International Journal of Research
Available at https://edupediapublications.org/journal
p-ISSN: 2348-6848
e-ISSN: 2348-795X
Volume 03 Issue 18
December 2016

# Turn to Turn fault analysis and comparison of Single Phase PMSG for two different poles

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***Abstract:***

*This paper is a study and comparison of the turn to turn fault in Single phase Permanent magnet synchronous generator for lower as well as higher number of poles. Single phase PMSG have a lot of application in generation of the power for fractional kilowatt systems and household purpose. Fault analysis is one of the most important factor for designing of the PMSG for these application. With advancement in the technology of higher poles machine construction, it has become necessary to study the effect of turn to turn fault on the Single phase PMSG with large number of poles for their proper design. Fault often goes unnoticed at its inception in the single phase PMSG due to their low power and current rating, which leads to the necessity to analyze the effect of fault for long running operations. For this purpose, we propose a generalized mathematical model for an unhealthy generator using the Winding Function Theory. The effect of fault severity on terminal voltage, fault current in shorted windings and counter-torque has been analyzed and compared for 4 pole and 24 pole PMSG in order to clarify the effect of higher number of poles on the fault. The prototype of PMSG has been procured and run for both 4 poles and 24 poles in faulted conditions for obtaining the experimental results. Theoretical modelling has been analyzed and validated by simulation as well as experimental results. Appropriate explanations have been provided for the obtained results.*

***Keywords***

*Single Phase, PMSG, inter-turn fault, Poles, Winding Function Theory*

## 1. Introduction

There is a growing pressure for the highly efficient generators for industrial and household appliances [1]-[4]. Single phase Permanent magnet Synchronous Generators has a variety of features which can make it an attractive choice for house hold appliances that are generally running on the single phase supply. Single phase PMSG are finding their applications in wind energy, induction heating [2] and hydro energy generation [3][4]. They are also used for the mobile battery charging purpose. Demand of Single Phase PMSG on such a large scale requires the study of every aspect of the generator performance.

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 detereorates in continous manner and the final breakdown of the insulation occurs, creating turn-to-turn fault. 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 continous 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].

Research on large scale has been conducted for the study of the turn to turn fault in different generators. Most of the research are commited on the study of turn to turn fault in Three phase or higher phase generators. Less focus has been made on the study of the turn to turn fault in fractional kilowatt generators like single phase PMSG. Effect of turn to turn fault on Single phase PMSG is not drastic because of which it goes unnotiecd. If turn to turn fault prevails for longer times ,then it may result in large ohmic losses in shorted windings which will make the performance of generator inefficient. It will also result in further detereoration if the insulation causing more short circuit. Large amount of short circuit may result in detereoration of magnetic material.

In this paper, the turn to turn fault has been analyzed for Single phase PMSG for two different

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poles using winding function theory. Winding function theory has been successfully applied for mathematical modelling of inductances in different machines for analyzing the fault [8]-[18]. It has been successfully implemented in the fault analysis of other machines including BLDC motor [10] and induction machines [14]. Winding function theory provides more convenient approach than FEM method as it is quick in various situations [14] - [18]. This theory takes into account the magneto motive force distribution in the windings of the generator.

Section 2 involves the calculation of stator inductances during fault by using the winding function theory. A generalized model of Single Phase PMSG with P poles has been developed for theoretical study [19]-[23]. Section 3 involves the derivation of relevant mathematical formula to study the performance of generator for pole P during the turn to turn fault [10]. Section 4 includes the analysis of mathematical models for determining the generators performance by different plots and simulation. Section 5 involves the experimental verification of the results. Fault has been carried out for 8% short circuit. Plots have been obtained for 4 pole and 24 pole generators. These two generators have been compared on every aspect during operation in fault to determine their relative performance. The effect on short circuit current, terminal voltage as well as counter torque has been studied in this section. Section 6 includes the conclusion of the research work conducted on PMSG.

## 2. Evaluation of the Stator inductances using Winding Function Theory

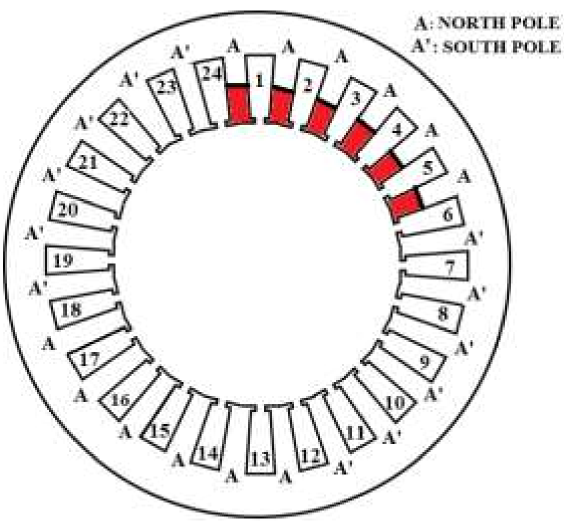


**Fig.1. Winding pattern for 24 slot machine for 4 Pole stator construction.**

A stator of the 24 slot PMSG has been considered for the modelling purpose. Rare earth materials which are mounted on rotor have permeablity similar to the air [10]. Therefore air gap can be considered as uniform in nature. Single phase winding distribution has been considered for 24 slotted stator to create 4 poles and 24 poles. Fig.1 shows the winding pattern for the stator of 4 pole machine and the way in which the number of short circuited turns have been created in the machine. Red zone indicates the shorted windings for 8% fault. Fig.2 shows the similar winding pattern diagram of the 24 pole machine and the number of short circuited turns created for analyzing the turn to turn fault. For P pole single phase PMSG, the number of pole pairs come out to be P/2. Localized winding has been prefferd in the stator for experimental purpose. Turn function represents distribution of windings in the stator of generator [9]. Winding Function represents distribution of the MMF along air gap of generator.

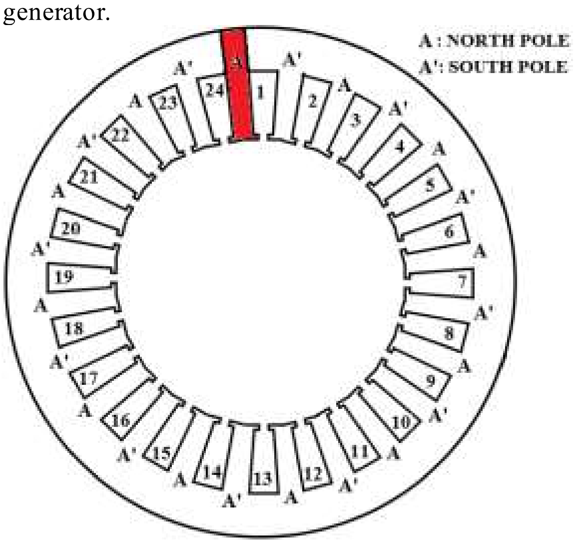


**Fig.2. Winding pattern for 24 slot machine for 24 Pole stator construction.**

Fig.3 shows the distribution of the Turn Function in the stator of PMSG for P poles. Amplitude of the Turn function is coming out to be

$$\text{Amplitude}=\frac{2N_s}{P}$$

Due to short circuit in the healthy windings, the amplitude of turn function reduces at place where short circuit has occurred. Short circuited windings have been represented as separate phase as per Winding Function Theory.

Fig.4 represents the distribution of the Winding Function in stator of the generator. Winding Function is the representation of MMF distribution in stator of the generator. Fault has been assumed to occur corresponding to only one pole pair.

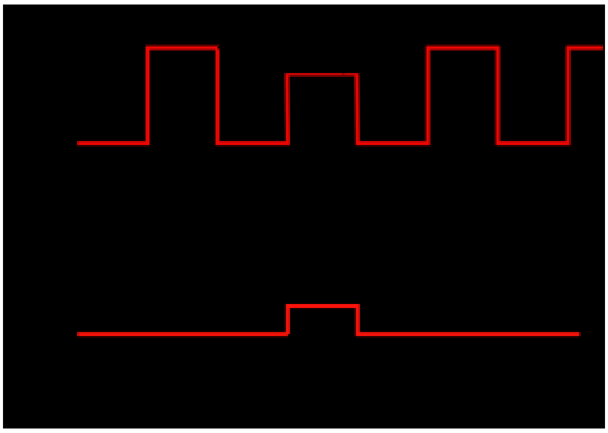

**Fig.3. Turn Function representation of the stator of Single phase PMSG for P poles.**

Winding function theory has been applied on the generator under unhealthy conditions.Since windings are present only in stator, therefore fault is being analyzed only for stator windings. The generalized s% of short circuit has been assumed to have occurred in stator of the generator.

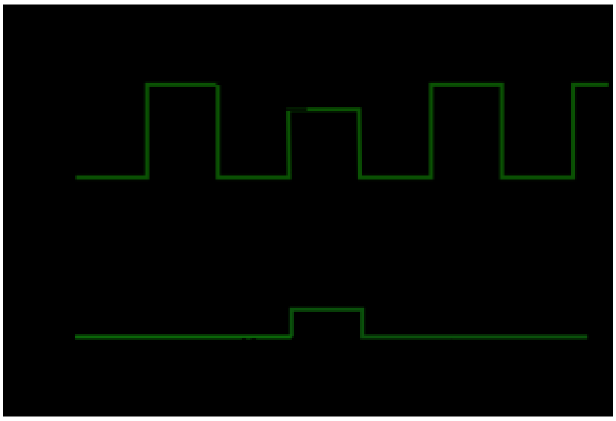

**Fig.4. Winding Function representation of the stator of Single phase PMSG for P poles.**

Turn Function at the point where the windings are short circuited will be [20]-[23]

$$\frac{2N_s}{P} - \frac{N_s s}{100}$$

Average value of the Turn Function for the s% of the fault is ([20]-[23])

$$\langle n_t(\theta)\rangle = \frac{1}{2\pi}\int_0^{2\pi} n_t(\theta)d\theta = \frac{N_s}{P} - \frac{N_s s}{P \cdot 100} \quad (1)$$

Winding Function at s% fault for short circuited part will be [20]-[23]

$$N_w(\theta) = n_t(\theta) - \left(\frac{N_s}{P} - \frac{N_s s}{P \cdot 100}\right) \quad (2)$$

Value of the terms that come in expression of Winding Function { $N_w(\theta)$ } are as follows [20]

$$\frac{2N_s}{P} - \left(\frac{N_s}{P} - \frac{N_s s}{P \cdot 100}\right) = \frac{N_s}{P}\left(1 + \frac{s}{100}\right)$$

$$\frac{2N_s}{P} - \frac{N_s s}{100} - \left(\frac{N_s}{P} - \frac{N_s s}{P \cdot 100}\right) = \frac{N_s}{P}\left(1 - \frac{(P-1)s}{100}\right)$$

Self Inductance of the healthy stator winding can be calculated as [20][21]

$$L_{ss} = \mu_o r l \left(\int_0^{2\pi} \frac{n_t(\theta) N_w(\theta)}{g(\theta)} d\theta\right) =$$

$$\frac{\mu_0 r l}{g} \pi N_s^2 \left[\frac{2\pi}{P}\left(\frac{P-1}{P}\right)\left(\frac{s}{100}\right)^2 - \frac{s}{100} + \frac{P}{4}\right] \quad (3)$$

There exists a Mutual Inductance between the healthy stator winding and the faulty stator winding which will be [20]

$$L_{ssc} = \mu_o r l \left(\int_0^{\frac{2\pi}{P}} \frac{n_t(\theta) N_{sc}(\theta)}{g(\theta)} d\theta\right)$$

$$= \frac{2\pi \mu_0 r l}{100 P^2 g}(s)(N_s)^2\left[\frac{P}{2} - \frac{(P-1)}{100}(s)\right] \quad (4)$$

Self-Inductance of the faulty stator winding will be [20]

$$L_{scsc} = \mu_o r l \left(\int_0^{\frac{2\pi}{P}} \frac{n_{sc}(\theta) N_{sc}(\theta)}{g(\theta)} d\theta\right)$$

$$= \frac{\mu_0 r l N_s^2 11\pi}{g P} \frac{s^2}{100^2} \quad (5)$$

Where

$\mu_0$: Permeability of the air = $4\pi \times 10^{-}$

$r$: Radius of the stack

$l$: Shaft Length

$g$: Air gap

$N_s$: Total number of turns in the generator.

The generalized models of turn function and winding function developed for analyzing the fault in PMSG can modelled for 4 pole and 24 pole PMSG by substituting P with 4 and 24 poles.

Fig.5 shows the mathematical plot of the self-inductance $L_{ss}$ for different number of magnetic poles in machine. The plot has been done for the short circuit of 8% in the windings of the generator. The magnitude of $L_{ss}$ increases for the higher pole generators. Curve is asymptotic at for the large value

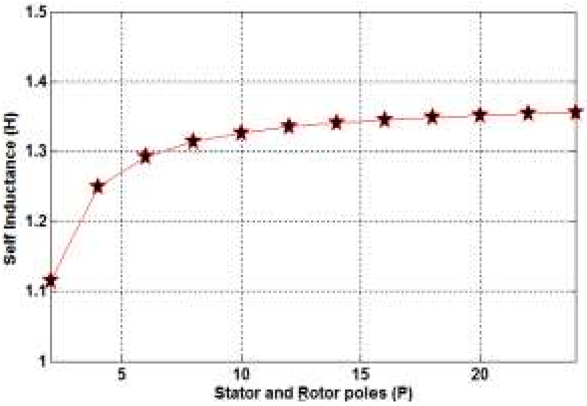


**Fig.5 Self Inductance of the healthy phase in single Phase PMSG.**

of poles P. Asymptotic value of self-inductance, $L_{ss}$ for very high pole generators comes out to be:

$$\lim_{P\to\infty} L_{ss} = \frac{\mu_0 r l}{g}\left(N_s\right)^2 \frac{2\pi}{4} \quad (6)$$

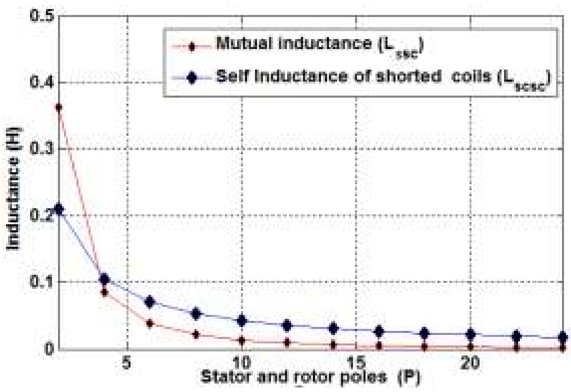


**Fig.6. Mutual inductance ($L_{ssc}$) and short circuit inductance ($L_{scsc}$) for the Single Phase PMSG.**

Fig.6 shows the mathematical plot of mutual inductance, $L_{ssc}$ and the short circuit inductance, $L_{scsc}$ for different poles, P. Both of the inductance decrease for the higher number of poles. The value of $L_{ssc}$ and $L_{scsc}$ for 24 pole generator is a very small fraction of 4 pole generator. This represents that the fault creating factors are less effective for 24 pole generators compared to 4 pole generators.

The graph that is approached by the curve for higher number of poles can be obtained by taking the limit $P \to \infty$ which comes out to be:-

$$\lim_{P\to\infty} L_{ssc} \to 0$$
$$\lim_{P\to\infty} L_{scsc} \to 0 \quad (7)$$

## 3. Analysis of the Dynamic Equations during Fault

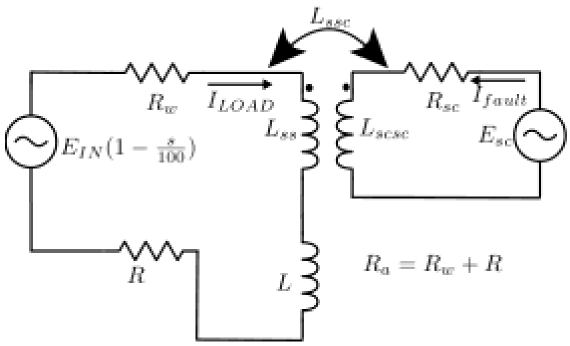

**Fig.7. Equivalent circuit model for turn to turn fault analysis in single phase PMSG.**

Fig.7 shows the equivalent circuit model of the PMSG during turn to turn fault. Short circuited wires have been taken as separate phase. Equivalent circuit is analogous to the transformer windings with some mutual inductance between them. Governing Equations for fault analysis of the PMSG are [10]

$$\left(1-\frac{s}{100}\right)E_{IN}(t) = L_{ss}\frac{dI_{LOAD}}{dt} + R_a I_{LOAD} + L_{ssc}\frac{dI_{fault}}{dt} + V_t$$

$$E_{sc}(t) = L_{ssc}\frac{dI_{LOAD}}{dt} + L_{scsc}\frac{dI_{fault}}{dt} + I_{fault}R_{sc}$$

$$V_p(t) = L\frac{dI_{LOAD}}{dt} + R_a I_{LOAD} \quad (8)$$

Where,

$$E_{sc}(t) = \frac{s}{100} E_{IN}(t) \quad (9)$$

$I_{LOAD}$ : Armature Current

$I_{sc}$ : Fault current

$$V_p(t) = \sqrt{V_{l1}^2 + \left(\frac{V_{l2}}{\omega_s}\right)^2}\sin\left(\omega_s t + \tan^{-1}\left(\frac{\omega V_{l1}}{V_{l2}}\right)\right) + e^{-\frac{R}{2A}}\left(V_{l3}\cos h(\omega_d t) + \frac{V_{l4} - V_{l3}\frac{B}{2A}}{\omega_d}\sin h(\omega_d t)\right) \quad (10)$$

Where,

$$V_{l1} = \omega_s \left(\frac{[A(C - A\omega_s^2) + R_2] - B[R_3 - M_1\omega_s^2]}{[C - A\omega_s^2]^2 + [B\omega_s]^2}\right)$$

$$V_{l2} = \omega_s \left(\frac{[BA\omega_s^2 + R_2] - [C - A\omega_s^2] + [R_3 - K_1\omega_s^2]}{[C - A\omega_s^2]^2 + [B\omega_s]^2}\right)$$

$$V_{l3} = \omega_s \frac{B[R_3 - R_1\omega_s^2] - [A(C - A\omega_s^2) + R_2]}{[C - A\omega_s^2]^2 + [B\omega_s]^2}$$

$$V_{l4} = R_1 - V_{l2} - (B/A) V_n \quad (11)$$

Value of load current comes out to be

$$I_{fault}(t) = \sqrt{\left(I_{l1}^2 + \left(\frac{I_{l2}}{\omega_s}\right)^2\right)}\sin\left(\omega_s t + \tan^{-1}\left(\frac{\omega_s I_{l1}}{I_{l2}}\right)\right) + e^{-\frac{R}{2A}}\left(I_{l3}\cos h(\omega_d t) + \frac{I_{l4} - I_{l3}\frac{B}{2A}}{\omega_d}\sin h(\omega_d t)\right) \quad (12)$$

Where,

$$I_{l1} = E_o \frac{[C - A\omega_s^2]\omega_s B_2 - B\omega_s A_2}{[C - A\omega_s^2]^2 + [B\omega_s]^2}$$

$$I_{l2} = E_o \frac{[C - A\omega_s^2]\omega_s A_2 + B\omega_s^3 B_2}{[C - A\omega_s^2]^2 + [B\omega_s]^2}$$

$$I_{l3} = -E_o \frac{[C - A\omega_s^2]\omega_s B_2 - B\omega_s A_2}{[C - A\omega_s^2]^2 + [B\omega_s]^2}$$

$$I_{l4} = -1\left(I_{l2} + \frac{I_{l1}B}{2A}\right) + M_{net} \quad (13)$$

Values of $B, A, B_2, A_2, R_1, R_2, R_3, R_4, M_{net}$ and C have been mentioned in Table.1

The counter-torque on generator is due to power generated for load and the power dissipated in short circuited winding of the generator. Counter torque developed on the generator will be

$$T_{counter} = \frac{\left(1 - \frac{s}{100}\right) E_{IN}(t) I_{LOAD} + E_{sc} I_{sc}}{\omega_r} \quad (14)$$

Torque applied on generator is highly pulsating in nature with its frequency being twice of the generator's frequency. Higher magnitude of the pulsating torque during fault creates rapid oscillations in generator and thus hampers the electric power generation operation.

## 4. Theoretical and Simulation analysis of the dynamic mathematical models

Theoretical modelling of turn to turn fault has been evaluated for real conditions by obtaining the plots regarding terminal voltage and short circuit current. Theoretical results have been validated by simulation and experimental results.

Fig.8 shows the terminal voltage for long run in the PMSG during faulty conditions. The terminal voltage during healthy condition is 220V which is the rated voltage supply for home applications. The effect of fault is severe in the case of less pole generators compared to higher pole generator. The dip in voltage comes out to be nearly 29V for the 4 pole PMSG. This dip reduces to 10V in the case of 24 pole PMSG. Therefore, theoretical analysis shows that the higher pole generators are more tolerant to the fault.

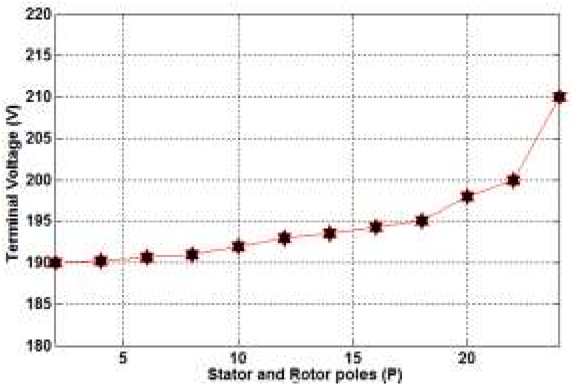


**Fig.8. Terminal voltage of PMSG after turn to turn fault.**

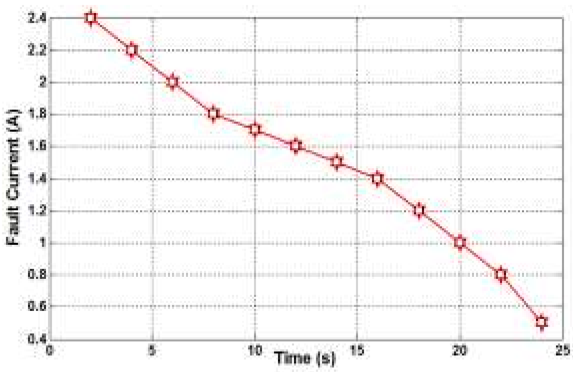


**Fig.9. Fault current in PMSG after turn to turn fault.**

International Journal of Research
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e-ISSN: 2348-795X
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Fig.9 shows the theoretical plot of the fault current present in the short circuited winding of the PMSG. The fault current plot is done for the long run of PMSG after the occurrence of fault. Therefore, the transient effect are negligible in the given plot. Fault current is excessive for the lower pole generators. These fault currents create a large dip in the terminal voltage by their undesirable MMF. Fault current is very less (0.5A) in the case of 24 pole PMSG in long running hours as per the theoretical analysis.

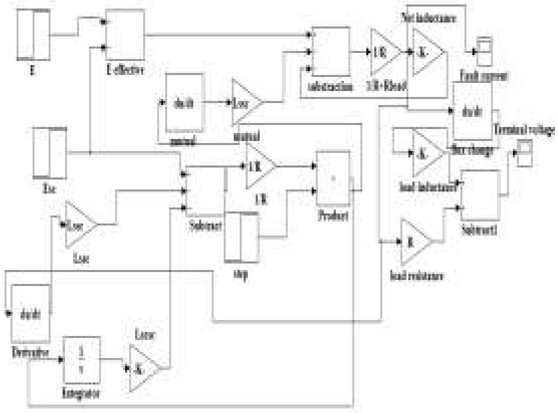

**Fig.10. Matlab/Simulink model for the fault simulation**

Simulation of dynamic equations has been carried out in Matlab/Simulink. Parameters have been calculated by mathematical models developed for dynamic equations. Parameters have been evaluated for prototype of the PMSG used to get experimental results. Simulations results have been compared with the experimental results for verification. Fig.10 shows the Matlab/Simulink diagram of the dynamic equations.

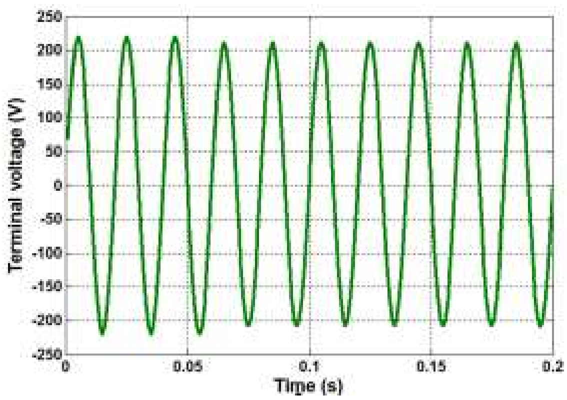


**Fig.11. Waveform of the terminal voltage of 24 pole single phase PMSG for 8% fault.**

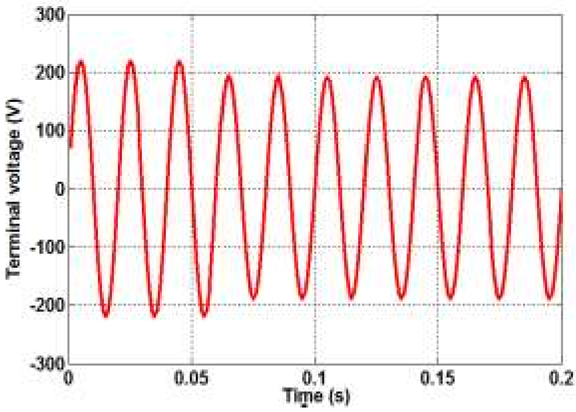


**Fig.12. Waveform of the terminal voltage of 4 pole single phase PMSG for 8% fault.**

Fig.11 shows simulation result for the terminal voltage of 24 pole PMSG for 8% fault. The fault has been simulated to occur after 0.06 s. The simulation result shows 10V dip in the terminal voltage after fault. The voltage drop in the fault verifies with theoretical results. The terminal voltage at 0.2s is 210V.

Fig.12 shows simulation result for the terminal voltage of 4 pole PMSG for 8% fault. Severity of fault is high in 4 pole PMSG that is observable in the simulation. A voltage dip of 27V has been occurred after the fault has occurred. The terminal voltage is 193V at 0.2s of fault.

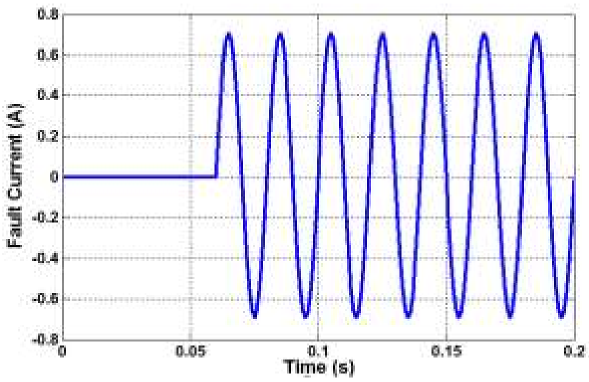


**Fig.13. Waveform of fault current for 24 pole PMSG during turn to turn fault.**

Fig.13 shows the fault current simulation for 24 pole generator. Fault current amplitude is 0.7A in the generator and the fault has occurred at 0.06s. Simulation results are near to the calculated values.

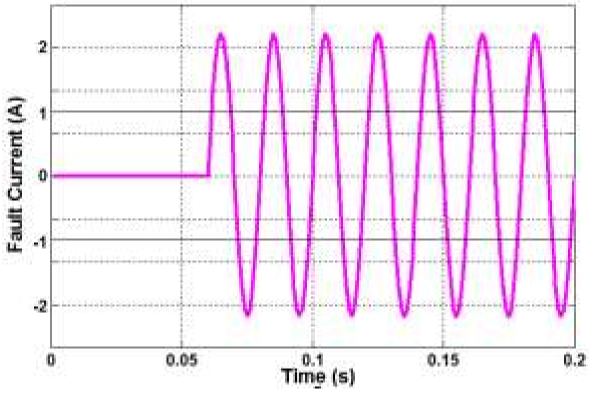


**Fig.14. Waveform of the fault current for 4 pole PMSG during turn to turn fault.**

Fig.14 shows the fault current simulation for 4 pole generator. Fault current amplitude is 3.3A in shorted windings which is highly severe. Compared to Fig.13 the 4 pole generator is more prone to turn to turn fault for same amount of short circuit.

## 5. Experimental performance analysis for prototypes

Specifications of both PMSG used in experiments have been mentioned in Table.2 and Table.3. A PMSG with desirable power rating has been constructed for making it sure that fault current generated persists in the winding without harming the generator in long term process. Copper windings are appropriate to sustain the current during fault. The winding patterns in the PMSG are as drawn in Fig.1 and Fig.2. The size and shape of both PMSG are same except the number of poles in stator and rotor. Three terminals other than output terminals have been drawn out from the turns to create short circuit in the generator windings for 8% short circuit. A D.C. motor with specifications mentioned in Table.3 has been used as prime mover. Generator is being constantly run on 50Hz frequency. The data have been captured for the 200ms of the operation in which fault has occurred after 60 ms very similar to the simulation.

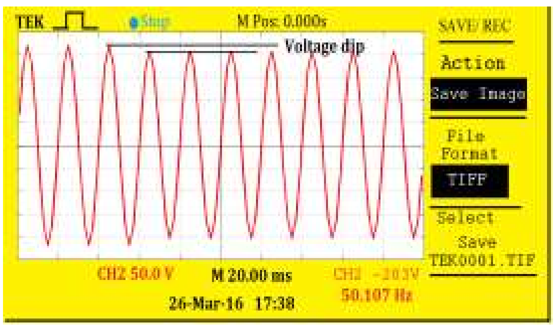


**Fig.15. Experimental waveform during turn to turn fault for 24 pole Single phase PMSG.**

Fig.15 shows the experimental waveform of the 24 Pole Single phase PMSG for operation during turn to turn fault.

The approximate calculations give the terminal voltage after fault is:

50V/div * 4.16div= 208V

There has been a dip in the terminal voltage of 12V after the fault has occurred. The experimental results are closer to the simulation results discussed in the Fig. 11.

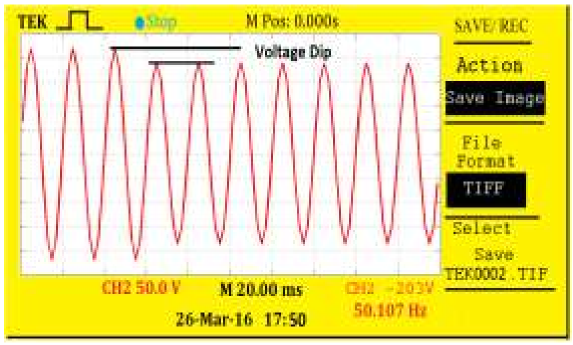


**Fig.16. Experimental waveform during turn to turn fault for 4 pole Single phase PMSG.**

Fig.16 shows the experimental waveform of the 24 Pole Single phase PMSG for operation during turn to turn fault.

The approximate calculations give the terminal voltage after fault is:

50V/div * 3.8div= 190V

The dip in terminal voltage after fault comes out to be 30V which is very closer to the simulation results showing the dip in the voltage to be 29V.

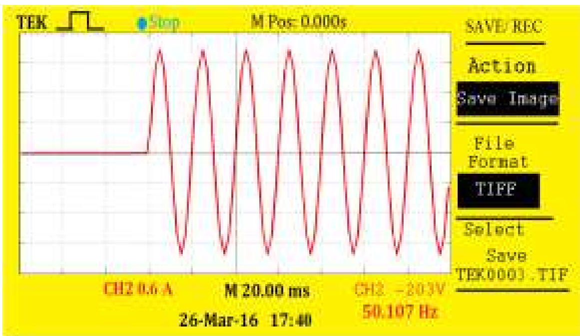


**Fig.17. Experimental waveform of the fault current for 4 Pole PMSG during turn to turn fault.**

Fig.17 represents the fault current waveform for the 4 pole PMSG for turn to turn fault. The fault current amplitude calculated comes out to be:

0.6A/div*3.2div=1.92A

Fault current for 8% fault is more severe in 4 pole generator as shown in the figure compared to 24 pole generator.

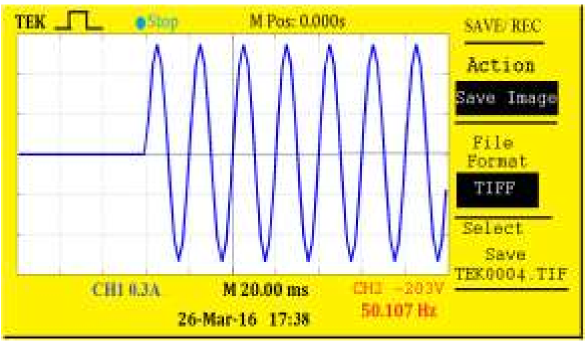


**Fig.18. Experimental waveform of fault current for 24 pole PMSG during turn to turn fault.**

Fig.18 shows the short circuit current in the 24 pole PMSG. Results have been captured by the current probes and have been observed at the C.R.O. The fault current is zero up to 60 ms but rises to the value calculated as:
0.3A/div*2.8=0.84A.

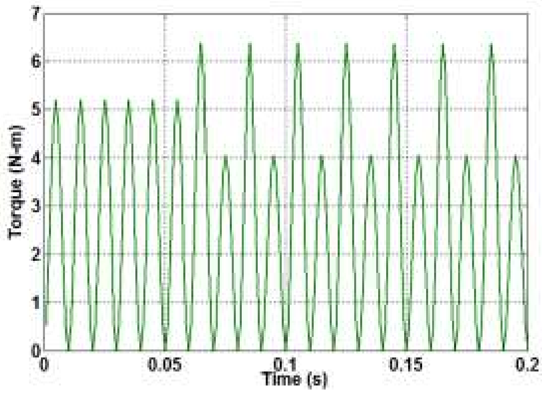


**Fig.19. Waveform of counter torque in 4 Pole PMSG during turn to turn fault.**

The experimental results are much closer to the simulation where the fault current peak was about 0.7A.

The counter torque generated in the 4 pole generator has been shown in the Fig.19. The counter torque generated is much distorted after the fault has occurred. The torque generated before fault was 4.5 N-m whereas after fault the maximum value of torque comes out to be nearly 6 N-m.

The Fig.20 shows the torque generation in 24 pole PMSG. For the same power large torque is required for higher pole generators. During healthy operations, the max amplitude of torque required for power generation is 30 N-m. The distortion in torque is very less after fault has occurred. Therefore, the 24 pole PMSG is more stable in during post fault operation.

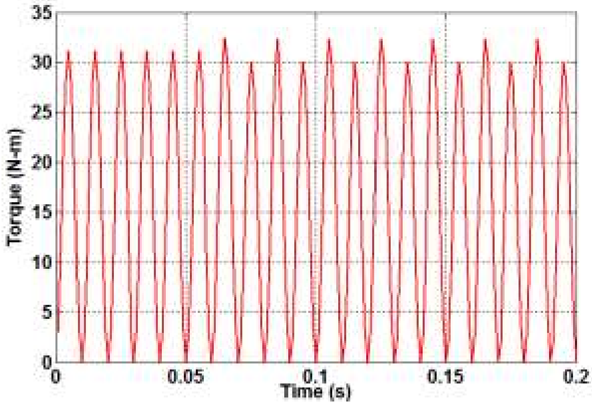


**Fig.20. Waveform of counter torque in 24 Pole PMSG during turn to turn fault.**

## 6. Conclusion

Winding Function approach provides a convenient method to analyze the inter-turn fault in Single Phase PMSG for different number of poles. The stator inductances derived by Winding function Theory can be used for the dynamic equations to obtain mathematical results which provide a clear view of the effect of different parameters on the performance of the machine during short circuit in windings. This paper describes the variation of short circuit fault current, terminal voltage and counter torque on the generator during fault by taking an example of 4 pole and 24 pole generator. The behavior of stator inductances have been studied by the theoretical plot. Various fruitful results have been investigated by the simulation and experimental analysis. Fault current is very large for 4 pole generator as compared to 24 pole generator for the same percentage of short circuit. It means that unhealthy windings are more prone to damage and burning in case of the PMSG with low number of poles. Similarly, it has been observed that reduction in the terminal voltage is more for the 4 pole PMSG compared to 24 pole PMSG. This means that PMSG with large number of poles are able to cope the fault compared to low pole PMSG. Distortion in counter torque is more for the 4 pole generators compared to 24 pole generators. In other words, PMSG with large number of poles are more tolerant to inter turn fault. The drawback with higher pole PMSG is that they are more complex in construction and are costly due to large number of magnets on rotor. Therefore, the application where the PMSG are more prone to the turn to turn fault should have suitable trade-off between number of poles and the cost of construction as per the need of application.

| | |
|---|---|
| Shaft Radius | 8.2 cm |
| Rotor width | 18 cm |
| Magnet | NdFeB |

## 7. Table

**Table 1. List of Variables**

| Variables | Values |
|---|---|
| $A$ | $L_{net} \square L_{scsc} \cdot L_{ssc}^{2}$ |
| $B$ | $R_a \square L_{scsc} \bullet R_{sc} \square L_{ssc}$ |
| $C$ | $R_a \square R_{sc}$ |
| $L_{asc}$ | $\frac{L_{ssc}}{1. \, s/100}$ |
| $R_1$ | $\frac{A_2}{A} \square L$ |
| $R_2$ | $\frac{A_2}{A} \square R_a \bullet \frac{R_{sc}}{A} \square L$ |
| $R_3$ | $\frac{R_{sc}}{A} \square R_a$ |
| $M_{net}$ | $R_a \square L_{ssc} \square i(0)^{-}$ |
| $A_2$ | $(\frac{2 \square s}{P \square 100} \square L) \cdot L_{ssc}$ |
| $B_2$ | $\frac{2 \square s}{P \square 100} \square R_a$ |

**Table.2 Details of the 4 Pole and 24 pole PMSG**

| **Stator Details** | |
|---|---|
| No. of Slots | 24 |
| No.of turns | 2400 |
| Inner Stator Diameter | 12 cm |
| Outer Stator Diameter | 15 cm |
| Width of Stator | 20 cm |
| Slot Opening | 8mm |
| Area of Slot | 180 mm$^2$ |
| Short circuited turns | 192 |
| **Rotor Details** | |
| **4 Pole Rotor** | |
| No. of Poles | 4 |
| Outer Radius of Rotor | 110 mm |
| Shaft Radius | 8.2 cm |
| Rotor width | 18 cm |
| Magnet | NdFeB |
| **24 Pole Rotor** | |
| No. of Poles | 8 |
| Outer Radius of Rotor | 110 mm |

**Table.3 Details of the prime mover (DC Motor)**

| **Test Machine Ratings** | |
|---|---|
| Phase | 1 |
| Rated Current | 2A |
| Generated EMF | 220V |
| Winding Resistance | 1.2Ω |
| Rated Power | 440W |
| Maximum current | 4 A |
| **Prime mover rating** | |
| Rated Voltage | 440V |
| Rated speed | 800 R.P.M |
| Rated current | 2.5A |

## 8. Acknowledgements

This work was supported by IIT (BHU), Varanasi. We are grateful to Dr. R.K. Srivastava for giving valuable guidance for completion of project.

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