p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03 Issue 18
December 2016

Turn to turn fault modelling of three Phase PMSG having rotor Magnets of non-uniform strength

Sanket Parasher[1], Sanjeev Kumar Mittal[2]
[1]Department of Electrical Engineering, Indian Institute of Technology (BHU), Varanasi, India
2Department of Electrical Engineering, Indian Institute of Science (IISc), Bangalore, India
Email: sanket.parasher.eee11@iitbhu.ac.in, rsr.skm@gmail.com

Abstract:

This paper studies the turn to turn fault for Three phase PMSG for the rotor magnets with non-uniform field strength. The high frequency Permanent Magnets are becoming more popular because of their small size and high power density. They are used for the brushless excitation of synchronous motors and generators. The exceeding use of PMSG in various application makes necessary to analyze their fault stability conditions for practical aspects like variation in the rotor magnetic strength. For better comprehension, fault have been carried out and studied at different frequency and detailed study of terminal voltage and short circuit current has been done which are also verified experimentally. For experimental purpose, a prototype of three phases PMSG has been constructed, coupled by a DC motor acting as a prime mover. The experimental results have been validated by theoretical derivation and simulation results.

Keywords

PMSG; Turn to turn fault; Simulation; DC Motor

1. Introduction

Permanent magnet generators are playing a major part in electrical power generation process. They are being widely used for wind power generation purpose [1]-[9]. The doubly-fed induction generator (DFIG) is presently a very popular wind turbine generation system for large-scale wind farms but it has a great disadvantage that the system is more vulnerable to the grid disturbances [2]. The high speed PMSG are widely investigated because they have high speed, lower size and high power density [3]. Some of the advantages of PMSG include the higher efficiency; less maintenance and high density of the NdFeB magnets [4]. High frequency PMSG are used in the brushless excitation of the synchronous generators and motors. In such systems, fault tolerance of machine is desired for safety considerations.

PMSG does not require additional excitation for production of power. Therefore it is required that the magnets mounted on the rotor should have equal strength corresponding to each pole. The presence of the magnet of unequal strength results in the production of the harmonics in the terminal voltage. The reason for different field strength is due to procurement of the rotor magnets from different vendors. Another reason for the varying strength of the rotor magnets is because of incessant demagnetization in the generators after longer use which makes the field strength of magnets different. The demagnetization of the magnets is the result of the combination of thermal, electrical, mechanical, and environmental stresses on the generators [5]. There has been numerous techniques to analyze the magnetic deformation and the defect detection [6] [7].Turn to turn fault in stator windings is a general technical problem occurring in PMSG. Due to certain conditions like ageing, vibrations and heating, winding insulation of the machine deteriorates in continuous manner and the final breakdown of the insulation occurs, creating turn-to-turn fault. This breakdown results in the short circuiting of the coil which creates turn to turn fault in generator. Inter-turn fault leads to reduction in the voltage provided by the generators to the consumer. Fault in the machine windings may also lead to the burning of the shorted coils if it prevails for large time. Strength of magnetic material is affected by the continuous flow of the short circuit current [5], [6]. For a low power PMSG where fault current may not be severe, efficiency of the generator is affected due to dissipation of power in windings for long run process. It may lead to altering the property of insulation materials [7].

Numerous methods have been introduced to study the turn to turn fault in the permanent magnet synchronous generator with the rotor magnets of same strength [7]-[13]. There has been no modelling devised for the study turn to turn fault of PMSG with the defective or non-uniform rotor magnets. This paper focuses on the study of the turn to turn fault in the Three Phase PMSG with the non-uniform rotor magnets. A mathematical model has been devised to analyze the turn to turn fault using winding function theory. This method has been validated by the simulation analysis. A prototype of PMSG has been procured for obtaining the experimental results.

2. Winding function approach for fault analysis

Fig.1 shows the pattern of windings in the stator of the Three Phase PMSG for 4 pole rotor construction. Fault has been carried out in the one of the phase termed as phase 'A'.

The pattern of windings have been shown as turn function in Fig.2. Localized winding has been assumed while devising the turn function diagram. Since windings are present in stator,fault will be calculated only for stator winding. The x% of short circuit has been assumed to have occurred in phase 'A' of the stator.

Turn Function of phase 'A' at the point where the windings are short circuited will be[10]

$$\frac{N_x}{2} - \frac{N_x x}{100}$$

Average value of the Turn Function for phase 'A' will be [10]

$$\langle n_{ph}(\phi)\rangle = \frac{1}{2\pi}\int_0^{2\pi} n_{ph}(\phi)d\phi = \frac{N_x}{4}\left(1 - \frac{x}{100}\right)$$

(1)

The Winding Function for phase 'A' at x% fault comes out to be[10]

$$N_a(\phi) = n_a(\phi) - \langle n_a(\phi)\rangle = n(\phi) - \frac{N_x}{4}\left(1 - \frac{x}{100}\right)$$

(2)

Some of the terms in winding function will be as follows

$$\frac{N_x}{2} - \frac{N_x}{4}\left(1 - \frac{x}{100}\right) = \frac{N_x}{4}\left(1 + \frac{x}{100}\right)$$

$$\frac{N_x}{2} - \frac{N_x x}{100} - \frac{N_x}{4}\left(1 - \frac{x}{100}\right) = \frac{N_x}{4}\left(1 - \frac{3x}{100}\right)$$

In similar way, the turn functions and winding functions can be evaluated for phase 'B' and 'C'.

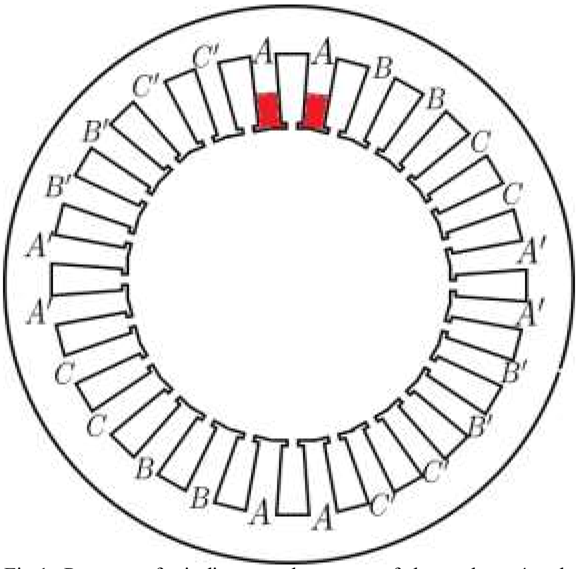

Fig.1. Pattern of windings on the stator of three phase 4 pole PMSG used for testing the fault.

Fig.3 shows the winding function of the windings of three phase PMSG for 4 poles.

The corresponding stator inductances in the faulty generator can be evaluated as follows [8] [9]

$$L_{aa} = \mu_o(R \cdot g)l \cdot \left(\int_0^{2\pi} \frac{N_a(\phi)\cdot N_a(\phi)}{g(\phi)} \cdot d\phi\right)$$

$$\frac{\mu_0(R \cdot g)l}{g} \cdot N_x^2 \cdot \frac{\pi}{2}\left[\frac{3}{4}\left(\frac{x}{100}\right)^2 - \frac{x}{100} + 1\right]$$

(3)

Short circuit has been assumed to occur in phase 'A'. Therefore self-inductances of other two phases 'B' and 'C' will be same as healthy generator

$$L_{bb} = L_{cc} = \mu_o(R \cdot g)l \cdot \left(\int_0^{2\pi} \frac{N_b(\phi)\cdot N_b(\phi)}{g(\phi)} \cdot d\phi\right)$$

$$= \frac{\mu_0 \cdot (R \cdot g) \cdot L \cdot N_x^2 \cdot \pi}{288 \cdot g}$$

(4)

Mutual inductance between unhealthy phase and short circuited winding can be evaluated as follows [10]

$$L_{asc} = \mu_o(R \cdot g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{n_a(\phi)\cdot N_{sc}(\phi)}{g(\phi)} \cdot d\phi\right)$$

International Journal of Research
Available at https://edupediapublications.org/journal
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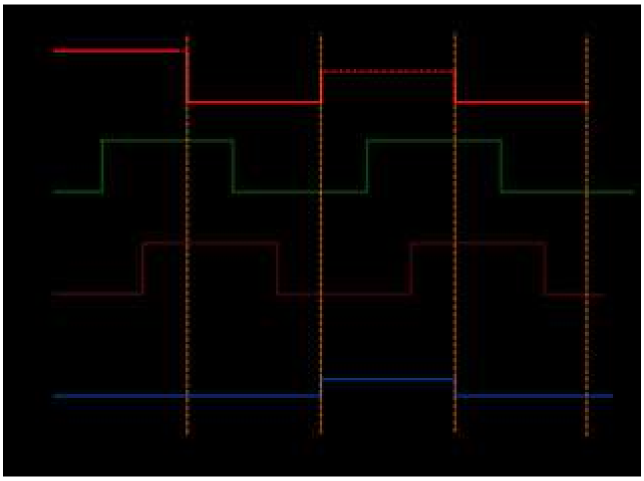

Fig.2. Turn function of 4 pole three phase PMSG.

$$= \frac{\pi\mu_0(R.\ g)l}{800g} x N_x^2 \left(2.\ \frac{3}{100} \cdot x\right)$$ (5)

Mutual inductance between the healthy phases 'B' and short circuited winding comes out to be [10]

$$L_{bsc} = \mu_o(R.\ g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{u_b(\phi) N_{sc}(\phi)}{g(\phi)} d\phi\right)$$

$$= . \frac{\mu_0(R.\ g)l\ x\ N_x^2}{g \cdot 1200} \cdot \frac{\pi}{2}$$ (6)

Mutual inductance between phase 'C' and short circuited windings comes out to be similar as of phase 'B'

$$L_{csc} = \mu_o(R.\ g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{u_c(\phi) N_{sc}(\phi)}{g(\phi)} d\phi\right)$$

$$= L_{bsc}$$ (7)

Self-inductance of the short circuited coil will be [10]

$$L_{scsc} = \mu_o(R.\ g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{u_{sc}(\phi) N_{sc}(\phi)}{g(\phi)} d\phi\right)$$

$$= \frac{\mu_0 \mathrm{r} l}{g} N_x^2 \frac{3\pi}{8} \left(\frac{x}{100}\right)^2$$ (8)

Mutual inductance between the phase 'A' and phase 'B' as well as phase 'A' and phase 'C' comes out to be [10]

$$L_{ab} = L_{ac} = \mu_o(R.\ g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{u_a(\phi) N_b(\phi)}{g(\phi)} d\phi\right)$$

$$= . \frac{\mu_0(R.\ g)l N_x^2}{g} \frac{\pi}{3}\left[1.\ \frac{x}{100}\right]$$ (9)

Mutual inductance between phase 'B' and phase 'C' will remain same as in the case of the healthy machine [10]

$$L_{bc} = \mu_o(R.\ g)l \cdot \left(\int_0^{\frac{2\pi}{P}} \frac{u_a(\phi) N_b(\phi)}{g(\phi)} d\phi\right)$$

$$= . \frac{\mu_0(R.\ g)l N_x^2}{g} \frac{\pi}{24}$$ (10)

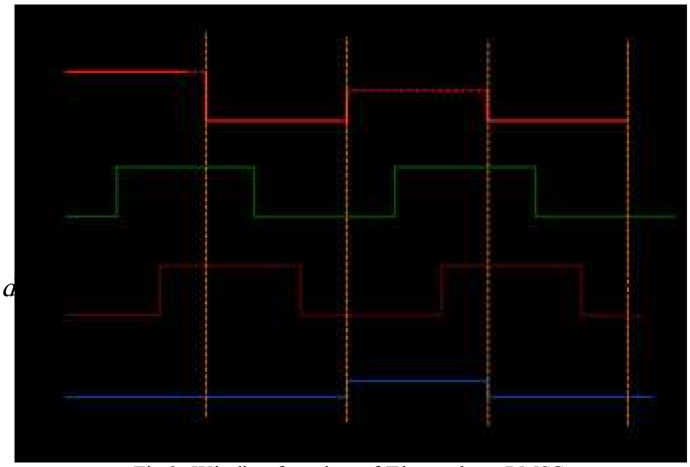

Fig.3. Winding function of Three phase PMSG.

Where,

μ_0 : Permeability of the air = $4\pi \times 10^{-}$

R : Radius of the stator bore.

l : Shaft Length

g : Air gap

N_x : Total number of turns per phase in the generator.

3. MODELLING OF THE EMF FOR ROTOR MAGNETS OF DIFFERENT STRENGTH

The varying strength magnets produce the magnetic flux density of different strength which causes some dips in the output voltage. This leads the production of the undesirable harmonics in the system. Fig.4. represents the voltage dips due to variation in flux density caused by varying strength of magnets on the rotor of the machine. For the analysis, the variation of flux density has been assumed to be sinusoidal instead of having undesirable harmonics in the air gap.

As we know, the open circuit EMF follows the waveform of flux density on the time axis [9]. The Laplace transform has been applied for the single sinusoidal wave with positive part extended from (p-1) π to pπ. For all the other components individually determined and summed together to get the desired results. The inverse Laplace transformation of the signal is taken finally in (11), (12) and (13) to get the desired results.

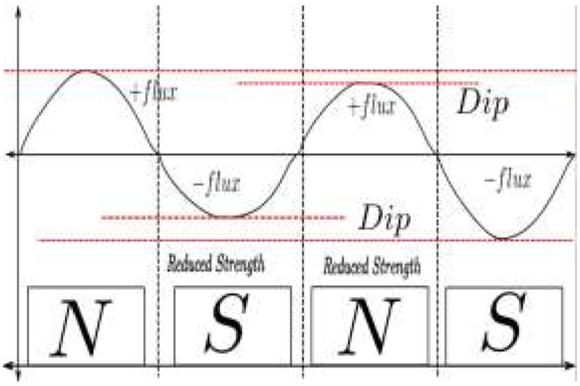

Fig.4. Variation of flux density with the non-uniform magnets on rotor

Corresponding inverse Laplace of the waveform, during non-fault condition comes out to be:-

1) Phase 'A'

$$E_a(t) = \sum_{p=1}^{P} E_p[\sin(\omega t)\, u(t-\frac{(p-1)\pi}{\omega}) + \sin(\omega t - \pi)\, u(t-\frac{p\pi}{\omega})] \quad (11)$$

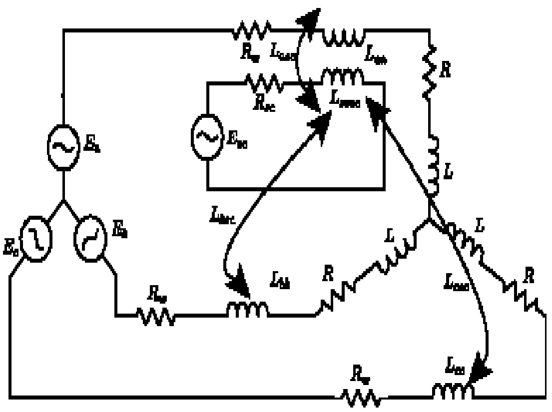

Fig.5. Equivalent circuit diagram of the three phase PMSG for fault analysis.

2) Phase 'B'

$$E_b(t) = \sum_{p=1}^{P} E_p[\sin(\omega t-\frac{2\pi}{3})\, u(t-(\frac{2\pi}{3\omega}+\frac{(p-1)\pi}{\omega})) + \sin(\omega t - [\frac{2}{3}+1]\pi)\, u(t-(\frac{2\pi}{3\omega}+\frac{p\pi}{\omega}))] \quad (12)$$

3) Phase 'C'

$$E_c(t) = \sum_{p=1}^{P} E_p[\sin(\omega t+\frac{2\pi}{3})\, u(t-(\frac{(p-1)\pi}{\omega}-\frac{2\pi}{3\omega})) + \sin(\omega t + [\frac{2}{3}-1]\pi)\, u(t-(\frac{p\pi}{\omega}-\frac{2\pi}{3\omega}))] \quad (13)$$

4) $E_p = K_p \omega \phi$ (14)

4. Mathematical modelling of fault using the dynamic equations

The fault analysis can be mathematically modelled by the given equations

$$(1-\frac{x}{100})E_a(t) = L_{aa}\frac{dI_a}{dt} + L_{ab}\frac{dI_b}{dt} + L_{ac}\frac{dI_c}{dt} + L_{asc}\frac{dI_{sc}}{dt} + R_aI_a + V_a(t)$$

$$E_b(t) = L_{bc}\frac{dI_c}{dt} + L_{bb}\frac{dI_b}{dt} + L_{ac}\frac{dI_a}{dt} + L_{bsc}\frac{dI_{sc}}{dt} + R_bI_b + V_b(t)$$

$$E_c(t) = L_{cc}\frac{dI_c}{dt} + L_{bc}\frac{dI_b}{dt} + L_{ac}\frac{dI_a}{dt} + L_{csc}\frac{dI_{sc}}{dt} + R_cI_c + V_c(t)$$

$$E_{sc}(t) = L_{csc}\frac{dI_c}{dt} + L_{bsc}\frac{dI_b}{dt} + L_{asc}\frac{dI_a}{dt} + L_{scsc}\frac{dI_{sc}}{dt} + R_{sc}I_{sc}$$

(15)

Fig.5 shows the equivalent circuit for the modelling and simulation of the turn to turn fault in PMSG. The inductances involved in the circuit calculations have been obtained by winding function calculations. The equivalent circuit includes the winding resistances. There is a mutual coupling between the coils of three phases. The shorted coils have been represented by the different phases.

Fig.6 shows the simulation diagram of the equations mentioned in (15). Simulation has been carried out in Matlab/Simulink. The parameters have been calculated for 4 Pole PMSG with the specifications given in Appendix Table. I and Table. II. The load has been assumed to be 4 Ohm as

International Journal of Research
Available at https://edupediapublications.org/journal
p-ISSN: 2348-6848
e-ISSN: 2348-795X
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resistances and 2H as inductance. The fault has been carried out for 10% short circuit.

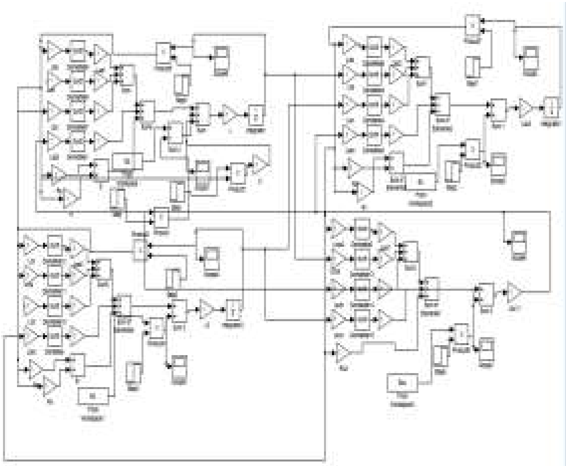

Fig.6. Simulation diagram of the Three phase PMSG.

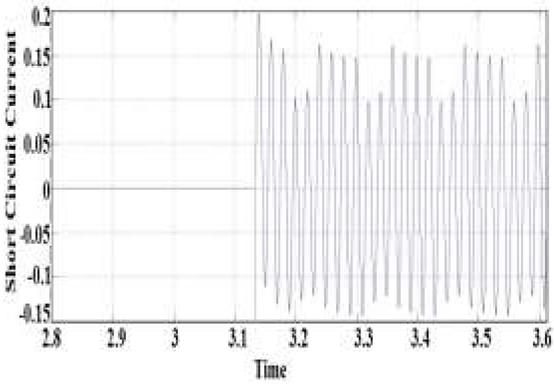

Fig.7. Simulation of the short circuit current for three phase PMSG.

Fig.7 shows the short circuit current for the turn to turn fault occurring in three phase PMSG through simulation. The peak value of current comes out to be 0.2 A by simulation. It can be observed that there is also a variation in the amplitude of the peak to peak current due to the variation in the strength of the magnets during fault in the machine. It can be observed that the transients have also been generated during the turn to turn fault because of the different mutual and self-inductance generated in the circuit.

The given Fig. 8 represents the variation of the terminal voltage during open circuit condition for the PMSG having defective magnets on the rotor. The output voltage of phase 'a' has been shown for the clarity .The output voltage is a sinusoid with different amplitudes at different times then voltage reaches maximum value. The graph will repeat after every six maximum values for the 4 pole generator. The fault causes dip in the voltage for all of the phases but it affects the phase 'a' worst where the windings have got short circuited.

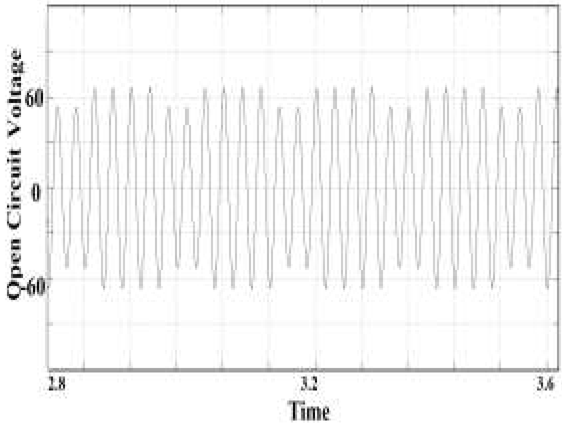

Fig.8. Simulation of the open circuit voltage for three phase PMSG.

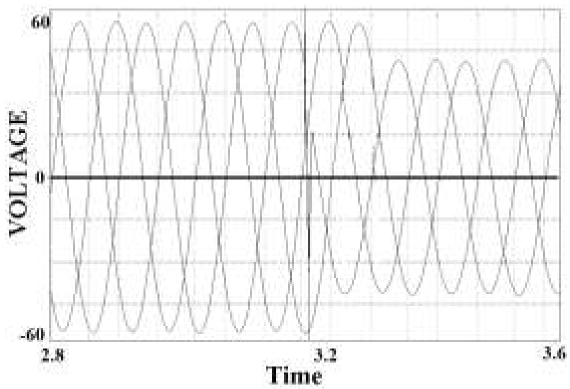

Fig.9. Simulation of the terminal voltage of three phase PMSG for turn to turn fault.

The Fig. 9 shows the simulation result of the output voltage for PMSG having the magnets of equal strength on the rotor. The open circuit voltage has constant amplitude because it follows flux density on the time scale. The simulation shows the generation of transients in only phase 'A' because the transients of phase 'B' and phase 'C' are very small and similar in nature. Therefore their values are not visible in simulation results.

VI. EXPERIMENTAL RESULTS

Experiment has been performed on a prototype of the PMSG with the specifications given in Table. I and Table. II. The given PMSG has total number of 4 poles on the rotor and is running at the frequency of 50 Hz. The open circuit voltage is 60V.

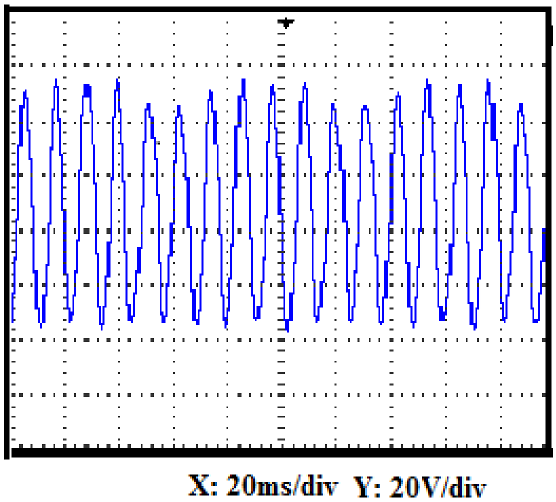

Fig.10. Terminal voltage of the three phase PMSG for 10% fault with magnets of varying strength.

Fig.10 represents the terminal voltage of the faulty phase 'A' for three phase PMSG. The simulation results are complying with the experimental results. The terminal voltage after fault comes out to be

20V/div*2.5div=50V.

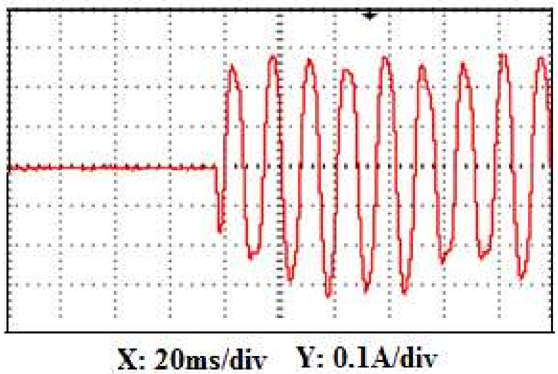

Fig.11. Short circuit current of three phase PMSG for the magnet of varying strength.

The Fig. 11 shows the variation of the short circuit current on the time scale for the rotor having defective magnets. The short circuit current is repeating its nature after 4 topmost points that is because the generator has 4 poles and the same pole gets repeated after certain interval. The experimental observations taken by C.R.O are shown in the Fig.20. The observation has been taken after long time to ensure the absence of the transients in the short circuit current in order to show the effect of the rotor magnets of different strength on the short circuit current during the fault. The short circuit current seems to be a waveform having different amplitude after different time. The wave form is repeated after four cycles. The peak value of short circuit current comes out to be

0.1A/div*2.8div = 0.28A.

The simulation results are complying with the experimental result.

5. Acknowledgement

I would also like to express my sincere gratitude to **Prof R.K.Srivastava,** Professor, Department of Electrical Engineering IIT (BHU), Varanasi for his whole hearted support and suggestions. I feel extreme pleasure to owe my profound gratitude and indebtedness for his scholastic guidance, affection and constant source of inspiration. I also feel my heartily indebtedness to **Sovit Kumar Pradhan,** Postgraduate from IIT (BHU), Varanasi for procuring his PMSG to conduct our experiments.

6. Conclusion

Winding function theory provides a convenient way to analyses the turn to turn fault in electrical machines. Similarly, the analytical modelling of the PMSG with non-uniform magnets help in determining the fault for practical motors with non-uniform magnetic strength. Mathematical modeling of the voltage induced due to rotor magnets of varying strength provides a simple way to analyze the effect of the non-similar magnets on the output voltage of the generator for different frequencies. It has been observed that the dip in the voltage varies in the same ratio in spite of the magnets having similar or different magnetic strength. The rotor magnets having varying strength induce undesirable harmonics which are augmented during fault. The transient voltage is more dominant in the case if the rotor magnets have the non-similar strength. Hence the similarity of the rotor magnets during construction of the PMSG should be taken into consideration. The mathematical analysis of the generator has been done with the load connected to the supply due to providing the unbalanced voltage. The circuit analysis of the generator is useful for the high frequency PMSG for excitation use. Here, the circuit modeling of the generator provides an easy way to study the effect of generator during healthy as well as unhealthy condition.

7. Machine details

TABLE I. STATOR CORE DETAILS

NO. OF SLOTS	24	INNER RADIUS	38 mm
OUTER RADIUS	45mm	WIDTH OF STATOR	20 mm
WIDTH OF TEETH	2mm	AREA OF SLOT	52 mm
AREA OF INSULATION	18 mm^2	AREA FOR WINDING OF A SLOT	36 mm^2

TABLE II. WINDING DETAILS

NO OF TURNS IN THE SLOT	1000	NO OF POLES FORMED	4
MATERIAL OF WIRE	COPPER	WIRE USED FOR THE WINDING	32 SWG
TYPE OF WINDING	LOCALISED	NO. OF PHASES	3
WEIGHT OF THE WINDING WIRE	60 gm.	RESISTANCE IN PHASE	0.32 Ω

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