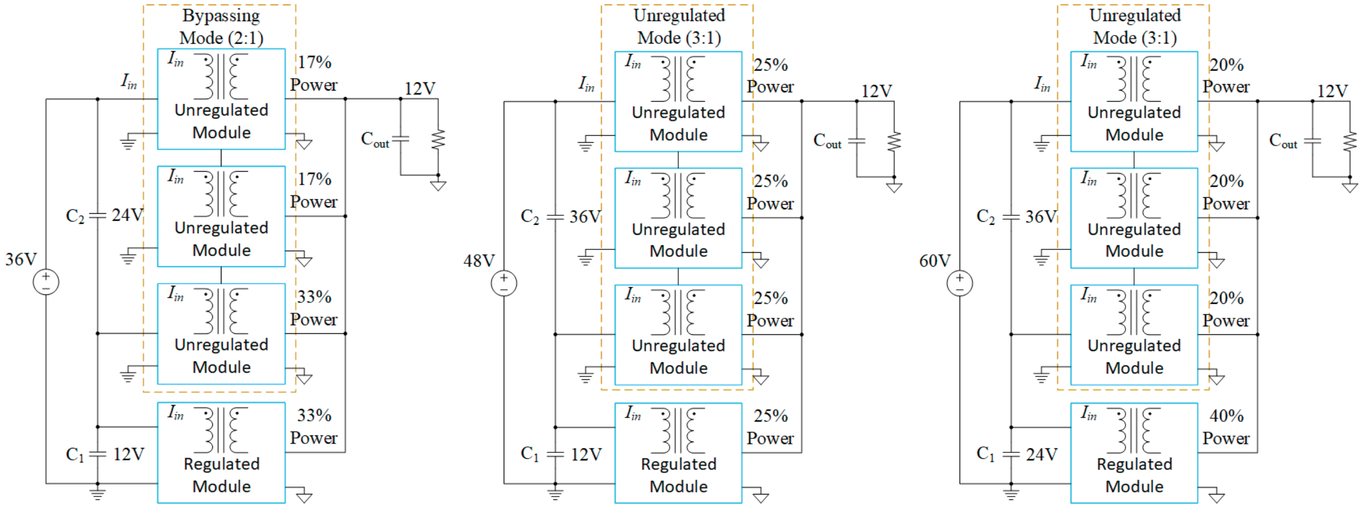
(b) Input voltage is 48V



(c) Input voltage is 60V

Fig.4 Regulated module processes more than 50% of the power when input voltage is high

The total semiconductor power stress of multiple state of the art converters are compared, as shown in Fig. 5. In this comparison, three scenarios are considered, which are $V_{in} = 36V$, $V_{in} = 48V$ and $V_{in} = 60V$. One can tell that when input voltage is 36V, the proposed converter, converter with input-series-output-parallel (ISOP) architecture and the converter shown in [7] have the lowest total power stress. When input voltage changes to 48V and 60V, the total stress of proposed solution is always the lowest and almost unchanged under different input voltage. However, the total stress of other converters become higher as input voltage increases. Note that



(a)Input voltage is 36V (b) Input voltage is 48V (c) Input voltage is 60V

Fig.5 The proposed structure reduces the power needs to be processed by the regulated module

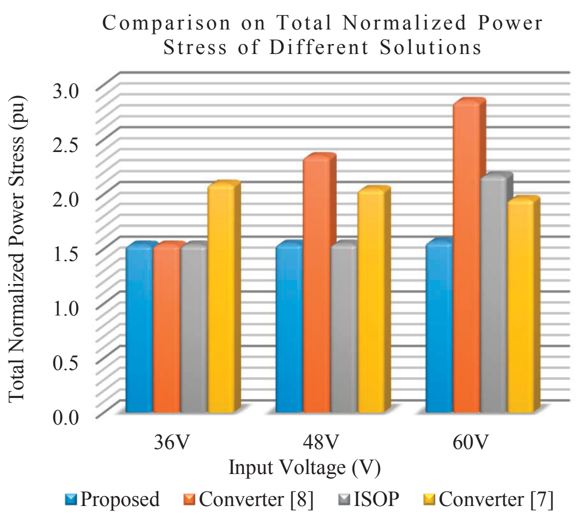


Fig. 6 Comparison on total normalized power stress of different solutions

TABLE I PARAMETERS OF GAN DEVICES USED IN ANALYSIS

Part#	Q_g (nC)	V_{gs} (V)	f_s (kHz)	R_{ds_on} (mΩ)	Coss (pF)
EPC2023 (30V)	19	5	328	1.15	1724@12V
					1174@24V
EPC2024 (40V)	18	5	328	1.2	2169@12V
					1381@24V
EPC2020 (60V)	16	5	328	1.5	1820@12V
					1175@24V
					939@36V

TABLE II VOLTAGE STRESS OF SWITCHING DEVICES IN DIFFERENT CONVERTERS

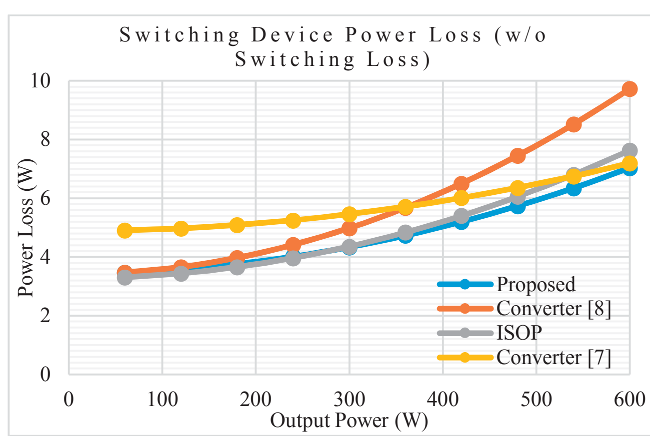
Converter	Voltage Stress	Switching Device Used
Proposed	12V, 24V	EPC2023, EPC2024
Converter [7]	36V	EPC2020
ISOP	12V, 24V	EPC2023, EPC2024
Converter [8]	36V	EPC2020

in this comparison, stress of the secondary side devices for all solutions are assumed to be the same and is not included in the comparison.

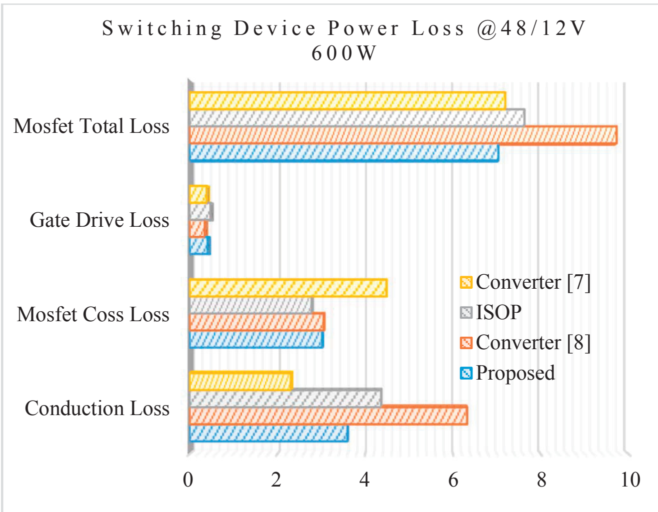
B. Detailed Power Loss Analysis and Power Loss Breakdown

Power loss analysis and loss breakdown has been performed when input voltage is 48V since this would be the nominal input voltage. Table I shows the information of GaN devices that are used to perform the switching devices power loss estimation. Table II shows that the proposed converter and the converter with input-series-output-parallel (ISOP) architecture can use lower voltage rating device than that in the other two converters.

Fig.7(a) shows the calculated total switching device power loss using different converter architectures. The proposed solution has the best performance among all the solutions. It is worth mentioning that switching loss is not included in the calculation since there is not a very accurate way to predict it. And under the nominal condition, all switching devices in the proposed solution as well as the ISOP solution achieve ZCS. On the other hand, the other two solutions can only achieve ZCS on part of the devices, as shown in Table III. Also, power loss



(a) Semiconductor power loss of different analyzed converters



(b) Power loss breakdown of different analyzed converters

Fig.7 Power loss estimation and power loss breakdown comparison between GaN and Si based converter

TABLE III POWER LOSS INFORMATION WHEN V_{IN}=48V, P_{OUT}=600W, f_s=328KHZ

Converters	Proposed	[8]	ISOP	[7]
Conduction Loss	3.60W	6.32W	4.36W	2.31W
GaN C_{oss} Loss	3.02W	3.06W	2.78W	4.49W
Gate Drive Loss	0.41W	0.35W	0.48W	0.39W
All Devices ZCS	Y	N	Y	N

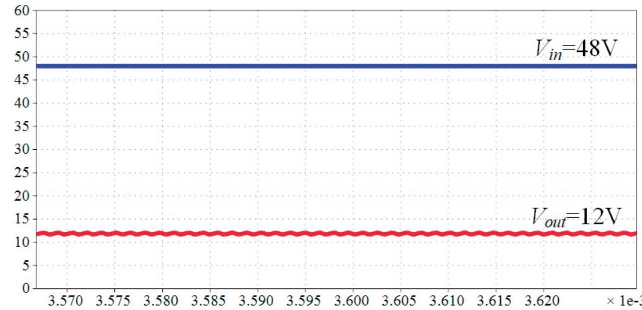
TABLE IV PARAMETERS USED IN THE SIMULATION

Description	**Items**	**Values**
Input voltage Range	V_{in}	36V ~ 60 V
Nominal input voltage	V_{in_nom}	48V
Output voltage	V_{out}	12 V
Output Power	P_{out}	600 W
Resonant capacitor	C_r	2.35 μF
Resonant inductor	L_r	100 nH
Magnitizating Inductance	L_m	10 μH
Resistor load	R_{load}	0.24 Ω
Resonant frequency	f_r	328.3 kHz
Switching frequency	f_s	316.5 kHz

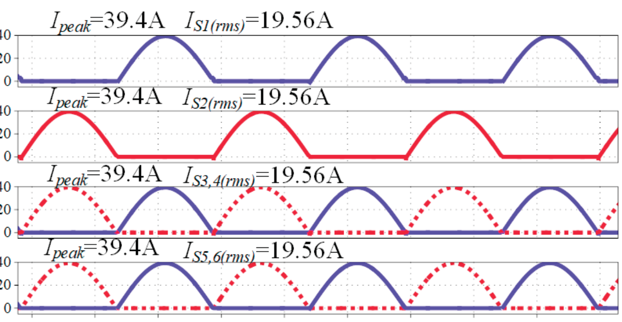
breakdown has been performed to show the loss difference between different converters, as shown in Fig.7(b). The detailed loss information can be found in Table III.

IV. SIMULATION RESULTS AND EFFICIENCY OF THE PROPOSED CONVERTER

Simulation has been performed to verify the theoretical analysis of the proposed converter operating at 600W. Table IV shows the detailed parameters used in the simulation. Fig. 8(a) shows that when the converter has 48V input, it generates 12V output. At this input voltage, ICRMC operates in unregulated mode. ZCS is realized on all the switching devices, as shown in Fig. 8(b). Fig. 9(a) shows that when the ICRMC is working in bypassing mode, the converter converts 36V to 12V. And ZCS is achieved on all switching devices, as shown in Fig. 9(b).

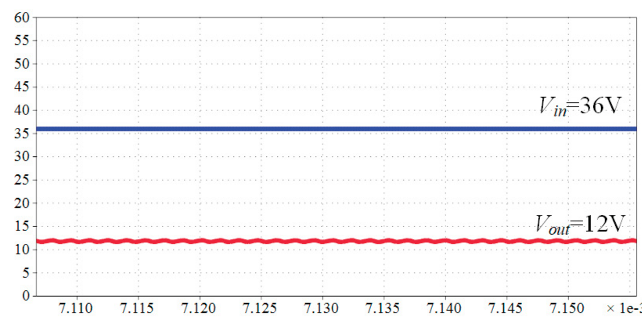


(a) Input and output voltage

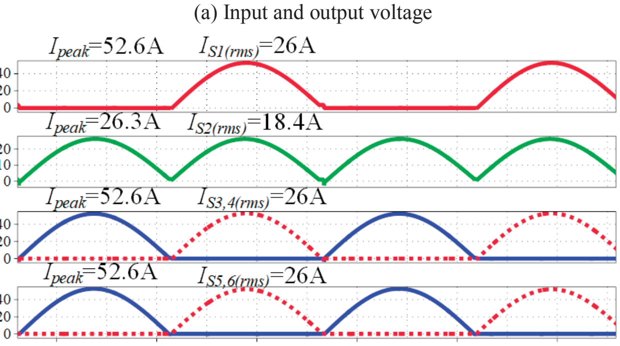


(b) Switch devices' current waveforms

Fig. 8 Simulation results of the proposed converter operating at 48/12V 600W (Unregulated Mode)



(a) Input and output voltage



(b) Switch devices' current waveforms

Fig. 9 Simulation results of the proposed converter operating at 36/12V 600W (Bypassing Mode)

In Fig. 10, the estimated efficiency curve shows that the proposed converter with 600W rating can reach 97.65% efficiency. Improvements regarding efficiency and power density can be further performed based on the power loss breakdown of the proposed converter that is shown in Fig. 11.

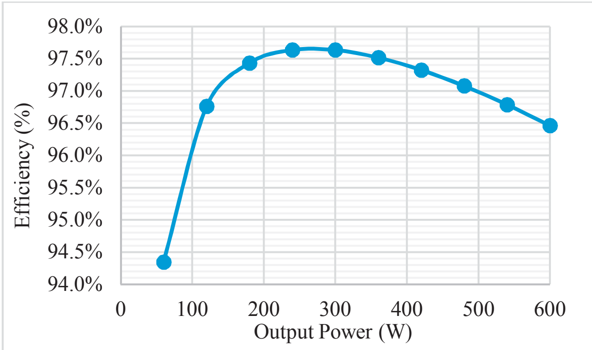


Fig. 10 Efficiency estimation of the proposed converter (48V input)

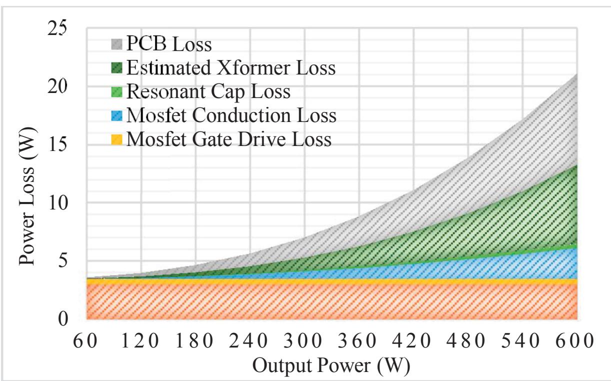


Fig. 11 Power loss breakdown of the proposed converter (48V input)

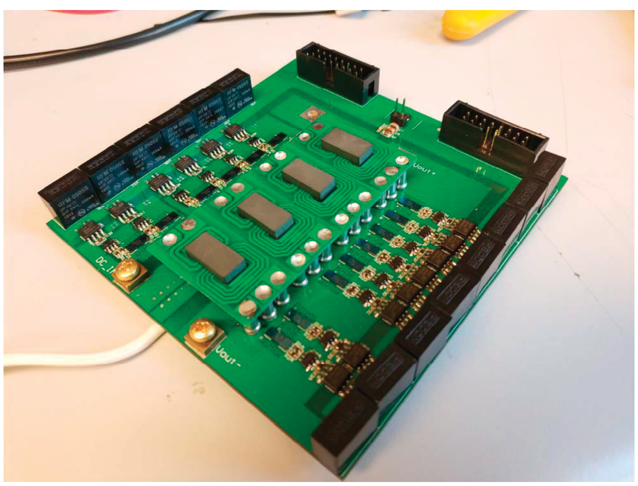


Fig. 12 Designed 300W prototype

A GaN based prototype has been developed to verify the theoretical analysis, as shown in Fig. 12. Note that the maximum power of the prototype is limited to 300W due to limited PCB layers (4-layer). A planar transformer using ML95S material from Hitachi is used in the prototype. In Fig. 13, when then input voltage of the converter is 48V, the converter generates 12V at the output side. And Fig. 14 shows the current waveforms of resonant capacitor in the ICRMC and PPVR. According to this figure, soft-switching of the switching devices is validated. More detailed prototype design and experimental results will be included in future publications.

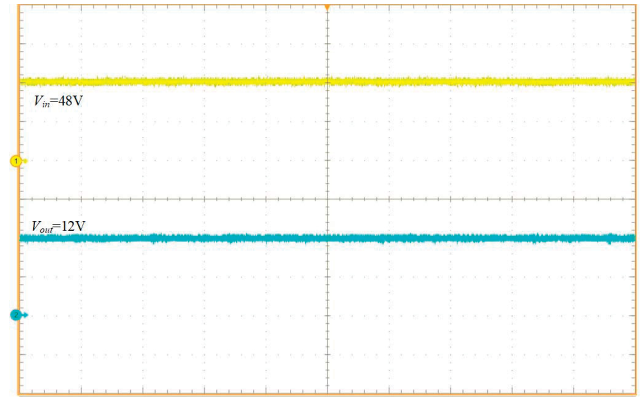


Fig. 13 Input and output voltage

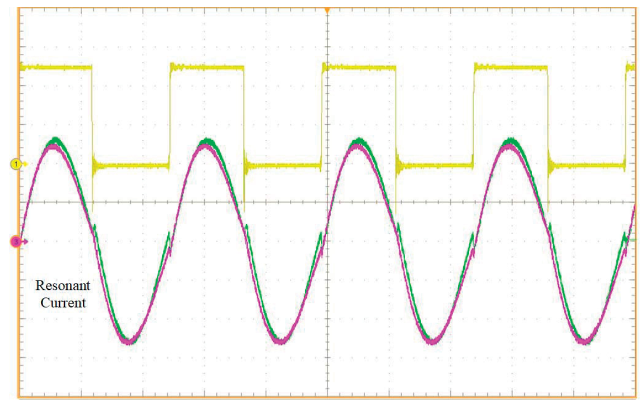


Fig. 14 Resonant current of unregulated module and PPVR

V. Conclusion

This paper presents an isolated composite resonant multilevel converter with partial power voltage regulation for 48/12V application. The contribution of this paper are threefold. First, composite converter concept is used to effectively reduce total semiconductor power stress in the new converter to ensure its high efficiency operation. Second, the proposed topology allows the partial power voltage regulator to process less power than traditional solution. This means more power can flow through highly efficient ICRMC. Thus, power loss can be reduced. Third, the proposed converter has the capability to achieve fine voltage regulation. At last, A GaN based converter prototype is built to validate the theoretical analysis.

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