Abstract - As far as medium voltage converters are concerned, it is known that, in general, their switching frequency is generally limited to a few hundred Hz. Therefore, the harmonic distortion of its output voltage may be inadequate for supplying electric motors, requiring the use of filters. In this work, the performance of such filters is evaluated in fault conditions and also for different connection types and grounding of the filter and the transformer. Issues such as displacement of voltage levels, potentially dangerous to the integrity of the filter, converter and motor, along with the behavior of the common mode quantities in the system, are also evaluated. A comprehensive case study covering such aspects was conducted in Matlab / Simulink® through the appropriate modeling of the whole system. The results and corresponding conclusions are shown in detail throughout the paper.

Keywords - Common mode quantities, filter connection, inverter output filters, medium-voltage drive systems, transformer grounding.

I. INTRODUCTION

The effects of undesired harmonic distortion in the supply voltage of motors have been identified a long time ago, characterized as oscillations in the developed electromagnetic torque and additional losses both in the core and windings of the machine, which raises its temperature of operation and reduce its life time [1].

Historically, the replacement of the “six pulses” switching by PWM, as well as the gradual and continuous increase of the switching frequency of the latter, allowed the generation of voltage waveforms much more suitable for the motor supply, since the harmonics components are shifted to increasingly higher frequencies, for which the input impedance of the machine is proportionally higher. Commercial low-voltage frequency converters currently operate at frequencies up to 10 kHz [2], what virtually eliminates the problems mentioned in the previous paragraph.

However, medium voltage converters, due to technological limitations, typically operates at frequencies corresponding to a few hundreds Hz [3]. Thus, low-order harmonics are synthesized by the converter and applied to the motor, subjecting the latter to the problems discussed above.

In such cases, the solution typically adopted is the use of filters at the output of the inverter bridge, which substantially reduces the THD of the voltage applied to the motor, allowing it to run safely and optimally. Moreover, such filters also eliminate the high frequency components associated to the pulses rise time, which interact with the converter-to-motor cable and generate transient overvoltages at the machine terminals, oscillating current peaks at the inverter output and several other problems [4-9].

In this paper, the operation of output filters for medium voltage converters will be evaluated on aspects such as (i) filtering performance, (ii) voltage level displacement and (iii) the behavior of the common mode voltages and currents present in the system for situations involving (i) faults in the filter output, (ii) different types of filter connection and (iii) different ways of grounding the filter and transformer.

Concerning the analyzed system, especially with regard to the topology and other characteristics of the filter, more details can be found in [10]. All cases were simulated in Matlab / Simulink® platform, using sophisticated models [7, 11], appropriate for the study in focus.

II. SYSTEM OPERATION UNDER NORMAL CONDITIONS (WITHOUT FAULT)

All situations covered in this section consider the system operating under normal conditions, i.e., without the occurrence of faults. However, among the cases studied, the configurations of the grounding and connection of the filter are different, as described in each item. The topology of the filter under study is shown in Fig. 1.
A. Case 1 – Operation under normal conditions; filter with star connection

This situation corresponds to the base case, whose results serve as reference for comparison with the other situations evaluated in the next items. In this case, the system operates with the filter connected in star without any connection to the ground or to the midpoint of the converter DC bus. Furthermore, there is no occurrence of a phase-to-ground fault in the cable connecting the motor to the filter. Figure 2 illustrates this situation.

Figures 3-6 show the waveforms of the inverter and filter output voltages, along with the corresponding harmonic spectrum. Figures 4 and 6 show the THD of the output voltage of the inverter and filter, whose values are approximately 33.0 and 4.5 %, respectively. These results show that the filter operates efficiently in the differential mode, eliminating both the switching harmonics and the very high frequencies associated to the pulses rise time.

However, it is possible to notice, by means of Fig. 7, that the filter has no influence on the common mode voltage generated by the inverter. Thus, the grounding of the neutral point of the filter, without the addition of a limiting impedance, becomes impractical due to the prohibitive currents that would flow to the ground, generated by the high-level common mode voltage. Moreover, it can be concluded that the filter has no effect on the reduction of the common mode currents that will flow through the parasitic capacitances of the cable, converter and machine to the ground, generated by the fast voltage variations of the common mode voltage.

Figure 8, which refers to the converter DC bus voltage (positive, negative and medium points), allows, indirectly, the analysis of the voltages in the components inside the inverter bridge. Thus, this result may be used as reference for the subsequent cases, enabling the observation of displacements and voltage levels potentially dangerous to the integrity of the converter. It is worthy to mention that, as a result from the reference that was used in the simulations for the voltage measurement, all the obtained voltages present an offset equal to VCC / 2, as can be easily observed in the curve corresponding to the midpoint of the DC bus voltage (blue) in Fig. 8.

It is worth to stress that similar results were obtained when the filter star connection was replaced by the “hydrid”, illustrated in Fig. 9.
B. Case 2 – Normal operation and filter with star connection, whose neutral is connected to the DC bus through a limiting resistor

In this case, the system operates with the filter connected in star, being its neutral point connected to the midpoint of the converter DC bus through a 60 kΩ resistor. As in the previous case, there is no fault occurrence in the output of the filter; this situation is illustrated in Fig. 10.

For this type of filter connection, the harmonic distortion of the phase-to-phase voltage at both the inverter and filter output remained similar to that of the previous case (Figs. 4 and 6), i.e., the filter performance was not affected by this changing of its connection.

It was observed that the DC bus voltages (positive, negative and neutral), as well as the phase voltages at the inverter output, showed no significant variations in relation to the results obtained in the previous case. With regard to the motor and the filter neutral point voltage, both remained similar to those observed in the previous situation (Fig. 7).

The insertion of the 60 kΩ resistor is intended to limit the current flow between the neutral point of the filter and the converter DC bus. If there is no ohmic value added within this connection, such current would present a prohibitive magnitude, as shown in Fig. 11. However, the levels of the common mode voltage would not alter significantly, but only the profile of its oscillations, as can be seen by comparing Figs. 7 and 12.

III. SYSTEM OPERATING UNDER FAULT CONDITIONS

All situations evaluated in this item include the occurrence of a fault-to-ground in the connection between the cable and the motor. However, similar results would be obtained if the short circuit was located at any other point after the inverter output; in this way, the conclusions presented here can be extended to such situations.

C. Case 3 – Filter in star connection with its neutral point connected to the DC bus through a limiting resistor

This case is similar to that studied in the previous item, except for the faulty condition of the system. Figure 13 depicts this situation.

In this operating condition, the results for the filtering performance were close to those obtained in case 1, i.e., with the filter working efficiently in the differential mode and not having any effect on the magnitude of the common mode quantities.

However, due to the operation of the system under fault, the investigation of the voltage levels at the motor, DC bus and the inverter bridge terminals is necessary.

Figure 14 reveals that isolation problems between the neutral and the motor frame may arise, since the common mode voltage follows the voltage variations of the faulty
phase, thus presenting an amplitude equal to the system phase-to-neutral voltage.

Figure 15 shows that the phase voltages at the inverter output reach very high levels, alerting for potentially harmful voltage magnitudes within the inverter bridge; therefore, a more detailed analysis regarding the voltage distribution on its internal components is recommended.

Furthermore, as can be seen in Fig. 16, the converter DC bus voltage becomes modulated by the voltage of the faulty phase, reaching high amplitudes. This suggests potential problems with regard to the insulation-to-ground of capacitor terminals, busbars, connections in general, etc.

However, it is noteworthy that although the system be operating under phase-to-ground fault conditions, the phase-to-phase voltage at the inverter and filter output and at the motor terminals remained the same of those corresponding to the normal operation of the system.

For the sake of illustration, Fig. 17 shows the voltage between phases "a" (faulty) and "b" at the inverter bridge output. It may be noted that this result is similar to that shown in Fig. 2.

D. Case 4 – “Hybrid” connection of the filter

In this situation, the system operates under fault, being the filter in “hybrid” connection, and, therefore, without any connection to the ground or to the midpoint of the converter DC bus. This case is represented by Fig. 18.

Fig. 18. Diagram representing the system operating according to case 4.

All results for this case are quite similar to those concerning the filter in star, connected to the DC bus by means the limiting resistor (case 3), thus dismissing their presentation.

E. Case 5 – System operating with grounded transformer secondary through an impedance and filter connected in star, with or without grounding

The operating conditions associated with this item are illustrated by the diagram of Fig. 19, where the secondary winding of the transformer is grounded through a 4 kΩ resistor, in order to limit the short-circuit current.

Fig. 19. Diagram representing the system when operating under the conditions of case 5.

For this situation, when the filter is ungrounded, it was observed that, despite the huge change in the faulty phase voltage (Fig. 20), both the amplitude and the waveform of the voltage between phases at the inverter and filter output, as well as at the motor terminals, are equivalent to those of normal operation. In addition, the filter performance was not altered, so that the THD of the filter output phase-to-phase voltage remained around 4.5%. Moreover, it is worthy to mention that the grounding resistor of the transformer limited the short-circuit current values below 1.5 A, as shown in Fig. 21.

Figure 22 shows that the harmonic orders present in the short-circuit current are those multiple of three, which are of
zero-sequence, as expected. Moreover, as shown in this same figure, the THD becomes 6.8 % for the phase-to-phase voltage involving the faulty phase and 9.4 % for the voltage between the non-faulty phases.

When considering, for the present case, the grounding of the filter neutral, changes in its phase-to-phase voltage appear. As shown in Figs. 23 and 24, in this case there is a degradation in the filter performance. The available voltage for the motor shows higher levels of harmonic distortion than those observed in all previous cases.

Since the phase-to-ground fault was imposed on phase “a” and the filter neutral is grounded, there is no voltage applied to the filter branches belonging to phase “a”. Thus, their current becomes zero. In this way, the current in the other phases of the filter branches increases, warning about possible damage of their components, as shown in Fig. 25, corresponding to phase “b”.

Fig. 20. Waveform of the faulty phase voltage at the inverter output for (i) operation without fault (in black) and (ii) short-circuit (in blue).

Fig. 21. Current flowing to the grounding point of the transformer.

Fig. 22. Harmonic spectrum of the current in the grounding of the transformer.

Fig. 23. Voltage between phases “a” and “b” after the filter (THD = 6.8%).

Fig. 24. Voltage between the non-faulty phases (THD = 9.4%).

Fig. 25. Current in phase “b” in the first branch of the filter: (i) operation without fault (in blue) and (ii) short-circuit (in black).

IV. SYSTEM CONFIGURATION FOR THE COMMON MODE VOLTAGE ELIMINATION

As a further study, an additional analysis was conducted with respect to the system illustrated in Fig. 18: the fault was eliminated and the common mode voltage was measured in the grounded filter terminals, which was compared to that corresponding to case 1 (filter and transformer ungrounded).

When the transformer is grounded (through an impedance in this case), the common mode voltage applied to the cable/motor is cancelled (Fig. 26), eliminating the common-mode current circulation in the system. Since these currents are responsible for several undesired phenomena [6, 9, 11], this configuration shows to be quite advantageous from the standpoint of eliminating such high frequency problems.
In this paper, output filters for medium voltage were evaluated from the viewpoint of electromagnetic compatibility and the system supportability to faults. In each of the case studies, results from computational analysis covered the following aspects:

(i) Filtering performance for different grounding conditions for both transformer and filter, and also under faults;
(ii) Behavior of the common-mode voltages and currents in different parts of the system, for several filter connections and also under short-circuit conditions;
(iii) Analysis of quantities at the input and output of the inverter bridge, in order to observe possible prohibitive voltage levels and potential damage of its components integrity.

The comments and conclusions presented in each studied case represent important information for the characterization of the system operation from the perspective of EMC, integrity of its components and operational continuity.

REFERENCES


