A Family of Novel Switch Capacitor Based Integrated Matrix Autotransformer LLC Converter for Data Center Application

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***Abstract*— Switched Tank Converter(STC) is one kind of Resonant Switch Capacitor(ReSC) that can be considered as a good candidate for data center application with high power efficiency and high power density. On the other hand, LLC converter can also realize very good performance for low voltage application. Although STC can realize relatively higher efficiency than LLC converter in the light load since the core loss is saved, LLC can keep relatively higher efficiency in the heavy load than STC does since the conduction loss of LLC is smaller. The main reason is because transformer's winding resistance is smaller than semiconductor devices' resistance, and this is very important for high current application.**

In order to utilize the benefits of the STC and the LLC converter together, this paper proposes a family of the novel Switch Capacitor based Integrated Matrix Autotransformer LLC Converters (SCIMAC). The proposed converters share the same high voltage side circuit of the STC with low voltage stress devices. Different from the traditional LLC converter with an isolated transformer, the proposed SCIMAC utilizes one autotransformer with only the secondary side windings similar to LLC's secondary side. There are several advantages that can be realized of the SCIMAC: 1). Low figure of merit (FOM) devices can be adopted to realize higher efficiency due to the low voltage stress of the SCIMAC. 2). Higher power efficiency can be realized when compared with STC converter in heavy load because the resistance of the autotransformer's windings is lower than semiconductor devices' resistance. 3). The primary side winding loss of the transformer is saved to further increase the efficiency. 4) ZVS turning on can be realized by the magnetizing current of the core.

Keywords—Data Center Application, Resonant Switch Capacitor(ReSC), Switched Tank Converter(STC), LLC converter, Switch Capacitor based Integrated Matrix Autotransformer LLC Converters (SCIMAC).

I. Introduction

Switched tank converter(STC) is a good candidate for low voltage application like Data Center application due to its high efficiency and power density [1]-[4], and it belongs to one kind of resonant switched capacitor converter(ReSC). STC is usually adopted as intermediate bus converter (IBC), i.e. 12V with very high efficiency, and there are also some other topologies that can realize nearly 99% power efficiency for 12V DC bus structure as well [5]-[7]. With the development of the Artificial Intelligence (AI) and machining learning, lower CPU voltage is highly required. Early in 2000, CPU with 1.8V on average can already realize high performance but now, it requires CPU with 0.8V to perform heavy computation task [8]. As a result, the IBC with 12V is not suitable anymore, instead, lower intermediate DC bus voltage is needed to decrease conversion ratio of the point of load(POL) stage and the whole system efficiency can be improved as a result [9]. On the other hand, LLC converter can also realize high efficiency and high conversion ratio [21]-[17]. The power efficiency of LLC converter is lower than STC or other ReSC converters in the light or medium load since the transformer's core loss accounts a large part among the total power loss, while the power efficiency of LLC converter is higher in heavy load since the conduction loss dominates. As a result, there are two main trends which are divided into ReSC converters and LLC converters to develop the IBC for Data Center application. Moreover, there also appears a new method that merges both IBC stage and POL stage together [10]-[14], and the soft charging technology [15]-[16] is realized by the buck inductor in the POL stage. By this way, not only high efficiency and very high-power density can be realized, but also the current spike issue of switched capacitor converter can be overcome. On the other hand, the LLC converter with matrix transformer also tries to directly convert 48V to 1V in one stage[20].

Therefore, one idea that adopts autotransformer to merge the benefits of both LLC converter and ReSC has been proposed for the IBC of data center application. There are several reasons for the autotransformer-based converter solution: 1) Isolation is not necessary [2], so primary side windings of LLC converter can be removed to increase power efficiency; 2) The resistance of winding is lower than semiconductor devices. In other words, the total conduction loss of LLC converter is lower than ReSC converter's in heavy load, and this is very important for high current application area since the conduction loss dominates. 3)The low figure of merit (FOM) devices can be adopted to increase the power efficiency. LLC converter requires higher FOM devices while the ReSC converter can adopt lower one. As a result, the autotransformer-based converter solution can further increase the power efficiency. Different kinds of autotransformers based LLC converters are proposed in [21], and the switch capacitor combined with autotransformer converters are proposed in [22]-[23]. However, the winding turns of the circuit are not the same, and it's difficult to extend the conversion ratio unless more independent inductors are added in the circuit[24].

In this paper, a family of Switch Capacitor based Integrated Matrix Autotransformer LLC Converters(SCIMAC) is proposed. It takes the advantage of both LLC converter and STC: 1). The conduction loss of the transformer's primary side is saved. 2). Resonant inductors are integrated into the matrix autotransformer, so the conduction loss of the resonant inductors is also saved. 3). Low FOM devices are adopted due to the low voltage stress of the switches compared with LLC converter. 4). ZVS turning on can be realized by the magnetizing current in full load range. A 9x conversion ratio DC-DC prototype is built to show the feasibility of these proposed circuits. And the calculated power efficiency with 9x is up to 99% at 270W. Section II shows the family of the proposed circuits. Section III shows the simulation result. The prototype is in built to verify the feasibility of the proposed topology.

II. THE FAMILY OF THE SCIMAC

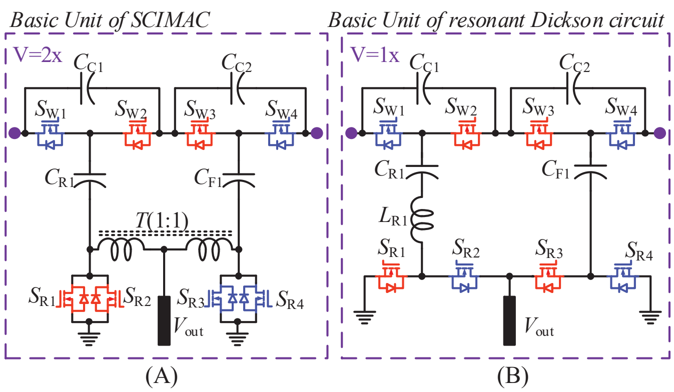


Fig. 1 (A)The basic unit of SCIMAC (B) The basic unit of Dickson converter

Fig. 1 shows the basic unit of the SCIMAC and resonant Dickson circuit. The C_{R1} means the resonant capacitor and the C_{F1} means the non-resonant capacitors which should be 10 times larger than resonant capacitor. The voltage stress of switches shown in Fig. *1*(A) is equal to $2\times V_{out}$, which can be named as 2x, and the voltage stress of switches shown in Fig. *1*(B) is equal to V_{out}, which can be named as 1x. Moreover, the current RMS stress of all the switches shown in both Fig. *1*(A) and Fig. *1*(B) is input RMS current-I_{input}, which is named as 1x. However, the basic unit of SCIMAC can realize 4:1 while the basic unit of Dickson converter realizes 2:1.

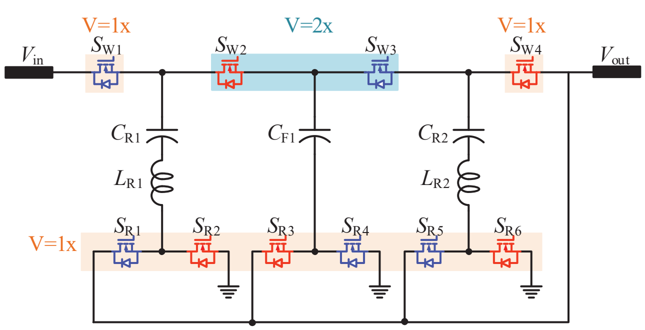


Fig. 2 The 4:1 Dickson converter

Therefore, if the high voltage side switches S_{W2} and S_{W3} in Fig. 1 are merged together, the 4:1 STC converter is shown in Fig. 2 while the 4:1 SCIMAC is shown in Fig. *3*.

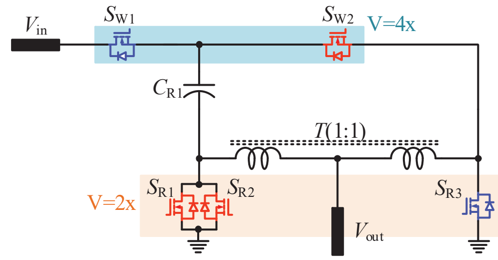


Fig. 3 The 4:1 SCIMAC

For 8x conversion ratio, the STC converter is shown in Fig. *4*, the voltage stress of majority high voltage side switches is 2x while the voltage stress of low voltage side switches is 1x. The 8:1 SCIMAC is shown in Fig. 5, the voltage stress of high voltage side switches is 4x while the voltage stress of low voltage side switches is 2x. Although both the two kinds of circuits can realize 8:1, the switches counts of SCIMAC are just half of the STC while the voltage stress is doubled.

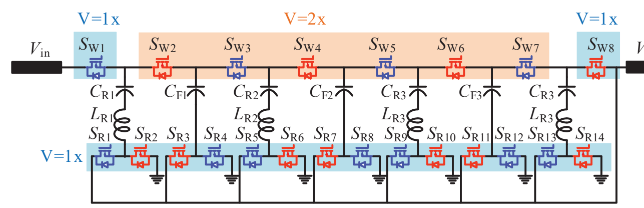


Fig. 4 The 8:1 STC converter

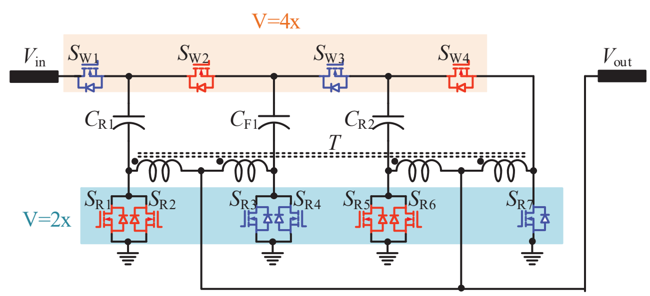


Fig. 5 The 8:1 SCIMAC

Fig. 6 shows the 16:1 SCIMAC, and all the windings are also just one turn. The voltage stress of both high voltage side switches and low voltage side switches are the same as 8:1 SCIMAC.

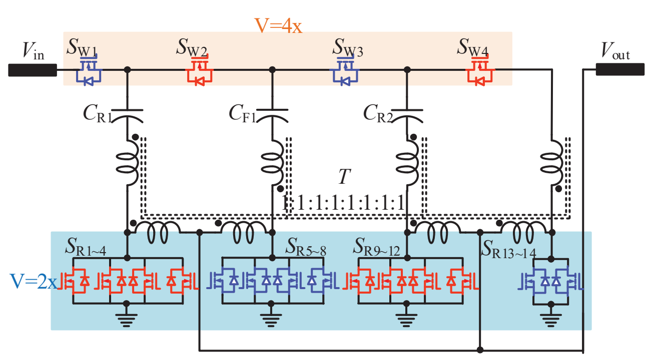


Fig. 6 The 16:1 SCIMAC

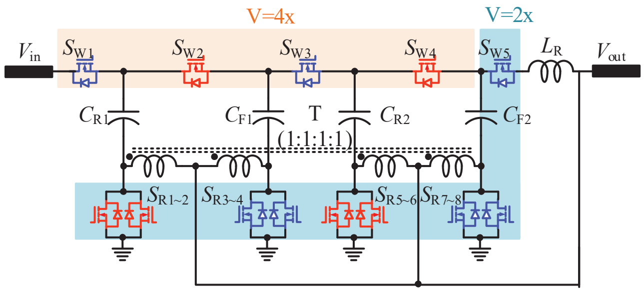


Fig. 7 The 9:1 SCIMAC

For the conversion ratio as 4N can add more modules like Fig. 5 does or more wingdings on the capacitor branch like Fig. 6 does. For the converter that the conversion ratio is 4N+1, an additional independent L_R is required to make all the current loops realize soft switching which is shown in Fig. 7. If the 17:1 is required, another basic unit of SCIMAC in Fig. 1(A) is required to add into the circuit.

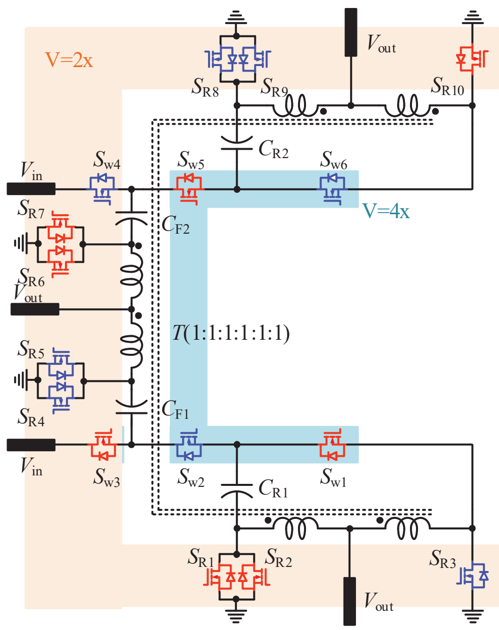


Fig. 8 The 6:1 interleaved SCIMAC

For the converter that the conversion ratio is 4N+2, an interleaved SCIMAC converter is proposed which is shown in Fig. 8 and Fig. 9. For the converter that the conversion ratio is 4N+3, the circuit topology as Fig. 10 can be adopted. It should be pointed out that all circuits descripted in this paper can realize ZCS switching. The converter that the conversion ratio is 4N+2 or 4N+3, the two-phase interleaved SCIMAC is required. Furthermore, the converter with the conversion ratio as 4N+1 or 4N+3 needs extra independent inductors which is labeled as L_R in the circuit. Moreover, all the windings of the transformer can be merged into one core, and the resonant inductors are also integrated into the core except the independent inductors L_R. The current stress of all the switches in this paper are the same, which is equal to input current RMS value. If higher conversion is needed, we just need to add the basic unit of SCIMAC in Fig. 1(A) to the specific conversion ratio type. For example, for the converter with 4N+2 conversion ratio, one more basic unit of SCIMAC is added into the circuit when the 6:1 converter and 10:1 converter are compared.

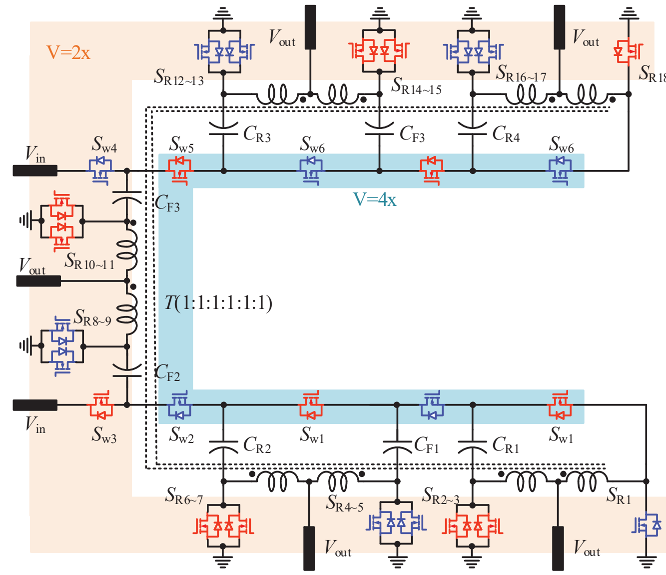


Fig. 9 The 10:1 interleaved SCIMAC

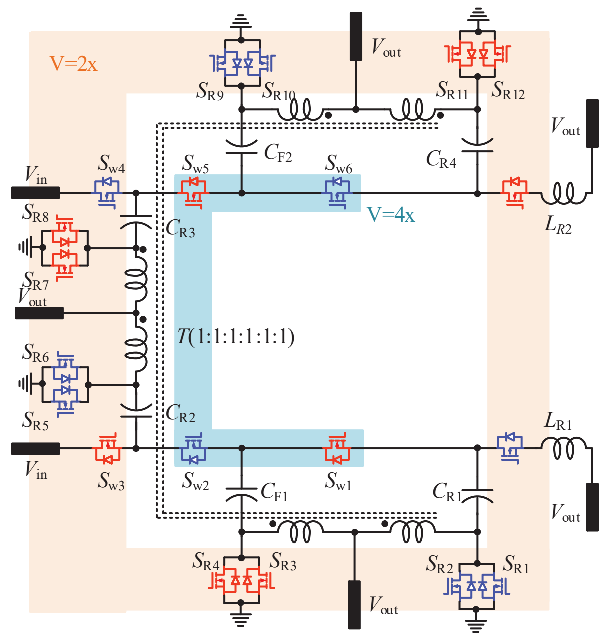
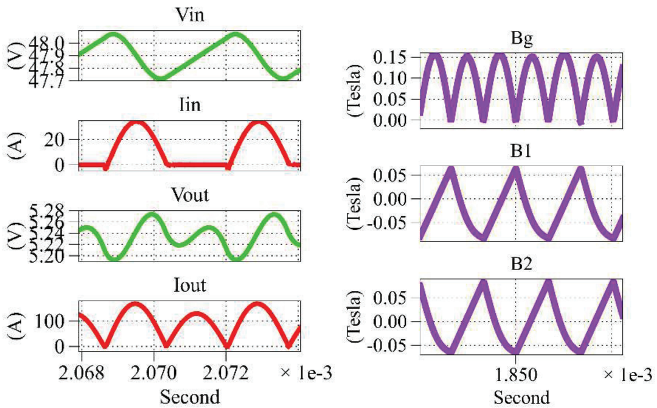


Fig. 10 The 7:1 interleaved SCIMAC

III. The Simulation of 9:1 SCIMAC

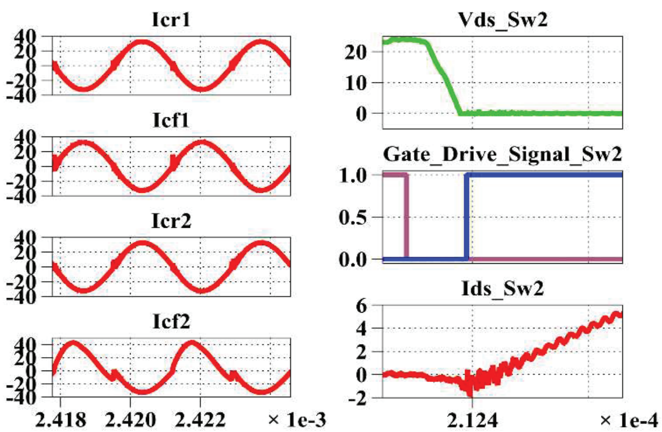
Take the 48V to 5.33V(9x/'4N+1'type) as an example, the circuit topology shown in Fig. 7 is adopted to realize it. Suppose the resonant frequency is 300kHz, and the input power is set as 500W. Then input and output voltage as well as current is shown in Fig. 11(A). The integrated auto-transformer shape is shown in Fig. 13, and the flux density waveform of center cylinder as well as side cylinder is shown in Fig. 11(B). The matrix auto-transformer design is not introduced here. Fig. 12(A) shows the current waveforms of the capacitor C_{R1}~C_{R2} and C_{F1}~C_{F2}. Fig. 12(B) shows the waveform when the high voltage side switch

S_{W2} turns on, and it proves the ZVS soft switching can be realized for the high voltage side switches.



(A) (B)

Fig. 11 The simulation voltage and current of input and output in Fig. 7 (B) The flux density of the magnetic core



(A) (B)

Fig. 12 (A) The simulation current waveform of the resonant and non-resonant capacitors

IV. The Hardware Design and The Experimental Result

Fig. 13 The model of integrated transformer

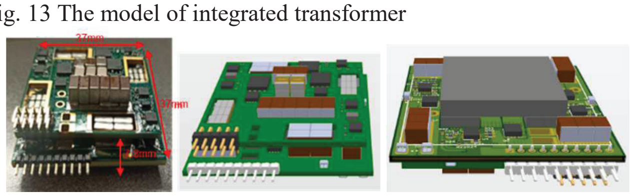


Fig. 14 The prototype and its 3D model of the circuit in Fig. 7

The prototype and its 3D prototype is shown in Fig. 14. The prototype is made of two boards. The high voltage side circuit is placed on one board while the low voltage side circuit is placed on the other board. The capacitors C_{R1}, C_{R2}, C_{F1}, C_{F2} are connected between the two boards. Table I shows the parameters of the prototype and the total size is around 37×37×7.8mm^3.

Table I The parameters of the components

V_{in}	46V~50V
V_{out}	5.1V~5.5V
P_{in}	500W
f	300kHz
C_{in}	22uF×6 (X7S,100V)-C5750X7S2A226M280KB
C_{out}	47uF×18(X5R,10V)-C4532X5R1A476M280KA
C_{F1} & C_{F2}	22uF×4×2(X7R,50V)-C5750X7S2A226M280KB
C_{R1} & C_{R2}	1.4uF×3×2(U2J,50V)-C1812C145J5JLC7805
S_{R1}~S_{R8}	BSZ010NE2LS5ATMA1(25V,1mΩ)
S_{W1}~S_{W5}	BSC0500NSIATMA1(30V,1.3mΩ)
Gate Driver	13×1EDN7136GXTMA1
Core	ML95S@Hitachi Company

The experimental result is shown in Fig. 15. The resonant capacitor C_{R1} and non-resonant capacitor current C_{F1} are shown in green and red waveforms respectively, and the voltage of low voltage side switch S_{R1} is shown in black waveform.

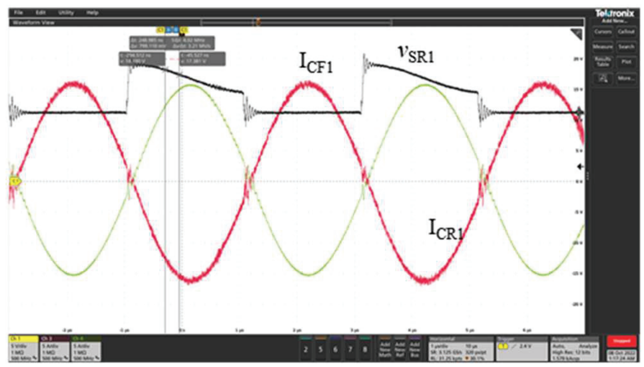


Fig. 15 The experimental result for 48V to 5.33V

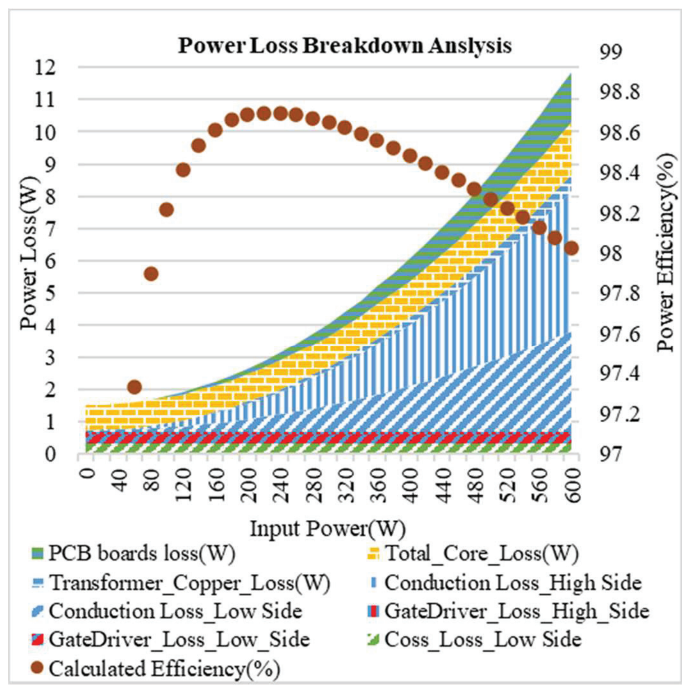


Fig. 16 The calculated power efficiency and its power loss distribution

Fig. 16 shows the calculated power efficiency and its power loss distribution for 48V to 5.33V (9x) DC-DC converter, and the maximum calculated power efficiency can reach around 98.7% at around 240W. The conduction loss dominates among all the power loss in heavy load.

V. Conclusions and Future Work

This paper derives a family of SCIMACs, which are divided by its conversion ratio as 4N, 4N+1, 4N+2 and 4N+3. The converter with the conversion ratio as 4N and 4N+1 can be realized in single phase way while the converter with the conversion ratio as 4N+2 and 4N+3 can only be realized in two phase way. All the matrix autotransformer windings are integrated into one core while the resonant inductors are also merged into the core. Therefore, the power efficiency as well as power density can be increased. Moreover, the primary side windings of the transformer are removed to save the power loss, and the low FOM devices are adopted for better performance. All the loops can keep the same resonant frequency. The simulation of 9x ('4N+1' type) in Fig. 7 is performed by PLECS. A 48V to 5.33V with maximum power as 500W is built to verify the feasibility of the proposed circuit, and the maximum calculated power efficiency can reach 98.8% at around 240W. Finally, the experimental waveforms are shown in Fig. 15.

References

[1] S. Jiang, S. Saggini, C. Nan, X. Li, C. Chung and M. Yazdani, "Switched Tank Converters," in IEEE Transactions on Power Electronics, vol. 34, no. 6, pp. 5048-5062, June 2019, doi: 10.1109/TPEL.2018.2868447.

[2] Y. Li, X. Lyu, D. Cao, S. Jiang and C. Nan, "A 98.55% Efficiency Switched-Tank Converter for Data Center Application," in IEEE Transactions on Industry Applications, vol. 54, no. 6, pp. 6205-6222, Nov.-Dec. 2018, doi: 10.1109/TIA.2018.2858741.

[3] Y. Li, X. Lyu, Z. Ni, D. Cao, C. Nan and S. Jiang, "Adaptive On-Time Control for High Efficiency Switched-Tank Converter," 2018 1st Workshop on Wide Bandgap Power Devices and Applications in Asia (WiPDA Asia), 2018, pp. 169-175, doi: 10.1109/WiPDAAsia.2018.8734623.

[4] M. Wei, Z. Ni, S. Yang, M. Qiu, X. Liu and D. Cao, "Performance Evaluation and Analysis for Resonant Switched Capacitor Converter," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1889-1893, doi: 10.1109/APEC42165.2021.9487181.

[5] T. Ge, Z. Ye and R. C. N. Pilawa-Podgurski, "A 48-to-12 V Cascaded Multi-Resonant Switched Capacitor Converter with 4700 W/in3 Power Density and 98.9% Efficiency," 2021 IEEE Energy Conversion Congress and Exposition (ECCE), 2021, pp. 1959-1965, doi: 10.1109/ECCE47101.2021.9595943.

[6] M. H. Ahmed, F. C. Lee, Q. Li, M. de Rooij and D. Reusch, "GaN Based High-Density Unregulated 48 V to x V LLC Converters with ??? 98% Efficiency for Future Data Centers," PCIM Europe 2019; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management, 2019, pp. 1-8.

[7] O. Jong, Q. Li and F. C. Lee, "Resonant Switched-Capacitor Converter with Multi-Resonant Frequencies," 2019 IEEE Applied Power Electronics Conference and Exposition (APEC), 2019, pp. 2177-2184, doi: 10.1109/APEC.2019.8722070.

[8] M. Ursino, R. Rizzolatti, G. Deboy, S. Saggini and K. Zufferli, "High density Hybrid Switched Capacitor Sigma Converter for Data Center Applications," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), 2022, pp. 35-39, doi: 10.1109/APEC43599.2022.9773659.

[9] J. Koomey. (2011 Aug). Growth in data center electricity use 2005 to 2010. Analytics Press. Oakland. CA, USA. [Online]. Available: http://www.analyticspress.com/datacenters.html

[10] Y. Elasser, J. Baek and M. Chen, "A Merged-Two-Stage LEGO-PoL Converter with Coupled Inductors for Vertical Power Delivery," 2020 IEEE Energy Conversion Congress and Exposition (ECCE), 2020, pp. 916-923, doi: 10.1109/ECCE44975.2020.9236294.

[11] Y. Elasser et al., "Vertical Stacked 48V-1V LEGO-PoL CPU Voltage Regulator with 1A/mm2 Current Density," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), 2022, pp. 1259-1266, doi: 10.1109/APEC43599.2022.9773677.

[12] J. Baek, Y. Elasser and M. Chen, "3D LEGO-PoL: A 93.3% Efficient 48V-1.5V 450A Merged-Two-Stage Hybrid Switched-Capacitor Converter with 3D Vertical Coupled Inductors," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1321-1327, doi: 10.1109/APEC42165.2021.9487080.

[13] Y. Chen et al., "Virtual Intermediate Bus CPU Voltage Regulator," in IEEE Transactions on Power Electronics, vol. 37, no. 6, pp. 6883-6898, June 2022, doi: 10.1109/TPEL.2021.3130213.

[14] Y. Chen, H. Cheng, D. M. Giuliano and M. Chen, "A 93.7% Efficient 400A 48V-1V Merged-Two-Stage Hybrid Switched-Capacitor Converter with 24V Virtual Intermediate Bus and Coupled Inductors," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 1308-1315, doi: 10.1109/APEC42165.2021.9487345.

[15] Y. Lei and R. C. N. Pilawa-Podgurski, "A General Method for Analyzing Resonant and Soft-Charging Operation of Switched-Capacitor Converters," in IEEE Transactions on Power Electronics, vol. 30, no. 10, pp. 5650-5664, Oct. 2015, doi: 10.1109/TPEL.2014.2377738.

[16] R. C. N. Pilawa-Podgurski and D. J. Perreault, "Merged two-stage power converter with soft charging switched-capacitor stage in 180 nm CMOS," 2011 Proceedings of the ESSCIRC (ESSCIRC), 2011, pp. 479-482, doi: 10.1109/ESSCIRC.2011.6045011.

[17] C. Fei, F. C. Lee and Q. Li, "High-Efficiency High-Power-Density LLC Converter With an Integrated Planar Matrix Transformer for High-Output Current Applications," in IEEE Transactions on Industrial Electronics, vol. 64, no. 11, pp. 9072-9082, Nov. 2017, doi: 10.1109/TIE.2017.2674599.

[18] M. H. Ahmed, F. C. Lee, Q. Li and M. d. Rooij, "Design Optimization of Unregulated LLC Converter with Integrated Magnetics for Two-Stage 48V VRM," 2019 IEEE Energy Conversion Congress and Exposition (ECCE), 2019, pp. 521-528, doi: 10.1109/ECCE.2019.8912785.

[19] M. H. Ahmed, F. C. Lee and Q. Li, "Two-Stage 48-V VRM With Intermediate Bus Voltage Optimization for Data Centers," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 9, no. 1, pp. 702-715, Feb. 2021, doi: 10.1109/JESTPE.2020.2976107.

[20] X. Lou and Q. Li, "300A Single-stage 48V Voltage Regulator with Multiphase Current Doubler Rectifier and Integrated Transformer," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), 2022, pp. 1004-1010, doi: 10.1109/APEC43599.2022.9773419.

[21] D. Huang, X. Wu and F. C. Lee, "Novel non-isolated LLC resonant converters," 2012 Twenty-Seventh Annual IEEE Applied Power Electronics Conference and Exposition (APEC), 2012, pp. 1373-1380, doi: 10.1109/APEC.2012.6165999.

[22] M. Ursino, R. Rizzolatti, G. Deboy, S. Saggini and K. Zufferli, "High density Hybrid Switched Capacitor Sigma Converter for Data Center Applications," 2022 IEEE Applied Power Electronics Conference and Exposition (APEC), 2022, pp. 35-39, doi: 10.1109/APEC43599.2022.9773659.

[23] C. Rainer, R. Rizzolatti, S. Saggini and M. Ursino, "Lossless Current Sensing Method for Hybrid Switched Capacitor Converter," 2021 IEEE Applied Power Electronics Conference and Exposition (APEC), 2021, pp. 934-938, doi: 10.1109/APEC42165.2021.9487368.

[24] A. Dago, M. Leoncini, S. Saggini, S. Levantino and M. Ghioni, "Hybrid Resonant Switched-Capacitor Converter for 48–3.4 V Direct Conversion," in IEEE Transactions on Power Electronics, vol. 37, no. 11, pp. 12998-13002, Nov. 2022, doi: 10.1109/TPEL.2022.3186790.