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Inter Turn Fault Analysis of a Permanent Magnet Machine Using Finite Element

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ABSTRACT

In critical applications, such as aerospace and military, the reliability of a permanent magnet machine is quite important. Inter turn short circuit fault has been classified as one of the worst faults that may occur in the machine winding. In this paper, a l20kW permanent magnet machine is used to study the effect of partial inter turn short circuit. A single tum short circuit is shown to be the most serious case. Hence, a remedial action is taken by shorting the whole winding involved in the single turn fault. Finite element is used to predict steady state currents of shorted single tum and rest of turns. Although shorting the whole winding significantly reduces the shorted single turn current, it is still many times greater than the rated value.

Keywords: *Fault tolerance, Finite Element, Permanente magnet machine, Turn faults.*

1. INTRODUCTION

Permanent magnet synchronous machine PMSM is quite similar to the conventional synchronous machine except that the rotor is excited by permanent magnets instead of the normal field windings. Hence, the field current excitation is assumed to be constant. Because of its high power density as well as high efficiency, PMSM is becoming more recognized in many applications [1].

In critical applications such as aerospace applications where any type of fault may lead to a disaster, reliability is extremely important. According to *Mecrow, B.C.et al*., faults in PMSM may either occur inside the machine itself or within the power converter circuit [2]. Another paper [3] classified open and short circuit faults as primary faults and introduced secondary class of faults which may occur as a result of the primary ones. These secondary faults include permanent magnet and shaft bearing faults. In general, PM machines should be designed to have a very good level of fault tolerance. According to [2], phases of a fault tolerant machine should be electrically, magnetically, thermally and physically isolated.

Moreover, the machine, if possible, should be designed with one per unit armature self-inductance in order to limit the steady state current to one per unit in case of a phase terminal short circuit. However, it has been proved that a partial inter turn short circuit can cause fault current many times greater than the rated value [4]. Thus, a remedial action must be taken in order to avoid a permanent damage of the machine and discontinuity of its operation.

This paper studies the consequence of partial inter tum short circuit in PMSM. The study considers the effect of number of turns being shorted as well as their locations in the slot. In addition, the effect of remedial action is investigated. The analysis is done by two dimension finite element 2DFE simulation.

2. THE 120KW PM MACHINE

A l00kW fault tolerant PMSM was designed and constructed by *Atkinson,G.J*, for the degree of engineering doctorate at Newcastle University , England [5]. Based on this machine, a new design has been made in order for the machine to deliver 120kW. *MagNet* software (2DFE) is used to achieve the new design. Table 1 summarizes the main parts of the design while the materials used in the model are listed in Table 2.

Table 1: The 120kW PMSM design data

Motor	Output power	120 kW
	Rated speed	30000 rpm
	Rated Current at 125 Vrms, 3 phases on	320 Arms
Stator	Phases	4 isolated phases, one coil per phase
	Teeth	Eight, four wound , four spacer
	Bore	80 mm
	Stack length	81 mm
	Outer diameter	166 mm

Rotor	Magnet arrangement	6 pole halbach array , 2 magnets per pole
	Active length	81 mm
	Magnet diameter	71 mm
	Rotor diameter	76 mm
Windings	Turns	10 Turns / phase
	Copper cross section	13.2 mm²

Table 2: Materials for the 120kW PMSM parts

Part name	Material type
Stator core back and teeth	0.35mm Rotelloy 3 Cobalt iron [6]
Magnet	Samarium Cobalt Sm2Co17 (Recoma® 28) Residual flux density = 1.1 Tesla Demagnetization flux density = 0.265 Tesla [7]
Windings	Insulated 260 strand using copper 5.77e07 Siemens/m
Rotor sleeve	Inconel 718, 2.2mm thick
Rotor shaft	Grade 303 – S – 31 stainless steel

The 120kW fault tolerant PM motor expected performance and characteristics have been predicted by using a 2DFE. Figure 1 shows the 2DFE model of the l20kW, 4-phase PMSM stator.

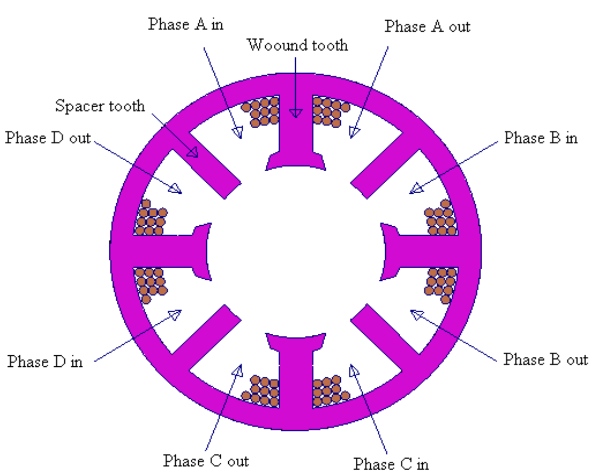

Figure 1: Stator 2DFE model of the 120kW machine.

The four phases of l20kW PMSM are physically, magnetically and electrically isolated. Each phase has a one per unit self-inductance and driven by a separate single phase bridge converter. This model has been used to study the effect of partial inter turn short circuit as detailed in the following sections.

3. MAGNETIC COUPLING TURNS

Since the four phases are magnetically isolated from each other, the mutual inductance between them can be neglected, For this reason, a single phase winding is only considered to predict the inter turn short circuit current. However, the magnetic properties of a single phase should be predicted first. Figure 2 shows a single phase of the l20kW machine designed in 2DFE.

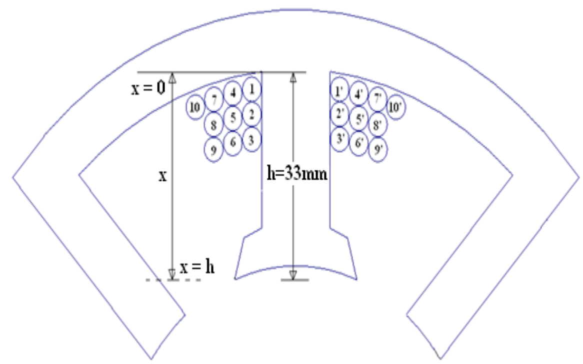

Figure 2: Distribution of Turns per phase in 2DFE.

The self and mutual inductances of each turn predicted by static 2DFE are shown in Table 3.

Table 3: 2DFE predicted self and mutual inductance of turns

Turn no.	Self inductance (µH)	Mutual inductance (µH)	Total inductance (µH)
1	0.601	4.12	4.72
2	0.527	4.06	4.59
3	0.492	3.85	4.34
4	0.538	4.10	4.64
5	0.487	4.01	4.50
6	0.454	3.78	4.23
7	0.503	3.99	4.49
8	0.460	3.88	4.31
9	0.431	3.61	4.04
10	0.487	3.75	4.24

Considering Figure 2 and Table 3 and starting by the highest inductance, turns are ordered as following: Turn 1 - Turn 4 - Turn 2- Turn 5- Turn 7- Turn 3 -Tum 8 - Turn 10 - Turn 6 - Turn 9. Therefore, the inductance is highest in the turn located in the outermost position (i,e. x=0) and lowest in the one located in the innermost position (i.e. x=h). In other words, the closer the tum is located from the slot opening, the less inductance it has. This is absolutely true if the turns are assumed to be uniformly distributed. In practice, however, turns are not uniformly distributed. Therefore, the variation of the self and mutual inductance with respect to the position (x) from the slot bottom is not a smooth linear line. This can be clearly seen in Figure 3 and Figure 4 where the self and mutual inductances of turns are both approximately sketched versus the position from the slot bottom.

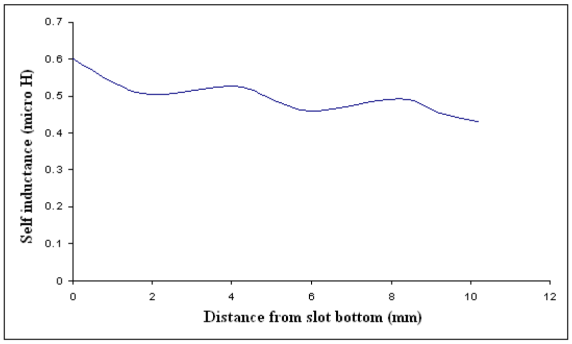

Figure 3: Variation of self-inductance of turn versus its position

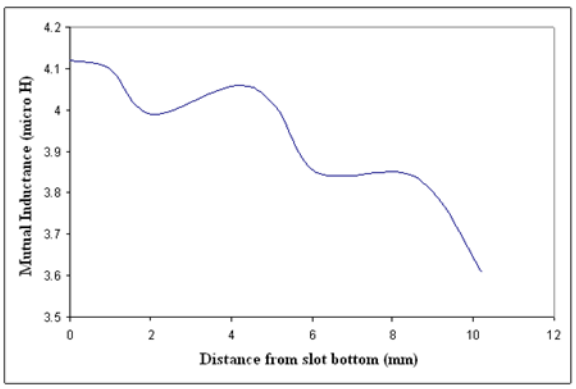

Figure 4: Variation of mutual inductance of turn versus its position.

Although the two figures show nonlinear curves, it can generally be noticed that the inductance decreases as the turn is farther from the slot bottom (i.e. closer to slot opening).

4. PREDICTION OF INTER-TURN SHORT CIRCUIT CURRENT

The equivalent circuit of a single phase of one coil can be represented as shown in Figure 5.

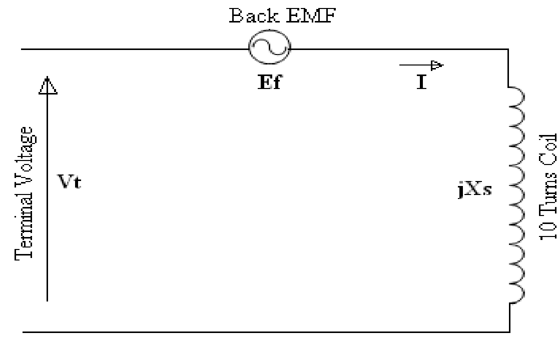

Figure 5: Equivalent circuit per phase

While the motor runs at rated speed and torque, a short circuit test has been carried out for each turn. As a fault tolerant machine, it is found that the current in the healthy turns is kept at rated value (i.e. 320Arms) and in phase with the Electromotive Force (EMF or Ef). However, the current in the shorted turn can be much higher than the rated value. Table 4 lists the 2DFE predicted values of steady state short circuit current in each of the Ten turns. The Table shows that the highest short circuit current occurs in turn 9 while the lowest one occurs in turn 1. Referring to the position of each turn as shown in Figure 2, it can be clearly observed that the worst case happens when the short circuited tum is closest to the slot opening. This observation has been analytically confirmed by *Chat, J. et al* [8]. Short circuit current in each turn with respect to its location is shown in Figure 6. Because of non-uniform distribution of turns in the slot, the curve in Figure 6 is not a smooth line.

Table 4: Short circuit current in single turn

Shorted turn no.	Steady state current (Arms)
1	3142
2	3507
3	3707
4	3504
5	3830
6	4043
7	3681
8	3963
9	4188
10	3726

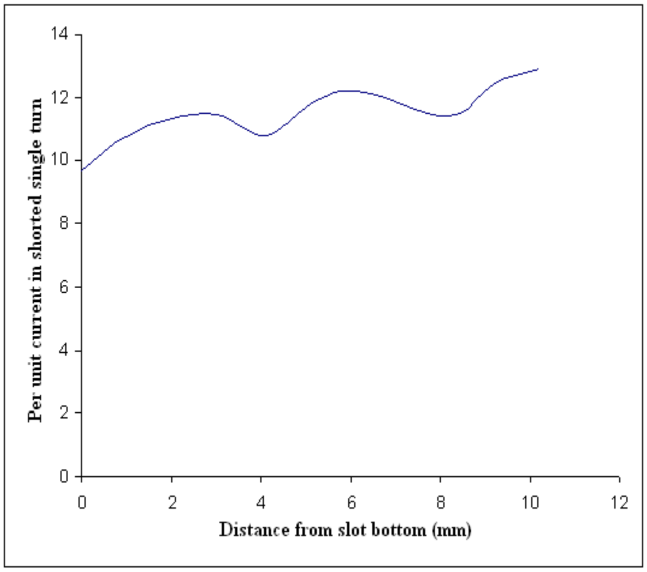

Figure 6: Variation of Current in Shorted Turn versus its position

In addition to the turn position, the number of turns being shorted affects the level of short circuit current. Turn 7, 8 and 9 are chosen to examine this effect. Turn 9 is firstly shorted and then 8 and 9 together and finally 7, 8 and 9 are all shorted. A comparison between the short circuit current under the three conditions is shown in Table 5.

Table 5: Short circuit current with different number of shorted turns

No. of shorted turns	Current (Arms)	Comment
Single turn only (turn 9)	4188	Short circuit current in the three turns is less by 37% than two turns and 69% than single turn.
Two turns (turns 8 and 9)	2023	
Three turns (turns 7 ,8 and 9)	1281	

Table 5 shows that short circuit current in the three turns is less by 37% than two turns and by 69% than single turn. In other words, the inter turn short circuit current is inversely proportional to the number of turns being shorted. The fault current driven by the back EMF is limited by the reactance of faulty turns. More shorted turns means higher reactance and hence less fault current. Therefore and as it has been concluded by [9], single shorted turn is the worst case. Figure 7 illustrates the current waveforms for the three cases listed in Table 5.

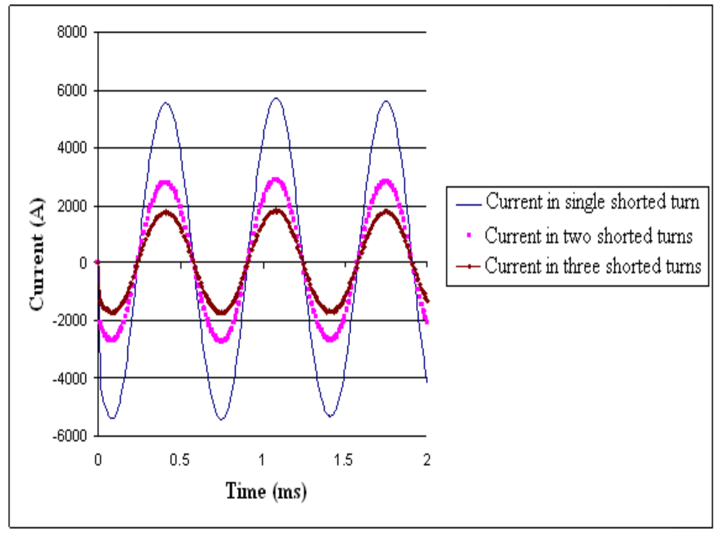

Figure 7: Currents in different number of short circuited turns.

By reconsidering Figure 6, it can be seen that short circuit current in single turn is almost 10 to 13 times the rated value. Therefore, if no recovery action is taken, the winding insulation could be degraded and the reliability of the machine will be compromised.

The following section discusses the type of remedial action which should be taken and its effects.

5. INTER-TURN SHORT CIRCUIT ANALYSIS AFTER APPLICATION OF BALANCED SHORT

Once inter turn short circuit is detected, a balanced short should be applied [4] - [10].i.e. the whole winding involved in the fault is shorted at the machine terminal. Thereafter, the shorted turn and the rest of turns are supposed to carry equal currents assuming that they are uniformly distributed. The validity of this assumption has been investigated by applying 2DFE prediction to the ten turns coil shown in Figure 2 earlier. Due to its most risk, the case of single turn short circuit is considered. The equivalent circuits representing the single shorted turn and the healthy nine turns after application of balanced short are shown in Figure 8. The self-inductance of the shorted single tum is represented by **Ls** while **Lh** denotes to the self-inductance of the nine healthy turns and **Lm** stands for the mutual coupling between them. Since the resistance is very small and has very minor effect, it can be neglected. Equivalent circuits (a) and (b) are both for Figure 8.

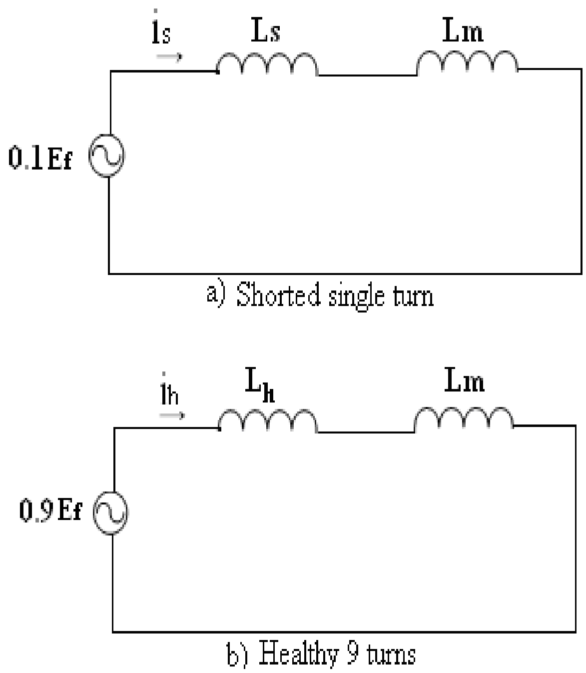

Figure 8: Equivalent circuits after application of balanced short

From circuits (a) & (b) operating at 30000 rpm (i,e. 1500 Hz),

$$\begin{bmatrix} 0.1E_f \\ 0.9E_f \end{bmatrix} = j2\pi f \begin{bmatrix} L_s & L_m \\ L_m & L_h \end{bmatrix} \begin{bmatrix} i_s \\ i_h \end{bmatrix} \quad (1)$$

Where $E_f, i_s \& i_h$ stand for Back EMF, shorted turn current and healthy remaining turn current respectively. If the ten turns are assumed to be uniformly distributed within the slot area and the total inductance of them is presented by **L**, then,

$$\begin{bmatrix} 0.1 \\ 0.9 \end{bmatrix} E_f = j2\pi f L \begin{bmatrix} \frac{1}{10^2} & \frac{9}{10^2} \\ \frac{9}{10^2} & \frac{9^2}{10^2} \end{bmatrix} \begin{bmatrix} i_s \\ i_h \end{bmatrix} \quad (2)$$

OR

$$0.1E_f = j2\pi f L\,(0.01i_s + 0.09i_h) \quad (3)$$

$$0.9E_f = j2\pi f L\,(0.09i_s + 0.81i_h) \quad (4)$$

Adding (3) to (4) yields,

$$E_f = j2\pi f L\,(0.1i_s + 0.9i_h) \quad (5)$$

But $E_f = j2\pi f L i$ and hence,

$$i = 0.1i_s + 0.9i_h \quad (6)$$

i is the total current flowing in the circuit during the short circuit event. In other words,

$$i = i_s + i_h \quad (7)$$

Equations (6) & (7) are true if and only if $i_s = i_h$. This implies that the shorted single turn and rest of winding should carry the same current after application of balanced short assuming winding uniform distribution. In practice, however, the ten turns are not uniformly distributed in the slot and therefore the current in the shorted single turn is expected to be different from the current in each the nine remaining turns. The percentage of difference depends on the location of the shorted turn in the slot. Theoretically, currents i_s & i_h can be found by (8) given that X is the reactance which is equal to $2\pi f L$.

$$\begin{bmatrix} i_s \\ i_h \end{bmatrix} = j \begin{bmatrix} X_s & X_m \\ X_m & X_h \end{bmatrix}^{-1} \begin{bmatrix} 0.1E_f \\ 0.9E_f \end{bmatrix} \quad (8)$$

2DFE predicted values of **Ls**, **Lh** and **Lm** at each short turn condition are shown in Table 6.

Table 6: 2DFE predicted inductance of each turn, rest of turns and mutual between them

Shorted turn no.	**Ls** (µH)	**Lm** (µH)	**Lh** (µH)
1	0.601	4.12	35.3
2	0.527	4.06	35.5
3	0.492	3.85	35.9
4	0.538	4.10	35.4
5	0.487	4.01	35.6
6	0.454	3.78	36.1
7	0.503	3.99	35.7
8	0.460	3.88	36.0
9	0.431	3.61	36.3
10	0.487	3.75	36.1

At rated speed, magnitude of steady state currents are calculated based on the 2DFE predicted inductances given in Table 6. They are also directly predicted by 2DFE. A comparison between the values obtained from the two methods is shown in Table 7 and Table 8 respectively. During calculations, it has been noticed that any minor change in one of the inductance, especially the inductance of healthy turns and mutual inductance, greatly affects the resultant current. Electrically, this can be explained by the sensitive relation between the inductance of the shorted turn and the inductance of rest of turns and how they are coupled during short circuit event. This relation is strongly dependent of the position of the shorted single turn within the slot.

Table 7: Steady state currents of the single shorted turn after applying balanced short

	Current in faulty single turn (Arms)		
Faulty turn no.	Calculated based on 2DFE inductance	2DFE directly predicted	% difference
1	548	560	2.2
2	610	600	1.6
3	574	576	0.4
4	876	854	2.5
5	509	494	3.0
6	1292	1311	1.5
7	135	134	0.74
8	936	907	3.1
9	1903	1967	3.4
10	872	892	2.3

Table 8: Steady state currents of the healthy turns after applying balanced short

	Current in each of healthy turns (Arms)		
Faulty turn no.	Calculated based on 2DFE inductance	2DFE directly predicted	% difference
1	397	409	3.0
2	401	405	1.0
3	266	267	0.4
4	433	428	1.2
5	387	375	3.1
6	190	196	3.2
7	344	341	0.87
8	225	233	3.6
9	134	139	3.7
10	235	240	2.1

Referring to the results presented in Tables 7 & 8 as well as the distribution of the ten turns shown in Figure 2, following points are observed:

a. A good agreement, between the calculated and directly predicted 2DFE currents, is observed within a maximum difference of less than 4%.

b. After applying a balanced short, Currents in the healthy turns are within the rated current (i.e. 320Arms) of the machine or slightly higher depending on the position of the shorted turn.

c. Even after application of balanced short, the shorted single tum and rest of turns don't carry equal current because of non-uniform distribution of them within the slot. The difference between the two currents is highest in the case of shorted turns 9 & 6 respectively. This is expected as turns 9 & 6 are much closer to slot opening than other turns.

d. Even after shorting the nine healthy turns, current in the shorted turn is still many times greater than the rated value. The variation of the current depends on the turn location with respect to the slot wedge. Faulty turns 6 & 9, in particular, have the most sever currents due to their closeness to the slot opening. In practice, however, it is not always possible to determine the faulty turn and hence the worst scenario ought to be assumed.

Figure 9 compares the steady state currents in the faulty turn obtained by calculations with currents directly obtained from 2DFE simulation. The two curves are sketched with respect to the turn position in the slot. Similarly, currents in the nine healthy turns are sketched in Figure 10.

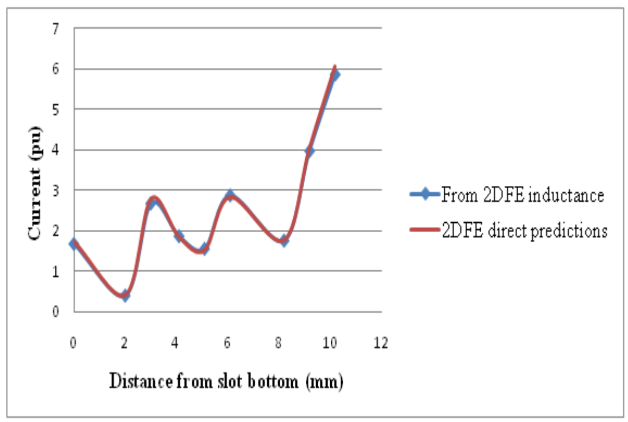

Figure 9: Variation of current in single faulty turn after applying balanced short

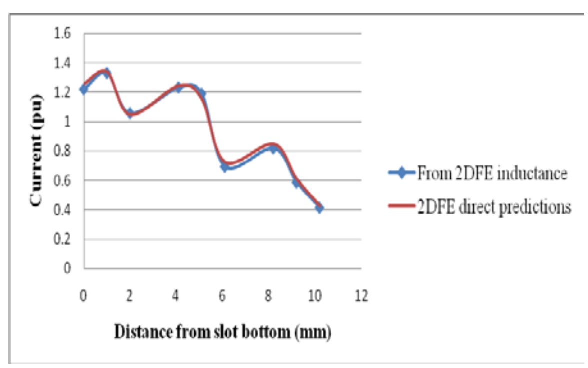

Figure 10: Variation of current in healthy turns after applying balanced short.

Compared to Figure 6, Figure 9 shows that the current in the faulty turn is reduced from the range of 10-13 times into a maximum of 6 times the rated current after balanced short is applied. Due to its closeness to the slot wedge, turn 9 is chosen to demonstrate the effect of balanced short. See Figure11.

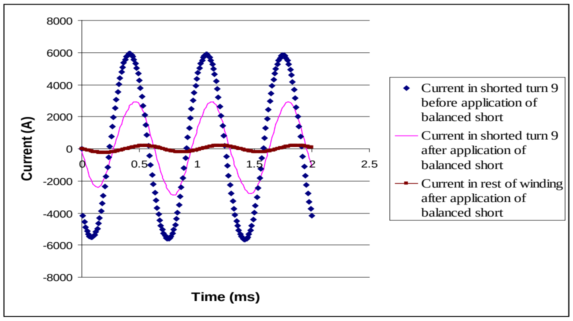

Fig.11. Single faulty turn predicted currents before and after application of balanced short.

6. CONCLUSION

The main target of this paper has been accomplished by testing a 120kW PM machine under inter turn short circuit. 2DFE has been used to predict the steady state short circuit current under different number of shorted turns. It has been confirmed that there is an inverse proportion between the short turn current and the number of turns being shorted and hence the worst case occurs when a single turn is shorted. When the motor runs at rated speed, the short circuit current in the faulty turn is many times greater than the rated value depending on the shorted turn position in the slot. The highest short circuit current occurs when the shorted turn is closest to the slot opening. However, the current in the rest of turns stays at the rated value.

When balanced short is applied by shorting the rest of the winding, the resulting current in the rest of winding is within the rated value or slightly varying with respect to the position of shorted turn. Although the shorted single turn current is significantly reduced by applying balanced short, it is still many times greater than the rated value and its value strongly depends on the location of faulty turn with respect to the slot wedge. The closer the shorted turn to the slot opening, the more short circuit current it carries.

Since the single turn short circuit current is still dangerous even after shorting the whole coil, a further action must be taken in order to reduce the effect of this current. Therefore, different power converter topologies suitable for aerospace applications have been developed in many researches. For further information, a comparison of such topologies is presented in [11].

REFERENCES

[1] Bianchi, N., Bolognani, S., Zigliotto, M., Zordan, M.,’’ Innovative remedial strategies for inverter faults in IPM synchronous motor drives,’’ *IEEE Transaction on Energy Conversion*, Vol. 18, No. 2, pp. 306-314, June 2003.

[2] Mecrow, B.C., Jack, A.G., Haylock, J.A., and Coles, J.,"Fault Tolerant Permanent Magnet Machine Drives,"*IEE Proceedings Electric Power Applications*, Vol.143, No. 6, pp.437 - 442, Nov 1996.

[3] Neely, J.D., and Strangas, E.G., “Fault Types and Mitigation Techniques of PMAC Machines”, *IEEE International Conference on Electro/information Technology*, pp. 97 – 102, May 2006.

[4] Haylock, J.A., Mecrow, B.C., Jack, A.G., and Atkinston, D.J., "Operation of Fault Tolerant Machines With Winding Failures," *IEEE Transactions on Energy Conversion*, Vol. 14, No. 4, pp. 1490 – 1495, Dec 1999.

[5] Atkinson, G.J; "High Power Fault Tolerant Motors for Aerospace Applications", ENG.D Thesis submitted to Newcastle University, 2007,pp 166 - 191.

[6] Carpenter Specialty Alloys “Cobalt Iron Alloys” Manufacture’s brochure.

[7] Recoma “The Complete Range of SmCo5 and Sm2Co17Alloys”Manufacture’sbrochure.www.precisionmagnetics.com/pdf/recoma.pdf.

[8] Chai, J., Wang, J., Sun, Z., and Howe, D., "Analytical Prediction of Inter-turn Short- circuit in Fault Tolerant Permanent Magnet Brushless Machines", *Power Electronics, Machines and Drives, IET Conference* , pp 1 – 5, 2008.

[9] Mellor, P.H., Allen, T.J., Ong, R., and Rahman, Z., "Faulted Behavior of Permanent Magnet Electric Vehicle Traction Drives", *IEEE International Electric Machines and Drives Conference*, Vol. 1, pp. 554 – 558, June 2003.

[10] Craig, E., Mecrow, B,C., Atkinson, D.J., and Jack, A.G., "A fault Detection Procedure For Single Phase Bridge Converters", *The European Power electronics Association*, pp. 466 – 471, Sep 1993.

[11] Aten, M., Towers, G., Whitley, C., Wheeler, P., Clare, J. and Bradley, K.,’’ Reliability Comparison of Matrix and other converter Topologies,’’ *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 42, No. 3, pp 867-875, July 2006.