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Analysis of Five-Phase Synchronous Reluctance Motor under Multi-Phase Faults

G. D. Umoh[1], E. G. Ekpo[2]

[1]Dept of Electrical Engineering, Maritime Academy of Nigeria, Oron, Akwa-Ibom State – NIGERIA

[2]Dept of Electrical/Electronic Engineering, Akwa Ibom State Polytechnic Ikot Osurua, Ikot Ekpene, Akwa Ibom State

ABSTRACT: The model of a five-phase synchronous reluctance motor is presented, modelled to investigate the machine characteristic during multi-phase fault. The machine is modelled for a five phase supplied, with ACEBD winding configuration. The model considers the utilization of the third harmonics of the air-gap MMF as well the fundamental component, and a neglect of the third harmonics. These two models speed performance characteristics are monitored for multi-phase faults and their subsequence restorations. The fault pattern of losing $\frac{2\pi}{5}$ phases from the first faulty before the $\frac{4\pi}{5}$ radian phase and the losing of $\frac{4\pi}{5}$ phase radian first before the $\frac{2\pi}{5}$ radian phase. These phases were subsequently restored according to the considered fault patterns. The machine was then monitored on load and on no load using MATLAB/SIMULINK software for the analysis. The effect of the utilization of the third harmonic of the air-gap MMF is pronounced especially at fault and restorations.

KEYWORDS: Five-Phase, Synchronous Reluctance machine, Multi-phase Fault, Transient analysis, Air-gap.

I. INTRODUCTION

The synchronous reluctance machine has found prominence especially in high-speed drives. Its various advantages include reduces losses especially when using a squirrel cage rotor, and fault tolerances especially with the multi-phase system.

The high cost of permanent magnet machine, as well as other disadvantages of the switch reluctance machine has led researchers to consider the Synchronous reluctance Machine (SYNRM) as a viable alternative to the Induction motor.

The SYNRM has the ability to utilize the reluctance torque for energy conversion in additional to the torque developed by the magnetizing component of the circuit (P. Krause, O. Wasynczuk, and S. Sudhoff, 2013). Improvement in the machine saliency of the rotor increases to availability of reluctance torque for energy conversion, and the rotor can be modelled in the simplest form (E. Obe, and A. Binder, 2011; E. S. Obe, 2009; T. Matsuo and T. A. Lipo, June 1994).

Various models by many researchers have contributed to an acceptable representation of the performance characteristics of the machine for further research and improvement. Winding function (WF) model (E. Obe, and A. Binder, 2011; H. A. Toliyat, L. Xu and T. A. Lipo, 1992), phase variable models (E. Obe, and A. Binder, 2011; H. A. Toliyat, S. P. Waikar and T. A. Lipo, 1998; G. Umoh, G. Ekpo and A. Akhikpemelo,, 2022), d-q model (P. Krause, O. Wasynczuk, and S. Sudhoff, 2013) (T. Camarano, T. Wu, S. Rodriguez, J. Zumberge, and M. Wolff, 2012) Finite Element Model (E. Obe, and A. Binder, 2011) etc.

The FE model has been used to verify a used of a combination of the direct-phase variable model and winding function model, proving to give a more accurate result than the d-q model (E. Obe, and A. Binder, 2011; G. Umoh, C. Ogbuka, and E. Obe., 2020; G. Umoh, C. Obe , C. Ogbuka , G. Ekpo, , E. Obe , 2020).

The use of the direct-variable model for the multi-phase system does not necessitate the transformation to the d-q frame, as was applicable due to high computational requirements. In fault predictions and analysis of machine performance during the unbalance conditions, the direct-phase variable model is greatly appreciated (E. Obe, and A. Binder, 2011).

The utilization of the multi-phase system in fault analysis gives a wider degree of freedom as losses of up to n-1phases can be considered. In addition, the additional harmonics are available for torque production as phase increases (H. A. Toliyat, S. P. Waikar and T. A. Lipo, 1998; G. Umoh, E. Obe, and O. Okoro, 2017; H. A. Toliyat, M. M. Rahimian and T. A. Lipo, 1991)

Analysis of Five-Phase Synchronous Reluctance Motor under Multi-Phase Faults

This study analyses a five-phase Synchronous Reluctance Motor characteristic performance during fault and unbalanced conditions, operating on load and no load. Model of not utilizing and utilizing the third harmonics of the air-gap MMF are considered for different fault pattern of successive loss of $\frac{2\pi}{5}$ rad phases and $\frac{4\pi}{5}$Rad phase loss pattern.

II. THEORETICAL ANALYSIS

The dynamic behaviour of the motor can be described by the parameter equations such as voltage and torque which is time-dependence in nature. Iron saturation is assumed to be neglected and only fundamental component of air gap flux is be taken into account.

Under balanced condition, five phase stator voltage of SynRM is expressed as fellow:

$$V_a = \sqrt{2}\, V_{rms} \sin(\omega t) \qquad (1)$$

$$V_b = \sqrt{2}\, V_{rms} \sin\left(\omega t - \frac{2\pi}{5}\right) \qquad (2)$$

$$V_c = \sqrt{2}\, V_{rms} \sin\left(\omega t - \frac{4\pi}{5}\right) \qquad (3)$$

$$V_d = \sqrt{2}\, V_{rms} \sin\left(\omega t + \frac{4\pi}{5}\right) \qquad (4)$$

$$V_e = \sqrt{2}\, V_{rms} \sin\left(\omega t + \frac{2\pi}{5}\right) \qquad (5)$$

III. MATERIALS AND METHODS/METHODOLOGY

A. Model of Five-Phase Synchronous Reluctance Motor

The machine was modelled using the direct-phase variable model as a 40 slots,4-pole, 5-phase synchronous reluctance motor, with cage rotor.

The machine has a $\frac{2\pi}{5}$ Radian separation for the windings.

The general voltage equation of the machine is given in equation (6)

$$V = RI + p\lambda \qquad (6)$$

Where,

$$p = \frac{d}{dt} \qquad (7)$$

Where λ is the flux linkage, V is the voltage matrix, R is the resistance matrix and I is the current matrix.

$$pI = [L(\theta_r)]^{-1}\left(V - \left\{R + \omega_r\left[\frac{dL(\theta_r)}{d\theta_r}\right]\right\} I\right) \qquad (8)$$

$$\omega_r = \frac{d\theta_r}{dt} \qquad (9)$$

$$I = [i_{as}; i_{bs}; i_{cs}; i_{ds}; i_{es}; i_{kq}; i_{kd}] \qquad (10)$$

$$V = [v_{as}; v_{bs}; v_{cs}; v_{ds}; v_{es}; v_{kq}; v_{kd}] \qquad (11)$$

$$L(\theta_r) = \begin{bmatrix} L_{ss} & {L_{sr}}' \\ \frac{2}{5}(L'_{sr})^T & L'_r \end{bmatrix} \qquad (12)$$

$$L_{ss} = \begin{bmatrix} L_{asas} & L_{asbs} & L_{ascs} & L_{asds} & L_{ases} \\ L_{bsas} & L_{bsbs} & L_{bscs} & L_{bsds} & L_{bses} \\ L_{csas} & L_{csbs} & L_{cscs} & L_{csds} & L_{cses} \\ L_{dsas} & L_{dsbs} & L_{dscs} & L_{dsds} & L_{dses} \\ L_{esas} & L_{esbs} & L_{escs} & L_{esds} & L_{eses} \end{bmatrix} \qquad (13)$$

The self-inductances are arranged on the leading diagonal of the matrix of equation (13).

$$L'_r = \begin{bmatrix} L'_{lkq} + L_{mq} & 0 \\ 0 & L'_{lkd} + L_{md} \end{bmatrix} \qquad (14)$$

$$L'_{sr} = \begin{bmatrix} L_{mq}cos\theta_r & L_{md}sin\theta_r \\ L_{mq}cos\left(\theta_r - \frac{2\pi}{5}\right) & L_{md}sin\left(\theta_r - \frac{2\pi}{5}\right) \\ L_{mq}cos\left(\theta_r - \frac{4\pi}{5}\right) & L_{md}sin\left(\theta_r - \frac{4\pi}{5}\right) \\ L_{mq}cos\left(\theta_r + \frac{4\pi}{5}\right) & L_{md}sin\left(\theta_r + \frac{4\pi}{5}\right) \\ L_{mq}cos\left(\theta_r + \frac{2\pi}{5}\right) & L_{md}sin\left(\theta_r + \frac{2\pi}{5}\right) \end{bmatrix} \quad (15)$$

Where L_{ss} is the stator inductance matrix, L'_r is the rotor inductance matrix referred to the stator and L'_{sr} is the mutual inductances between the stator and the rotor referred to the stator.

$$R = \begin{bmatrix} R_{as} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & R_{bs} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & R_{cs} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & R_{ds} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & R_{es} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & R_{kq} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & R_{kd} \end{bmatrix} \quad (16)$$

R is the resistance matrix. The electromagnetic torque is given in equation (17)

$$T_e = \frac{1}{2} {I_s}^T \frac{\partial[L_{ss}(\theta_r)]}{\partial\theta_r} I_s + {I_s}^T \frac{\partial L_{sr}(\theta_r)}{\partial\theta_r} I_r \quad (17)$$

$$I_s = [i_{as},\ i_{bs},\ i_{cs},\ i_{ds}, i_{es}]^T \quad (18)$$

$$I_r = \left[i_{qr},\ I_{dr}\right]^T \quad (19)$$

$$T_e = J\left(\frac{p}{2}\right)\frac{d\omega_r}{dt} + T_l \quad (20)$$

Where,

I_s is the stator current matrix and I_r is the rotor current matrix.

J is the inertia expressed in kilogram-metre square $(kg - m^2)$ or joule-second square $(J\ S^2)$, while p is the no of poles of the machine.

A general sinusoidal form approximation of the inductances as given in equation (21) (T. Camarano, T. Wu, S. Rodriguez, J. Zumberge, and M. Wolff, 2012; G. Umoh, E. Obe, and O. Okoro, 2017).

$$L_{xy} = LA_{xy} + LB_{xy}\cos(2\theta \pm \theta_p) \quad (21)$$

$$LB_{xy} = C_{a\theta_p}LB \quad (22)$$

$$LA_{xy} = C_{b\theta_p}LA \quad (23)$$

Where $C_{a\theta_p}$, $C_{b\theta v}$ are the phase dependent parameter, and depends on the phase shift θ_p.

B. Simulation of the Dynamic Process

The machine parameters for the considered machine are given in table 1

Table 1. 5-Phase Machine parameters

Quantities	Value
Stator Outer / inner radius	105.02 / 67.99mm
Rotor Radius	67.69mm
Effective stack length	160.22mm
Number of slot	40
Number of turns	48
Main air-gap length g_a	0.4mm
Inter polar slot space g_b	21.3mm
Stator slot depth	18mm
phase voltage	370 v
Number of poles	4
Frequency	50Hz
The stator resistance R_s	0.83Ω
Stator leakage inductance L_{ls}	10.98mH
rotor q-axis leakage inductance L_{lqr}	6.2mH,
Rotor q-axis leakage inductance L_{ldr}	5.5mH
Rotor q-axis resistance R_{qr}	0.25 Ω
rotor d-axis resistance R_{dr}	0.12 Ω
moment of inertia J	0.089kg/m2

Analysis of Five-Phase Synchronous Reluctance Motor under Multi-Phase Faults

The speed characteristics of the model was investigated using MATLAB/SIMULINK, creating loss of phases fault, and subsequent restoration in the order of fault occurrence. The machine was loaded with a load torque of 5Nm after synchronism at 2.5 seconds, after which the four phases fault is subsequently created. The model was also modified to accommodate the 3rd harmonics of the air-gap MMF, and subjected to the same fault conditions.

Based on the configuration of the windings and the power supply, $\frac{2\pi}{5}$rad and $\frac{4\pi}{5}$Rad phase shift exists between the phases of interest.

The machine was wound as ACEBD configuration with$-\frac{2\pi}{5},-\frac{4\pi}{5},\frac{4\pi}{5},\frac{2\pi}{5}$ arrangement.

The fault pattern was created with e-phase as the first faulty phase before the subsequent phases.

The EDAC fault pattern shows a $\frac{4\pi}{5}$ radian phase loss after the e-phase fault, while ECBA fault pattern shows a $\frac{2\pi}{5}$Radian phase loss after the e-phase fault. The EADC fault pattern considers the loss of a positive $\frac{4\pi}{5}$ Radian phase immediately after an e-phase fault.

The fault occurrences and restoration patterns are tabulated in table 2.

Table 2: Fault and Restoration Pattern for the 5-Ph SYNRM

Fault and Restoration Pattern				
Time (Seconds)		Fault and Restoration Pattern		
Fault	Restoration	Phase	Phase	Phase
3	25	E	E	E
5	26	D	A	C
7	27	A	D	B
9	28	C	C	A

IV. RESULTS AND DISCUSSION

1) Speed characteristics for EDAC fault pattern without load

The Speed characteristic of the EDAC fault and restoration pattern was monitored without load for both the models without the 3rd harmonics of the air-gap MMF (model A) and with the 3rd harmonics of the air-gap MMF (Model B).

At fault 1, model B show a higher transient rise of 345.719 rad/s as compared to a value of 321.200 rad/s for model A. during the subsequent faults, model B still record a greater value than model A.

O the loss of the 4th phase, the speed of Model A drop to 55.72% of the synchronous speed of the machine, and rises to 66.13% of the synchronous speed on first phase restoration. On the restoration of the second phase, the speed of Model A returned to the synchronous speed of the machine as seen Fig. 1. Speed performance characteristics of on no load with and without 3rd harmonics.

For Model B, despite the loss of all the four phases, the machine still maintains synchronism. It can be noted that, on the first phase loss, the machine operates with an unbalance four-phase system and as a result, greater oscillation is observed. On the loss of the second phase, the 5 ph machine is supplied by a 3-phase supply, and as a result, a reduction in the oscillation is observed. Conversely, on the loss of an additional phase, an increase in the oscillation is also recorded, which still increased as the 4th phase is lost. The speed performance characteristics on no load for EDAC fault pattern is shown in Fig. 1.

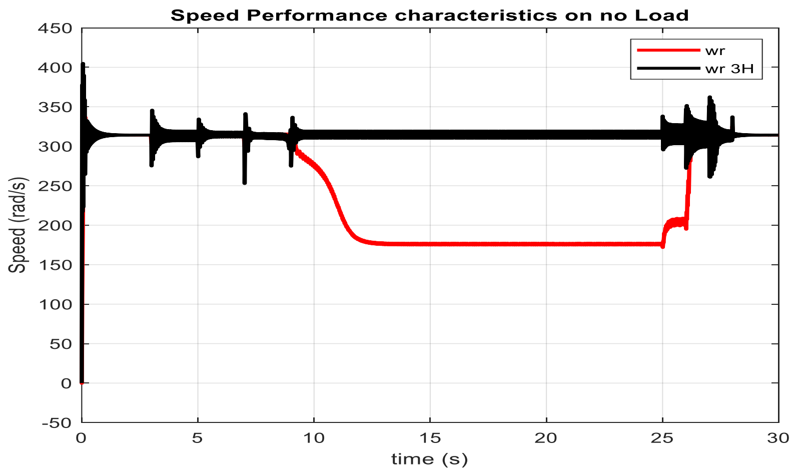

Figure 1. Speed performance characteristics on no load with and without 3rd harmonics.

2) Five-phase speed characteristics on load

For the loaded machine of both model A and model B, the machine still runs with oscillations at synchronous speed when three of the phases are lost, but drops to a negative value of the synchronous speed on the loss of the fourth phase. The machine does not return to the positive speed value even when the 1stphase fault is cleared, but on an additional phase restoration, it returns to positive speed value and records a gradual decrease in oscillation as faults are cleared. The speed characteristics of model A and Model B, when loaded with a load torque of 5Nm is presented in Fig. 2, while the Speed characteristics with emphasis on transient at fault and restoration is shown in fig. 3(a) and fig. 3 (b) respectively.

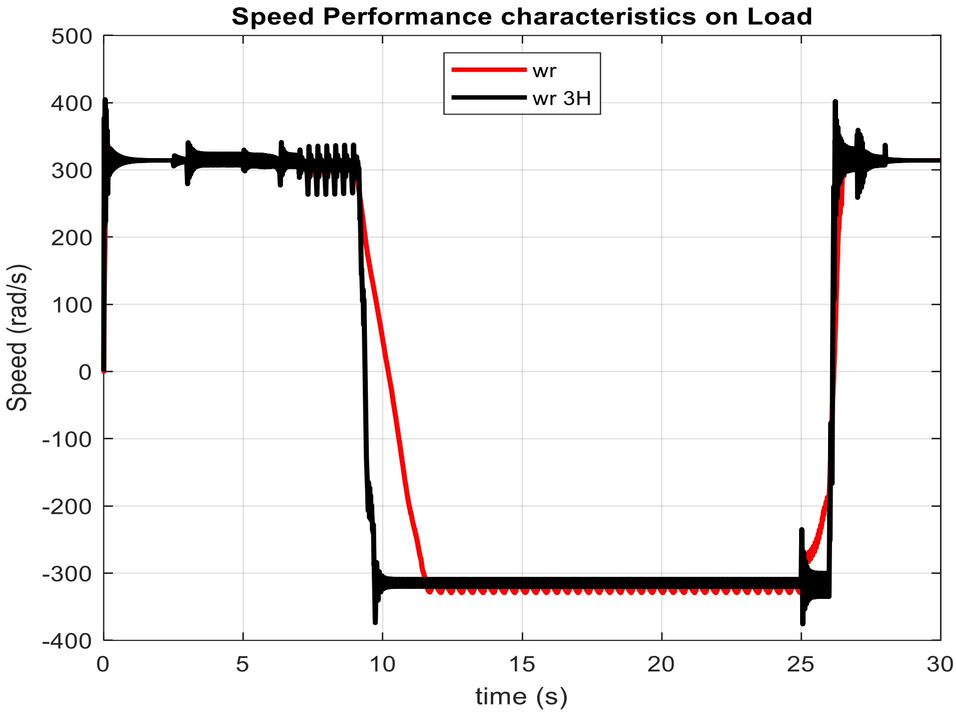

Figure 2. Speed performance characteristics on load with and without 3rdharmonics.

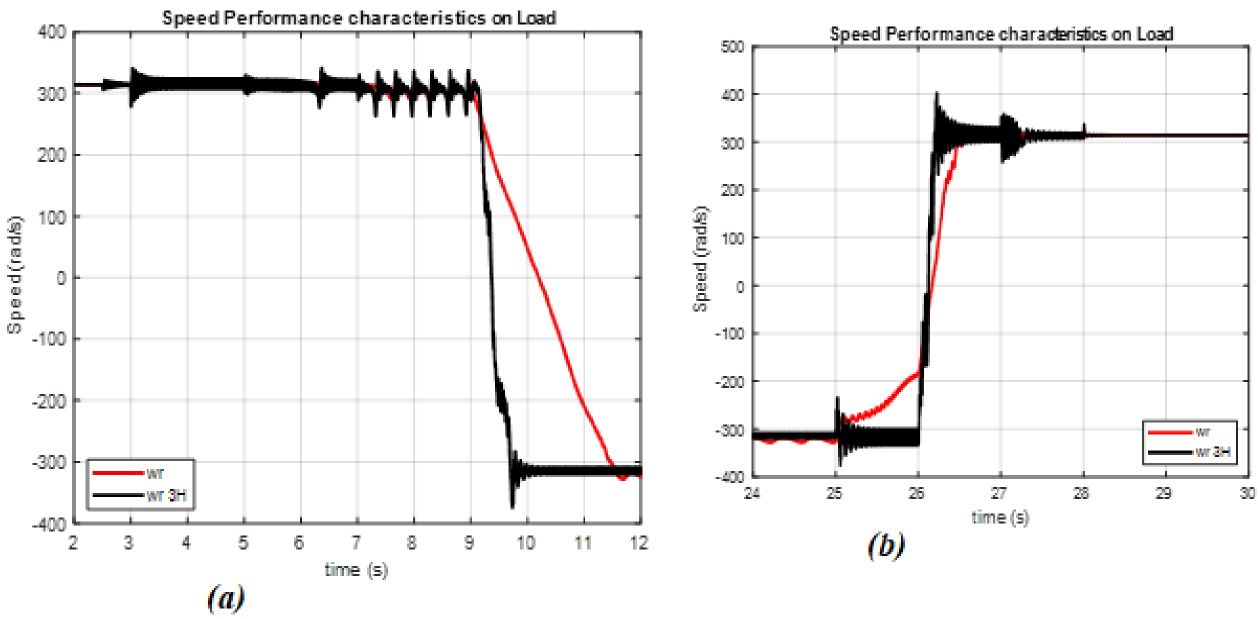

Figure 3. Speed transient on load with and without 3rdharmonics ((a) at fault (b) restoration)

3) Speed characteristics on load with fault patterns (without 3rd harmonics)

The Machines models were loaded at 2.5 seconds with a load torque 5N before the introduction of faults as stated in table 2.

The speed characteristics of model A is shown in Fig. 4. It can be observed that on the loss of the second phase 'D' in EDAC and 'A' in EADC, the machine still operates with $\frac{4\pi}{5}$Rad phase shift from the reference phase 'B' for both EDAC and EADC. Conversely, for the ECBA fault pattern, on the loss of the second phase the machine operates with a $\frac{2\pi}{5}$Rad phase shift from the reference phase 'D'. The ECBA fault pattern shows a drop in speed 173.815 rad/s before dropping to the negative value of the synchronous speed at the loss of the 4th phase.

On restoration of last lost phase, the ECBA fault pattern model, show a sharp rise to the synchronous speed, while the EDAC and EADC rises to -273.745rad/s and -279.879 rad/s respectively, before rising to the synchronous speed on the restoration of additional phase.

In all considered faults, model B records the highest transient values as well as greater oscillations during faults and restorations. The Speed characteristics with emphasis on transient at fault and restoration is shown in Fig. 5(a) and Fig. 5 (b) respectively.

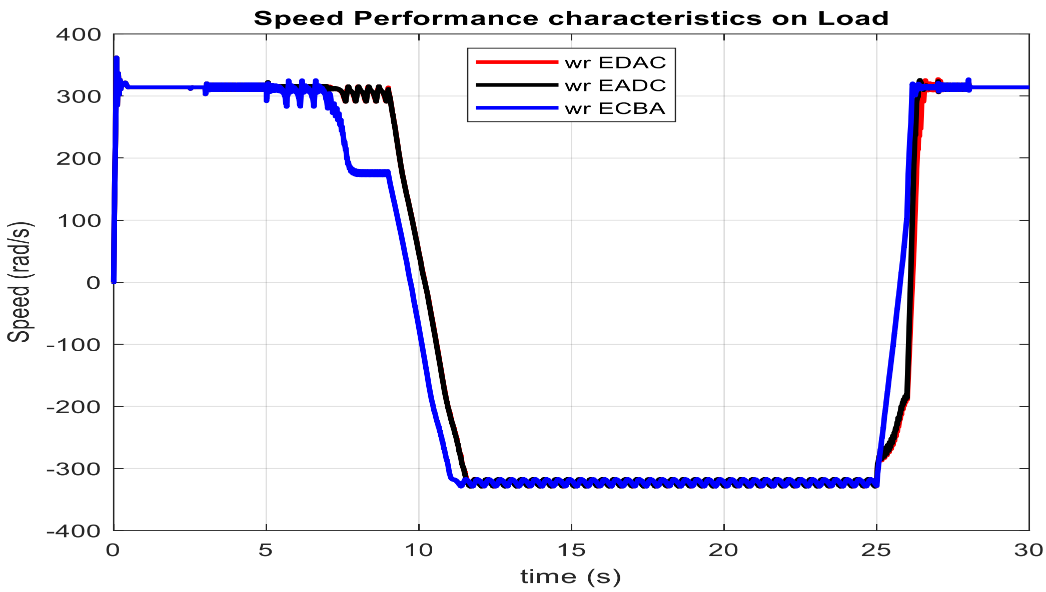

Figure 4. Speed performance characteristics on load without 3rdharmonics (EDAC, EADC and ECBA fault pattern)

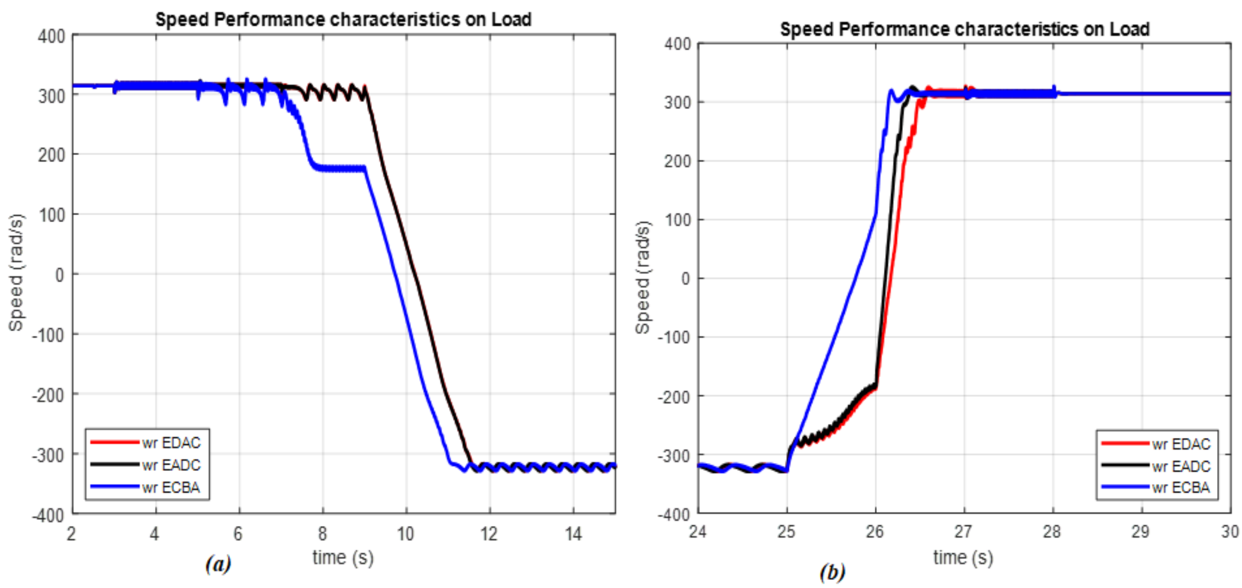

Figure 5. Speed performance characteristics on load without 3rdharmonics fault pattern((a) at fault (b) restoration)

4) Speed characteristics on load with fault patterns (with 3rd harmonics)

The speed characteristics of model B is shown in Fig. 6, as a co-plot of all the considered faults pattern. It can be observed that on the loss of the phases, reluctance characteristics still sustain the machine in synchronism for all the fault pattern until a loss of synchronism is experienced at the loss of the fourth phase, as can be seen in figure11. After loss of synchronism, the speed of the models, drops to a negative synchronous speed with a recorded oscillation. On restoration of last lost phase, no fault pattern return to positive synchronous speed until the restoration of an additional phase. However, the EADC fault pattern only returned to the positive synchronous speed on the restoration of the third lost phase, while the ECBA pattern had settled at 290.742 rad/s on second restoration and returned to a positive synchronous speed on the restoration of the third phase. On complete restoration, the observed oscillation settles at the synchronous speed. The Speed characteristics with emphasis on transient at fault and restoration for the different fault pattern is shown in Fig. 7(a) and Fig. 7 (b) respectively.

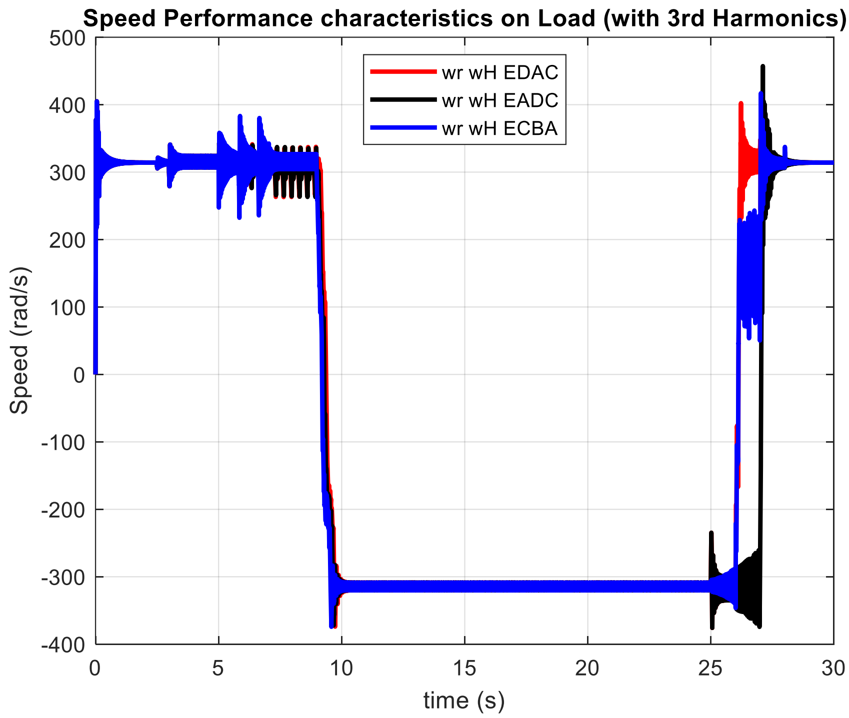

Figure 6. Speed performance on load with 3rd harmonics (EDAC, EADC and ECBA fault pattern)

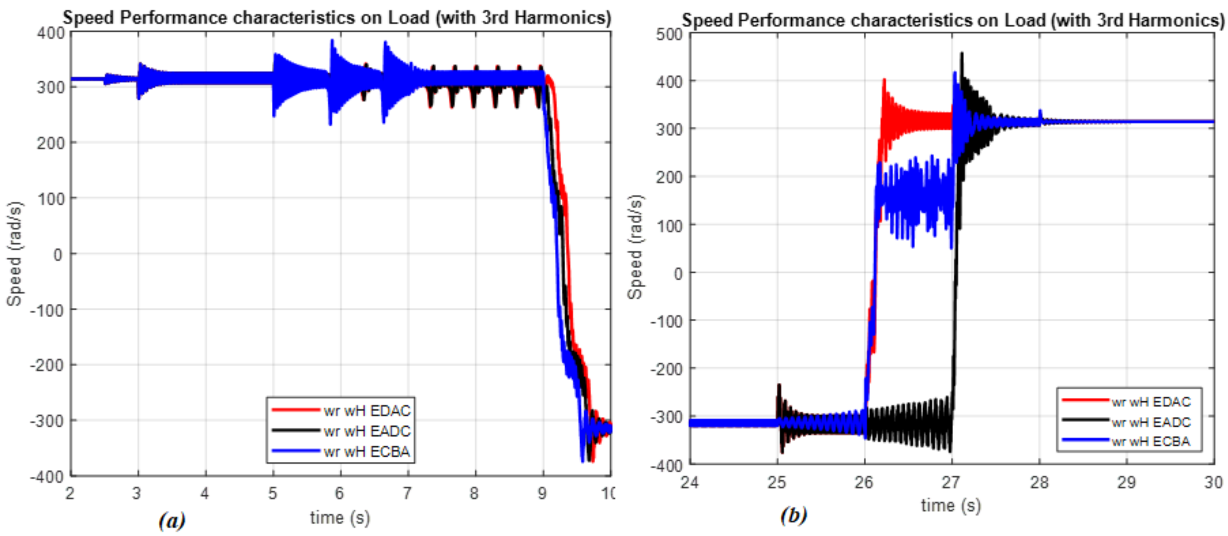

Figure 7. Speed performance on load with 3rdharmonics (EDAC, EADC and ECBA fault pattern)

V. CONCLUSION

The Synchronous reluctance machine models of ignoring the third harmonics of the Air-gap Magneto Motive force (MMF) as well as utilizing the MMF model, considered for multi-phase fault show similar characteristics of dropping to a negative synchronous speed at phase loss of up to four phases. The Synchronous reluctance motor has the ability to utilize it reluctance torque as a contribution to the electromagnetic torque. The effect of this reluctance torque is greatly observed.

Analysis of Five-Phase Synchronous Reluctance Motor under Multi-Phase Faults

On no load, Model A (not utilizing the 3rdharmonics of the Air gap MMF (Model A) remains on synchronism until the loss of the fourth phase, as a drop to 55.72% of the synchronous speed of the machine is recorded. On restoration of a phase fault, a rises to 66.13% of the synchronous speed is recorded, and returns to synchronous speed on additional phase restoration.
For Model B (ignoring the 3rdharmonics of the Air-gap MMf), despite loss of all the four phases, synchronism is maintained but with oscillations.
In Model Aof not utilizing the 3rd harmonics of the air-gap MMF, the ECBA drops to a speed of 173.815 rad/s and restores to a speed of 233.228 rad/s before settling at synchronism on additional phase restoration in Model B.
The effect settling at a speed other than the synchronous speed or it negative synchronous speed is only observed in the ECBA fault pattern which considers a $\frac{2\pi}{5}$Radian loss of phase with respect to the first lost phase.
When two of the phases were lost, the machine assumed an uneven three phase arrangement as fewer oscillations were observed, as compared to a phase, three phases and four phases loss.
These two models of A and B and can be used to predict the nature of the phase fault experience by the machine.
These characteristics of the machine can be harnessed for variable drives and regenerative breaking.

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