ICEMG 2023-XXXXX

Reliability and Lifetime Analysis on Permanent Magnet Motors in Elevator: Case Study PMA-SynRM & IPMSM

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Abstract
Nowadays, Permanent Magnet (PM) motors are taken into attention and are widely used in various systems with high-efficiency concerns. In elevator systems, a direct connection is between fault tolerability and human lives, so reliability and lifetime management are significant concerns. The electric motor is the core of traction in the elevator. Although Induction Motors (IMs) are used more in the elevator, PM motors can be a suitable alternative due to their higher efficiency, control-ability, and power density. Accordingly, in this study two types of PM motors, Interior Permanent Magnet Synchronous Motor (IPMSM) and PM-Assisted Synchronous Reluctance Motor (PMA-SynRM) are regarded and analyzed to use in the elevator system. After specifying a satisfactory assessment modeling, their significant failure modes are investigated as lifetime analysis. In order to identify the reliability status of the above motors under faulty conditions, reliability criteria are appropriately chosen. Based on the reliability statuses, the Markov chains will be yielded, and the reliability study gives Mean Time to Failure as a metric for lifetime estimation. Finally, the best PM motor from a reliability view is suggested for elevator usage as a guide for engineering.
Keywords: Permanent Magnet Synchronous Motors (PMSM), Permanent Magnet Assisted Synchronous Reluctance Motor (PMA-SynRM), Elevator. Reliability, Markov chain.

Introduction

Nowadays, with the progression of society, the use of elevators has dramatically grown. So, designing and building a satisfactory elevator system is necessary. The electric motor is the core of the traction system in the elevator. An Induction Motor (IM) is used with a mechanical gearbox in older elevator systems, in which the rotor shaft is made to contain a traction sheave. The velocity changes between the rotor and the drawbar. Accordingly, customary elevator systems are known as weak systems in terms of efficiency. In [1], the overall efficiency of a typical elevator system with a load capacity of 630 Kg is 56%.

Accordingly, in the last years, the desire to use gearless Permanent Magnet (PM) motors has grown owing to high efficiency, high power density, high torque, less noise, and lower Torque Ripple (T_{ripple}) in the elevator system [2]–[4]. Removing the gearbox brings significant progress in terms of efficiency in gearless systems. Among PM motors, Permanent Magnet Synchronous Motors (PMSMs) have been widely used in traction motors in recent years owing to their satisfactory reliability and low inertia (high dynamic) [5], which have two types of interior and surface mount magnets. The Interior PMSM (IPMSM) has higher superiority over Surface Mounted PMSM (SM-PMSM), owing to producing Reluctance Torque ($T_{reluctance}$) beside PM Torque (T_{PM}). PM-Assisted Synchronous Reluctance Motor (PMA-SynRM) is also paying attention among PM motors, especially in traction systems such as elevators. Placing PMs in SynRM flux barriers obtain PMA-SynRM, improving its behavior and producing T_{PM} besides $T_{reluctance}$. PMA-SynRM offers advantages, including low eddy current losses, relatively low T_{ripple}, low noise, low inertia moment and fast dynamic, high efficiency and safety, and simplicity.

Fault tolerability and reliability are two significant factors in choosing an electric motor to use in the elevator, owing to the direct connection with human lives. Reliability study is categorized into fault management and lifetime management. The former contains fault isolation, diagnosis, and mitigation, relating to after-design and usage. Avoiding damages and protecting the system is so-called fault isolation. In [6], a safety circuit, including a relay, control system, and limiters, is suggested to give the elevator safe usage, as seen in Figure 1. Detecting fault occurrence and location is fault diagnosis in a safety circuit, cabin, and electric motors of the elevator. In fault mitigation, tries are to save the elevators' operating in the range of safety during faulty conditions. In [7]–[9], drive control systems are designed and suggested to have more safety and reliability under faulty conditions, especially in the electric motor. Predicting and extending the lifetime of a system is more useful and cost-effective than fault management. Lifetime management focuses on this matter, including lifetime extension, lifetime analysis, and lifetime estimation. The most significant and effective way is reliable design as a lifetime extension. In [10] and [11], new designs and topologies are suggested for PMA-

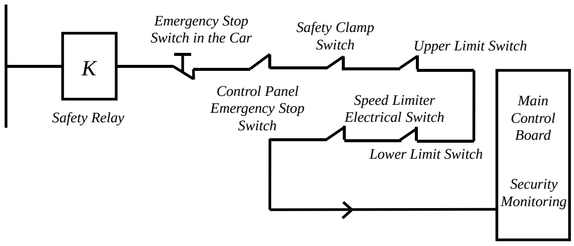


Figure 1. Safety circuit of elevator.

SynRM and IPMSM, respectively, in order to higher torque and lower noise, vibration, and T_{ripple}. Lifetime analysis shows the failure modes and their effect on operating electric motors. Subsequently, estimation of a lifetime in the sub-system and system level can be yielded.

In the following study, after specifying a satisfactory assessment of PM motor reliability modeling and failure modes, reliability criteria are chosen to identify the reliability statuses of the regarded PM motors under faulty conditions. IPMSM and PMA-SynRM are our case studies designed to use in the elevator. Subsequently, failure rates as the basis of reliability study are used in Markov chains to assess the reliability. Finally, outcomes suggest a better PM motor from a reliability viewpoint for elevator usage.

Reliability Analysis Methodology

In order to conduct a reliability analysis, specifying the assessment reliability modeling, failure rates, and reliability criteria are necessary.

A. Assessment Reliability Modeling

The first stage of designing a gearless elevator system with a lift capacity of 5 men (about 357 Kg) is to define the technical data based on elevator capacity [12], [13]. Accordingly, motor torque is written as below:

$$T_{motor} = \left[r_{pulley} \times g \times \frac{(m_L + m_C - m_{B.Weight})}{u \times \eta}\right] \quad (1)$$

Where $T_{motor}\,(N.m)$ is the minimum/rated torque, r_{pulley} (m) is the radius of the drive pulley, g is the force of gravity, m_L (Kg) is the load mass, m_C (Kg) is the cabin mass, $m_{B.Weight}$ (Kg) is the balancing mass, η is well and rope system efficiency, and u is the coefficient for suspension (1 for direct suspension and 2 for 2:1 suspension). In this design u=2. In (1), $m_L + m_C - m_{B.Weight}$ can be regarded as half of the lift capacity or load mass of the elevator. By considering $\eta = 80\%$, $r_{pulley} = 0.1036\,m$, and $g = 9.88$, T_{motor} will be 120 N.m. Accordingly, motor angular velocity is written as follows:

$$\omega = \left[U \times (V / r_{pulley})\right]\left[\frac{rad}{s}\right] \quad (2)$$

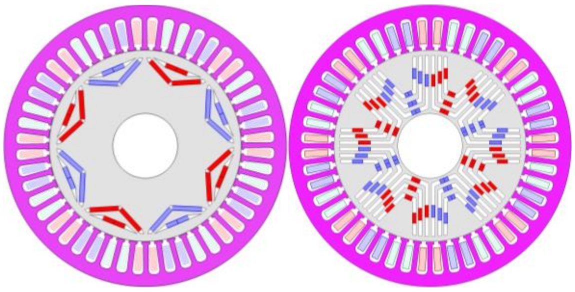
Where V is the cabin vertical velocity as *m/s* (between 0.508 *m/s* to 1.016 *m/s*) [14]. In this system V is 0.95 *m/s*. By considering u=2, ω will be about 18.325 rad/s. According to $T_{motor} = 120\,N.m$ and $\omega = 18.325\,rad/s$, P_{out} will be 2.1 *KW*.

Based on the given design data in Table 1, and the technical data of T_{motor}, ω, and P_{out}, two electric PM motors, including PMA-SynRM and IPMSM, are designed with an analogous stator and investigated in the same operating conditions. The designed motors' configuration is shown in Figure 2. As can be seen, excepting flux barriers and magnet arrangement, the designed electric motors are entirely analogous even in the used magnet volume (to have a fair analysis between the regarded PM motors). In the following investigations, the control strategy of both electric motors is Maximum Torque Per Ampere (MTPA).

Among the PM motor, drive system, cabin, cables, and sensors in the elevator, owing to energy conversion duty,

Table 1. Technical data of the investigated PM motors.

Designed Parameters	Unit	Value
Number of Phases	-	3
Number of Pole	-	8
Rated Torque	Nm	120
Rated Speed	RPM	175
Rated Power	Kw	2.2
Line Peak Current	A	300
Winding Layers	-	1
Parallel Paths	-	2
Stator Outer Diameter	mm	193.42
Stator Inner Diameter	mm	132.4
Stator Slots	-	48
Slot Depth	mm	22.5
Tooth Width	mm	3.32
Slot Fill	%	42.7
Stator Stack Length		160
Magnet	-	NdFeB
Magnet Weight	Kg	1.542
Air Gap	mm	0.5



(a) (b)

Figure 2. Topology of the suggested PM motors: (a) IPMSM and (b) PMA-SynRM.

the PM motor is more subjected to faults and stresses, electrically and mechanically. A PM motor commonly consists of PMs, windings, bearings, stators, and rotors, and any failure in them will lead to the failure of the entire electric motor system. So, the reliability block diagram in this study is a series, as displayed in Figure 3. Accordingly, the motor reliability (R_{motor}) and Mean Time to Failure (MTTF) are written as below:

$$R_{motor}(t) = \prod_{i=1}^{N} R_i = e^{-\sum_{i=1}^{N} \lambda_i t} \quad (3)$$

$$MTTF = \int_0^{\infty} R(t)dt \quad (4)$$

Where λ is the failure rate and N is the number of failure modes.

B. Failure Modes

In a PM motor, winding and PMs have more sensitivity and vulnerability in a harsh environment than the others. Accordingly, the investigated failure modes in this study are Shor Circuit (SC) in the stator winding, Open Circuit (OC) in the stator winding, and demagnetization in rotor PMs.

B.1. Short Circuit (SC)

The most common faulty condition in electric machines is SC. Based on the location of SC occurrence, it is categorized as Turn to Turn SC (TTSC), Phase to Phase SC (PPSC), and Branches SC (BSC). Insulation weakness is

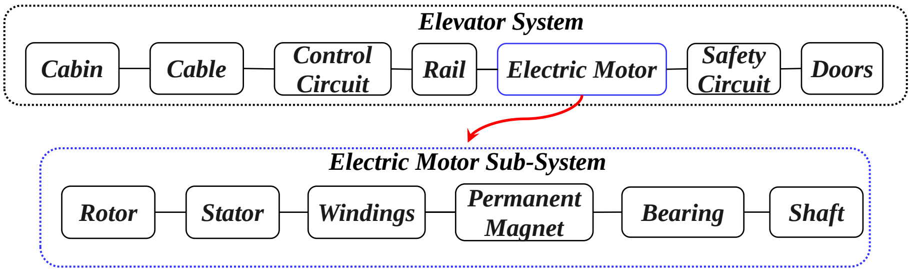


Figure 3. Reliability block diagram of system levels in the elevator.

known as the main cause of SC. Imposing a severe electromagnetic force and following vibrations result from SC occurrence. In the high intensity level of SC, damaging core and insulations, raising warmth, and demagnetization faults are significant [15].

B.2. Open Circuit (OC)

During OC occurrence in the stator winding, owing to asymmetric voltage and electromagnetic field, a low-frequency vibration emerges, leading to unitability in electric motor operating conditions.

B.3. Demagnetization

Demagnetization specifically occurs in PM motors, whose reliability highly relies on PMs' health. Some conditions, such as high starting current and armature reaction effect, can easily lead to PM demagnetization. The armature reaction can inject an irreversible magnetic flux weakening and finally reducing electromagnetic torque. As shown in Figure 4, if the PM's operating point is above the knee point, just once reversible demagnetization can occur, and after removing the external field, the residual magnetic flux density can be recovered. The magnetic flux density below the knee point is significantly reduced with increasing the external field. So, if the PM's operating point is below the knee point, PMs don't follow the prior path, reducing residual magnetic flux density [16].

In worst-case SC, while the whole stator excitation current is in reverse of the d-axis and environment condition of 150℃, IPMSM and PMA-SynRM will be demagnetized 71.3% and 49.1%, respectively. According to Figure 5, there is a clear connection between demagnetization's level and residual flux density.

C. Reliability Criteria

The fault tolerability of the elevator, owing to its close connection to human lives, is highly necessary. The failure modes directly affect the electric motor operating condition and endanger human lives. Output torque in the elevator has a significant key role in elevator reliability. Accordingly, Maximum Torque (T_{Max}) during demagnetization and T_{ripple} during SC and OC faults are the criteria for identifying the reliability states. This study's reliability criteria constraints are a lower T_{Max} than 120 *N.m* and a higher T_{ripple} than 20%.

D. Failure Rate

The basis of reliability analysis is the failure rate. Considering a system in the useful life operating stage of the bathtub curve gives a constant failure rate. Calculating failure rate is costly and time-consuming, so most failure rates are given by the known standards [17]-[18]. As

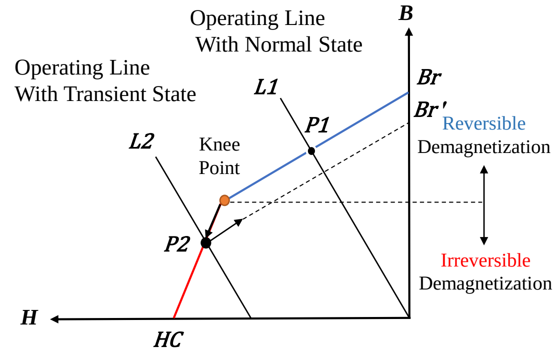
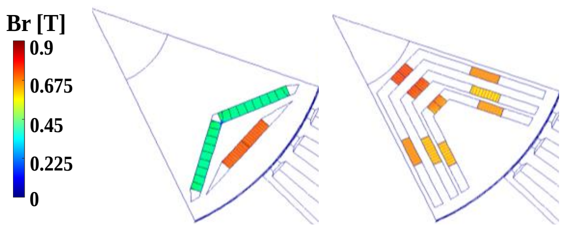


Figure 4. Demagnetization diagram [16].



(a) (b)

Figure 5. Residual flux density of the investigated PM motors during the worst-case SC and 150℃: (a) IPMSM and (b) PMA-SynRM.

PMA-SynRM belongs to a new generation of electric PM motors, the common tests such as Part Count Analysis (PCA) and Part Stress Analysis (PSA) are not yet explicitly regarded for it. Accordingly, the suggested failure rates for PMSM and induction motor are usable in reliability analysis of PMA-SynRM, which fortunately do not affect assessment validity. The failure rate is written as below [19]:

$$\lambda = \lambda_{base} \times \alpha \times \prod_i \pi_i \tag{4}$$

Where π_i is stress factor, α is the probability occurrences of each failure mode, and λ_{base} is the base failure rate given by manufacture. The regarded failure rates in this study are given in Table 2 [20].

Table 2. Failure rates of PM motor under faulty conditions.

Failure Mode	Failure Rate λ $(1 \times 10^{-9}/Hours)$
Diamagnetization	1360
Open Circuit	1100
Short Circuit	1100

Table 3. Comparison of the employed PM motor in elevator: IPMSM and PMA-SynRM

Type of PM Motor	Advantages	Disadvantages
IPMSM	High Power Density and Efficiency High Power Factor Low Losses, Noise, Cogging Torque, and Torque Ripple	High sensitivity to warmth Risk of demagnetization High cost High usage of rare earth free PMs
PMA-SynRM	Relatively High Efficiency Satisfactory with using rare earth free PMs Sufficient Torque Lower PMs' usage	Manufacturing challenges Higher Torque Ripple than IPMSM Risk of demagnetization

E. Reliability Assessment Method

Reliability assessment can be analytically and numerically. Markov modeling is more satisfactory where the system changes with time, such as in the electric motor. In Markov modeling, the next state relies on the current state, which means a constant failure rate. Also, Markov modeling can consider faulty conditions. The most common way to obtain Markov modeling is Chapman–Kolmogorov as follows [21]:

$$P'(t)^T = A^T.P(t)^T \tag{3}$$

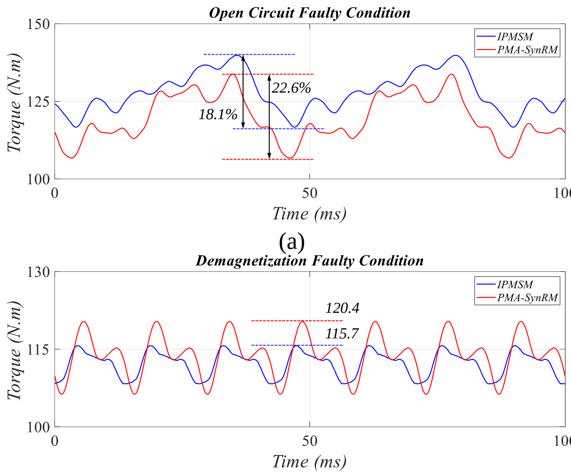
Where $P(t)$ is state probability matrix and A is transition matrix. If the Markov modeling has n states, the matrix of P will be written as (4), which shows the probability of being in the i^{th} state at the t^{th} time [22].

$$P(t) = [P_1(t) \quad P_2(t) \quad \dots \quad P_n(t)] \tag{4}$$

Accordingly, A will be written as (5).

Reliability Analysis and Lifetime Prediction of PM Motors in Elevator

The designed PM motors have some advantages and disadvantages against each other in elevator, as given in Table 3. Additionally, reliability is a significant factor in choosing an electric motor to employ in the elevator. Injecting faulty conditions and identifying the reliability states through reliability criteria will yield reliability analysis. The faults are injected through increasing intensity until system failure is based on reliability criteria. For instance, by injecting 2nd degree of demagnetization, IPMSM will fail (denoting by F), and PMA-SynRM will remain reliable (signified by R), as shown in Figure 6. Reliability states of the designed motor in failure modes is given in Table 4, as the basis of drawing Markov chains in Figure 7. In Figure 7, P1 defines the R state for each scenario with no-fault, P2 and P3 define the R states of demagnetization fault in PMA-SynRM, P4 defines the R states of SC fault, and P5 defines the R states of OC fault, and P6 defines the F state.



(a) (b)

Figure 6. Torque of the suggested PM motor under faulty conditions: (a) 25% OC and (b) 18% Demagnetization.

According to (5), matrix sizes for PMA-SynRM and IPMSM are 6×6. By substituting A into (4), the probability of each state can be written. Accordingly, starting from state one (R state), the probability of being in the R

Table 4. Reliability Status of the investigated PM motors in elevator under faulty conditions.

Type of PM Motor	Type of Fault	Intensity	T_{Max} $(N.m)$	T_{ripple} (%)	Status
IPMSM	Healthy	-	143.6	6	R
	Demagnetization	15%	120.3	-	R
		18%	115.7	-	F
	Open Circuit	17%	-	13.6	R
		25%	-	18.1	R
		33%	-	23	F
	Short Circuit	8T	-	18.9	R
		16T	-	33.3	F
PMA-SynRM	Healthy	-	137.1	10	R
	Demagnetization	15%	123.9	-	R
		18%	120.4	-	R
		33%	118.3	-	F
	Open Circuit	17%	-	17.7	R
		25%	-	22.6	F
	Short Circuit	8T	-	20.2	R
		16T	-	32	F

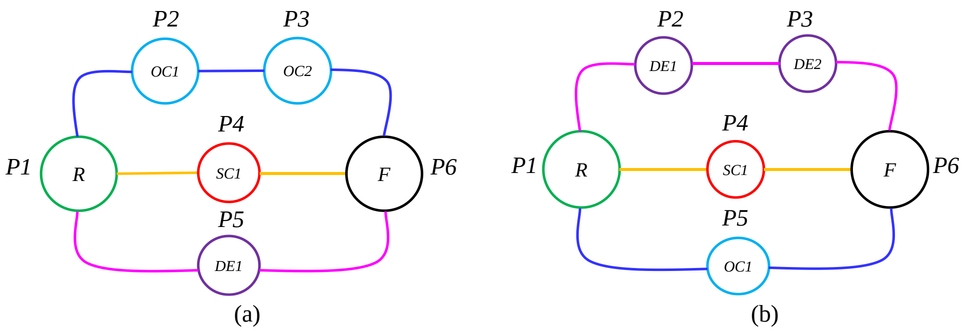


Figure 7. Markov chains under reliability analysis of the suggested PM motors in elevator: (a) IPMSM and (b) PMA-SynRM.

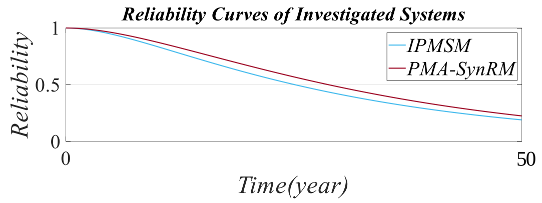


Figure 8. Reliability curve of the suggested PM motors in elevator.

state is decreasing while the probability of being in other states (P2-P5) grows, namely transient states, and then goes to a constant value, namely steady state. Finally, after a long time (20 years), the system converges to the absorbing state (P6) and stays in it. By substituting the probability of each state into (3), the reliability of the investigated PM motors will be yielded. According to Figure 8, in the same operating time (50 years), PMA-SynRM has higher fault tolerability and reliability.

Conclusion

In this study, after designing two PM motors to use an elevator, their lifetime management is regarded, especially lifetime analysis and estimation. Accordingly, the reliability statuses of the designed and investigated PM motors are given under faulty conditions and failure modes as lifetime analysis after specifying satisfactory reliability modeling and criteria. Identifying the reliability statuses leads to drawing Markov chains and lifetime estimation. Based on the MTTFs of PMA-SynRM and IPMSM, the best choice in the elevator is PMA-SynRM, owing to its higher reliability and fault tolerability.

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