Cost Analysis Based Algorithm for Load Shared Multiple Induction Motor Set-up

Roopa Nayak, Andhe Pallavi

Abstract*: Majority of the industrial processes are generally carried out using a motor-drive arrangement. The quality of the final output of a process largely depends on the performance and reliability of the motor drive sets. Failure of motor running the process can result in a complete shutdown of the process. Certain processes may not even afford to offer downtime for maintenance. Downtime of motors can severely affect the quality of the end-product of a process. Although there are many tools and algorithms to predict the failure and maintenance patterns for motor, this paper presents a novel means to increase the reliability of motor-drive arrangements. It also presents a cost analysis framework in choosing a motor-drive arrangement for a particular load.*

Keywords: Load Sharing, Optimization of load shared motors, Downtime reduction.

Abbreviations
IM(SC)- Induction Motor Squirrel Cage
SIM- Single Induction Motor
RIM-Replacement Induction Motor
LTR-Load Torque Requirement
TL- Load Torque
FLT- Full Load Torque
BDT-Breakdown Torque
Symbols:
n- Number of motors
η-efficiency of motors

I. INTRODUCTION

A major concern for any industrial process, military, naval, aerospace and satellite application, at various stages of process is the reliability. A stall in the process at any stage of production in an industrial process would result in a product with low quality. A stall of the motor in military applications such as radar, naval applications such as ship or submarine propulsions can result in a major disaster [1]. As most of the processes are run using a motor-drive arrangement, reliability of motors is of utmost importance. A high demand for reliability calls for a very strategic maintenance system. Repair, discard and servicing of motors are a part and parcel of maintenance. There are various tools available to predict the failure and optimize maintenance operations [2][3]. However, the problem of downtime and provision of standby motors continues to exist and are not eliminated completely, which suggests that having only prediction-based

maintenance does not suffice to ensure reliability. To overcome these problems, this paper suggests a novel method

of replacing a single motor-drive arrangement of higher capacity with multiple motor-drive sets of lower capacity. In applications such as propelling a ship, multiple lower capacity motors can be used. A cable/ladder reeling drums can be driven by multiple motors of lower capacity offering redundancy and reliability.

In all these applications, motor-drive sets should be chosen such that, when one or two out of multiple motor-drive sets are pulled out of the process for maintenance, the remaining motor-drive sets should share the load and keep the process running. With such a strategy of multiple motor-drive sets sharing a load, the process remains unaffected by the downtime of motors.

While replacing a single motor with multiple motors, two factors should be considered

(i) Capacity of the motor to be replaced with multiple motors
(ii) No. of replacement motors to share the load

To have knowledge of minimum capacity of motor that can be replaced by multiple motors and to optimize the number of replacement motors, cost analysis of motors and drives, a study of probability of failure of motors and cost analysis of multiple motor-drive arrangements sharing a common load is carried out in the following sections. Three phase squirrel cage induction motors and variable frequency drives are considered for the cost analysis as they are most widely used in industries

II. JUSTIFICATION FOR LOAD SHARING WITH MULTIPLE MOTORS FOR A COMMON LOAD

Usage of multiple induction motors for sharing a common load is provided in this paper with study of life-expectancy, maintenance and cost analysis framework for motors.

A. Cost Analysis of 3-Ø IM(SC) and Drives

Cost analysis of motors and drives is carried out on the basis of data available in the catalogues of motor and drive manufacturers. Table-I provides the price List of ABB IE2 three phase squirrel cage induction motors as effective from 18-01-2019 used for cost analysis of motors [4]. Price List of Mitsubishi Variable Frequency Drives F700 and A700 series is employed for cost analysis of Drives.

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The performance parameters employed for the cost analysis of motors is also obtained from the manufacturer [5] which is presented in the Table-II

Fig.1. below shows the bar graph for the cost of motor and drive for various power rating. From the bar graph we can observe that there is no huge difference in the cost of motor and drives up to a power rating of 10hp. The variation in cost is large for power rating exceeding 100hp.

Table-I Price List of 3-Ø IM(SC)

TWO POLE			
kW	H.P	Frame size	Price (Rs)
0.37	0.50	M2BAX71MA2 IE2	12550
0.55	0.75	M2BAX71MB2 IE2	14050
0.75	1.00	M2BAX80MA2 IE2	15100
1.10	1.50	M2BAX80MB2 IE2	16800
1.50	2.00	M2BAX90SA2 IE2	20450
2.20	3.00	M2BAX90LA2 IE2	24700
3.70	5.00	M2BAX100LC2 IE2	31000
5.50	7.50	M2BAX132SA2 IE2	51200
7.50	10.00	M2BAX132SB2 IE2	53950
9.30	12.50	M2BAX160MLJ2 IE2	92350
11.00	15.00	M2BAX160MLA2 IE2	101200
15.00	20.00	M2BAX160MLB2 IE2	114300
18.50	25.00	M2BAX160MLC2 IE2	141800
22.00	30.00	M2BAX180MLA2 IE2	152400
30.00	40.00	M2BAX200MLA2 IE2	231000
37.00	50.00	M2BAX200MLB2 IE2	264050
45.00	60.00	M2BAX225SMA2 IE2	347100
55.00	75.00	M2BAX250SMA2 IE2	477750
75.00	100.00	E2HX280SMB2	667800
90.00	120.00	E2HX280SMC2	754000
110.00	150.00	E2BA315SMA2	913300
125.00	170.00	E2BA315SMB2K	1113000
132.00	180.00	E2BA315SMB2	1119900
160.00	215.00	E2BA315MLA2	1221700
180.00	240.00	E2BA315MLC2k	1286500
200.00	270.00	E2BA315MLC2	1429700
250.00	335.00	E2BA355SMA2	1663000
315.00	425.00	E2BA355MLA2	1810900
355.00	475.00	E2BA355MLC2	2225000
375.00	500.00	E2BA355MLD2	2271800

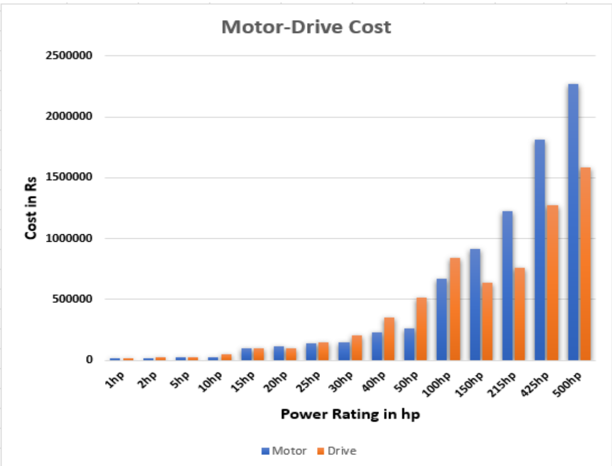

Fig. 1. Variation of motor drive cost with hp rating

B. Life Expectancy and Maintenance of Motors

Operating life-time of a 3-Ø IM(SC) is typically around 12-20 years. The downtime of a motor is around 0.5% to 4% per year [5]. The downtime of a motor can vary with the variation of its capacity and operating conditions [6]. There are also instances where the motors employed in industries are more than 20 years old, which implies that the number of times they are serviced or repaired is more than expected. Hence the overall downtime of these motors has gone past the expected downtime.

Major causes of a motor breakdown are overloading, insulation failure of stator windings, inter turn short circuits and bearing faults. Some of the conditions such as dampness, deposition of oil, chemicals, grease and dust can further increase the probability of breakdown of motors. Methods such as Failure Mode and effective Analysis (FEMA), Hazard Operability Studies (HAZOP) and Fault Tree Analysis (FTA) are used to predict and diagnose the faults which only ensures fault free operation of motors and not maintenance free operation [2]. Duration of maintenance operation of motors should also be considered as downtime as the motors are not available for the process. Hence the problem of downtime continues to exist and cannot be eliminated completely. To reduce the downtime and increase the reliability, a novel method of replacing a single induction motor (SIM) with multiple replacement induction motors (RIM) is proposed in this this paper which is as shown in the Fig. 2.

Table II. Performance Parameters of 3-Ø IM(SC)

Output kW	Frame Size	Speed r/min	Efficiency Full load 100%	Efficiency 3/4 load 75%	Efficiency 1/2 load 50%	Power factor cos φ	Current I_n, A	Current I_s/I_n	Torque T_n, Nm	Torque T_l/T_n	Torque T_b/T_n	Moment of inertia J=1/4GD² kgm²	Weight kg
3000 r/min	415V, 50Hz												
0.37	E2BA71A2	2660	72.2	72.2	72	0.80	0.92	3.9	1.3	2.2	2.3	0.00039	11
0.55	E2BA71B2	2680	74.8	74.8	74	0.85	1.2	4.3	2	2.4	2.5	0.00051	11
0.75	E2BA80B2	2895	77.4	77.4	73	0.74	1.8	6.5	2.5	2.4	4.2	0.001	16
1.1	E2BA80C2	2870	79.6	79.6	78	0.80	2.4	6.5	3.7	2.7	3.5	0.0012	18
1.5	E2BA90SLB2	2900	81.3	81.3	79.9	0.86	3	6.5	4.9	2.5	2.6	0.00254	24
2.2	E2BA90SLC2	2885	83.2	83.2	82.2	0.87	4.2	7.0	7.3	1.9	2.5	0.0028	25
3.7	E2BA100LC2	2905	85.5	85.5	85	0.86	7	7.0	12.2	2.9	3.2	0.00575	37
5.5	E2BA132SMB2	2865	87	87	85.8	0.86	10.2	7.0	18.3	2	2.7	0.01275	68
7.5	E2BA132SMC2	2890	88.1	88.1	86.3	0.84	14.1	7.0	24.80	2	3.6	0.01359	70
11	M2BAX160MLA2	2925	89.4	89.7	88.2	0.88	19.6	7.0	36	2.4	3.0	0.0415	105
15	M2BAX160MLB2	2930	90.3	90.7	90.0	0.90	25.9	7.0	49	2.4	3.0	0.0544	120
18.5	M2BAX160MLC2	2934	90.9	91.2	90.4	0.90	31.7	7.0	60	2.6	3.1	0.0581	131
22	M2BAX180MLA2	2936	91.3	91.7	91.0	0.91	37.3	7.0	72	3.0	3.5	0.0679	152
30	M2BAX200MLA2	2940	92.0	92.4	91.5	0.90	50.7	7.0	97	2.5	3.2	0.1077	198
37	M2BAX200MLB2	2950	92.5	92.8	91.7	0.89	62.9	7.0	120	3.0	3.8	0.1332	232
45	M2BAX225SMA2	2956	92.9	92.6	92.0	0.90	75.7	7.0	145	2.4	3.2	0.2443	295
55	M2BAX250SMA2	2960	93.2	93.8	92.8	0.90	91.7	7.0	177	2.6	3.0	0.3160	344
75	E2HX280SMB2	2970	93.8	93.8	92.8	0.92	121	7.0	241	2.3	2.7	1.025	690
90	E2HX280SMC2	2970	94.1	94.1	93.1	0.92	145	7.0	289	2.3	2.5	1.2	685
110	E2BA315SMA2	2980	94.3	94.3	93.3	0.90	180	7.0	353	2.4	2.7	1.41	935
125	E2BA315SMB2k	2980	94.5	94.5	93.5	0.90	204	7.0	401	2.4	2.7	1.61	975
132	E2BA315SMB2	2980	94.6	94.6	93.6	0.90	216	7.0	423	2.4	2.7	1.610	975
160	E2BA315MLA2	2980	94.8	94.8	93.8	0.90	261	7.0	513	2.3	3.0	1.950	1150
200	E2BA315MLC2	2980	95.0	95.0	94.0	0.90	325	7.0	641	2.6	3.0	2.55	1275
250	E2BA355SMA2	2980	95.0	95.0	94.0	0.90	407	7.0	801	1.6	3.0	4.250	1645
315	E2BA355MLA2	2980	95.0	95.0	94.0	0.91	507	7.0	1009	1.7	3.0	5.75	1895
355	E2BA355MLC2	2982	95.0	95.0	94.0	0.90	578	7.0	1137	1.7	3.2	6.525	2000

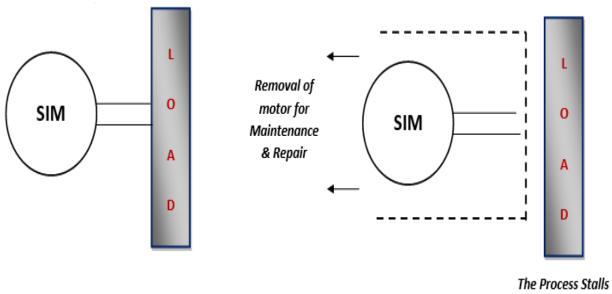

Fig.2a. Reliability Offered by SIM to an Industrial Process

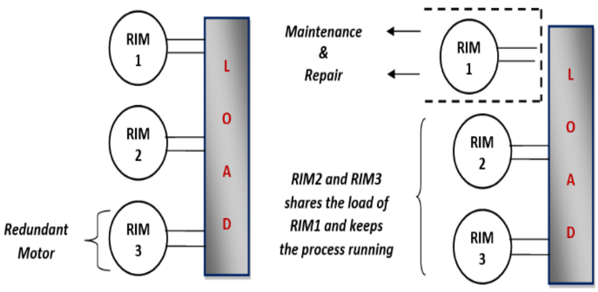

Fig.2b. Reliability Offered by Multiple RIM to an Industrial Process

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III.ALGORITHM FOR OPTIMISATION OF NUMBER OF MOTORS

Reducing the downtime implies higher reliability, which can be achieved by replacing SIM with multiple RIM. However, we cannot replace SIM with indefinite number of RIM. The number of RIM has to be optimal. Certain factors needs to be considered for fixing the number of replacement motors(n). The hp rating of the SIM, speed and torque requirement of the load driven by SIM, hp rating of RIM, availability of RIM and drive, cost of RIM and drive, efficiency and service factor (permitted overload) of RIM. Number of RIM also depends on the type of process. Replacing SIM with 'n' RIM is more beneficial in scenarios where there is cost benefit. In scenarios where the process is continuous and cannot afford to offer downtime for the repair of motors, a trade-off between the cost and the reliability should be considered. The algorithm to obtain the optimal number of motors is as follows: (service factor is taken as 1.1 for IE2 motors)

Step 1: Initialize n=2 , $LTR = TL$

Step 2: $hp(RIM) = hp(SIM)/n$

If the calculated hp(RIM) is not available, choose the nearest higher hp rating motor.

If the calculated hp(RIM) is not a whole number, increment n and recalculate the hp(RIM)

Step 3:

Calculate $\propto$

$$\propto = (Cost(SIM) - n \times Cost(RIM))/n$$

If $\propto$ is a positive value go to Step 4, else go to Step 6

Step 4:

If

$$BDT(RIM) \geq 2 \times FLT(RIM)$$

and

$$\eta(RIM) \geq 0.9 \times \eta(SIM)$$

then go to step 5, else go to step 8

Step 5:

If

$$n \geq FLT(SIM)/FLT(RIM)$$

Go to Step 9

Else increment n and go to step 2

Step: 6:

If the process is intermittent/ and does not require highly reliable motors, then go to step 10, otherwise go to step 7

Step 7:

If the process is continuous and requires highly reliable motors and cannot afford to spare downtime, then cost overrun is allowed. Go to step 4

Step8: Choose RIM such that

$$BDT(RIM) \geq 2 \times FLT(RIM)$$

and

$$\eta(RIP) \geq 0.95 \times \eta(SIM)$$

go to step 3.

Step 9: Replace SIM with n number of RIM to share the load and stop

Step 10: Do not replace SIM with multiple motors. Consider periodic maintenance and fault diagnosis and prediction. Stop

IV.RESULTS AND DISCUSSIONS

Case 1:

Let us consider an example of a cement plant rotary kiln. A small sized rotary kiln requires a power range of 500 to 2000 hp [8][9], for which a low voltage AC drive (460 to 690V) can be used. The cost of 500 hp motor and the drive is provided in the Table-III.

Table-III. Cost of 500hp SIM with Drive

Cost of 500hp motor in rupees	Cost of Drive for 500 hp	Total Cost
22,71,800 Rs	15,82,490 Rs	38,54,290 Rs

Rotary Kiln used for mixing the clinker at a particular temperature in cement plants calls for high reliability motors. A stall in the process due to motor downtime can affect the quality of cement. Hence, we can apply our proposed algorithm to find the optimum number of motors to drive the kiln.

Step1: n = 2, FLT=1137Nm at 3000rpm

Step2: $(RIM) = (500\ hp)/2 = 250hp$

Since 250hp ABB motors are not available, next higher hp rating, i.e. 270hp is chosen

Step3:

$$\propto = (38{,}54{,}290 - 2 \times 2191580)/2$$
$$\propto = -264435$$

Negative value of $\propto$, calls for step 6 and step 7. Since the reliability required is higher for rotary kiln process, a cost overrun is allowed.

Step4:

$$BDT(RIM) \geq n \times FLT(RIM)$$
$$BDT(RIM)/FLT(RIM) \geq 2$$
$$BDT(RIM)/FLT(RIM) = 2.55 > 2$$

and

$$\eta(RIM) \geq 0.9 \times \eta(SIM)$$
$$\eta(RIM)/\eta(SIM) \geq 0.9$$
$$(95\%)/(95\%) = 1 > 0.9$$

Step 5:

$$FLT(SIM)/FLT(RIM) \leq n$$
$$1137/647 = 1.75 < 2$$

Step 9: Replace SIM of 500hp with 2 RIM of 270hp to share the load.

Cost of 270hp motors with drive is given in Table-IV.

Table-IV Cost of 2 RIM of 270hp with Drives

Cost of 270 hp motor in rupees	Cost of Drive for 270 hp in rupees	Total Cost in rupees for Replacing one 500hp with two 200hp Motors
14,29700	7,61,880	#43,83,160

#(2*14,29,700)+(2*7,61,880)=43,83,160

In case1 we can infer that replacing a SIM of 500hp with 2 RIM of 270hp requires an additional cost of 5,28,870 which is 13.72% of the cost of SIM as shown in Fig.3. An additional 13.72% of expenditure in procuring 2 RIM with drives guarantees 100% reliability and minimal downtime. With a standby of 270hp motor, in the event of removal of one RIM for maintenance, the other RIM can take over the load along with standby motor without stalling the process.

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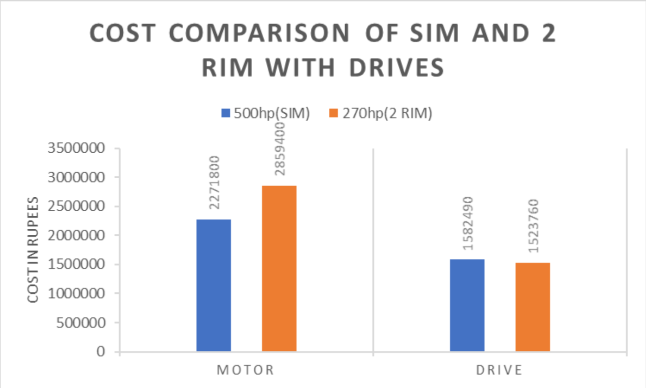

Fig.3. Cost Comparison of one 100hp SIM and ten RIM of 10hp with Drives

Case 2:

Consider a conveyor belt with a 100hp power requirement. Conveyor belts do not demand a high reliability and can offer downtime for motors. The proposed algorithm is applied to replace a SIM of 100hp with optimum number of motors.

The proposed algorithm gives n=10. SIM of 100hp can be replaced with 10 RIM of 10hp

Table-V. Cost comparison of one 100hp SIM and ten RIM of 10hp with Drive

	Cost of Motor in rupees	Cost of Drive in rupees	Total Cost in rupees
SIM (one 500hp)	6,67,800	687330	13,55,130
RIM (ten 10hp)	53950×10= 5,39,500	53,643×10= 5,36,430	10,75,930

$$\propto = (1355130 - 10 \times [53950 + 53643])/10$$
$$\propto = 27920$$

$\propto$ is positive

$$BDT(RIM) \geq n \times FLT(RIM)$$
$$BDT(RIM)/FLT(RIM) \geq 2$$
$$BDT(RIM)/FLT(RIM) = 3.6 > 2$$

and

$$\eta(RIM) \geq 0.9 \times \eta(SIM)$$
$$\eta(RIM)/\eta(SIM) \geq 0.9$$
$$(88.1\%)/(93.8\%) = 0.934 > 0.9$$
$$FLT(SIM)/FLT(RIM) \leq n$$
$$\frac{241}{24.8} = 9.71 < 10$$

In case 2, we can infer that replacing a 100hp SIM with 10 RIM of 10hp saves 2,79,200 Rs. Reliability is increased with reduced downtime of motors as motor can be serviced periodically without stalling the process. In the event of failure of 1 or 2 motors, the remaining motors will be able to share the load as the service factor for the motors is 1.1. 10hp motors and drives are readily available whereas 100hp motors and drives are not readily available in stock. Hence replacing a faulty 100hp motor and drive with a healthy 100hp motor and drive will take longer. On the contrary replacing a faulty 10hp motor and drive with a healthy 10hp motor and drive is much easier.

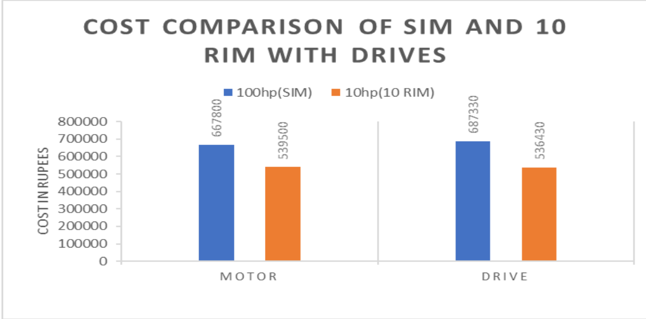

Fig.4. Cost Comparison of one 100hp SIM and ten RIM of 10hp with Drives

V. CONCLUSIONS

In this paper, a review of motor performance parameters, cost factor, life expectance and maintenance of induction motors is carried out to justify the need for replacing a SIM with multiple RIM in applications demanding high reliability such as defense applications and industrial production. An algorithm is developed to find the optimum number of RIM. Two case studies are presented to show how the developed algorithm can be applied to calculate optimum number of RIM.

REFERENCES

1. Akpama, E. J., “Six Phase Induction Motor Modelling for Submarine Application”, OSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 13, Issue 1 Ver. IV (Jan.–Feb. 2018), PP 61-66 DOI: 10.9790/1676-1301046166
2. Edwin Vijay Kumar, S.K. Chaturvedi, A.W Deshpande, “Failure Probability Estimation using Fuzzy Fault Tree Analysis (FFTA) with PDM Data in Process Plants”, International Journal of Performability Engineering, Vol. 4, No. 3, July 2008, pp. 271 – 284
3. Fernando J. T. E. Ferreira1, Ge Baoming, Aníbal T. de Almeida, “Reliability and Operation of High-Efficiency Induction Motors”, IEEE Transactions on Industry Applications, 2016. DOI: 10.1109/TIA.2016.2600677
4. ABB Price List for Energy Efficient Totally Enclosed Fan Cooled (TEFC) Squirrel Cage Induction Motors (IE2)
5. ABB Catalogue for Low voltage General Performance IE2 High Efficiency Motors
6. de Almeida, A. et al.: “Improving the Penetration of Energy Efficient Motors and Drives”, ISR-University of Coimbra, Report prepared for the Directorate General of Transport and Energy, SAVE II Progr. 2000, EC, Brussels, 2000.
7. Rockwell Automation, “Basics for Practical Operation – Motor Protection”, Publication WP
8. Barton J. Sauer, “Selection of AC Induction Motors for Cement Plant Applications”, IEEE Cement Industry Technical Conference Record, 2008. DOI: 10.1109/CITCON.2008.29
9. Mark Fanslow, Steve Drzymala , “Considerations in the Selection and Application of ac and dc Motors for Cement Plants”, IEEE Cement Industry Technical Conference Record, 2009. DOI: 10.1109/CITCON.2009.5116168

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