International Journal of Latest Research in Engineering and Technology (IJLRET)
ISSN: 2454-5031
www.ijlret.com || Volume 11 - Issue 08 || August 2025 || PP. 64-70

Analysis of Power Conversion Efficiency Characteristics of Large Capacity Bridgeless PFC Circuits using GaN Switches under Varying Switching Frequencies

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Abstract: In this paper, a GaN switch is applied to a 2kW class large capacity bridgeless power factor correction (PFC) circuit to report the comparative test results according to switching frequency variation from 50kHz to 100kHz. Especially the efficiency was 98.36% at a switching frequency of 60kHz and 98.2% at 100kHz while the efficiency was reduced to 98.29% at 50kHz. This was estimated because the core loss of the inductor and the switching loss of the GaN were proportional to the switching frequency. When the frequency was below a certain value, a decrease in efficiency was observed due to an increase in current ripple and power loss by the insufficient inductance in the test circuit. Therefore, in the bridgeless PFC with GaN FET, once the switching frequency and the optimum inductance value were determined, the power conversion efficiency was not improved even when the switching frequency was increased.
Keywords: bridgeless PFC, rectifier, efficiency analysis, GaN switch

I. Introduction

The power supplies using commercial mains power typically employ rectifiers to convert AC to DC. To meet harmonic reduction standards like IEEE 61000-3-2, switching rectifiers are used in power supply inputs to lower harmonic currents and boost power factor.Switching rectifiers can be categorized into two types: the bridge topology, which uses diode bridges, and the bridgeless topology, which does not include a diode bridge. Recently, Gallium Nitride (GaN) switches have gained attention as next-generation semiconductor devices, known for their low losses under high-speed switching conditions and minimal parasitic elements, which contribute to improved voltage and current waveforms [1-4].

GaN switches are ideal for switching power supplies because they offer low power loss and maintain strong electrical performance at MHz frequencies. This paper applies GaN switches to a bridgeless power factor correction circuit and investigates the efficiency characteristics with respect to switching frequency. Specifically, a 2kW-class high-capacity bridgeless power factor correction circuit incorporating GaN switches is constructed, and the experimental results are presented as the switching frequency varies. To compare efficiency characteristics, the switching frequency is varied from a minimum of 50 kHz to a maximum of 100 kHz, and a prototype switching rectifier with an output voltage of 400V and a maximum power of 2kW is fabricated for experimental evaluation.

II. Bridgeless switching rectifier

The bridgeless rectifier topology eliminates the use of diodes as in conventional bridge rectifier circuits, instead employing a boost inductor directly in series with the AC input side. Fig.1 illustrates the power factor correction circuit based on the bridgeless topology, and Fig.2 shows the steady-state operation waveforms[5-9]. In the bridgeless switching rectifier, as depicted in the figures, two switches operate selectively based on the phase of the input voltage. During the period when the selected switch is active, the circuit functions as a boost converter. From the waveforms in Fig.2, it can be observed that switching is performed selectively according to the switching control of the chosen switch. The phase shift and duty cycle are comparable to conventional bridge-based circuits.Phase shift is greatest at minimum input voltage and least at maximum input voltage, which reflects standard power factor correction circuit behavior [10-14].

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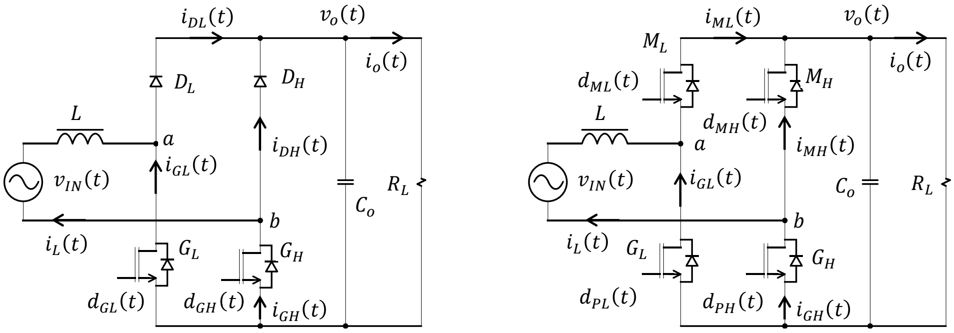

Fig.1: Basic circuit of bridgeless PFC and totem pole PFC.

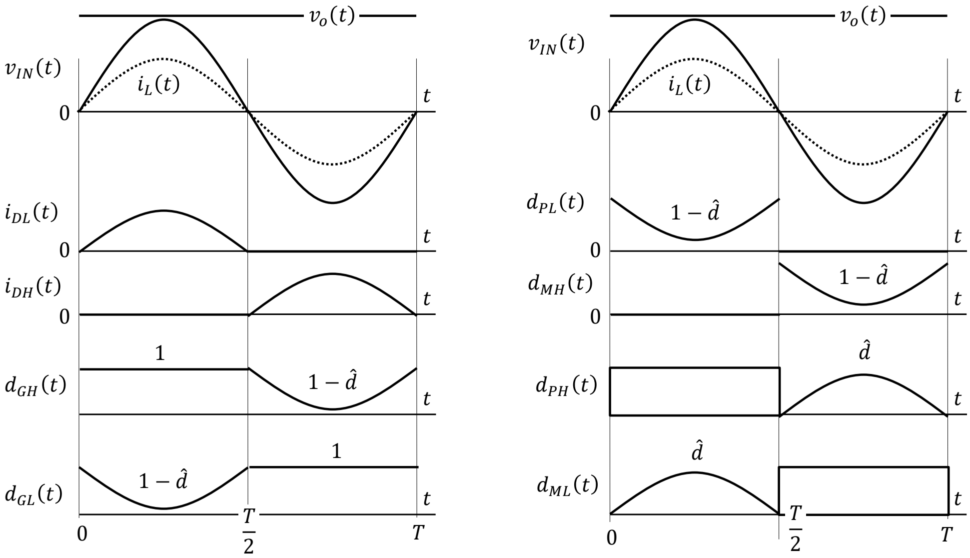

Fig.2: Main operating waveforms in the steady state of bridgeless PFC and totem pole PFC.

III. Electrical characteristics of GaN FETs

Gallium Nitride (GaN) FETs, which have recently been recognized as next-generation energy-saving semiconductors, are known for their numerous advantages, including low on-resistance, excellent high-frequency performance, and stable high-temperature characteristics[15-19].Table 1 presents the material properties of GaN devices compared to conventional Si and SiC devices. The bandgap energy of GaN FETs is 3.4 eV, which is three times that of Si FETs, and it also exceeds the higher energy level of SiC FETs, which possess wide bandgap characteristics. The critical breakdown electric field is eleven times higher than that of Si, making it superior to SiC devices, and the drift velocity surpasses that of any other material property. Due to these intrinsic characteristics, GaN FETs exhibit the lowest on-resistance among devices with similar breakdown voltages. Additionally, GaN FETs incorporating a two-tier electron gas structure demonstrate significantly higher electron mobility compared to SiC FETs, which allows for the realization of devices with extremely small sizes.Table 2 compares the characteristics of models among currently commercialized GaN FETs that are suitable for application in power factor correction (PFC) circuits. The analysis encompasses Si FETs, recognized for their widespread utilization and strong cost efficiency; SiC FETs, noted for enhanced high-speed switching capabilities; and two GaN FET models evaluated within the scope of this study. The criteria for model selection were based on similar form factors and relatively comparable voltage and current ratings. Particularly for SiC FETs, models with low voltage ratings were less common; therefore, the most similar models within the SiC product line were selected.

All models compared in the table share a TO-247 package, with voltage ratings around 700V and current ratings approximately 30A. The on-resistance, which determines the conduction loss of the switching device, was lowest in GaN FETs compared to Si and SiC devices. GaN FETs also exhibited lower output capacitance, which is predicted to reduce parasitic surge phenomena. Additionally, the gate charge (Q_g) of GaN FETs was less than 30% of that of other devices, and their reverse recovery time (t_{rr}) was approximately 60 times faster than that of Si devices.From these comparison results, it can be concluded that GaN switches possess the desirable characteristics required for power semiconductors, such as low conduction loss, high surge voltage capability, and rapid switching performance, outperforming Si and SiC FETs. Moreover, in designing high-capacity PFC circuits, increasing the switching frequency is necessary to reduce the size of energy storage devices like inductors and capacitors and to elevate power density. GaN FETs are ideal for high-frequency switching applications due to their superior performance. Generally, switching frequency and switching loss are proportional; however, increasing the frequency also raises core losses in magnetic components like inductors, requiring a complex, integrated design approach to improve overall efficiency.This paper demonstrates through experimental results that simply increasing the switching frequency in GaN FET-based switching rectifiers is insufficient to improve power density and power conversion efficiency. Instead, there exists an optimal switching frequency that maximizes these performance metrics.

Table 1: Physical characteristics of main switch

Substance	Unit	Si	SiC	GaN
Bandgap	eV	1.1	3.3	3.4
Electron mobility	cm^2/Vs	1350	700	1500
Electric field for breakdown	MV/cm	0.3	3.0	3.3
Figure of merit	$\varepsilon\mu_e E_c^3$	1	440	1130

Table 2: Key Specifications of Major Switches

Parameter	Si	SiC	GaN
Package	TO-247	TO-247	TO-247
Part name	65C7095	SCT2080KE	TP65H035WS
Voltage	700V	1200V	650V
current	24A	40A	46.5A
Resistance	95mΩ	80mΩ	41mΩ
Coss	33pF	95pF	150pF
Eoss	5.5μJ	10μJ	22μJ
Qg	45nC	106nC	24nC
Qrr	9μC	0.044μC	0.17μC
trr	800ns	31ns	12ns

IV. Analysis of Experimental Results

To verify the efficiency characteristics with respect to switching frequency by applying the GaN FET to the bridgeless PFC circuit discussed in the previous section, a test setup similar to Table 3 was assembled. In particular, the design allows operation over input voltages ranging from 110V to 220V, with an output voltage of 400V and a maximum power capacity of 2kW. The control circuit was configured to enable variable switching frequencies from a minimum of 50kHz to a maximum of 100kHz.The test circuit was designed with a focus on optimizing efficiency by configuring the PCB layout according to the power flow of the switching rectifier. The main power supply was placed on the top side of the PCB, while the current and voltage measurement circuits were located on the bottom side. Additionally, EMI filters, inductors, and capacitors were arranged along the power flow path on the top side. In the bridgeless PFC, two inductors were utilized, each with an inductance value of 360 μH.Heat dissipation components such as heat sinks for switches and diodes were mounted on one side of the circuit along with the devices. To facilitate experimental adjustments, the control circuit was designed on an auxiliary PCB with connectors that allow it to be detached from the main circuit.

Table 3: Specifications of switching rectifier

Parameters	Value	Unit
Input voltage range	90 - 265	Vac
Output voltage	400	Vdc
Maximum load current	5.0	A
Maximum output power	2	kW
Switching frequency	50-100	kHz

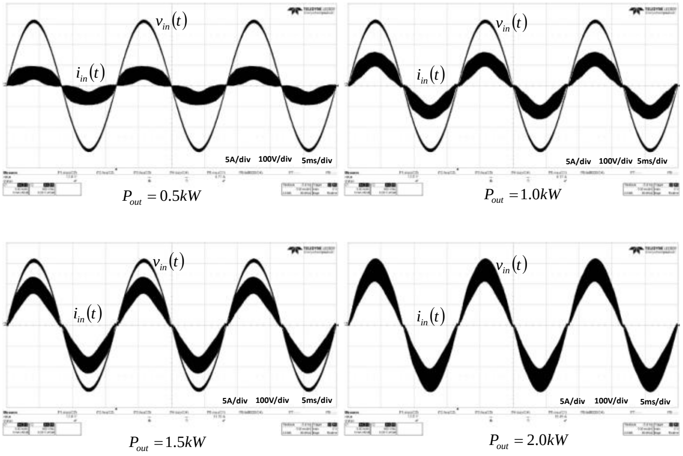

Fig.3: Input voltage and current waveform in 50kHz switching frequency

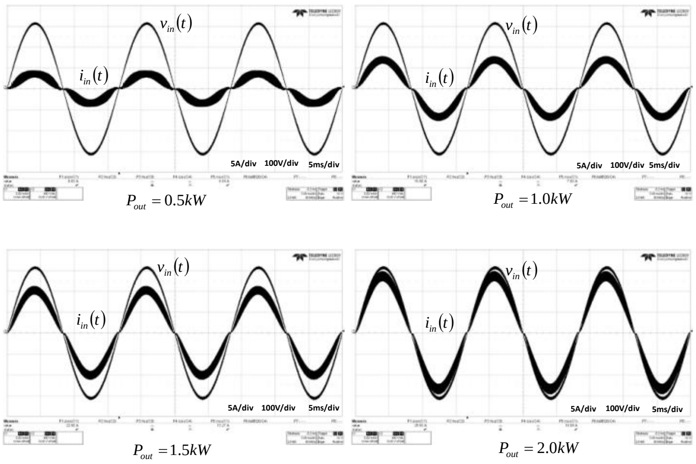

Fig.4: Input voltage and current waveform in 100kHz switching frequency

Fig.3 summarizes the input voltage and input current waveforms of the test circuit, measured across different switching frequencies and output capacities. In Fig.3, the circuit operates at a switching frequency of 50 kHz; due to this relatively low frequency, the current ripple increases, resulting in a wider and thicker current waveform. However, both current and voltage are in phase, and as the output power increases, the waveforms tend to approach a sinusoidal shape. Fig. 4 shows the waveforms at 100 kHz. As the switching frequency increases, the current ripple decreases, and both current and voltage waveforms remain in phase and resemble sinusoidal waveforms. From the results in Fig.4, it is observed that the input current in the bridgeless PFC circuit is sinusoidal and in phase with the input voltage, indicating a high power factor and typical of a power factor correction circuit.

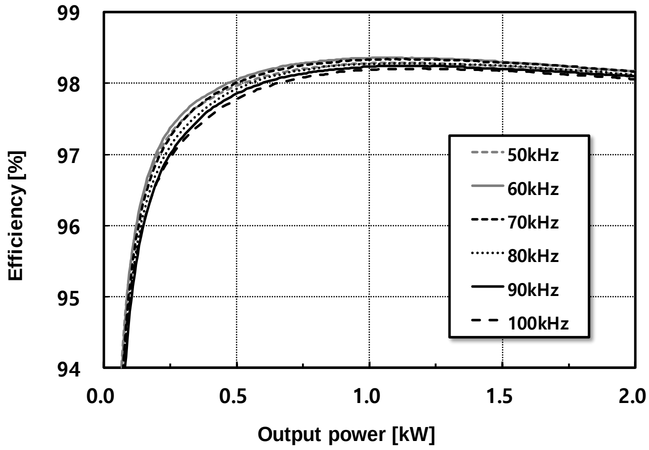

Fig.5: Power conversion efficiency in full range

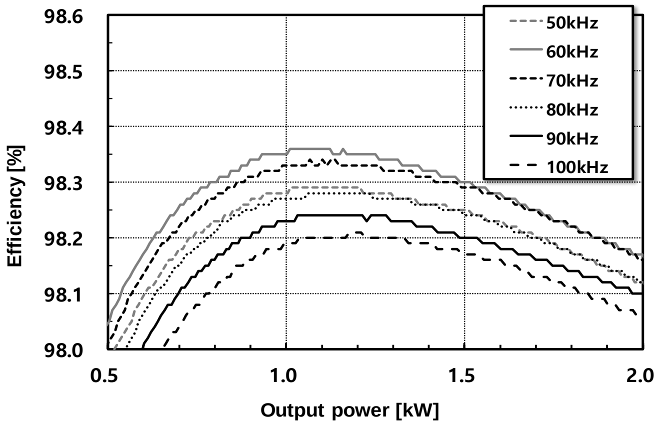

Fig.6: Power conversion efficiency in magnification range

Fig.5 shows the measured power conversion efficiency relative to load power. The switching frequency was increased in steps of 10 kHz from 50 kHz up to 100 kHz. In Fig.5, the efficiency over the entire load range is presented, while Fig.6 zooms in on the load capacity above 0.5 kW. Overall, the efficiency is lower at light loads but exceeds 98% when the load is above 0.5 kW, with the maximum efficiency of 98.35% observed at 60 kHz. As the switching frequency increases beyond this point, the efficiency tends to decline.Fig.6 presents the efficiency variation with respect to input voltage, measured at different switching frequencies. The data was collected at 50 kHz, with measurements taken in 10 kHz steps. Fig.7 shows the efficiency over the entire input voltage range, while Fig.8 zooms in on voltages above 210 V. The efficiency tends to increase proportionally with input voltage, particularly exceeding 98% at voltages above 220 V. The maximum observed efficiency of 98.60% occurs at a switching frequency of 60 kHz, and similar to previous results, the efficiency decreases as the switching frequency increases.Fig. 9 shows the relationship between internal power loss and input voltage. At 110 V input, the measured loss ranges from a maximum of approximately 150 W to a minimum of about 112 W, while at 260 V input, the loss drops to less than 10 W. Fig. 11 shows the relationship between switching frequency and efficiency measured at the maximum load power. The data shows that efficiency decreases as switching frequency increases; efficiency was measured at 98.36% for 60 kHz and 98.2% for 100 kHz.At 50 kHz, efficiency drops slightly to 98.29%. This behavior is attributed to the fact that conduction losses, are independent of switching frequency, whereas core and switching losses are proportional to it. Specifically, at frequencies below a certain threshold, the inductance required for the test circuit becomes insufficient, leading to increased ripple and losses, which decrease overall efficiency. From the above experimental results, it is concluded that in the bridgeless PFC circuit using GaN FETs, when the switching frequency is appropriately selected and the optimal inductance value is designed, increasing the switching frequency does not improve efficiency. Moreover, excessively high switching frequencies lead to increased losses, which can cause an increase in the power supply size.

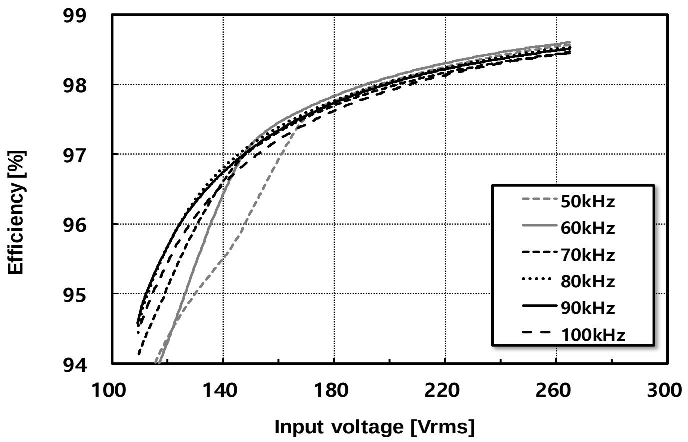

Fig.7: Power conversion efficiency according to input voltage

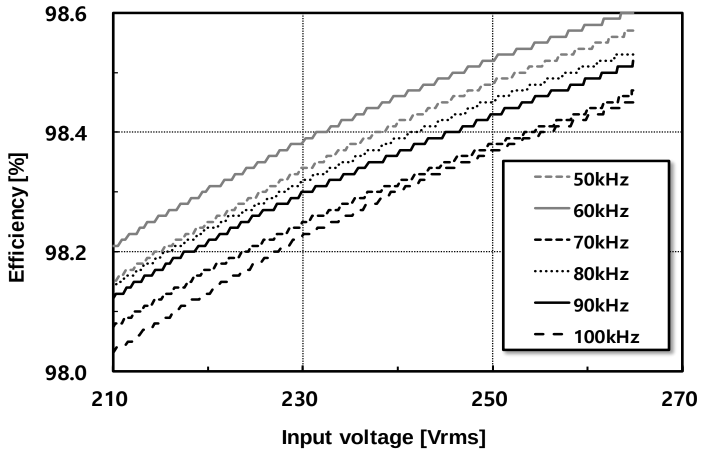

Fig.8: Power conversion efficiency according to input voltage in magnification range

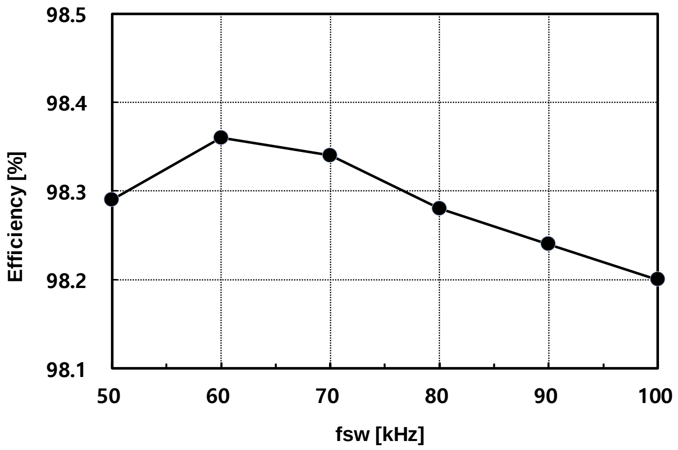

Fig.9: Switching frequency and power conversion efficiency

V. Conclusion

This paper reports experimental results on a 2kW-class high-capacity bridgeless power factor correction (PFC) circuit utilizing GaN switches, focusing on the effects of varying the switching frequency. To compare the power conversion efficiency characteristics, the switching frequency was varied from a minimum of 50 kHz to a maximum of 100 kHz. The experimental data reveal an inverse relationship between switching frequency and efficiency; specifically, the efficiency reached its peak at 98.36% at 60 kHz and was slightly higher at 98.2% at 100 kHz. At 50 kHz, the efficiency was measured at 98.29%.This behavior is attributed to the fact that conduction losses within the circuit are independent of switching frequency, while core losses of the inductors and switching losses of GaN devices are proportional to frequency. It was also confirmed that below a certain frequency threshold, insufficient inductance in the test circuit increases current ripple and associated losses, leading to a reduction in efficiency. Therefore, in a bridgeless PFC circuit using GaN FETs, once the switching frequency is optimized through proper selection and the inductance value is appropriately designed, further increasing the switching frequency does not improve efficiency. Excessively high switching frequencies, however, cause increased losses, which can lead to larger power supply sizes. These findings emphasize that for optimal performance and miniaturization, both switching frequency and inductance must be carefully balanced in GaN-based power conversion circuits.

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