NATIONAL BOARD FOR TECHNICAL EDUCATION
NIGERIAN JOURNAL FOR TECHNICAL EDUCATION
Volume 21 Nos. 1 2023
ISSN No. 2992 - 3522

PERFORMANCE OF FIVE-PHASE SYNCHRONOUS RELUCTANCE MOTOR WITH ECCENTRICITY CONDITIONS

Gideon. D. Umoh[1] and Ekpo, Edet George[2]
[1]Department of Electrical Electronics Engineering Maritime Academy of Nigeria, Oron.
umohgideon@gmail.com
[2]Department of Electrical Electronics Engineering, AkwaIbom State Polytechnic, IkotOsurua.
georgeekpo@gmail.com

Abstract

A five-phase synchronous reluctance machine is modelled with no eccentricity fault, as well as other modelled of the machine with Static, dynamic and mixed eccentricities. The machine is subjected to a direct-on-line starting, loaded with a ramp load at synchronism and subsequently subjected to a loss of phase fault. The dynamic performance characteristics of flux linkage, speed and torque are considered. The load carrying capacity of the various considered machine is also determined under the faulty conditions of the machines. The eccentricity conditions of the machine gives an indication as it deviates from the rated condition of the machine. These deviations observed in static, mixed and dynamic eccentricities are less significant to a 2 places of decimal for condition of synchronism at start and on load, but show significances to 1-place of decimal on loss of phase fault.The flux linkages separated by a

Keywords: Synchronous Reluctance Machine, Eccentricity, Finite Element Analysis, Flux linkage.

1. Introduction

The occurrences of eccentricity condition in a machine has always concern manufacturers, researcher as well as the users of electric machines. Being able to detection the occurrences and well as the effect of eccentricity is also of an advantage the both the manufacturer and the user of the machine.

The occurrences of eccentricity in electric machines go undetected when the displacing angle of the moving part or motion axis are small as compared to the air-gap. In such a situation, careful study of the machine performance characteristics will give indications of slight deviation from the rated parameters.However, these eccentricity conditions may be imperfections due to manufacturing, bearing tolerance or shaft bow,Mahmoud and Bianchi(2015).

The reluctance machine has as advantage of not having winding in the rotor, and harnessing the use of reluctance torque for its application has led to high consideration in many applicationsCamarano, Wu, Rodriguez, Zumberge and Wolff (2012), Mahmoud and Bianchi, June(2015), Obe and Binder (2011), Mahmoud and Bianchi (2015), Li, Mahmoud and Degano (2019), Li, Mahmoud, Degano, Bardalai, Zhang and Gerada(2020).

The synchronous reluctance machine (SYNRM) has shown to be suitable for high speed application, being advantageous in efficiency, high torque density, etc.Silwal, Ibrahim, and Sergeant (2018).

With relevance of the SYNRM, the issue eccentricity has been addressed by various researchers, especially concerning static and dynamic eccentricity,Mahmoudand

Bianchi(2017),Safa and Zarchi,(2021),López-Torres, Riba, Garcia and Romeral (2017),Naderi(2015). The works of Mahmoud and Bianchi(2017) considered eccentricity condition with inclusion of Iron saturation and Slotting effect. The detection of unbalance force presence during eccentricity, giving a non-uniform air-gap resulted as indication of eccentricity,Mahmoud and Bianchi(2015), Mahmoud and Bianchi(2017). The non-uniformity of the air-gap adversely affect the inductance and then the flux linkages because of their dependency on the air-gap. The influence of eccentricity conditions ontheloading capacityof an electrical machine has been neglected by researchers and it effects may bemisrepresented as depreciation, even if it's a manufacturing defect.

This study analyses a five-phase Synchronous Reluctance machine dynamic characteristic performance of flux linkage Speed and Torque for no eccentricity condition machine, as well as other modelled machines with Static eccentricity, dynamic eccentricity and mixed eccentricity conditions.

2. OBJECTIVES

The objectives of this study are to model a Synchronous Reluctance Machine and then investigated on the characteristic performance of the machine under Static, Dynamic and Mixed eccentricity conditions.

$\frac{2\pi}{5}$

3. MATERIALS AND METHODS

The considered machine is a five-phase (5-ph), 4-pole, 40 slots synchronous reluctance motor, with a cage rotor. The machine has a radian separation for the stator winding axes.

The synchronous Reluctance motor (SYNRM) model is without a field winding butwith one damper winding in the q-axis and d-axis [10].

The voltage equation for a conventional SYNRM is given in equation 1 the flux linkage ,

$$V = RI + p\lambda \quad (1)$$

Where,

$$p = \frac{d}{dt} \quad (2)$$

$\lambda$is the flux linkage v is the voltage matrix, R is the resistance matrix $\lambda = L(\theta_r)I$, whereθ_r is the rotor position $L(\theta_r)$ is the inductance matrix.The flux linkage equation show the dependency of the inductances on the rotor position.

The machine dimensions and circuit parameters are tabulated in table 1. These tabulated parameter represent the parameter of the normal machine without the eccentricity condition.

Table : 5-Phase SYNRM dimensions and circuit parameters

Quantities	Value	Quantities	Value
Stator Outer / inner radius	105.02 / 67.99mm	Number of poles	4
Rotor Radius	67.69mm	Frequency	50Hz
Effective stack length	160.22mm	The stator resistance ? ?	0.83Ω
Number of slot	40	Stator leakage inductance ? ?	10.98mH
Number of turns	48	rotor q-axis leakage inductance? ?	6.2mH,
Main air-gap length ? ?	0.4mm	Rotor q-axis leakage inductance ? ?	5.5mH
Inter polar slot space ? ?	21.3mm	Rotor q-axis resistance ? ?	0.25 Ω
Stator slot depth	18mm	rotor d-axis resistance ? ?	0.12 Ω

The machines were modelled with the eccentricity conditions as tabulated in table 2.

Table : Eccentricity value for the machine

Type of Eccentricity	Translation of moving parts		Translation of motion axis	
	x-axis(mm)	y-axis(mm)	x-axis(mm)	y-axis(mm)
Static	0.0212	0.0212	0.0212	0.0212
Dynamic	0.0212	0.0212	0.000	0.000
Mixed	0.0212	0.0212	0.010	0.010

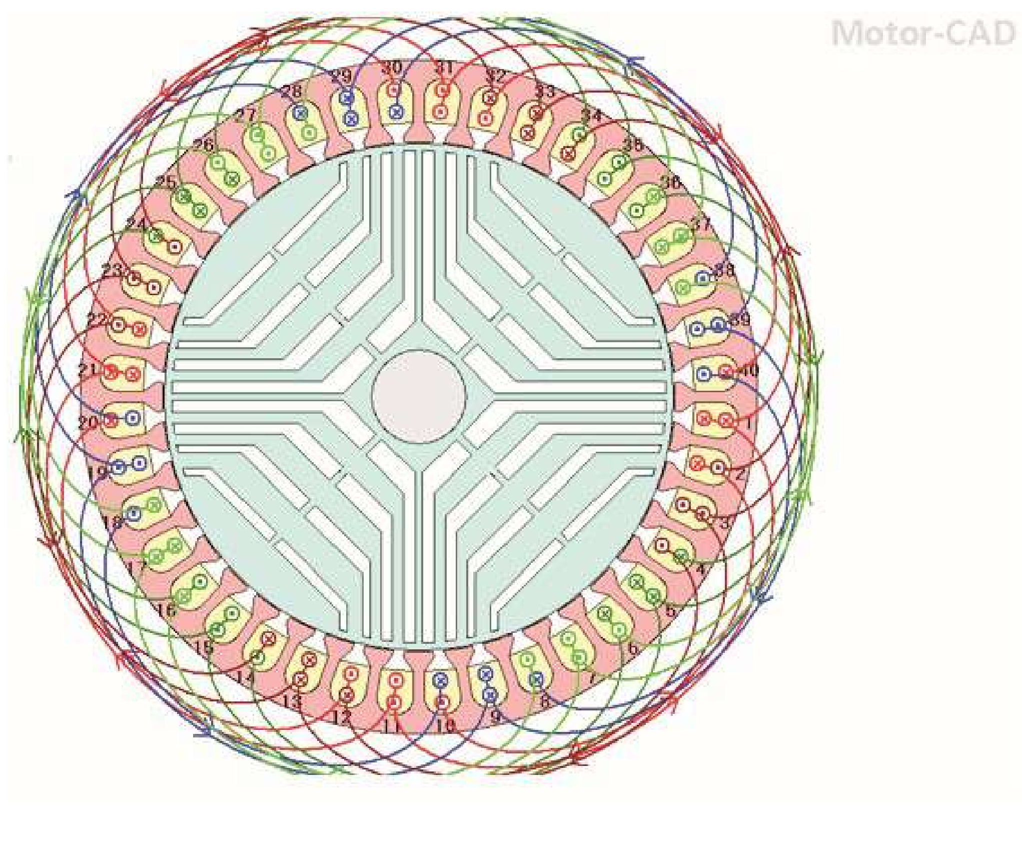

Figure : Figure showing winding arrangement

4. RESEARCH METHODOLOGY

These machines are considered from standstill, start, on load at fault and loss of synchronism. The machines are loaded with equal amount of ramp load to determine their loading capacities.

The machines was modelled using ANSYS Maxwell Finite Element Analysis (FEA) software and ANSYS motor CAD while the eccentricity condition analysis was carried out using ANSYS Maxwell FEA.

For the eccentricity conditions, the parameters for the translation of the moving part and the motion axis were adjusted to suit the various conditions, table 2.

To determine the loading capacity of the considered machines, a ramp load was modelled with a gradient of 10 Nm per seconds, introduced at 4 seconds after synchronism had been achieved.

The nature of introduced load for the analysis is shown in the plot of load figure 2.

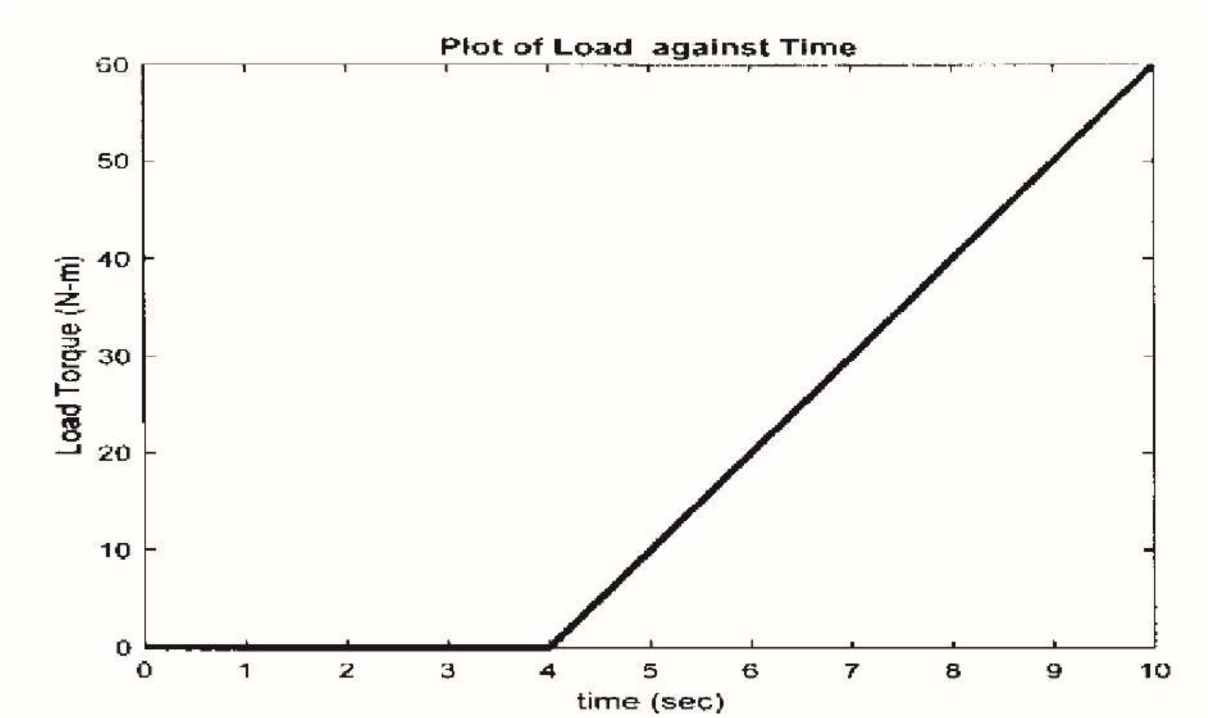

Figure : plot of Load

5. RESULTS

The various machine performance characteristics of flux linkage, speed and torque were considered for the various subjected conditions.

The flux linkage characteristics transient characteristics of λ_a, λ_b, λ_c, λ_d and λ_e at synchronism after start, on loading and on loss of e-phase fault are tabulated in 5-ph Synchronous reluctance machine flux linkages table 3.

At synchronism after start, the normal machine show the maximum transient rise of 1.1656 Wb, as well as a maximum drop of -1.1656Wb, is recorded for in all phases, while the eccentricity condition records negligible changes in their transient rise, only significant beyond 2 decimal places.

The same similar characteristics of negligible change is observed during loading, but at loss of e-phase fault the change is significant beyond 1 decimal place.
At loss of phase fault the flux linkages separated by a $\frac{2\pi}{5}$ phase shift show lesser rise than a $\frac{4\pi}{5}$ phase shift, recording 67%, 72%, 76% 97%, for e-phase, a-phase, d-phase and c-phase respectively, with b-phase recording to the highest transient rise of 1.13Wb.

Table :5-ph Synchronous Reluctance Machine flux linkage

Quantity		**Synchronism**		**On Loading**		**Loss of e-phase**	
		Max val. at start up	Min val. at start-up	Max val. at Load	Min val. at Load	Max val. at Load	Min val. at Load
$?_?$ (Wb)	Normal	1.16561	-1.16561	1.16554	-1.16554	0.824813	-1.06381
	Static	1.15409	-1.15409	1.15418	-1.15454	0.828242	-1.05254
	Dynamic	1.15563	-1.1555	1.15563	-1.15560	0.826433	-1.0512
	Mixed	1.15532	-1.15552	1.15555	-1.15563	0.82762	-1.05138
$?_?$ (Wb)	Normal	1.16559	-1.16555	1.16554	-1.16555	1.13774	-1.05556
	Static	1.15407	-1.15427	1.15446	-1.15476	1.13049	-1.04447
	Dynamic	1.15549	-1.15558	1.15569	-1.15564	1.12757	-1.04409
	Mixed	1.15548	-1.15569	1.15566	-1.15569	1.12816	-1.04385
$?_?$ (Wb)	Normal	1.16562	-1.16555	1.16554	-1.16554	1.11914	-1.07588
	Static	1.15422	-1.15458	1.15468	-1.15501	1.107	-1.06901
	Dynamic	1.15555	-1.15561	1.15565	-1.15565	1.10613	-1.06953
	Mixed	1.1556	-1.1557	1.1557	-1.15567	1.1059	-1.06895
$?_?$ (Wb)	Normal	1.16559	-1.16561	1.16549	-1.16554	0.860242	-1.07706
	Static	1.154	-1.15418	1.1543	-1.15461	0.856696	-1.06768
	Dynamic	1.15549	-1.15556	1.15557	-1.15559	0.856062	-1.06643
	Mixed	1.15536	-1.15554	1.15556	-1.15571	0.856541	-1.0662
$?_?$ (Wb)	Normal	1.1656	-1.1655	1.16556	-1.16557	0.706032	-0.358627
	Static	1.15415	-1.15439	1.15458	-1.15492	0.7005064	-0.363165
	Dynamic	1.15557	-1.1556	1.15558	-1.15557	0.704463	-0.363269
	Mixed	1.15552	-1.15563	1.15566	-1.15571	0.704412	-0.363157

The plot of a-flux linkage for all the eccentricity condition, consideration at start, loading and loss of phase is presented respectively in figure 3, figure 4, figure 5 and figure 6, while the plot of b-flux linkage for all the eccentricity condition, consideration at start, loading and loss of phase is presented respectively in figure 7, figure 8, figure 9 and figure 10.

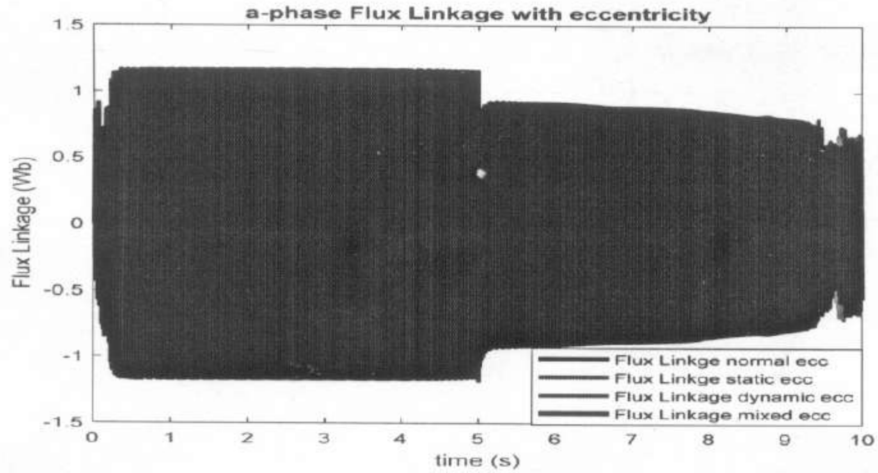

Figure 3: FEM showing Flux linkage λ_a, *(*$\frac{4\pi}{5}$ *rad phase shift)*

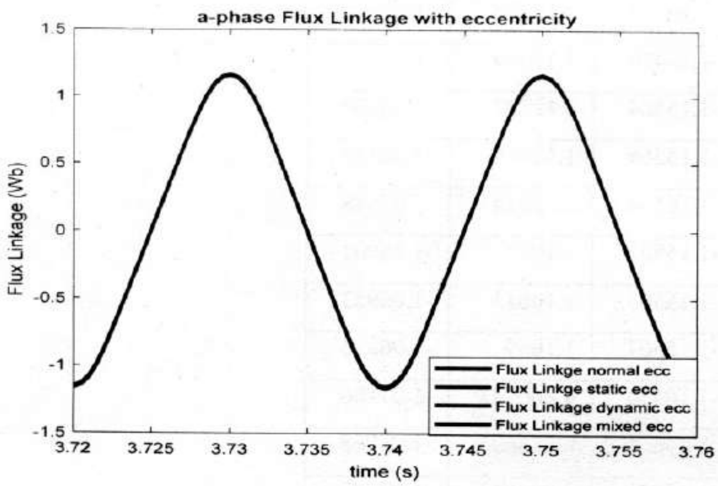

Figure 4: FEM showing Flux linkage λ_a*(*$\frac{4\pi}{5}$ ***rad phase shift)****at synchronism*

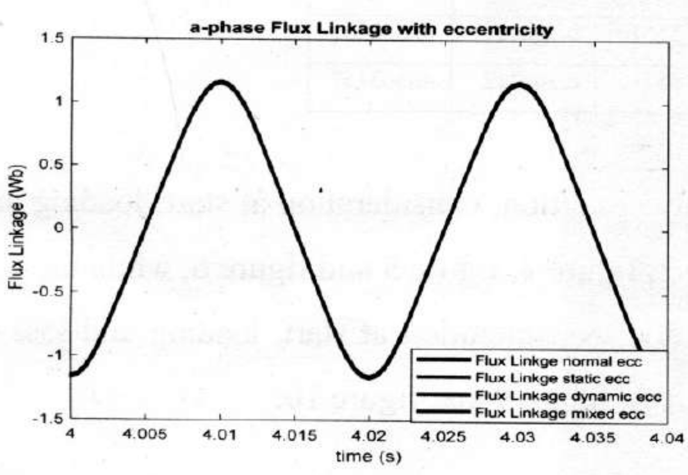

Figure 5: FEM showing Flux linkage $\lambda_a(\frac{4\pi}{5}$ *rad phase shift)on loading*

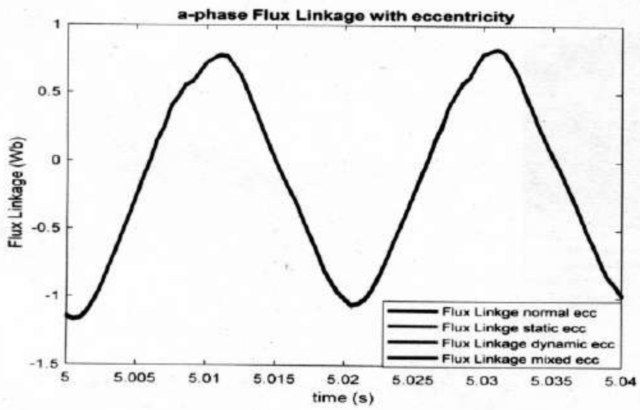

Figure 6: FEM showing Flux linkage $\lambda_a(\frac{4\pi}{5}$ *rad phase shift)on loss of phase fault*

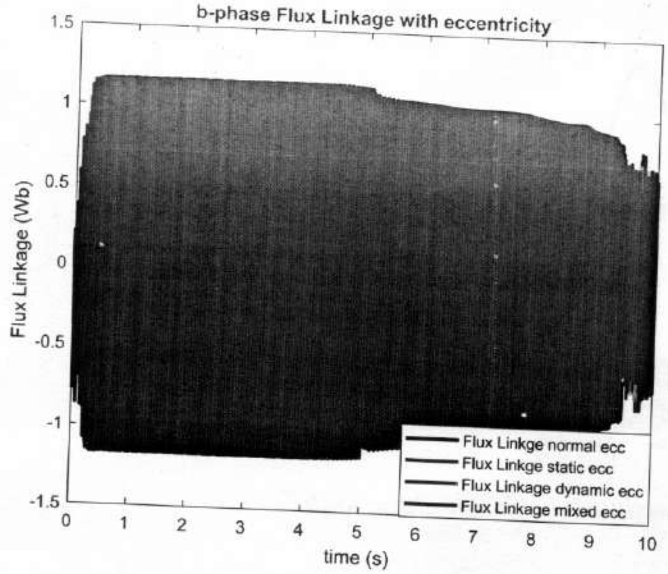

Figure 7: FEM showing Flux linkageλ_b, $(\frac{2\pi}{5}$ *rad phase shift)*

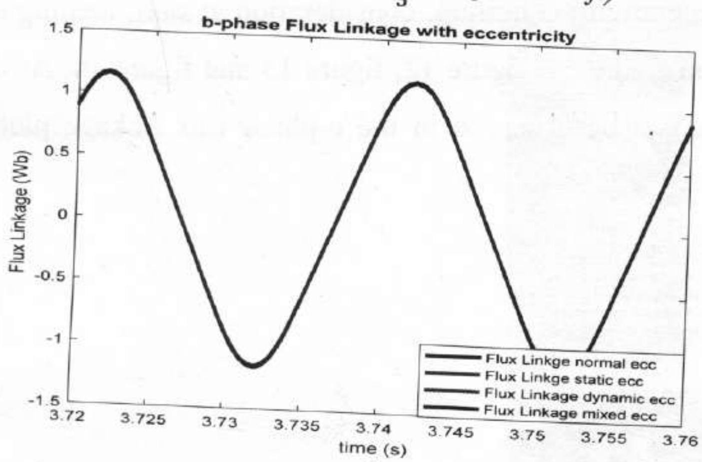

Figure 8: FEM showing Flux linkageλ_b, $(\frac{2\pi}{5}$ *rad phase shift) at synchronism*

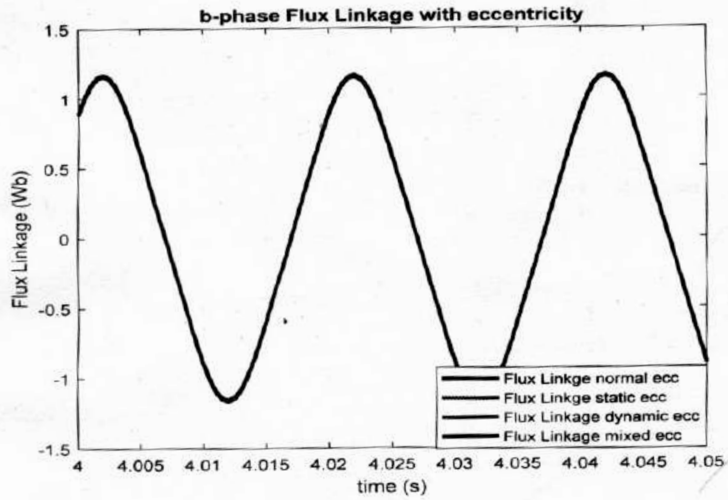

Figure 9: FEM showing Flux linkage λ_b, *($\frac{2\pi}{5}$ rad phase shift) on Loading*

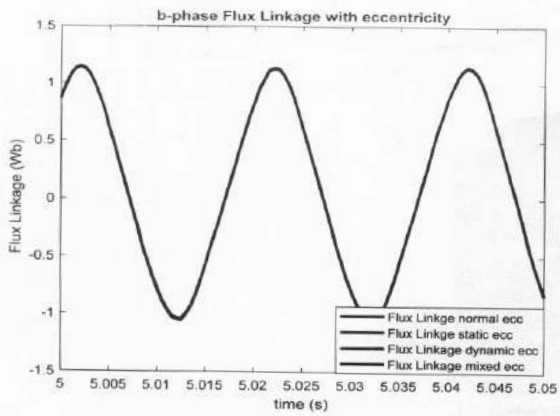

Figure 10: FEM showing Flux linkage λ_b, *($\frac{2\pi}{5}$ rad phase shift) on loss of phase fault*

The plot of e-flux linkage for all the eccentricity condition, consideration at start, loading and loss of phase is presented respectively in figure 11, figure 12, figure 13 and figure 14. At loss of e-phase fault, a significant decrease can be observed in thė e-phase flux linkage plot in figure 11.

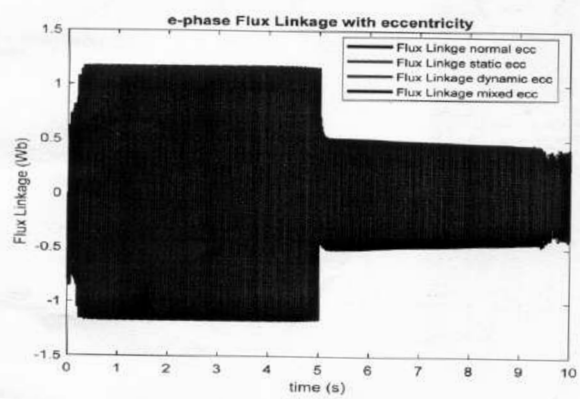

Figure 11: FEM showing Flux linkage λ_e

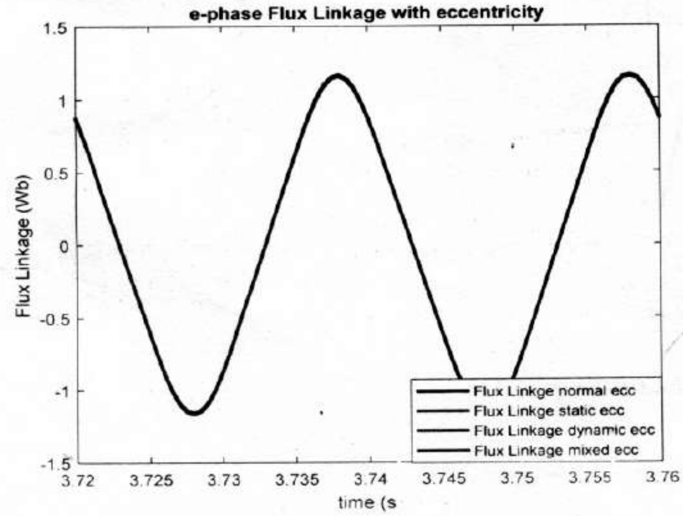

Figure 12: FEM showing Flux linkage λ_2, *at synchronism*

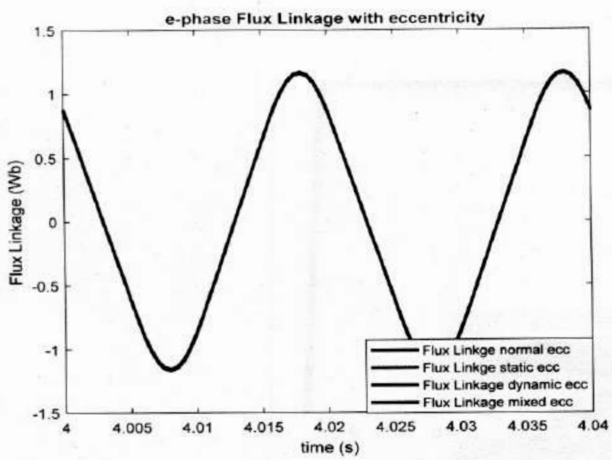

Figure 13: FEM showing Flux linkage λ_e, *on loading*

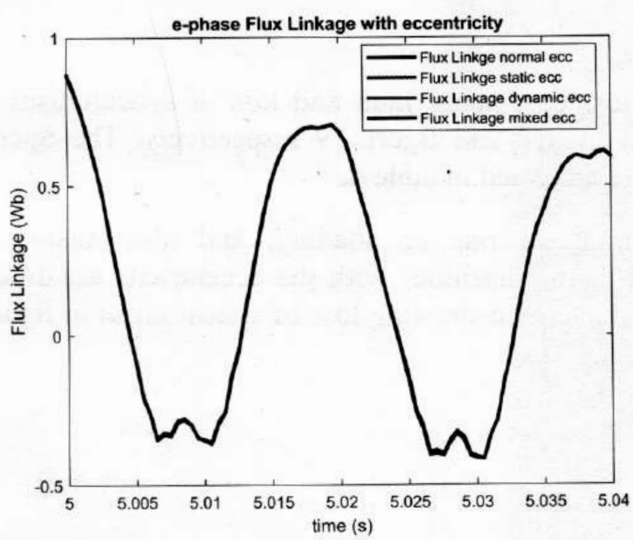

Figure 14: FEM showing Flux linkage λ_e, *on loss of phase fault*

The speed characteristics for the machines, is presented in figure 15, showing almost negligibility effect of eccentricity conditions on the machine performance.

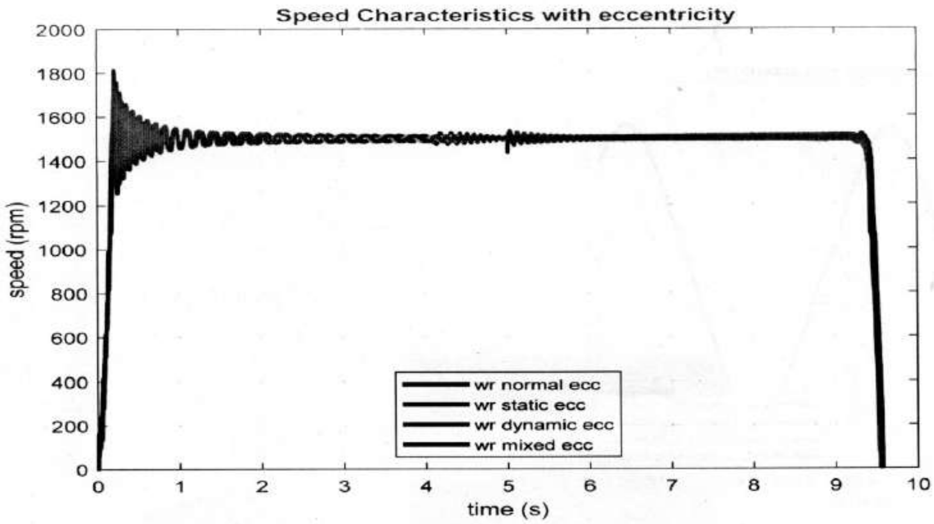

Figure 15: Speed performance characteristics

The speed transient at start, on loading, at loss of e-phase fault and loss of synchronism is shown in figure 15, figure 16, figure 17, figure 18 and figure 19 respectively. The Speed performance characteristics of the machinesare tabulated in table 4.

The normal machine records a highest transient rise on loading, and also maintains synchronism for a longer time as compared to the machines with the eccentricity condition during loss of phase faultas seen in speed characteristic showing loss of synchronism in figure 19.

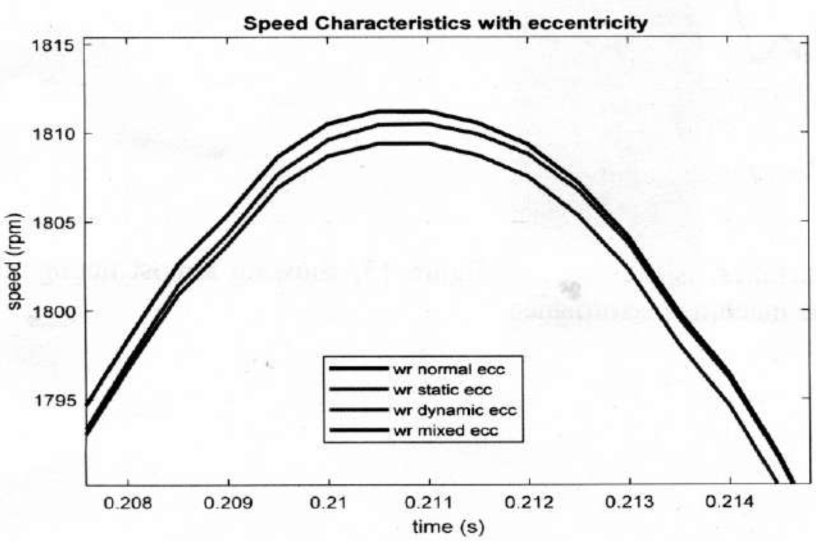

Figure 16: Speed characteristics showing transient at start for eccentricity conditions

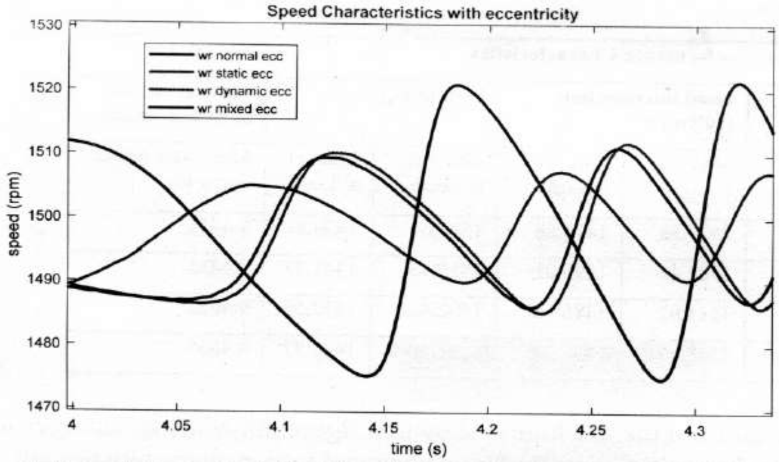

Figure 17: Speed characteristics showing transient on loading

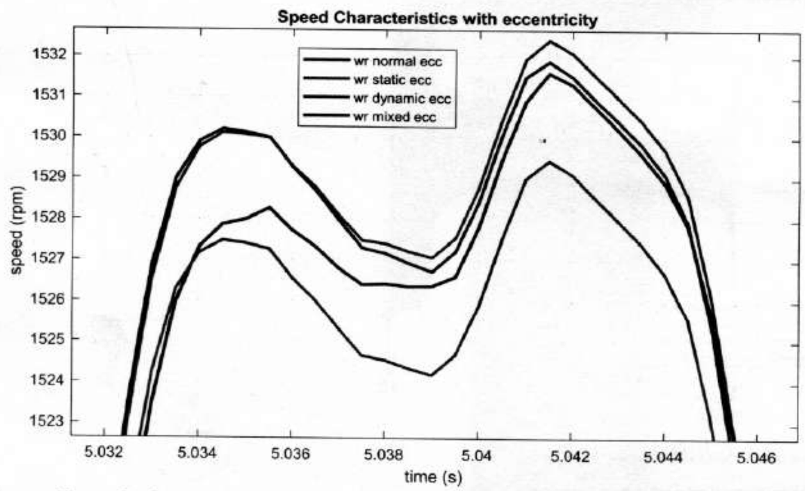

Figure 18: Speed characteristics showing transient on loss of e-phase (maximum transient)

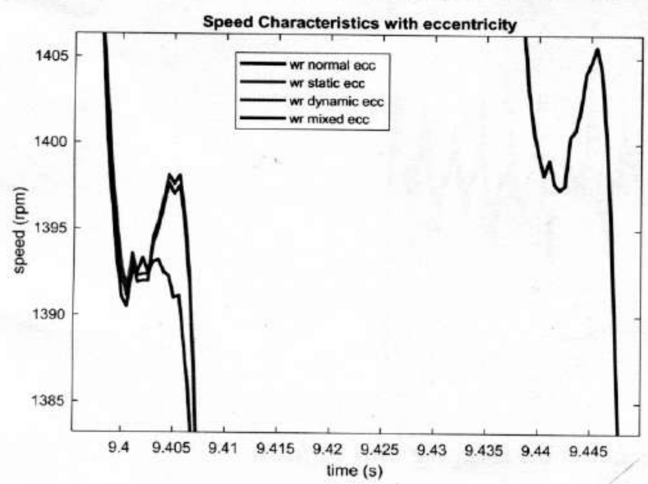

Figure 19: Speed characteristics showing loss synchronism

During loss of synchronism, the machine with mixed eccentricity records the least time value of 9.4035 seconds as to the other eccentricity conditions.

Table : 5-ph speed performance characteristics

Speed Performance Characteristics								
Quantity		Start – up		**Load introduction (10Nm)**		**Loss of e-phase**		**Time(s) of Loss of Synchronism**
		Max val. at start up	Min val. at start-up	Max val. at Load	Min val. at Load	Max val. at Load	Min val. at Load	Max value before decay (s)
Speed (rad/s)	Normal	1757.70	1300.35	1521.58	1474.88	1531.61	1436.81	9.4455
	Static	1809.40	1255.78	1507.43	1490.01	1529.45	1441.77	9.4055
	Dynamic	1810.52	1254.78	1511.93	1486.12	1532.43	1437.59	9.4055
	Mixed	1811.24	1254.19	1511.10	1486.94	1531.89	1438.72	9.4035

The Torque performance characteristics of the machine is shown in figure 20, while an enlarge view on loading and initiation of fault is shown in figure 21. These observed torque characteristics are tabulated in table 5.

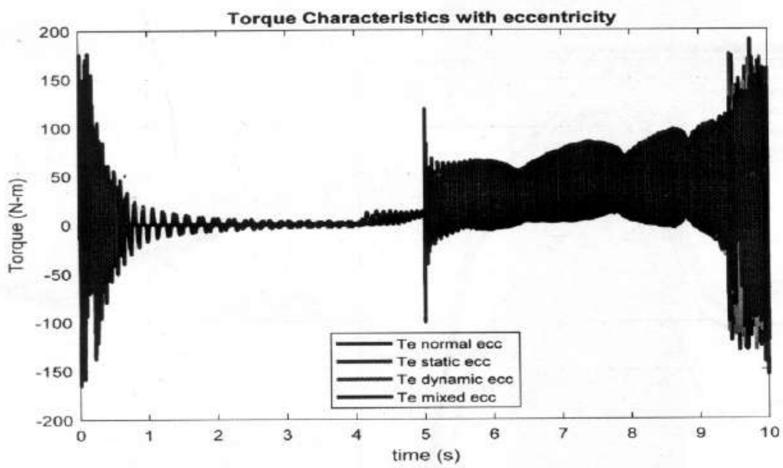

Figure 20: 5-ph Torque Performance Characteristics

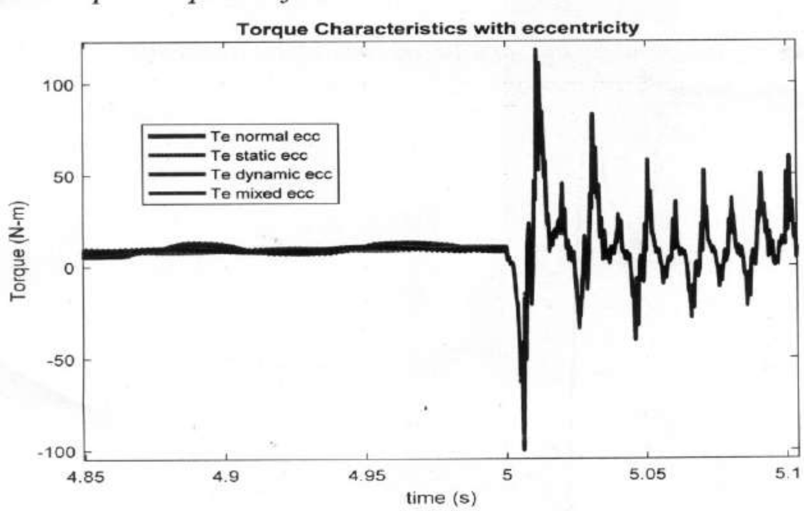

Figure 21: 5-ph Torque Performance Characteristics on loading and at fault

Table 5: Torque performance characteristics

Torque Performance Characteristics								
Quantity		**Start –up**		**Load introduction (10Nm)**		**Loss of e-phase**		**Time(s) of Loss of Synchronism**
		Max val. at start up	Min val. at start-up	Max val. at Load	Min val. at Load	Max val. at Load	Min val. at Load	Max value before decay (s)
Speed (rad/s)	Normal	175.882	-164.879	13.271	-0.3474	118.02	-99.974	9.4455
	Static	171.912	-152.346	9.77884	0.85685	114.174	-91.903	9.4055
	Dynamic	171.86	-150.414	10.5859	0.75059	115.922	-94.606	9.4055
	Mixed	171.844	-151.700	10.1898	0.73506	117.474	-90.974	9.4035

These considered eccentricity conditions of static, mixed and dynamic are less significant to a 2 places of decimal for condition of synchronism at start and on load, but show significances to 1-place of decimal on loss of phase fault.

The flux linkages separated by a $\frac{2\pi}{5}$ phase shift show lesser rise than a $\frac{4\pi}{5}$ phase shift, recording 67%, 72%, 76% 97%, 100%, for e-phase, a-phase, d-phase and c-phase and b-phase respectively.

For the speed characteristics, during loading, a greater transient is observed with the normal machine as compared to the eccentricity conditions, while on loss of phase fault, the greatest transient is recorded in the machine with dynamic eccentricity.

6. CONCLUSION

The 5-phase synchronous reluctance machine was modelled as normal, with static eccentricity condition, dynamic eccentricity condition and mixed eccentricity condition.

The various models of the machines with eccentricity condition showed acceptable result in the study of 5-ph synchronous reluctance machine performance characteristic, but with further investigation, characteristic differences can be observed within the models.

The normal machine still show a greater resilience during fault in remaining in synchronism after the machine with eccentricity had loss synchronism. The machine with static eccentricity condition was the first machine to lose synchronism, subsequently the dynamic and the mixed eccentricity machine lost at the same time.

It can be concluded that the eccentricity conditions affect the load carrying capacity of the machine, as a lower load carrying capacity is recorded with eccentricity as compared to the normal machine.

6. REFERENCES

Li, J., Mahmoud, H. and Degano, M. (2019)- Vibration Analysis of Permanent Magnet Assisted Synchronous Reluctance Machine. *22nd Iternational Conference on Electrical Machines and Systems (ICEMS) IEEE.*

Camarano, T., Wu,T. Rodriguez, S. Zumberge, J. and Wolff, M. (2012). Design and Modeling of a Five-Phase Aircraft Synchronous Generator with High Power Density. *IEEE Energy Conversion and Exposition (ECCE),* 1878-1885.

Li, J., Mahmoud, H., Degano, M., Bardalai, A., Zhang, X. and Gerada, C. (2020). Impact on vibration of eccentric permanent magnet assisted synchronous reluctance machine. *Proceedings- 2020 International Conference on Electrical Machines, ICEM 2020,* 476-480.

Lopez-Torres, C, Riba, J., Garcia A. and Romeral, L. (2017). Detection of Eccentricity Faults in Five-Phase Ferrite-PM Assisted Synchronous Reluctance Machines. *Applied Sciences,* 7(565).

Mahmoud H. and Bianchi, N. (2015). Analytical comparison of synchronous reluctance and surface permanent magnet machines with rotor eccentricity. 2075 *IEEE Energy Conversion Congress and Exposition, ECCE 2015,* 1765-1772.

Mahmoud, H. and Bianchi, N. (2015, June 13)- Eccentricity in Synchronous Reluctance Motors—Part II: Different Rotor Geometry and Stator Windings. *IEEE TRANSACTIONS ON ENERGY CONVERSION, 30(2),* 754-760. Retrieved March 13, 2023

Mahmoud, H. and Bianchi, N. (2017). Nonlinear Analytical Model of Eccentric Synchronous Reluctance Machines Considering the Iron Saturation and Slotting Effect. *IEEE Transactions on Industry Applications,* 53(3), 2007-2015.

Mahmoud, H. and Bianchi, N. (June, 2015). Eccentricity in Synchronous Reluctance Motors—Part.I: Analytical and Finite-Element Models. *IEEE TRANSACTIONS ON ENERGY CONVERSION,* 30(2), 745 -753.

Mahmoud, H. and Bianchi, N. (May/Jume, 2017). Nonlinear Analytical Model of Eccentric Synchronous Reluctance Machines Considering the Iron Saturation and Slotting Effect. *IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, 53(3),* 2007-2015.

Naderi, P. (2015). Eccentricity Fault Diagnosis and Torque Ripple Analysis of a Four-pole Synchronous Reluctance Machine in Healthy and Faulty Conditions. *Electric Power Components and Systems,* 43(11), 1236-1245.

Obe, E. S. and Binder, A. (2011). Direct-phase-variable model of a synchronous reluctance motor including all slot and winding harmonics. *Energy Conversion and Management, 52,* 284-291.