Analysis of Reliability, Cost and Performance of Three and Five-phase Synchronous Reluctance Machine Drive Systems

Kotb B. Tawfiq, Mohamed N. Ibrahim and Peter Sergeant

Abstract– **This paper compares and evaluates the cost, performance and reliability of three drive systems. The motor in these drive systems is a synchronous reluctance machine (SynRM). The first drive system (Drive-1) consists of a three-phase SynRM fed from rectifier-inverter. The second drive system (Drive-2) consists of a five-phase star-connected SynRM fed from rectifier-inverter. The third drive system (Drive-3) consists of a combined star-pentagon SynRM fed from indirect matrix converter. It is found that the average torque of Drive-2 and 3 is 6.56% and 13.35% higher than Drive-1, respectively. Drive-1, 2 and 3 have torque ripples of 7.94%, 6.58%, and 5.52%, respectively. At rated condition, Drive-2 and 3 are 0.32% and 0.58% more efficient than Drive-1. In terms of cost, Drive-2 and 3 are only 2.44 %and 2.19% more expensive than Drive-1. Moreover, Drive-3 is the most reliable drive system and Drive-1 is the least reliable system.**

***Index Terms*—Multiphase machines, Reliability, Cost combined star-pentagon configuration, synchronous reluctance machine (SynRM), Performance Comparison.**

I. INTRODUCTION

Multiphase synchronous reluctance machines (SynRMs) have been studied in recent years since they have shown to have several significant advantages over three phase machines, including improved reliability [1], a higher torque/volume relationship [2, 3], and less torque pulsations [4, 5]. Much research has gone into developing the five-phase machine, which is the next odd phase number after three, while simultaneously attempting to make the converter architecture and control as simple as possible. It has been proved that a five-phase machine may be running with one or two phases out of service [6]. Five-phase machines can be arranged in a star, pentagon, or pentacle configuration. During the healthy situation, a five-phase machine with star-connected windings performs well, but the pentagon and pentacle are favored during the defective scenario [7]. Recently, a combined star-pentagon configuration was shown in [8, 9]. The combined star-pentagon design incorporates the benefits of both star and pentagon winding.

Most of multiphase SynRM drive systems use the conventional rectifier-inverter [10, 11]. These multiphase drives' DC-bus, on the other hand, remains a single point of failure. The drawback of this converter was solved using the matrix converter [12-14]. Matrix converters convert the input voltage directly to the required output voltage without the use of a DC-link capacitor. In [15, 16], the performance of a five-phase SynRMs drive system based on a matrix converter was investigated at different loading conditions for both healthy and fault case. Different SynRM drive systems have been introduced in literature with either a three-phase or multiphase configuration and with conventional rectifier-inverters or with matrix converters [7-16]. The literature lacks the comparison between multiphase drives based on matrix converter and the conventional three-phase drives. As a result, a comparison between these drive systems in term of performance, cost and reliability is an interesting topic.

In this paper, the performance (efficiency, average torque and torque ripple), cost and reliability of three drive systems will be compared and analyzed. The description of these drive systems is as follows:

1) The first drive system (Drive-1) consists of a three-phase star-connected SynRM fed from three-phase conventional rectifier-inverter as shown in Fig. 1(a).
2) The second drive system (Drive-2) consists of a five-phase star-connected SynRM fed from five-phase conventional rectifier-inverter as shown in Fig. 1(b).
3) The third drive system (Drive-3) consists of a combined star-pentagon SynRM fed from three to five-phase indirect matrix converter as shown in Fig. 1(c).

The first part of this paper introduces the description of these drives. Then, in the second part, the performance of these drives will be compared for both healthy and fault cases. The cost comparison of these drives will be investigated in the third part. Finally, the reliability comparison will be discussed.

I. DESCRIPTION OF DRIVE SYSTEMS

This section describes the components of each drive system. There are two main components in each drive system, namely the machine and the power electronic converter.

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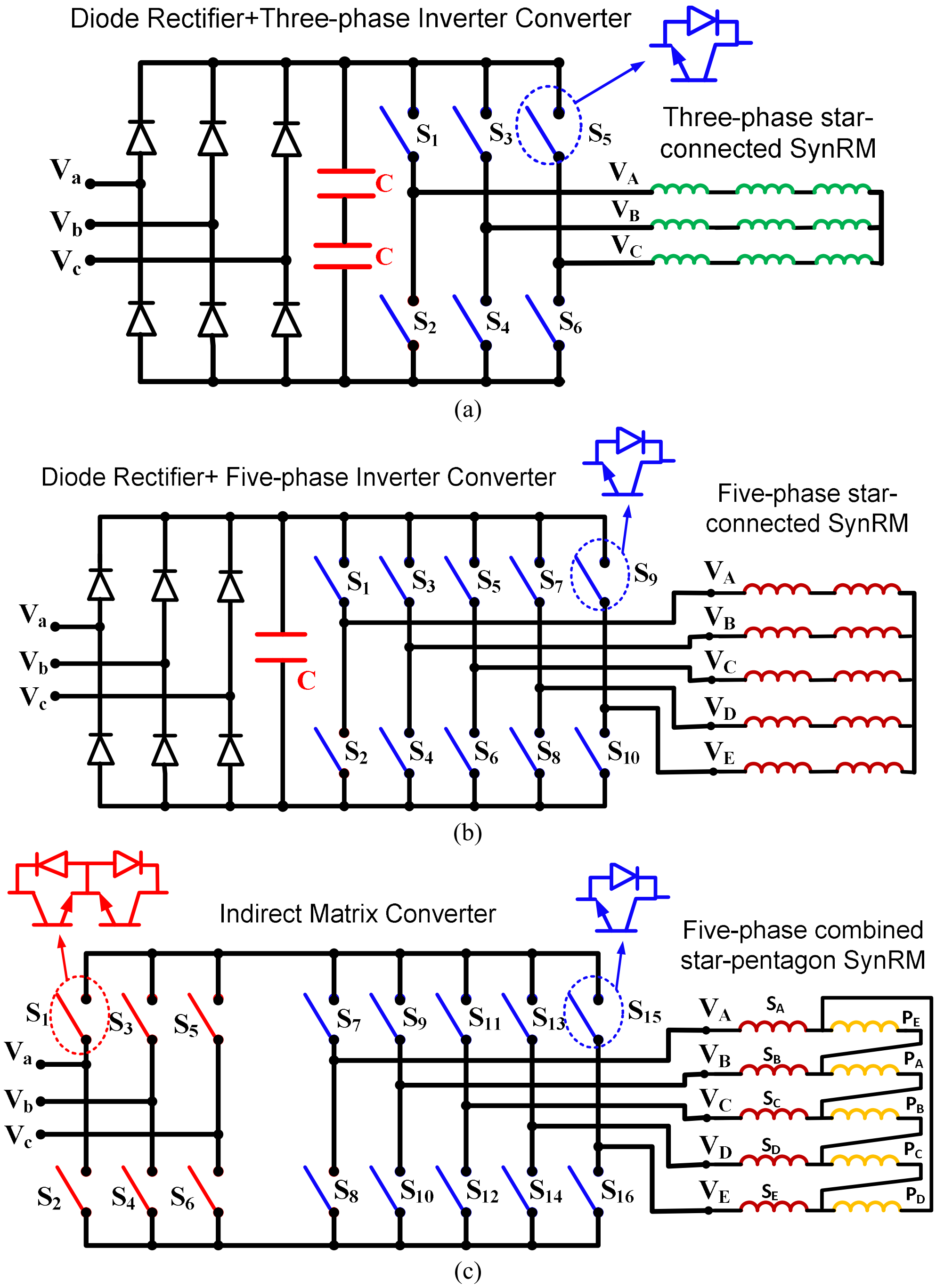

Fig. 1. The layout of the three drive systems (a) Drive-1, (b) Drive-2 and (c) Drive-3

A. Machines construction

The motor in these drive systems is a SynRM. The Drive-1 uses a three-phase star-connected SynRM. Drive-2 and Drive-3 use a five -phase star- connected and combined star-pentagon connected SynRMs respectively. For a fair comparison, the three machines are constructed using three identical 36-slot stators and a 4-poles rotor. The copper volume and the line current are kept the same in all machines. The specifications of the utilized stators and rotor are reported in Table I. The winding layouts for the three machines are shown in Table II, Table III and Table IV, with winding design details given in [2]. In Table III and Table IV, U and L represent the upper and lower layer, S and P represent the star- connected and the pentagon connected winding. The connection of these machines winding is illustrated in Fig. 1. In all SynRMs, the conductor's cross-sectional area of the star-connected winding is 1.573 mm2. The pentagon winding has a 1.31 mm2 cross-sectional area.

B. Power electronic converters

The power electronic converter in Drive-1 is the conventional diode rectifier and three-phase inverter with DC-link capacitor as shown in Fig. 1(a). The power electronic converter in Drive-2 is the conventional diode rectifier and five-phase inverter with DC-link capacitor as shown in Fig. 1(b). The power electronic converter in Drive-3 is a three-to-five-phase indirect matrix converter as shown in Fig. 1(c). A matrix converter is used as it increases the reliability of the drive system. This is owing to the lack of DC-link capacitors, which are a common source of failure in traditional drives especially in high ambient temperature where maintenance and replacement are limited. The indirect matrix converter is selected instead of the direct one as it has a smaller number of switches (22 compared to 30 switches). Moreover, it provides the same advantages with minimal switching losses compared to the direct topology and a simple clamping circuit can be used [17].

TABLE I: PARAMETERS OF THE EXISTING THREE-PHASE STATOR FRAME AND THE 4-POLES ROTOR.

Parameter	Value	Parameter	Value
Stator inner diameter	110 mm	Air gap length	0.3 mm
Stator outer diameter	180 mm	Slots	36
Rotor outer diameter	109.4 mm	poles	4
Rotor inner diameter	35 mm	Rated frequency	100 Hz
Axial length	140 mm	Rated power	5.5 kW
Rotor flux barriers per pole	3	Number of phases	3
Stator/ Rotor steel	M270-50A /M330-50A	Peak Rated current	17.3 A
Flux barriers angles	7.5°, 20.5° and 33.5°	Flux barriers widths	6, 4 and 3 mm
Flux barrier bridges distance from center	25, 19 and 12 mm	Distances between Flux barrier and the shaft centers	23.5, 36 and 46mm
Stator slot opening	2.8mm	Slot width	7.17 mm
Slot height at opening	0.5 mm	Copper height	12.99mm

TABLE II: WINDING OF SYNRM IN DRIVE-1

Phase(i)	A			C			B		
Slot (j)	1	2	3	4	5	6	7	8	9
N_{ij}	+ 26	+ 26	+ 26	- 26	- 26	- 26	+ 26	+ 26	+ 26

TABLE III: WINDING OF SYNRM IN DRIVE-2

Phase(i)		A, B, C, D, E								
Slot (j)		1	2	3	4	5	6	7	8	9
N_{ij}	U	+ 24	- 3	- 27	+ 8	+ 27	- 13	- 27	+ 18	+ 27
	L	- 3	+ 24		- 18		+ 13		- 8	

TABLE IV: WINDING OF SYNRM IN DRIVE-3

Phase(i)		A, B, C, D, E								
Slot (j)		1	2	3	4	5	6	7	8	9
N_{ij}	U	+ 24 S	- 3 S	- 21 S	+ 8 S	+ 16 S	- 13 S	- 11 S	+ 18 S	+ 6 S
	L	- 4 P	+ 29 P	- 7 P	- 22 P	+ 13 P	+ 16 P	- 19 P	- 10 P	+ 25 S

II. PERFORMANCE ANALYSIS OF DRIVE SYSTEMS

This section compares the performance of the three drive systems at healthy and fault cases using 2D Ansys Maxwell transient simulations. The output torque response of the three drive systems at rated condition and at optimal current angle (α=55°) is shown in Fig. 2(a). Fig. 2(b) shows the variation of the average torque of the drive systems at different current angles and at half and full rated current. Fig. 2(c) describes the average torque of the drive systems versus line current at the optimal current angle. Fig. 2 and Table V show that Drive-3 performs better than the other drives. Drive-2 and 3 provide a 6.56% and 13.35% higher average torque than Drive-1 respectively. The torque ripple of Drive-1, 2 and 3 is 7.94%, 6.58% and 5.52% respectively. Moreover, the power factor of Drive-1, 2 and 3 is 0.6622, 0.6664 and 0.6773 respectively and the efficiency at rated condition and optimal angle is 94.88%, 95.18% and 95.43% respectively. For Drive-1, 2 and 3, the average torque at the faulty case is reduced by 56.65%, 21.18% and 9.63%, respectively, from the healthy rated value of the Drive-1. At fault case and as shown in Fig. 3 and Table V, Drive-2 has less torque ripple than Drive-1, and Drive-3 has the lowest torque ripple of around 43%. The torque ripple of Drive-1 is substantial in the faulty case (228 %), resulting in increased noise, vibrations and mechanical issues.

Hence, the five-phase drive systems, especially Drive- 3, provide a significantly improved performance compared to the three-phase drive system (Drive-1).

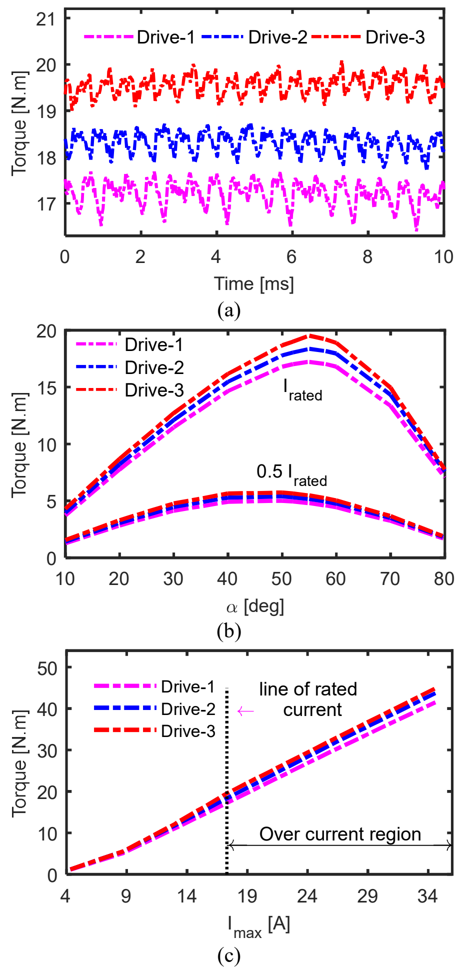

Fig. 2: Performance comparison of the three drive systems (a) torque response at rated condition, (b) average torque versus current angle and (c) average torque versus line current at optimal current angles.

TABLE V: PERFORMANCE, COST AND RELIABILITY COMPARISON OF THE THREE DRIVE SYSTEMS[11], [18-20].

Parameters		Drive-1	Drive-2	Drive-3
Cost	Copper volume (pu)	1	1.026	1.029
	Copper cost (€)	49.31	50.58	50.73
	Winding cost (€)	500	600	600
	Punching, cutting and iron cost (stator+ rotor) (€)	2000	2000	2000
	Machine cost in (€)	2549.31	2650.58	2650.73
	Diode bridge cost (€)	16.61	16.61	-
	Number of switches	6	10	22
	Switches *I*- rating (pu)	1	1	1
	Switches *V*- rating (pu)	1	0.6	0.6
	Switches cost (€)	38.88	34.30	75.46
	DC-link capacitor volume (pu)	1	0.5	-
	DC-link capacitor cost (€)	62.9	31.45	-
	Converter cost (€)	118.39	82.36	75.46
	Total initial cost (€)	2667.7	2732.9	2726.2
Performance	MMF Magnitude (pu)	1	1.0449	1.0729
	MMF THD (%)	9.880	8.140	7.914
	Winding factor	0.9598	0.9785	0.9906
	Average torque (N.m)	17.23	18.36	19.53
	Torque ripple (%)	7.94	6.58	5.52
	Power factor	0.6622	0.6664	0.6773
	Power flow direction	unidirectional	unidirectional	bidirectional
	Efficiency (%)	94.88	95.18	95.43
Reliability	Average torque with one phase open (pu)	1	1.818	2.08
	Torque ripple with one phase open (pu)	1	0.368	0.189
	Starting with one / two phase open	No	Yes	Yes
	Probability of fault occurrence (ε_i %)	39.65%	31.86%	28.49%
	Reliability	+	+++	++++

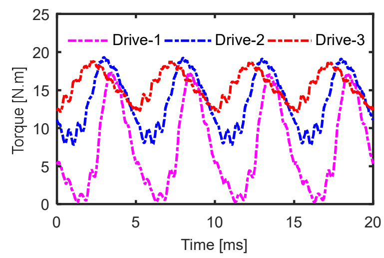

Fig. 3: Performance comparison of the three drive systems at one-phase open fault.

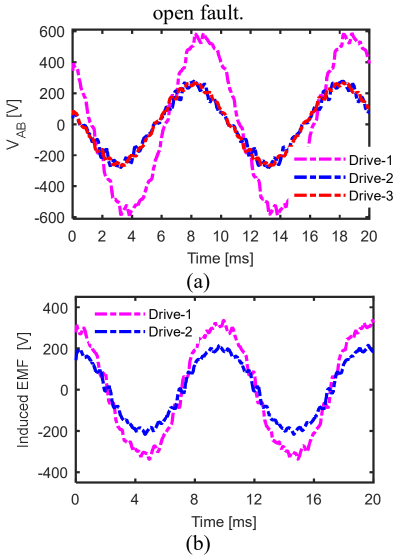

Fig. 4. (a) Line voltage and (b) induced EMF at optimal current angle and rated condition

III. COST ANALYSIS OF DRIVE SYSTEMS

In this section, the cost of the three drives is investigated and analyzed. The number of turns is chosen during the motor design of these drive systems so that the motor could operate at rated power and speed while maintaining the same current across all systems. As a result, the operating voltage of five-phase drives will be 60% of Drive-1's working voltage [2, 11]. This is obvious from Fig. 4. Note that working at the same voltage would be another design choice, that could be realized by modifying the numbers of turns.

From the point of view of converter cost, Drive-2 and 3 have 4 and 16 more switches respectively than Drive-1. However, the switches of Drive-2 and 3 have the same current ratings and lower voltage ratings compared to switches in Drive-1 [11, 19]. Notice that there is a three-phase rectifier bridge in Drive-1 and 2. Furthermore, the lower voltage of Drive-2 allows for the use of a DC-link capacitor with a 40% lower voltage than Drive-1. A 400V DC-link capacitor is utilized in Drive-2, whereas two capacitors are used in Drive-1, as indicated in Fig. 1 and Table V [11, 19]. Consequently, the overall cost of the power electronic converter in Drive-2 and 3 is 30.4% and 36.3% respectively cheaper than Drive-1 [19].

The machine design and construction cost are approximately the same in the three drives. Punching, cutting, iron and copper volume are the same in the three drives. The only difference between the three machines is that five-phase drives use a special type of winding which increases winding cost 20% more than the three-phase drive [20]. As a result, the machine design cost in Drive-2 and 3 is about 4% more expensive compared to Drive-1.

For the combined cost of machine and converter, Drive-2 and 3 are only 2.44% and 2.19 % respectively more expensive than Drive-1.

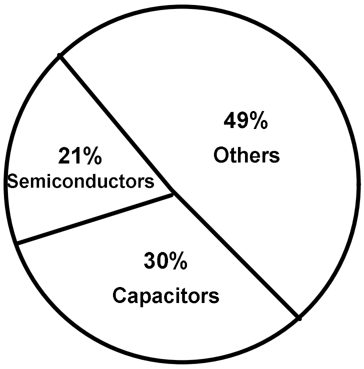

Fig. 5. Distribution of failures between components of power electronic converter [21, 22].

IV. Reliability Analysis of Drive Systems

This section investigates and studies the reliability of the three drive systems. The power electronic converter is the most fatal component in the drive system. According to a survey based on over 200 products from 80 companies at the same condition, it was found that capacitors and semiconductor failures are 30% and 21% respectively of the whole converter failures as shown in Fig. 5 [21, 22]. Consequently, capacitors are the weakest element in the power electronic converter. Hence, it is recommended to minimize number of capacitors in the power converter. The others factor of converter failures are PCB, soldering and connectors. Notice that, the three drive systems together have 3 capacitors and 38 semiconductors switches. Drive-1 has two capacitors and six semiconductors switches as shown in Fig. 1 and Table V. Drive-2 has one capacitor and ten semiconductors switches. Drive-3 has 22 semiconductor switches and there are no capacitors in this drive system as shown in Fig. 1 and Table V.

To determine the percent of fault occurrence in the three drive systems introduced in this paper, the presented ratios in Fig. 5 will be considered when a fault will occur in one of these drive systems. Then, the question is if a fault will happen in one of these drive systems, which drive system has the highest possible percent of fault occurrence (ε_i %)? The percent of fault occurrence in each drive system is calculated from (1-3). Drive-1 has the highest percent of fault occurrence, about 39.65%. Drive-3 has the lowest percent of fault occurrence which is 28.49% and Drive-2 has a 31.86%. The absence of capacitors in Drive-3 reduces the chance of a failure occurring in this drive, despite having the highest number of switches. On one hand, Drive-3 has the optimal reliability compared to other drives. On the other hand, Drive-1 is less reliable. Furthermore, with one or two phases open, Drive-2 and 3 can start and operate. This further enhances the reliability of five-phase systems. Moreover, the performance of Drive-2 and 3 under the fault case is better than Drive-1. Drive-2 and 3 provide an 81.8% and 108% higher torque respectively compared to Drive-1 at single phase open fault. At single phase open fault, the torque ripple of Drive-2 and 3 is 63% and 81% lower respectively compared to Drive-1.

Accordingly, Drive-3 is the most reliable drive system among these drives and Drive-1 is the least reliable system.

$$\varepsilon_1\% = \frac{2}{3} * 30 + \frac{6}{38} * 21 + \frac{1}{3} * 49 = 39.65\% \qquad (1)$$

$$\varepsilon_2\% = \frac{1}{3} * 30 + \frac{10}{38} * 21 + \frac{1}{3} * 49 = 31.86\% \qquad (2)$$

$$\varepsilon_3\% = \frac{0}{3} * 30 + \frac{22}{38} * 21 + \frac{1}{3} * 49 = 28.49\% \qquad (3)$$

V. Conclusion

This paper has compared and investigated the performance, cost and reliability of three drives with a synchronous reluctance machine. A three-phase star-connected SynRM is supplied by a three-phase conventional rectifier-inverter in the first drive system (Drive-1). In the second drive system (Drive-2), a five-phase star-connected SynRM is supplied by a five-phase conventional rectifier-inverter converter. The third drive system (Drive-3) is made up of a combined star-pentagon SynRM that is powered by a three-phase to five-phase indirect matrix converter. In this comparison, all drive systems have the same copper volume, line current, rotor, and stator iron.

At rated condition and at optimal current angle, Drive-2 and 3 have been determined to have 6.56% and 13.35% greater average torque than Drive-1, respectively. The torque ripple of Drive-1, 2 and 3 is 7.94%, 6.58% and 5.52% respectively. Drives-2 and 3 are 0.32 and 0.58 percent more efficient than Drive-1 respectively. The power factor of Drive-1, 2 and 3 at rated condition and at optimal current angle is 0.6622, 0.6664 and 0.6773 respectively.

Drive-2 and 3 are just 2.44% and 2.19% more expensive than Drive-1 in terms of overall initial cost (machine and converter cost).

Furthermore, Drive-3 is the most reliable drive system, whilst Drive-1 is the least reliable. When compared to Drive-1, the probability of a fault occurring in Drives-2 and 3 is 19.65 % and 28.15 % lower, respectively. When compared to Drive-1, Drive-2 and 3 deliver 81.8% and 108% more average torque, respectively, for single phase open fault. The torque ripple of Drive-2 and 3 is 63% and 81% smaller, respectively, compared to Drive-1 for single phase open fault. Additionally, Drive-2 and 3 can start and work with one or two phases open.

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