

The Occurrence of Faults in Permanent Magnet Synchronous Motor Drives and its Effects on the Power Supply Quality

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Abstract. The non-sinusoidal current drawn by variable speed drives has increase the concern about its effects on the distribution system power quality. On the other hand, electrical drives based on permanent magnet synchronous motors have become serious competitors against induction motors drives. This paper presents a study of the effects on the power supply quality due to the occurrence of faults in a permanent magnet synchronous motor drive. Only single open-circuit faults in the inverter are considered.

Key words

Power quality, harmonics, total harmonic distortion, power factor, permanent magnet synchronous motor drives.

1. Introduction

Power quality can be described as a certain condition of voltages and currents in the distribution network, absence of which can have a deleterious effect on utility as well as the consumer. With the exception of disruptions due to natural causes and stray accidents, the voltage generated and distributed by the utilities should have the desired shape and magnitude. Therefore, the only power quality issues were expected to be simply avoidance of transformer saturation and resonance at line frequency and also some displacement power factor correction measures to offset the tendency of linear reactive loads such as motors to introduce a phase difference between current and voltage [1].

However, the last few decades saw a definite change in the dynamics of consumer loads. The loading pattern has moved from simple linear loads to non-linear solid-state converters such as the devices used in variable speed/frequency drives. These became very popular in the last decades and are, nowadays, widely used in industry. An issue, however, that is giving increasing cause for concern is the harmonic distortion of voltage supplies caused by the non-sinusoidal currents drawn during the power conversion process inside drive converters. In general, the source of these current harmonics is the front-end 6-pulse uncontrolled rectifier

using either a full-wave diode or an SCR bridge followed by a large electrolytic capacitor [2], as shown in Fig. 1. This is the standard power circuit elementary configuration for most variable frequency drives with diode bridge rectifiers sold in the marketplace today.

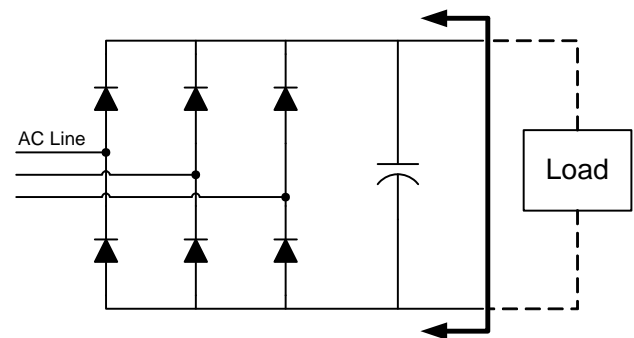


Fig. 1. Typical 6-pulse front-end converter for AC drives.

After one half cycle, the DC bus capacitors are charged to the peak of the AC voltage sine wave. The connected motor draws current from the DC bus to supply power to the load requirements.

Three-phase harmonics occur when incoming AC voltage is rectified by the three-phase full wave diode bridge, which charges the capacitor banks in the DC bus. As the motor draws the voltage from the DC bus supply, the potential on the capacitors is less than the incoming line voltage. Before reaching a lower regulated limit, the DC bus capacitors recharge again in the next half cycle of the voltage sine wave to the peak. This process is repeated twice in each peak of the sine wave from the process of continuously charging and discharging of the DC bus capacitors [3]. The capacitors draw a pulse of current (non-linear load) only during the first and second half peak of the voltage sine wave.

The degree and magnitude of the harmonics created by the variable frequency drive are a function of the drive design and the interrelationship of the non-linear load with the connected distribution system impedance. The power source line impedance ahead of the controller will determine the magnitude and amplitude of harmonic currents and voltages reflected back into the distribution

system. The distorted current reflected through the distribution impedance causes a voltage drop or harmonic voltage distortion. This relationship is proportional to the distribution system available fault current and to the industrial distribution system impedance design.

High levels of harmonic content can lead to overheating and destruction of power factor correction capacitors, overheating of cables, additional risk of failure due to resonance, overheating of transformers and fixed-speed electric motors, spurious tripping of electrical circuit breakers and interference with electrical, electronic and control system equipment [3]-[4]. Due to these negative consequences, building design and equipment specifications often require compliance with some standards which provide guidelines and acceptable limits of harmonic current and voltage distortion allowed back into the public power system [5].

Another parameter that is related to the supply network quality is the power factor. The typical 6-pulse front-end converter used in the majority of variable speed drives has an inductive power factor. As a result, the current tends to be higher than the current actually needed, and an excessive load current represents a loss for the consumer, who not only pays for the over-dimensioning of the cable, but also for the excess power loss in the cables [6]. Therefore, with power factor correction it is possible to reduce the amount of electric power used, increase the system capacity, reduce de heat losses and improve voltage quality [7].

The most common variable speed drives are based in induction motors. However, permanent magnet synchronous motors (PMSM) have been recently considered as an attractive alternative to the use of induction motors. Due to the replacement of the electromagnetic excitation with permanent magnets, this kind of motors has higher efficiency, electromagnetic torque and power density [8]-[9].

This paper presents a study on the occurrence of open-circuit faults in the inverter power switches of a 6-pulse static power converter, which feeds a PMSM (Fig. 2), and its effects on the power supply quality. Only single fault occurrences are considered.

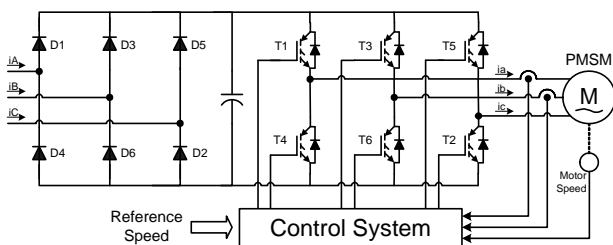


Fig. 2. Structure of the PMSM drive system.

2. Modelling and Simulation

The modelling and simulation of the PMSM drive system was developed in the Matlab/Simulink environment, in association with the Power System Blockset.

The permanent magnet synchronous motor mathematical model is similar to the mathematical model of a conventional synchronous motor with electromagnetic excitation, assuming that saturation is neglected, electromotive force is sinusoidal, eddy currents and hysteresis losses are negligible, and that there are no field currents dynamics and a cageless rotor [8]-[9]. The PMSM drive control system is basically comprised by an outer speed loop and an inner current loop (Fig. 3). Good dynamic performance is achieved controlling the PMSM like a separately excited DC motor by the implementation of vector control. Hysteresis current controllers generate the six pulse signals to command the inverter power switches, maintaining the three currents within a hysteresis band.

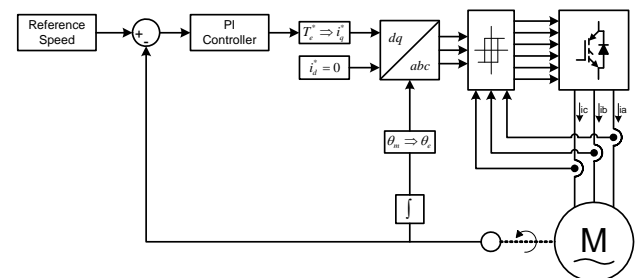


Fig. 3. PMSM drive control system bloc diagram.

A. Normal Operation

Under normal operating conditions, the characteristic harmonics of supply currents are related to the rectifier pulse number and can be determined by:

$$h = np \pm 1 \quad (1)$$

where h are the harmonics generated, n is an integer (1, 2, 3,...) and p is the rectifier pulse number. Consequently, for a 6-pulse rectifier converter, the supply current will have harmonics of order 5, 7, 11, 13, 17, 19 and so on. Fig. 4 presents a time-domain supply current waveform and its respective spectrum, obtained by simulation of a 2.2 kW, 4-pole PMSM at 600 rpm and at half nominal load torque.

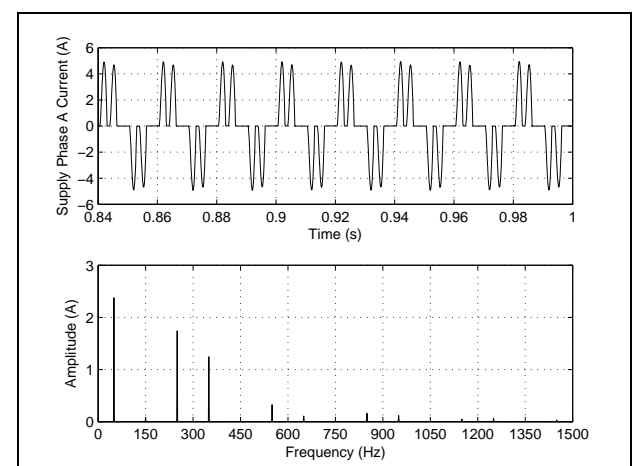


Fig. 4. Simulated results of mains supply phase A current, under normal operating conditions.

The typical line current waveform is narrow with high amplitude pulses due to the charging of the DC link capacitor and it is possible to identify the harmonics given by Eqn. 1.

In order to analyse the impact of harmonic content in the quality of the current, the Total Harmonic Distortion (THD) can be used. This parameter is given by:

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_1} \quad (2)$$

The values of this parameter for each mains supply current are presented in Table 1.

Table 1 – Simulated THD values of mains supply currents under normal operating conditions.

	Phase A	Phase B	Phase C
THD (%)	91.67	91.30	92.19

The simulation results show that the THD values of mains supply currents are approximately equal, because the supply system is almost perfectly balanced.

As mentioned before, the harmonic distortion of the mains supply current will depend on the drive design and its connection with the distribution system impedance. In a stiff system with high fault current, the distribution system impedance and voltage distortion is low and the harmonic current draw is high. On the other and, in a soft system the distribution system impedance and distortion is high and the harmonic current draw is low.

Fig. 5 presents the time-domain evolution of the power factor on the mains supply side.

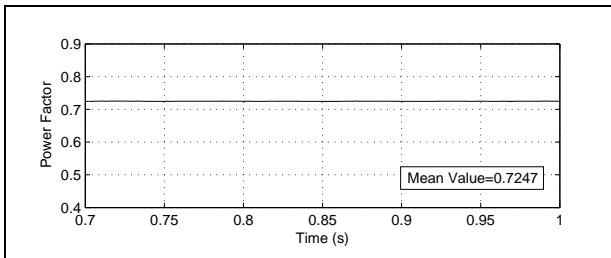


Fig. 5. Simulated results of power factor on the mains supply side, under normal operating conditions.

During normal operating conditions, the power factor on the mains supply side is constant with a mean value equal to 0.7247. This parameter value is strongly dependent on the PMSM load. If the machine load increases, the power factor will also increase.

B. Faulty Operation

In order to simulate an open-circuit fault in one inverter power switch, the gate command signal for transistor T1 is removed. The results of supply phase A current waveform and its respective spectrum under these conditions, are shown in Fig. 6.

This fault in the machine-side converter will be reflected in the normal DC link current pattern, introducing other harmonic components dependent on the machine speed. Although the currents in the PMSM phases are different, the mains supply currents will keep a similar waveform, containing interharmonics related to the motor speed.

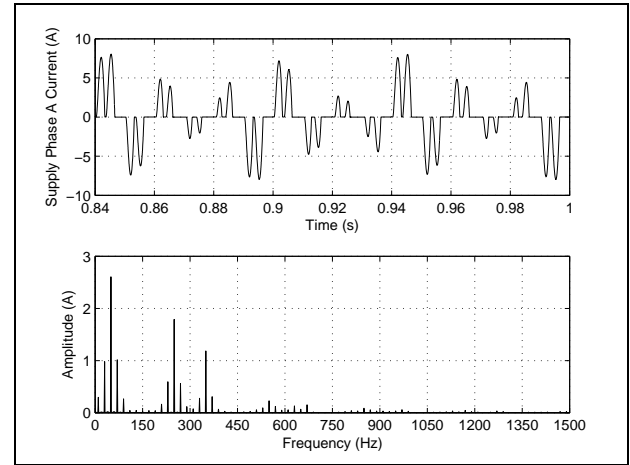


Fig. 6. Simulated results of mains supply phase A current with an open-circuit fault in transistor T1.

In the phase A current spectrum it is possible to identify these kind of harmonics. They are placed around the main harmonic components, at a distance related to the PMSM supply currents frequency. These interharmonics orders can be determined by:

$$i = h \pm n \frac{f_m}{f_s} \quad (3)$$

where i is the interharmonic order, h are the harmonics given by Eqn. 1 including the fundamental, n is an integer (1, 2, 3,...), f_m is the PMSM currents frequency and f_s is the mains supply frequency. So, for a speed of 600 rpm, interharmonics will appear at distances multiple from f_m (20 Hz), around the main components.

The THD values of the mains supply currents under this faulty operation are shown in Table 2.

Table 2 – Simulated THD values of mains supply currents with an open-circuit fault in transistor T1.

	Phase A	Phase B	Phase C
THD (%)	107.39	107.86	107.30

Comparing with the simulated results under normal operating conditions shown in Table 1, an increase of about 17% is obtained in the THD values. Subsequent simulation results demonstrate that the operation with higher PMSM load torque leads to a higher variation in THD results. On the other side, low load levels leads to a smaller variation in THD values between normal and faulty operation.

An open-circuit fault in the inverter leads to the appearance of oscillations in the time-domain evolution

of the power factor on the mains supply side, as shown in Fig. 7. The fundamental frequency of these oscillations is equal to the motor supply currents frequency f_m .

Comparing the power factor mean values under both operating conditions, the occurrence of the fault has a negative impact, reducing the power factor mean value by 4.23%. This variation is less significant under low load conditions.

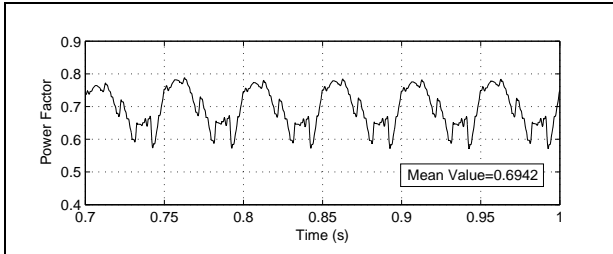


Fig. 7. Simulated results of power factor on the mains supply side, with an open-circuit fault in transistor T1.

A complete simulation proves that a single fault in any of the other five inverter semiconductors doesn't have a strong influence in the mains supply currents waveforms. Therefore, for faults in any other inverter power switch, the results are similar to the previous ones.

3. Experimental Results

A laboratory prototype for the aforementioned permanent magnet synchronous motor drive was implemented. A machine with 2.53 kW, 200 V, 50 Hz and with four poles was used.

This prototype was prepared for a digital control based on a personal computer, equipped with a National Instruments PCI 6071E board and a standard parallel port. The main control program was developed with Matlab, namely through the Simulink, Real-Time Workshop, and xPC Target toolboxes. All necessary signals for the control strategy implementation were acquired by both voltage and current probe sensors through the PCI 6071E board. The command signals of the controlled power switches were sent by the PC using the standard parallel port. Under both normal and faulty operating conditions, the PMSM reference speed was configured to 600 rpm.

Another instrumentation system based on a PC was used to acquire voltage and current signals on the mains supply side, with appropriate sensors.

A. Normal Operation

The experimental results related to the mains supply phase A current under normal operating conditions are illustrated in Fig. 8.

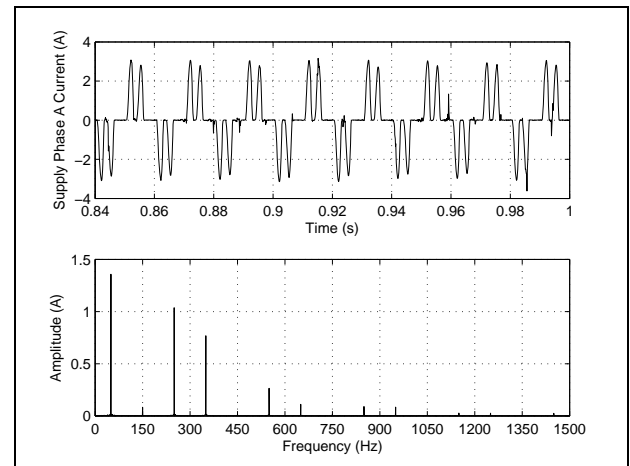


Fig. 8. Experimental results of mains supply phase A current, under normal operating conditions.

Comparing with the simulated results in Fig. 4, the obtained experimental results are very similar. All the harmonics orders are in accordance with the theoretical expression given by Eqn. 1.

The experimentally obtained THD results, presented in Table 3, show a noticeable unbalance in the mains supply system because these three values, ideally, should be equal.

Table 3 – Experimental THD values of mains supply currents under normal operating conditions.

	Phase A	Phase B	Phase C
<i>THD</i> (%)	98.55	103.04	105.67

As for simulation, the time-domain evolution of the experimentally obtained results of the power factor on the supply side during normal operating conditions (Fig. 9), is almost constant with a mean value equal to 0.6739. In relation with the results in Fig. 5, the experimental mean power factor is lower due to the fact that the PMSM load torque is also lower.

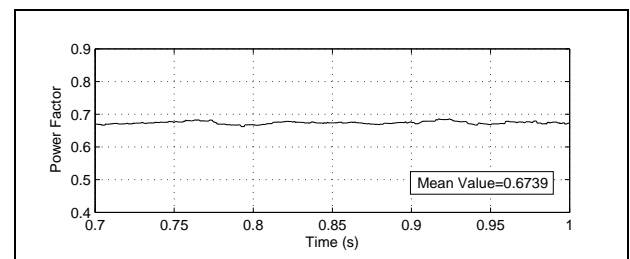


Fig. 9. Experimental results of power factor on the mains supply side, under normal operating conditions.

B. Faulty Operation

Experimental faulty operating conditions were achieved by removing the gate signal to transistor T1. This was simply implemented in the control program by setting to zero the corresponding T1 command signal at a specific time instant.

The results of supply phase A current waveform and its respective spectrum under these conditions, are shown in Fig. 10.

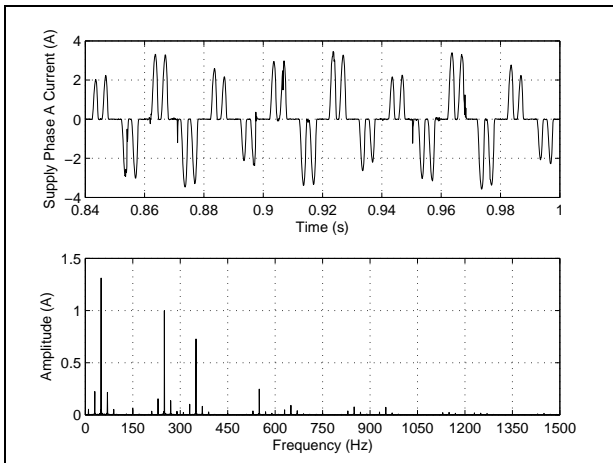


Fig. 10. Experimental results of mains supply phase A current with an open-circuit fault in transistor T1.

Besides the presence of the harmonics related to the unbalanced supply system, in the supply phase A current spectrum, it is possible to verify the existence of harmonics and interharmonics with their correspondent order given by Eqn. 1 and Eqn. 3, respectively. The interharmonics amplitudes will be higher as higher the machine load level.

As for the experimental THD results under normal operating conditions, the values in the Table 4 also show that the supply system is not balanced. However, due to the occurrence of an open-circuit fault in one of the six converter power switches, the supply currents THD values will suffer an increase, as theoretically predicted. Comparing with THD values under normal operating conditions, the fault occurrence introduces an average increase of about 6.62% in the supply currents distortion. As previously mentioned, this variation is proportional to the PMSM load torque.

Table 4 – Experimental THD values of mains supply currents with an open-circuit fault in transistor T1.

	Phase A	Phase B	Phase C
THD (%)	103.35	110.82	113.52

At last, Fig. 11 presents the experimental results of the time-domain evolution of the power factor on the mains supply side under faulty operating conditions.

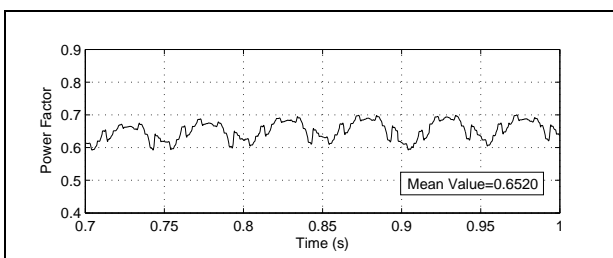


Fig. 11. Experimental results of power factor on the mains supply side, with an open-circuit fault in transistor T1.

The power factor evolution with an open-circuit fault in the power converter is not constant as in normal operating conditions. Instead, it will have oscillations as a consequence of the oscillating electromagnetic torque developed by the PMSM. Comparing the power factor mean value under both situations, the open-circuit fault in the converter causes a reduction of about 3.25%.

4. Conclusions

The results obtained and presented in this work show that the occurrence of an open-circuit fault in a transistor of the power converter of a PMSM drive will have a negative impact on the power supply quality. Under these operating conditions, interharmonics will be injected into the supply network which may lead to the need of installing power filters in order to reduce or eliminate them. The harmonic content injected into the supply system depends on the drive design, its connection with the distribution system impedance and its load operating conditions.

Operation under these fault conditions will also affect the power factor on the mains supply side, reducing its mean value and bringing more disadvantages, especially in facilities with no power factor correction equipment. Besides this fact, the resulting oscillation in the power factor may also have adverse effects on the supply system.

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