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Research Article

STUDY OF VOLTAGE STRESSES INSIDE REGENERATIVE DRIVE

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ABSTRACT

This paper investigates the effect of voltage stress on the voltage insulation components inside a regenerative active-front-end adjustable-speed drive (ASD). It shows that a high potential voltage insulation issue may exist on various components inside the ASD and cause earlier failures. A simplified system model to describe this phenomenon is described, and the voltage stresses of different components inside the ASD under different grounded conditions and filter capacitor are analyzed. It is concluded that among different grounding systems, a high-resistance grounded system gives minimum stress. Appropriately, designing the insulation components is critical to protect the drive.

Keywords: Active front end, Adjustable-speed drive, Insulation, Long cable, System grounding.

INTRODUCTION

The development of high frequency, pulse-width modulation (PWM)-based adjustable-speed drives (ASDs) has increased energy efficiency, performance, and controllability in the induction motor applications. However, high-speed switching used in PWM drive, however, can be accompanied by the serious problems such as ground current escaping to earth through stray capacitors inside motors, conducted and radiated electromagnetic interference (EMI), bearing current and shaft voltage, and voltage stresses shortening the insulation life of motors and protective components used inside drive. Numerous papers have been published to analyze these issues [1-12]. Chen *et al.* [3], Busse *et al.* [4], Kerkman *et al.* [5], Skibinski *et al.* [6] analyzed the PWM switching and cable length effect on bearing current, EMI emission, and motor insulation. In Busse *et al.* [4], Kerkman *et al.* [5], Skibinski *et al* [6], Skibinski *et al* [7], Ogasawara *et al* [8], Julian *et al.* [9], Swamy *et al.* [10], Son *et al.* [11], Hyypio *et al.* [12], various methods and topologies were proposed to reduce the effect of PWM switching on motor insulation, EMI performance, and bearing current effect. As insulation is also one of the factors, which decides the performance and service life of motor and protective components, it is necessary to study the voltage stresses caused by fast dv/dt switching in the drive. Paper [1] has analyzed PWM effect on voltage stresses considering static load, whereas this paper aims at the same but considering dynamic load so that results obtained will be realistic. Furthermore, studies the effect of filter capacitor and its type of grounding used at source side on voltage stresses.

However, the analysis of overvoltage failures of components inside the drive has not been fully addressed or discussed. One simple assumption made from these references is that the common-mode capacitance inside the drive is much higher than that of the cable and motor. This is true for the majority of applications. However, when an ASD is applied with a very long cable or multiple parallel cables, the common-mode capacitance of the cable and motor may be comparable or even higher than the common-mode capacitance inside the drive. Moreover, ASD manufacturers generally suggested customers to disconnect the

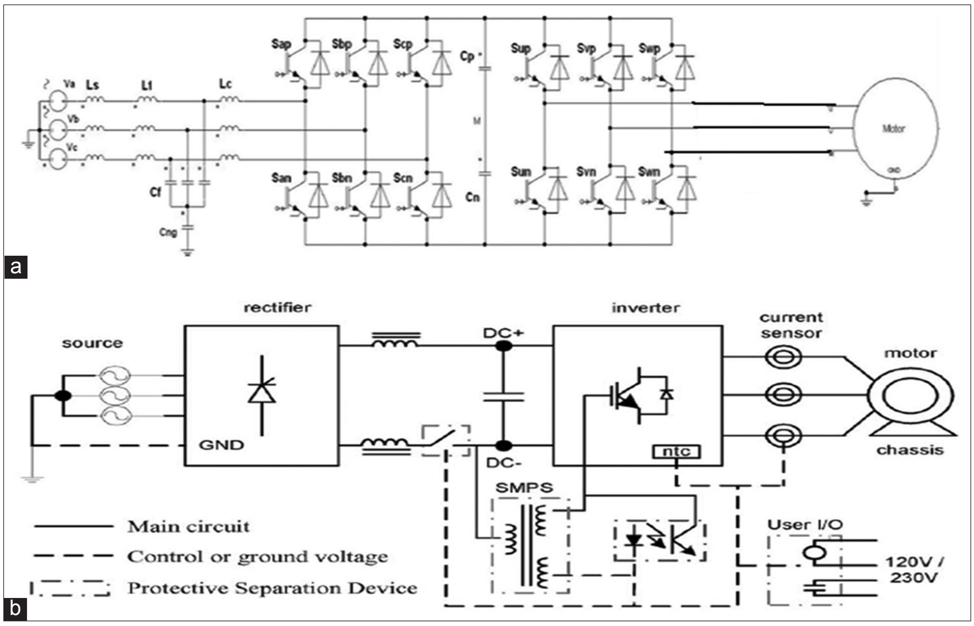

Fig. 1: Schematics of active-front-end (AFE) drive with common mode and cable models. (a) Diagram of ASD with AFE rectifier. (b) Components that are exposed to HV stresses

common capacitor from the ground under a high-resistance grounded (HRG) or ungrounded system. Under these conditions, the output cable and motor capacitance values are generally much higher than the ASD common-mode capacitance values. High-voltage (HV) stresses may be generated inside the drive instead of the motor side [2]. Thus, understanding the voltage stresses inside the drive under different grounding configurations is critical for design engineers.

As discussed in Wei *et al*. [2], there are two types of HV components in an ASD. The first type of component is the main circuit components that transfer power from the source to the load, including inverter insulated-gate bipolar transistor, rectifier diode/SCR, dc link choke, and dc bus capacitor. They are all located in the differential-mode circuit, and their voltage stresses are generally no higher than the dc bus voltage. The selection of voltage ratings for these components is straightforward. The second type of component provides protective separation between the control and main circuits, including optocoupler, print circuit board, sensors, voltage/current transducer, and switched-mode power

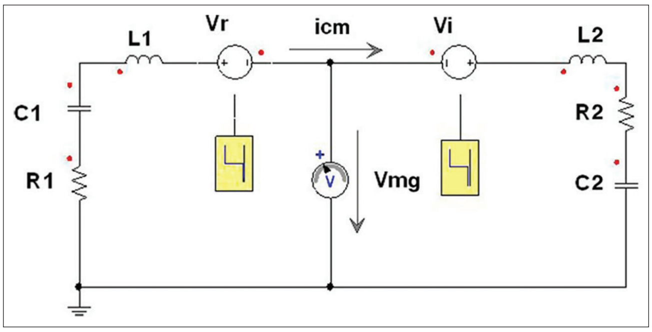

Fig. 2: Simplified common-mode circuit modeling voltage stresses of the drive

supply transformer. These components must be able to support voltage stresses between HV and the ground. Wei *et al*. [2] analyzed the voltage stresses inside an ASD with a diode/SCR. In this paper, the voltage stresses inside a regenerative ASD under different configurations are studied.

VOLTAGE STRESS ANALYSIS

In paper [1], the response of common-mode midpoint-to-ground voltage is analyzed, by considering a simplified common-mode circuit of considered drive. The system is analyzed for underdamped and overdamped conditions; thereby, the circuit was predicted for solid grounding and high-resistance grounding. According to Wei *et al*. [2], the HV sides of the protective separation components in the dc bus are either no higher than those in the positive bus or no lower than those in the negative bus. The low-voltage sides are the control voltages that are very close to GND voltage. Therefore, the insulation voltage of the bus components can be approximated as the voltage between the GND and the dc bus terminals. The voltage stresses between the ground and the dc bus terminals can be calculated by adding the common and differential-mode voltages.

Differential-mode voltage between dc bus terminals to the GND

For the differential-mode circuit, the middle or neutral point of the dc bus voltage is equal to the GND voltage. This voltage stress between dc bus terminals to the GND can be approximated as half the dc bus voltage for a Y-grounded system

$$Vpg\_DM=Vng\_DM=Vdc/2$$

Where, *Vpg*_DM is the maximum voltage between the positive dc bus and the GND in the differential-mode circuit and *Vn* is the minimum voltage between the negative bus voltage and the GND in the differential-mode circuit.

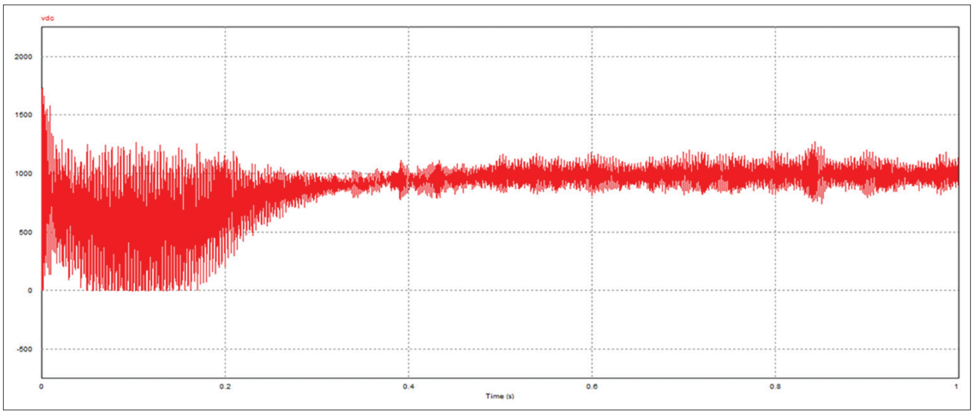

Fig. 3: DC bus voltage in differential mode

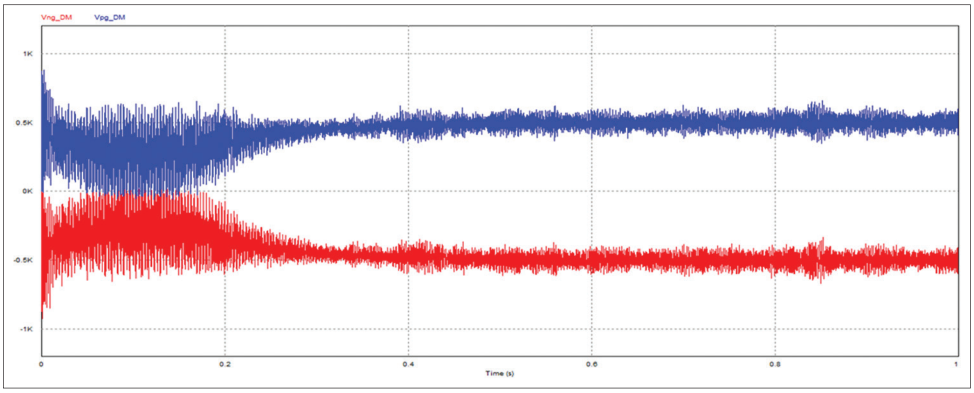

Fig. 4: DC bus-to-GND voltage in differential mode

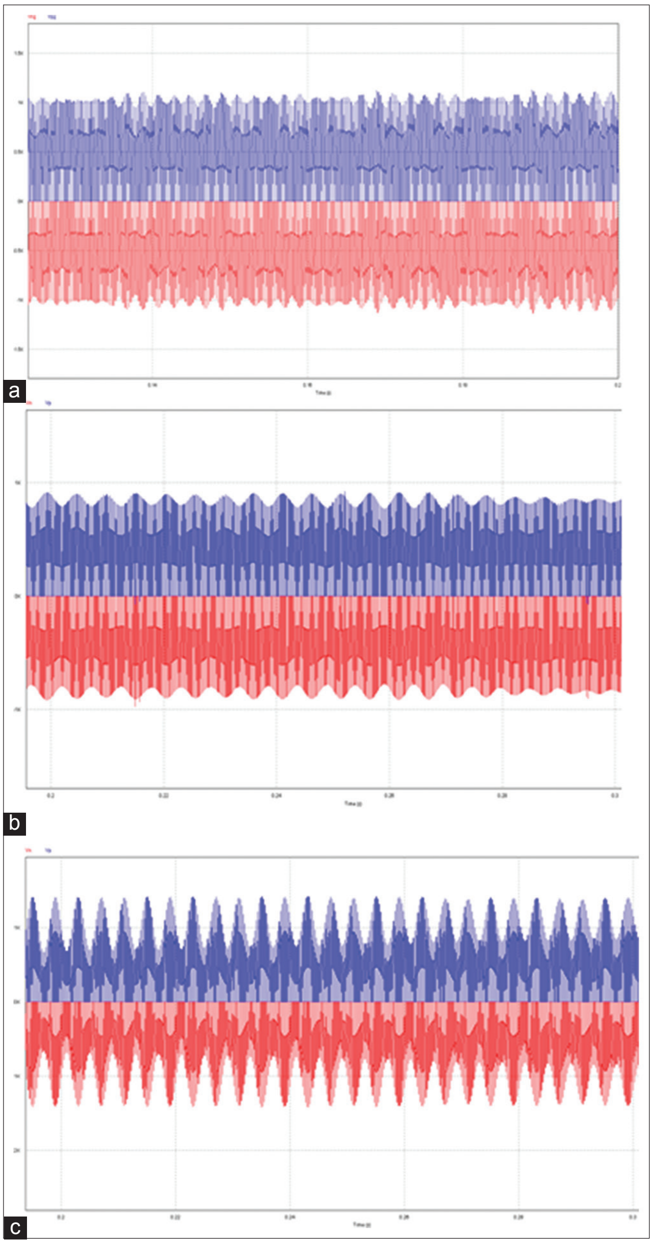

Fig. 5: DC bus-to-GND voltage stresses under different grounding *Vpg*: DC+ to GND and *Vng*: DC− to GND. (a) Solid Y-grounded system (peak voltage: 1.1 kV). (b) High-resistance grounded system (peak voltage: 0.890 kV). (c) Ungrounded system (peak voltage: 1.3 kV)

Common-mode voltage between dc bus terminals to the GND

Fig. 2 shows a simplified circuit of Fig. 1a that can explain the voltage stresses of different parameters to the voltage stresses of *V*mg (terminal to ground voltage) during switching of either side converter. In this figure, both the input and output are simplified as a simple *RLC* circuit. *Vi* and *Vr* are two voltage sources that represent the common-mode voltage generated by either the rectifier or the inverter of the drive.

The same circuit is referred for PSIM modeling of different grounding systems, wherein Table 1 is also considered to know line inductances and filter capacitors considered for different grounding systems. Paper [1] gives a single-line diagram for different grounding systems.

SIMULATION RESULTS

In the present work, the active-front-end (AFE) drive is modeled using PSIM. The model developed has been used to obtain the stresses for different grounding methods. During the study, the drive and motor data used are shown in Table 2.

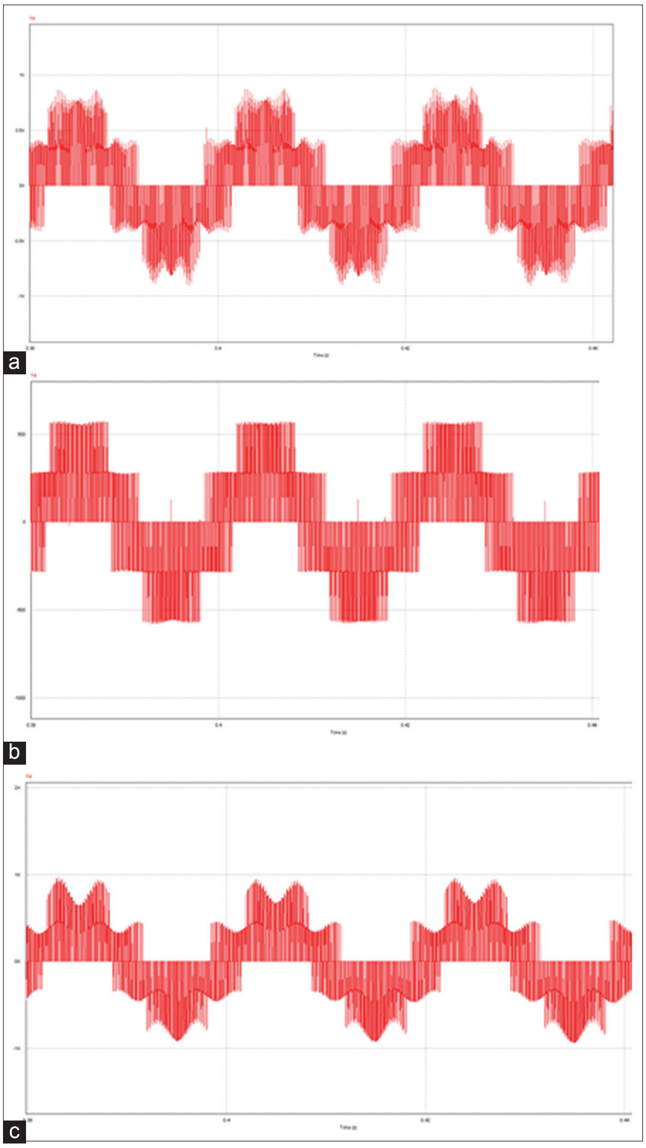

Fig. 6: AC input-to-GND voltage under different grounding. *Vag/Vbg/Vcg*: Input phases A, B, and C to GND, respectively. (a) Solid Y ground system (peak voltage: 0.794 kV). (b) High-resistance grounded system (peak voltage: 0.565 kV). (c) Ungrounded system (peak voltage: 0.924 kV)

DC bus-to-GND voltage in differential mode

In differential-mode operation, dc bus voltage is found as 1 kV and terminals to ground voltages are measured and are found to be half of dc bus voltage, i.e., 500 V and are shown in Fig. 3 and 4. This condition is true for all grounding conditions.

DC bus-to-GND voltage in common-mode for different ground systems

Fig. 5a-c shows the voltage stresses between dc bus terminals to the GND under solid Y, HRG, and ungrounded systems, respectively. From this figure, it can be found that the peak voltage under the ungrounded system is much higher than that of the HRG or solid system. Minimum stresses are found in HRG system. For all grounding conditions, the voltage stresses between the dc bus terminals to the GND are much higher than half the dc bus voltage and need special attention.

Input-to-GND voltage under different ground systems

Fig. 5a-c shows the voltage stresses between input terminals to the GND under solid Y-grounded, HRG, and ungrounded systems, respectively. It can be found that the peak voltage under the HRG system is much lower than that of the solid or ungrounded system. This is because the impedance of the source is less compared to the LCL filter.

The results are shown in Fig. 5 and 6 which are for 1.98 µF filter capacitor value. When measurements are done for other filter values toward infinity, it is found that voltage stresses increase beyond these results which are shown in Table 3.

Table 1: Equivalent inductance and capacitance values of different grounded systems

Grounding	Filter	C1	L1
Solid	Y	Inf	Lc
HRG	Y	Inf	Ls+Lf+Lc
Ungrounded	N	0	Lf+Lc

HRG: High-resistance grounded

Table 2: Ratings considered

ASD rating	480/150 hp
Rectifier switching frequency	4 kHz
Inverter switching frequency	2 kHz
Motor	460 V/200 hp
Line side inductor Lf	420 µH
Rectifier side inductor Lc	140 µH
Common-mode filter capacitor Cng	2 µF
Filter capacitor Cf	30 µF

ASD: Adjustable-speed drive

Input voltage to motor for different grounding systems

Input to motor is also of great concern. Proper input to motor fulfills the purpose of using the drive. Hence, motor input is measured for different grounding systems and for different filter capacitor values. Fig. 7 shows motor input voltage waveforms taken for 1.98 µF filter capacitor value. Figure shows that motor input is better for the HRG system compared to solid and ungrounded systems.

Furthermore, the HRG system gives voltage within motor rating in an acceptable range. For other values of filter capacitor values, waveforms will get more and more distorted resulting in increased harmonics. Total harmonic distortion (THD) for different grounding systems is shown in Table 4, and it shows that THD is very for ungrounded system and requires care. A detailed table of THD for different grounding systems is discussed in the next section.

Total voltage stresses on protective components

Total stresses acting on protective components are the sum of stresses measured in differential mode and in common-mode operation. Depending on total stresses obtained, protective components can be designed or can be chosen to withstand that much stresses, thereby, avoiding insulation failures and hence can minimize failure of process.

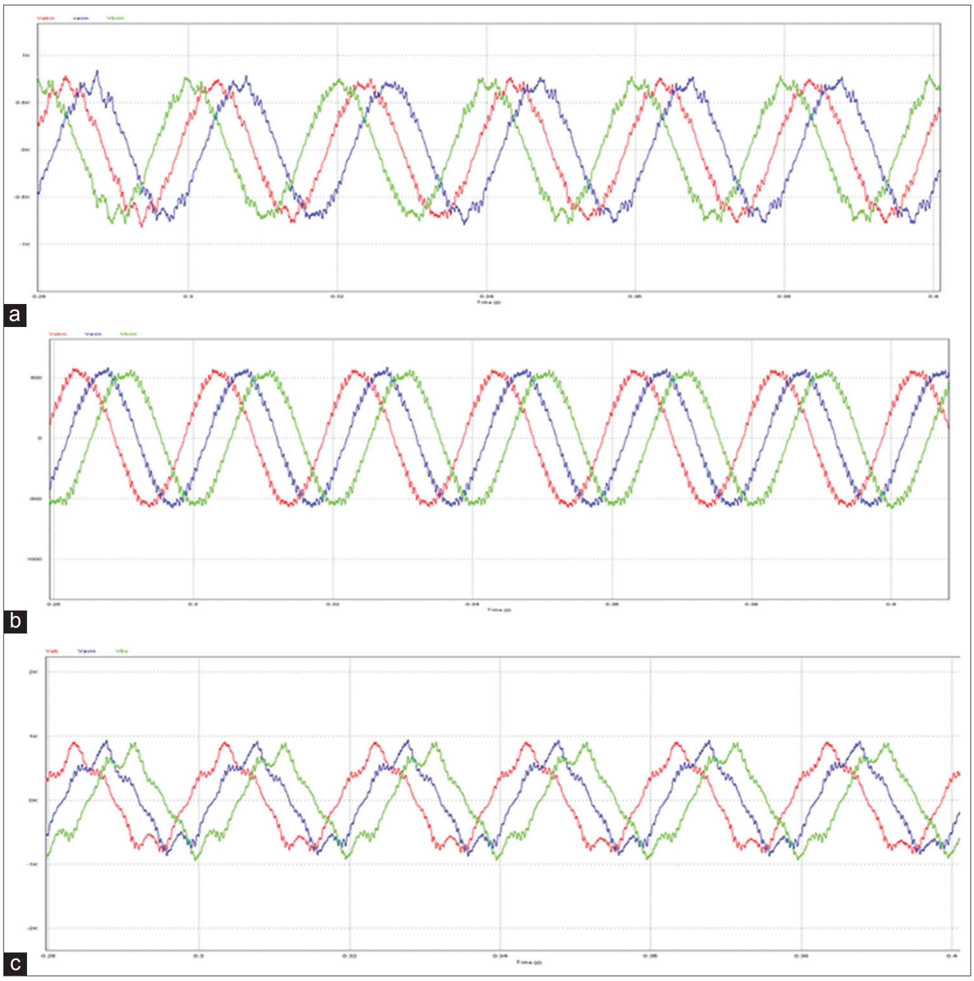

Fig. 7: Motor input voltage waveforms for (a) solid grounded system (RMS 492 V), (b) high-resistance grounded system (RMS 390.5 V), (c) ungrounded system (RMS 558 V)

Table 3: Voltage stress comparison

Type of GND	Solid	HRG						UnGnd
Value of filter capacitor	1.98 μf to ∞	1.98 μF	30 μF	100 μF	500 μF	1 mF	5 mF	No filter cap
Max. voltage stress	1.28 kV	1.7 kV	1.7 kV	1.7 kV	1.7 kV	2 kV	1.6 kV	1.75 kV
Min. voltage stress	1.1 kV	0.851 kV	1.3 kV	1.3 kV	1.3 kV	1.5 kV	1.38 kV	1.4 kV
Input to motor	497.3 V	390.5 V	556.5 V	563.9 V	546.9 V	557.6 V	539 V	558.73 V

HRG: High-resistance grounded

Table 4: THD comparison

Type of grounding	Filter capacitor value	THD
Solid grounding	1.98 μF toward infinity	7.0993
High-resistance grounding	1.98 μF	5.62
	30 μF	8.905
	100 μF	9.735
	500 μF	5.983
	1 mf	6.0154
	5 mF	5.3141
Ungrounded	No filter capacitor	22.9924

THD: Total harmonic distortion

CONCLUSIONS

This paper has investigated the voltage stresses inside a regenerative ASD under different grounding conditions and filter capacitor values. The work also involves to find the appropriate grounding system and the value of the filter capacitor which gives stresses within the specified limit and less total harmonic distortion (THD) in the input to the induction motor.

For a solid Y-grounded system, the dc-to-GND voltage is high for a regenerative AFE drive and requires special attention. The ac side-to-GND voltage is low compared to the ungrounded system and a common-mode filter can be designed to get proper input.

For an HRG grounded system, both dc-to-GND voltage and ac side-to-GND voltage are less compared to the other two grounding systems for regenerative drives with a dynamic load. The filter capacitor of value 1.98 μF helps in obtaining less stresses and better input to motor.

For an ungrounded system, the ac input-to-GND voltage is high for regenerative AFE drive and requires much special attention. The dc side-to-GND voltage is also high under a single drive condition; however, it may become high when a multiple drive system is applied.

Hence, a system with high-resistance grounding is suggestible to get minimum stresses and better input to motor. In future, more investigation can be made with multilevel inverter and by considering cable length.

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