



Article Analysis and Design of a Sine Wave Filter for GaN-Based Low-Voltage Variable Frequency Drives

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Abstract: Gallium nitride (GaN) devices have been widely adopted to achieve high efficiency and high power density as alternative solutions to silicon devices. When the GaN power devices are used for variable frequency drive (VFD) systems, the high dv/dt pulses at the motor terminal, which induce shaft voltage and common mode current, should be carefully considered to ensure system reliability. Although the high dv/dt issues can be mitigated with a dv/dt filter method, it leads to performance degradation depending on cable length. Meanwhile, a matrix converter also becomes a next-generation power converter for the VFDs which has a regeneration capability and unity power factor. Thus, this paper discusses the GaN-based matrix converter for the VFD as a study case considering the motor terminal voltage quality and the common mode current. Also, a sine wave filter is adopted to cope with the terminal voltage quality irrespective of cable length. The optimized design procedure of the sine filter considers practical issues. Experimental results are presented to suggest a suitable solution for the GaN-based VFDs in accordance with the cable length.

Keywords: common mode current; gallium nitride (GaN); motor terminal voltage; sine wave filter; variable frequency drive (VFD)

1. Introduction

With the development of wide bandgap materials for power electronics such as gallium nitride (GaN), significant improvements in variable frequency drive (VFD) systems are expected. There are various advantages of GaN power devices, which are a much faster switching speed, higher breakdown voltage, higher thermal conductivity, and lower conduction resistance than the conventional silicon (Si) power devices [1,2]. Their strength can be a comprehensive solution to meet the high demand in industrial drive systems since GaN-based VFDs offer high efficiency, high power density, and high temperature operation.

While the GaN-based VFDs (using a standard three-phase two-level voltage source inverter) are commercially available in the industry, a matrix converter is becoming a popular alternative for next-generation motor drive systems [3–7]. Figure 1 shows the typical two-level voltage source inverter and the matrix converter block diagram for the VFDs. Compared to standard three-phase voltage source inverters using pulsewidth modulation (PWM) techniques, the matrix converter not only provides sinusoidal input current, but also operates with a unity input power factor. Moreover, it has a regeneration capability which cannot be achieved in the standard VFDs configuration. The most interesting point of the matrix converter topology is that it does not have a dc-link structure by using a bidirectional switch configuration which has reverse blocking and current conduction capability in both directions. The benefits of the matrix converter match well with the purpose of the GaN-based VFDs, especially for the high power density requirements.



Figure 1. Power converter circuit for variable frequency drive (VFD). (**a**) Conventional two-level inverter; (**b**) Matrix converter.

However, there is a significant problem to address before the GaN power devices are adopted in the motor drive system. The advantage of fast switching speed for the VFDs would negatively affect the motor reliability due to its high speed switching which results in high dv/dt at the motor terminal. It is important to appropriately apply the motor terminal voltage which causes motor insulation problems and bearing fluting damage. When the high dv/dt (by the inherent characteristics of GaN-based VFDs and the parasitic elements in the board layout) is applied at the motor terminal, unequal voltage distribution occurs at the first motor winding turn which leads to insulation failures between phase to phase or phase to motor frame [8–10]. Also, it generates an unwanted shaft voltage and bearing currents (which induce excessive motor heating, audible noise, vibration, and common mode current) through parasitic capacitance and inductance inside the motor. As a consequence, an efficient system operation cannot be achieved due to its maintenance cost as well as a decrease of lifetime [11–21].

A long cable between the VFDs and motor also has a non-negligible effect on the performance and reliability of the motor considering the practical installation environments such as deep sea and manufacturing plants. Voltage reflection, which is a well-known phenomenon, occurs where there is an impedance mismatch between the VFDs and the motor [18–21]. It would cause undesired voltage amplification (nearly twice the magnitude of the switching voltage) at the motor terminal and become worse as the cable length increases. A simple way to deal with this high dv/dt issue is to adjust the switching speed of the GaN devices by increasing the gate resistance. However, this approach has an inherent tradeoff between the terminal voltage quality and the switching loss of the GaN devices.

To address this issue, various output filter options have been studied in the literature. In [22–27], a dv/dt filter is proposed to mitigate the high dv/dt issues by using a damping resistor. Although it could provide the desired dv/dt slope (the rise time and fall time of the terminal voltage variations), the damping performance is vulnerable to the cable length, which cannot provide the designed dv/dt slope and settling time. On the other hand, a sine wave filter was studied to overcome the limitation of the dv/dt filter regardless of the cable length [25–29]. It is possible to apply a pure sinusoidal voltage to the motor terminal without the high dv/dt issues. Table 1 compares the characteristics of the dv/dt and sine wave filter. The sine wave filter option is mostly used for the high power machines and the high speed motor drives. For the high power machines where the stator winding inductance is small, the sine wave filter can effectively mitigate the motor's current ripple. Also, it is usually adopted for the high speed motor drives where high switching frequency is needed for high speed control bandwidth. Meanwhile, with the emergence of the GaN power devices for the VFDs, it has become easier to use the sine wave filter in the GaN-based VFDs for the low power machines though it has some difficulties for the Si-based VFDs due to the size and cost of the filter, where the switching frequency cannot be increased to reduce the filter size. In other words, the GaN-based VFDs with the sine wave filter meet industrial and commercial demands for the high power density and high reliability of the motor drive systems.

	dv/dt Filter	Sine Wave Filter	
Switching frequency Output voltage of filter Compliance with motor standard	Several kHz Voltage pulses Limited by cable length	Several tens of kHz Sinusoidal Guaranteed	

Table 1. Comparison of dv/dt filter and sine wave filter.

This paper contributes to the understanding of the output sine wave filter for the GaN-based VFD using the matrix converter topology as a study case. The main objective of this paper is to evaluate the comprehensive performance on the GaN-based VFD for the drive system considering the motor terminal voltage quality and common mode current with regard to sine filter and cable length. With this purpose, a suitable design consideration and a detailed performance analysis for the low power general purpose motor drives are discussed in this paper. In Section 2, the design of the sine wave filter and practical considerations are introduced to optimize the output filter considering the GaN-based VFDs. Section 3 presents experimental results of the GaN-based VFD in accordance with the output filter and cable length, and the performance analysis. Section 4 concludes and summarizes this paper.

2. Sine Wave Filter in GaN-Based VFD Applications

The sine wave filter with the GaN-based VFD configuration is shown in Figure 2, where the matrix converter is used for the VFD and the induction motor is connected to the VFD through the power cable. Various parasitic elements exist in the induction motor as illustrated in Figure 2. As mentioned earlier, if there is no proper way to mitigate the high dv/dt, it worsens the motor winding insulation and induces the common mode current i_{common} due to the parasitic capacitances. The International Electrotechnical Commission (IEC) standards were developed to manage the VFD systems of a sustainable environment [30]. Table 2 shows the IEC standards for motor terminal voltage quality according to the motor rated voltage V_{rated} . Thus, the use of the GaN devices in the VFDs should be carefully designed to meet the standards.



Figure 2. System configuration of GaN-based VFD with sine wave filter.

Table 2. IEC Standards for motor voltage quality.

V _{rated}	Peak Voltage	Rise Time	dv/dt
< 460 V	≤ 1.6 kV	$\geq 0.1 \ \mu s$	≤ 5.2 kV/µs
460 V <v<sub>rated < 575 V</v<sub>	≤ 1.8 kV		≤ 6.5 kV/µs
575 V <v<sub>rated < 690 V</v<sub>	≤ 2.2 kV		≤ 7.8 kV/µs

2.1. Effect of High dv/dt on Motor Drive System

As mentioned in the previous section, the high dv/dt pulses worsen the motor system reliability through interactions with the motor parasitic elements which lead to the bearing and the common mode current [8,12–14,31]. Figure 3 shows a simplified equivalent circuit of the common mode current and the leakage current in the electric motor, where R_S is the winding resistance, L_S is the winding inductance, C_{SG} is the stator to ground capacitance, C_{SR} is the stator to rotor capacitance, C_{RG} is the rotor to ground capacitance, and S_B represents the dielectric breakdown between the inner and outer race. As shown in Figure 3a, the bearing voltage can be generated from the common mode voltage as the ratio of the parasitic capacitances. As the switching speed increases, the common mode current increases due to its low common mode impedance at the high frequency region [14].



Figure 3. Simplified equivalent circuit of (a) common mode and (b) leakage current.

Also, it is confirmed that the motor terminal voltage $v_{terminal}$, which has a high dv/dt from the VFDs, induces the leakage current $i_{leakage}$ and the bearing current $i_{bearing}$, as shown in Figure 3b. The leakage current can be expressed by using the motor parasitic elements in the time domain as follows.

$$i_{leakage}(t) = \frac{v_{terminal}(t)}{\sqrt{1 - \zeta^2 Z_o}} e^{-\zeta \omega_n t} \sin \sqrt{1 - \zeta^2} \omega_n t \tag{1}$$

$$C_{eq} = \frac{C_{SG}C_{SR} + C_{RG}C_{SG} + C_{SR}C_{RG}}{C_{SR} + C_{RG}}, \quad \omega_n = \frac{1}{\sqrt{L_S C_{eq}}}$$

$$\zeta = \frac{R_S}{2} \sqrt{\frac{C_{eq}}{L_S}}, \quad Z_o = \sqrt{\frac{L_S}{C_{eq}}}$$
(2)

Equation (1) indicates that the high dv/dt spikes at the motor significantly increase the magnitude of the leakage current, even without consideration of the bearing voltage and the cable impedance. In terms of the voltage reflection phenomenon which is caused by the impedance mismatch between the motor surge impedance and the power cable, small power motor drive systems are more likely to suffer from the high dv/dt. Since it has much larger surge impedance compared to a high power electric motor, the ratio of the impedance mismatch deteriorates further. Table 3 summarizes the typical surge impedance of the induction motor and the cable which is used in this paper [21].

Table 3. Typical surge impedance of motor and cable.

	Cable		Motor	
	10 AWG ¹	< 3.7 kW	93 kW	373 kW
Surge impedance (Ω)	80	2000~5000	800	400
¹ American wire gauge (AWG).				

2.2. Design of Sine Wave Filter

Figure 4 shows a per-phase equivalent circuit of a sine wave filter, where L_f is the filter inductance, C_f is the filter capacitance, and R_L is the parasitic resistance of the filter inductor. From Figure 4, the transfer function of a sine wave filter can be derived as follows.

 $G(s) = \frac{1}{L_f C_f s^2 + R_L C_f s + 1}$



Figure 4. Per-phase equivalent circuit of sine wave filter.

For the parameter selection of the sine filter, it is important to determine the resonant frequency of the sine wave filter, because the fundamental purpose of the filter is to achieve a pure sinusoidal voltage for the motor by rejecting the high frequency PWM voltage. The resonant frequency should be determined to avoid filter resonance between the fundamental frequency to the switching frequency. Meanwhile, the conventional Si-based VFDs make it difficult to select the resonant frequency for the sine filter due to its low switching frequency (e.g., 2 kHz to 8 kHz is usually used for the Si-based VFDs). In other words, it is not a suitable option for the industrial VFDs because of the large filter size and parameters.

Figure 5 shows the curves of the filter inductance and the filter capacitance in accordance with the resonant frequency, which is determined to avoid filter resonance as one-fourth of the switching frequency. In Figure 5, the higher filter inductance is preferred to reduce the filter capacitor current. However, the filter inductance should be limited by considering the voltage drop across the filter inductance at the rated output current. Although it can restrict the maximum value of the filter inductance, it cannot decide the minimum available value of the filter inductance and volume which can be the design parameters to achieve high power density. It is also not a proper approach for the small power motors, where the voltage drop is significantly low due to the low output current magnitude.



Figure 5. Curves of (**a**) capacitance versus inductance for sine wave filter at 2 kHz, 8 kHz, and 25 kHz, (**b**) zoomed in view.

(3)

In order to achieve the optimum value of the sine wave filter, the filter inductance can be chosen considering the inductor volume and the switching frequency. In terms of the flux density, the physical volume of the inductor can be determined by the rated output current and the current ripple. Figure 6 shows the filter inductance and volume for the rated output current and the current ripple according to the switching frequency. The volume of the filter inductor is calculated by using the inductor design tool from Magnetics [32]. Here, the maximum ripple current is assumed not to exceed 4 A which is 40% of the peak current (10 A) at the rated condition in this paper. As the switching frequency increases from 10 kHz to 25 kHz, the inductor volume and the inductance are reduced to about 50% for the specified current ripple of 4 A. Although the required inductance is continuously reduced as the switching frequency increases, the volume of the inductor is nearly constant in the frequency range from 25 kHz to 40 kHz. Because of the flux density at the rated current, the volume of the inductor cannot be reduced further even with the higher switching frequency. Hence, by considering the inductor size and the system switching frequency, and the inductances for the sine filter can be selected as 25 kHz and 250 µH, which are used in this paper. Also, the filter capacitance can be chosen as 2.2 μ F which offers the required filter resonant frequency as one-fourth of the switching frequency, 25 kHz.



Figure 6. Relation of inductance and volume according to switching frequency.

Figure 7 shows a frequency response of a designed sine wave filter ($L_f = 250 \mu$ H, $C_f = 2.2 \mu$ F), where f_o is the fundamental output frequency, f_r is the resonant frequency of the sine filter, and f_{sw} is the switching frequency. It is confirmed that the cut-off frequency of the filter is 8.32 kHz, which is located between f_o and f_{sw} . Therefore, the high frequency PWM voltage of the VFDs is sufficiently mitigated by the sine wave filter without the resonance problem.



Figure 7. Frequency response of sine filter.

3. Experimental Results

To validate the designed sine wave filter (Set 1. $L_f = 250 \mu$ H, $C_f = 2.2 \mu$ F) and GaN-based VFD in the motor drive system, the experiments were performed using a 1 kW induction motor and three phase 200 V input voltage source, as illustrated in Figure 8. Table 4 summarizes the system parameters of the GaN-based VFDs. For the bidirectional switches of the GaN matrix converter, the GaN power devices (Infineon, IGT60R070D) were used as shown in Figure 9a. One board is composed of three bidirectional GaN switches, and the matrix converter can be operated with the three board setup. Since the gate loop inductance and the power loop inductance influence gate-drive dynamics and voltage stress, the power and gate loop were carefully designed to minimize the loop inductance as much as possible. Based on the above design procedure, the prototype of the sine wave filter is employed as shown in Figure 9b.



Figure 8. Experimental setup.

Table 4.	System	parameters.
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Figure 9. Photograph of (a) GaN-based VFD using matrix converter and (b) sine wave filter.

Experiments were carried out to evaluate the motor terminal voltage quality and common mode current according to 5 m and a 25 m cable length. Also, two sets of comparative tests were conducted

between the two sine filters with the same filter resonant frequency, as shown in Figure 8. The voltages and common mode current were measured with differential voltage probes (Lecroy, HVD3106A: 120 MHz bandwidth) and a current probe (Lecroy, CP150: 10 MHz bandwidth).

3.1. Motor Terminal Voltage

Figure 10 shows the measurement results of the line-to-line VFD output voltage v_{con_uv} , the line-to-line motor terminal voltage v_{mot_uv} , and the motor phase current i_{mot_u} , where the sine wave filter was not adopted. In Figure 10a, where a cable length is about 5 meters, the rise time and the peak voltage of v_{con_uv} are 120 ns and 290 V. Although it has a sufficiently short cable length, the high frequency ringing and the voltage reflection phenomenon are observed in the motor terminal voltage v_{mot_uv} due to the high dv/dt pulses of the GaN-based VFD (where the rise time and the peak voltage of v_{mot_uv} are 60 ns and 365 V, respectively). For the 25-m cable length as in Figure 10b, the motor terminal voltage quality becomes even worse due to the voltage reflection phenomenon where the rise time and the peak voltage of v_{mot_uv} are 70 ns and 492 V are seen. Considering the practical installation environments, the GaN-based VFDs may bring motor insulation breakdown (the dv/dt in 5-m cable: 6.1 kV/µs, and the dv/dt in 25-m cable: 7 kV/µs). Both Figure 10c,d, show the steady-state waveforms according to 5-m and 25-m cable length. As shown in the figure, the motor terminal voltage cannot be guaranteed by the motor standards.





(c)

(**d**)

Figure 10. Measurement results of GaN-based VFD without filter. (a,c) 5-m cable and (b,d) 25-m cable.

Figure 11 shows the experimental results of the GaN-based VFD with the two sets of the sine wave filters, where the line-to-line VFD output voltage is v_{con_uv} , the line-to-line motor terminal voltage is v_{mot_uv} , and the motor phase current is i_{mot_u} . In both sine filters, the GaN-based VFD generates a pure sinusoidal voltage to the induction motor without the filter resonance. Compared to the no filter cases, the high frequency current ripple, which may induce the motor core and winding losses, cannot be observed in the motor current i_{mot_u} with the sine filter. Accordingly, as shown in the figure, it could deal with the IEC standards and improve the system reliability regardless of the cable length.





Figure 11. Experimental results of GaN-based VFD with two sets of sine wave filter; (**a**) 5-m cable length, with sine filter ($L_f = 250 \ \mu\text{H}$, $C_f = 2.2 \ \mu\text{F}$); (**b**) 25-m cable length, with sine filter ($L_f = 250 \ \mu\text{H}$, $C_f = 2.2 \ \mu\text{F}$); (**c**) 5-m cable length, with sine filter ($L_f = 117 \ \mu\text{H}$, $C_f = 4.7 \ \mu\text{F}$); (**d**) 25-m cable length, with sine filter ($L_f = 117 \ \mu\text{H}$, $C_f = 4.7 \ \mu\text{F}$); (**d**) 25-m cable length, with sine filter ($L_f = 117 \ \mu\text{H}$, $C_f = 4.7 \ \mu\text{F}$); (**d**) 25-m cable length, with sine filter ($L_f = 117 \ \mu\text{H}$, $C_f = 4.7 \ \mu\text{F}$); (**d**) 25-m cable length, with sine filter ($L_f = 117 \ \mu\text{H}$, $C_f = 4.7 \ \mu\text{F}$).

3.2. Common Mode Current

In order to experimentally evaluate the common mode current in the motor drive systems, a measurement configuration was established, as shown in Figure 8. As discussed before, it could be expected that the common mode current would decrease by using the sine wave filter. To further discuss, Figure 12 compares the frequency spectrum of the common mode current with and without the sine wave filters (Set 1. $L_f = 250 \mu$ H, $C_f = 2.2 \mu$ F, Set 2. $L_f = 117 \mu$ H, $C_f = 4.7 \mu$ F). In Figure 12a, where the cable length is 5 meters, the common mode current decreases especially in a high frequency range above 1 MHz. Compared to the 5-m cable cases, the common mode current increases in the frequency range below 1 MHz, especially in the switching frequency harmonics, as shown in Figure 12b, where the cable length is 25 meters. Here, it is interesting to note that the magnitude of *i_{common}* is reduced in the frequency range above 1 MHz which is related to the conducted electromagnetic interference emissions (150 kHz to 30 MHz). Meanwhile, both Figure 12c,d compare the frequency spectrum of i_{common} between the two sets of sine filters. By using the sine filter (Set 2. $L_f = 117 \mu$ H, $C_f = 4.7 \mu$ F), it also reduces the common mode current in high frequency regions above 1 MHz compared to the without filter case in both cable length conditions. However, compared to the sine filter of Set 1, it has a larger magnitude of the common mode current in the frequency range above 1 MHz due to the higher filter capacitance.



Figure 12. Frequency spectrum comparison of common mode current with and without sine filter. (**a**,**c**) 5-m cable length and (**b**,**d**) 25-m cable length.

4. Conclusions

This paper investigates and discusses the comprehensive performance of the sine wave filter for the GaN-based VFDs using the matrix converter topology as a study case. The GaN-based VFDs offer various benefits of high efficiency and high power density. However, especially in the case of the GaN-based VFDs for the low power motor drive systems, the motor terminal voltage quality could become even worse due to a large impedance mismatch and the high dv/dt of the GaN devices. Thus, the sine wave filter is necessary to ensure the overall system reliability considering the practical installation environments where a long cable length is required for the deep sea and manufacturing plant. The design procedures are discussed to achieve optimal system parameters of the sine filter in the GaN-based VFD according to the switching frequency and filter volume. From the comparative performance evaluation of the terminal voltage and the common mode current, it is confirmed that the sine wave filter can be regarded as a suitable solution in GaN-based VFD applications for low power motor drives.

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