A Survey of Failure Mechanisms and Statistics for Critical Electrical Equipment in Buildings

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***Abstract*—Air-conditioning and mechanical ventilation (ACMV), power distribution systems, elevators, and lighting systems are critical electrical assets of a smart building. Based on electrical components of these assets such as electrical motors, transformers, solid-state lighting and power electronic converters, a detailed analysis of failure mechanisms and statistics is presented in this paper. Further, suitable electrical and mechanical signals along with prevalent condition monitoring methods are suggested for condition monitoring of these assets based on the presented statistical analysis. This paper lays down the necessary foundation to understand the operating model of critical electrical equipment in buildings and provides a holistic picture for implementation of a predictive and preventive maintenance paradigm. This will enable the building operators to identify potential failures of building equipment and their evolution in real-time, driving decisions on scheduling repair or replacement of components to minimize downtime, save maintenance costs, improve occupant satisfaction, save energy, and maximize resilience.**

I. Introduction

In developed nations, buildings consume substantial amounts of energy. In the United States of America, the buildings sector accounts for about 38.9% of energy consumption in 2017 [1]. In Singapore, buildings (including residential and non-residential) are responsible for around half of the country's electricity consumption [2]. Higher energy consumption occurs in commercial buildings and building types such as shopping malls, hotels, hospitals, and offices [2]. The electrical energy consumption in majority of non-residential building is attributed to cooling (60%) and mechanical ventilation (10%). In Singapore's tropical climate, the cooling and ventilation systems are critical in a building for maintaining thermal comfort-levels of its occupants. Appropriate and sufficient lighting is necessary for providing visual comfort for occupants to function. In the present-day high rise landscapes, not just the presence of lifts and escalators, but also their safe and reliable operation have became an absolute necessity. As these sub-components of buildings attribute to comfort, safety and security of occupants, the distribution system electrifying such sub-components is also a critical asset.

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In the electrical distribution system of a building, distribution transformer carries total power to the building 24 by 7 from utility grid. This transformer is a single point of failure, and thus needs to be monitored and maintained continuously based on its present conditions. Any unexpected failure in the transformer may lead to the building blackout and subsequent consequences. Other key electrical components in buildings are electrical motors and associated drives in lifts and escalators, pumps, and control systems.

From aforementioned discussions, it is observed that equipment health and condition monitoring is an important function to ensure minimum discomfort, minimum interruptions and associated downtime [3]. For buildings, improved reliability and up-time of critical electrical systems mentioned above is necessary to achieve this objective. For electrical equipment health and condition monitoring, a detailed analysis of failure statistics and mechanisms is required. These failure statistics

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TABLE I: Prioritized list of commercial building faults [4]

Fault Type	AEI (Tr BTU/yr)	AFI ($Mil./yr)	Prev.
Excessive infiltration	47	1,127	94%
Air-duct leakage	40.92	1,047	65%
Incorrect HVAC on/off modes	22.5	920	23%
Non-standard refrigerant charging	14.56	587	72%
Inappropriate lighting schedules	13.16	393	35%
Unsuitable thermostat's set points	12.04	492	23%
Condenser fouling	5.35	274	44%
Insufficient evaporator airflow	5.19	914	18%
Inappropriate electric line voltage	3.82	355	14%
Oversized equipment at design	3.27	90	68%
Improper time-delay from sensors	2.91	87	80%

and mechanisms constitute the domain knowledge of electrical equipment for advanced maintenance techniques.

In this paper, an attempt is made to provide the necessary foundations to understand the operating model of critical electrical equipment in buildings and the possible failure modes. Such a comprehensive analysis with focus on buildings has not yet been reported in literature. With a clear understanding of predictive models for failures in building equipment, it is possible to have a transition towards a predictive maintenance paradigm. Rest of the paper is organized as follows: prevalent faults in building environment are discussed in Section II, failure mechanisms in induction motors and different types of transformers are covered in Section III and IV, respectively. Section V covers discussion on lighting system and Section VI discusses power converters. Section VII concludes the paper.

II. Building Environment

Critical electrical assets in a building include (i) ACMV system, (ii) lighting systems, (iii) lifts (iv) transformers. In this paper, the sub-components of each asset are studied in details along with their health indicators for condition monitoring.

A list of faults prioritized based on estimates of the prevalence, energy impact and financial impact of each fault is presented in [4]. Among the presented indicators, annual energy impact (AEI) and annual financial impact (AFI) of each fault are two recommended metrics. Parameters such as fault prevalence, efficiency reduction, capacity degradation, load increase and equipment life span are considered. A total of 47 faults are classified by location (building envelope or ACMV or lighting system), stage (design or operational), and type (building or equipment or control or sensor). A prioritized list of 11 faults along with their energy-impact, financial-impact and prevalence is shown in Table I. From Table I, it may be observed that 8 out of 11 most-severe faults are related to air-conditioning system.

III. Air Conditioning and Mechanical Ventilation

The air condition and mechanical ventilation (ACMV) system accounts for a bulk of the electricity consumption in commercial buildings and faults in ACMV system can lead to significant additional electrical losses, inefficiency in operation and occupant discomfort.

TABLE II: Recommended monitoring variables for health monitoring of chiller [5]

Sub-components of chiller	Recommended monitoring variables
Chilled and condenser water (or other secondary coolant)	Flow, pressure and temperature at inlets and outlets
Evaporator and condenser	Pressure and temperature of refrigerant
Oil	Level, pressure and temperature
Purge	Exhaust time and discharge count
Ambient Temperatures	Dry bulb and wet bulb
Refrigerant	Level, compressor's discharge and suction temperature, PPM level
Motor	Currents and voltages per phase

A. Air-Conditioning System Failure Mechanisms and Statistics

There is limited literature consolidating the causes of system failures or needs for air conditioning equipment servicing [7]. Stouppe et. al. presented a study on 15,716 failures in air-conditioning systems between 1980 to 1987 [8]. In the failures related to hermetic air conditioning units, 76% were attributed to electrical components, 19% to mechanical components, and 5% to components in the refrigeration circuit. Following are some inferences:

1) Among the electrical failures, $\approx$87% failures were in motor windings (similar results are reported in [9]), which is one of the common failures in induction motors caused due to overloading of motors.
2) Most of the mechanical failures were due to compressor valves, bearings and connecting rods. The primary reasons stated for mechanical failures were general fatigue in valves and valve springs, liquid slugging and loss of lubrication.
3) Furthermore, the primary cause of mechanical failures in positive displacement compressors is liquid refrigerant in the compressor primarily due to degraded evaporator coils, fouled condenser coils, refrigerant overcharge, and a faulty thermal expansion valve (TXV).

In [9], the cost associated with ACMV failures was reported based on a service database with 6000 cases. It is interesting to note that even though the failures in compressor are linked to only 5% of service calls, they accounted for 25% of service costs. A detailed discussion of failure mechanisms and common causes of prevalent faults in an air-conditioning system were presented in [10]. An estimated increase in annual energy consumption due to faults is reported to be between 4% and 18% of the sum of ACMV, lighting, and refrigeration energy consumption and is consistent with the typical range of energy waste reported in building commissioning studies.

B. Monitored Signals

The ASHRAE Standard 147 recommends a list of signals to be monitored for condition monitoring of chiller as listed in Table. II. A Fault Detection and Diagnosis (FDD) algorithm based on temperature, air-flow and fan speed was proposed in [11]. For FDD of induction motor faults, typical signals identified in Section IV-A can be directly utilized in addition to above mentioned signals.

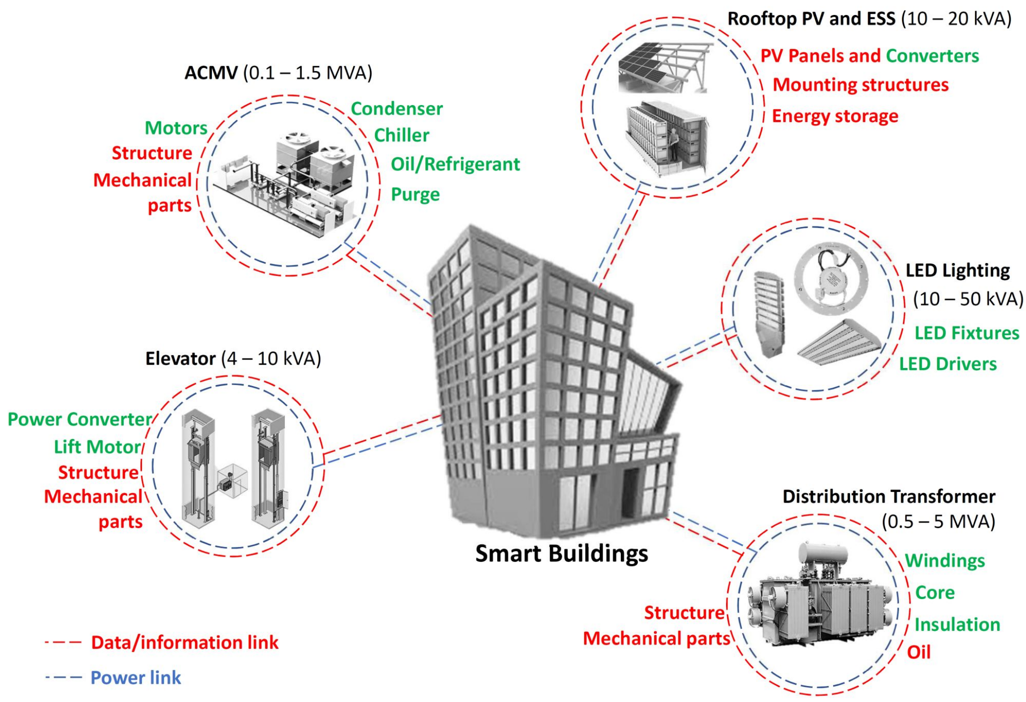
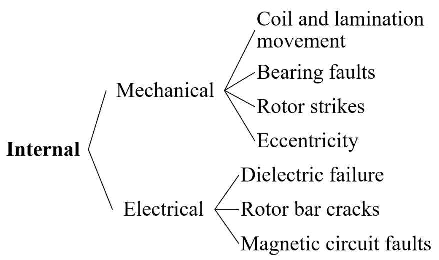
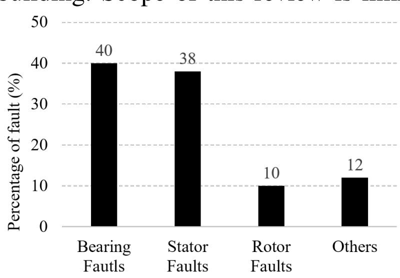


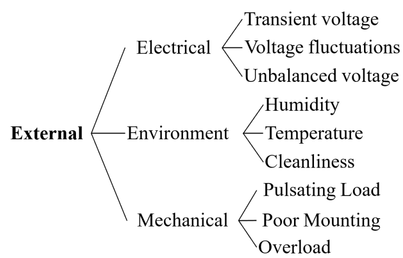
Fig. 1: Sub-components of a smart building. Scope of this review is limited to the sub-components in green.



(a) Internal faults



(b) Occurrences of faults



(c) External faults

Fig. 2: Classification of internal and external faults in IM [6]

IV. Induction motors

As a part of ACMV systems, lifts and elevators, and consumer appliances, induction motors (IM) are used in different power levels in buildings. For instance, power ratings of IMs in ACMV systems are up to hundreds of kW, lifts and elevators are up to 4-10 kW, and few kW in consumer appliances. These motors are simple, efficient, highly robust and rugged; thus offering a very high degree of reliability.

A. IM Failure Mechanisms and Statistics

Induction motors are subjected to heavy duty cycles, poor working environment, installation and manufacturing factors, etc. Faults in induction motors are broadly divided into internal and external faults. There categories are further explained in Fig. 2a and Fig. 2c [6], [12]. Probabilities of occurrences of different faults in induction motor are shown in Fig. 2b. From the statistics in Fig. 2b, it can be observed that bearing and stator faults are more probable in induction motors.

Induction motors faults are classified according to region of occurrence into following categories:

1) *Bearing faults:* Defects in bearing could be either distributed or localized. Distributed defects include misaligned races, waviness, surface roughness and off-size rolling elements. Localized defects include spalls, pits and cracks. Flawed bearings cause mechanical vibrations with frequencies dependent on bearing dimensions and rotation speed.
2) *Stator faults:* Faults in stator are attributed to stressful operating conditions including thermal, electrical, mechanical, and environmental [13]. Major faults in the stator winding are turn-to-turn, coil-to-coil, open circuit, phase-to-phase and coil-to-ground.
3) *Rotor Faults:* Faults in rotor can be induced by electrical failures such as a bar defect or bar breakage or mechanical failures such as rotor eccentricity [14]. Such failures changes torque significantly and became dangerous to the safety and consistent operation of electric machines [15]. The second type of rotor fault is related to air gap eccentricity, which is a common effect related to a range of mechanical problems in induction

TABLE III: Comparison of various induction motor fault detection techniques [6]

Fault Detection Techniques	Detected Faults	Monitored Signals
Motor-current signature analysis (MCSA)	Bearing, Rotor, Stator and Vibration Faults	Stator Currents
Park's Transform	Bearing and Stator Faults	Stator Currents & motor speed
Artificial Neural Networks	Bearing and Rotor Faults	Stator Currents
Wavelet Analysis	Bearing, Rotor, Stator and Vibration Faults	Stator Voltages, Currents & motor speed
Finite Element Method	Rotor, Stator and Vibration Faults	Magnetic flux
Vibration Testing and Analysis	Bearing and Vibration Faults	Motor Vibrations
Concordia Transform	Bearing Faults	Stator Currents
External Magnetic Field Analysis	Rotor Faults	Axial Flux Density and rotor currents
Multiple Reference Frames Theory	Eccentricity	Stator Voltages, Currents & motor speed
Power Decomposition Technique	Stator Faults	Stator Voltages & Currents
KU Transformation Theory	Stator Faults	Stator Voltages, Currents & motor speed
Zero Crossing Time Method	Stator Faults	Stator Currents
Modal Analysis Method	Vibration Faults	Variation of Vibration spectrum

motors such as load unbalance or shaft misalignment. Shaft misalignment refers to horizontal, vertical or radial misalignment between a shaft and its coupled load, which leads to displacement of motor from its normal position.

4) *Eccentricity faults:* Eccentricity is caused by unequal air gap between stator and rotor [16]. Eccentricity faults can be static, dynamic, mixed or inclined. Static air-gap eccentricity is caused due to erroneous positioning of the rotor or stator during the commissioning phase or stator core ovality. In dynamic eccentricity case, the centre of rotor and the centre of rotation do not coincide leading to minimum air-gap. This is caused due to bent shaft, bearing wear and movement, or mechanical resonances at critical speeds. A mixture of both forms is called mixed eccentricity [17] and the axial non-uniformity of air gap is known as inclined eccentricity [18].
5) *Vibration faults:* Vibrations are naturally caused by the movement of mechanical parts of the motor. These oscillations are propagated to the external system attached to the machine shaft. The frequency spectrum for vibrations for a faulty motor is dependent on the type of fault.

B. Monitored signals

The above mentioned faults produce one or more of the following symptoms [12]: (i) Unbalanced air-gap voltages and line currents, (ii) Increased torque pulsations, (iii) Decreased average torque, (iv) Increased losses and reduction in efficiency, and (v) Excessive heating. For the purpose of detecting each fault-related signal, methods shown in Table III may be utilized. Particularly, Motor Current Signature Analysis (MCSA) is popularly used for diagnosis purposes in IM, which utilizes spectrum of supply current to detect various faults. In the presence of any fault, the spectrum of stator current defers from the healthy conditions and each of above-mentioned faults induces specific frequencies in the current spectrum. In order to improve the accuracy of prediction, other specific methods as mentioned in Table III can be utilized.

Several other methods have also been developed based on the analysis of external magnetic fields [19], [20]. Their advantages are the non-invasive investigation and simplicity of implementation. It is important to note that most of the condition monitoring techniques are based on on-line measurements. Thus, selection of appropriate sensors and their placement in the motors is critical for successful implementation of any of the above-mentioned techniques.

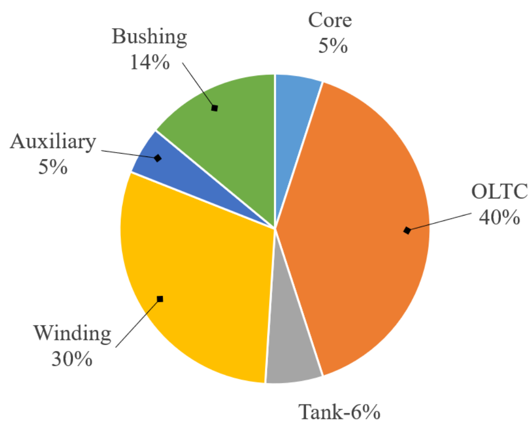


Fig. 3: Defective Components of Power transformers [21]

V. Distribution Transformers

Owing to substantial consumption of electrical power, buildings are now directly connected to the medium voltage (MV) grid such as 13/22 kV. For consumption, the MV is stepped down to 400/415 V using transformers. Thus, the transformer forms an important part of the power distribution within buildings. During its operation, transformers are subjected to thermal, mechanical, and electrical stresses, which can eventually deteriorate its condition and cause failures. To ensure reliability of power supply, condition monitoring (CM) and diagnosis are essential part of transformer asset management.

Considering the safety aspects for buildings, dry-type transformers (open-wound or cast coil in air) are preferred [22]. They are reliable, cost-effective, require lower maintenance, and lower fire risk [22], and are available for voltages up to few tens of kV and ratings up to few tens of MVA [21], which is the typical power rating of an urban building.

A. Transformer Failure Mechanisms and Statistics

Insulation break-down is the most serious failure for transformers in buildings, which can lead to substantial down times, high costs for repair and financial losses. Higher stress is a probable cause for MV insulation degradation in transformers and thus, utilities must evaluate and monitor the health of MV insulation periodically. Statistics collected in recent years illustrate that 75% of transformer faults are due to insulation failure [23]. CIGRE International survey shown in Fig. 3 reveals the probability of occurrence of faults in various components of power transformers [24].

The historical failure data of $11kV$, $22kV$ and $33kV$ transformers are scarcely available and one of the reasons could be that the utilities put less resource into maintaining records for the less expensive lower voltage transformer fleets [25]. Reliability data from 97% of the 6,057 utility-owned power transformers operating in mainland Australia and Tasmania, which includes some information on the distribution transformers, were collected and analysed [25]. To quantify the impact of each failure mode, the failure data was sorted as per frequently failed components into bushing, insulation, OLTC, other components and winding for different voltage classes, and are studied in terms of median ranks as shown in Fig. 4. Here, the factor β determines shape of the plot; $\beta < 1$ indicates infant mortality; $\beta = 1$ indicates random failures; and $\beta > 1$ indicates age-related failures. The predominating failures in transformers i.e., winding related faults follow two distributions, a nearly random failure pattern before 20 years ($\beta = 1.6$) followed by age-related failures after 20 years.

Tap changer is the moving part in a transformer which is subjected to mechanical stress in addition to electrical stress. The major mechanisms for ageing of tap changer are [21]: (i) Tap changer oil contamination due to switching arcs, (ii) Electrical treeing along supporting resin-bonded paper cylinder and insulating drive shaft, (iii) Wear of arcing contacts, and (iv) Long-term effect on changeover selector (in motionless tap changer) due to formation of organic film which may cause carbon deposits.

Winding failures are due to the ageing/weakness of the solid insulation system, which is caused due to stresses during operation and fault conditions. With ageing, the conductor insulation may be weakened to the point where it can no longer sustain mechanical stress due to faults. This results in turn-to-turn insulation failure. Repeated fault also causes loosening of winding clamping pressure, which reduces the transformer's ability to withstand further short-circuit forces.

B. Monitored Signals

The diagnostic techniques used for transformer condition monitoring fall into one of the three categories: (i) offline-offsite, (ii) offline-onsite, and (iii) online. Offline-offsite diagnostics require the equipment to be taken offline and samples are obtained for further laboratory analysis. Examples are degree of polymerization and tensile strength tests. Offline-onsite diagnostics require equipment to be taken out of service at site for diagnosis. Examples of such techniques are

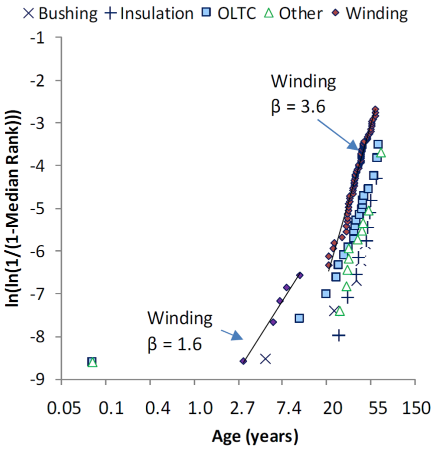


Fig. 4: Analysis of median ranks of failure modes for distribution transformers [25]

dielectric response measurements, frequency response analysis etc. Another method for estimation of transformer ageing and water content in transformer oil-paper insulation is based on measurements of polarization and depolarization currents [29] and frequency domain spectroscopy [30]. Frequency response analysis (FRA) may be applied for winding deformation and displacement detection [31]. These techniques require special connections to be made for condition assessment. Alternatively, online diagnostics techniques are non-invasive and can diagnose faults while the equipment is in service. Examples of online diagnostics techniques are dissolved hydrogen gas monitoring, infrared thermography and vibration analysis methods. Partial discharge (PD) measurements are utilized for transformer insulation diagnosis, and acoustic measurements for on-load tap-changer (OLTC) condition monitoring [32].

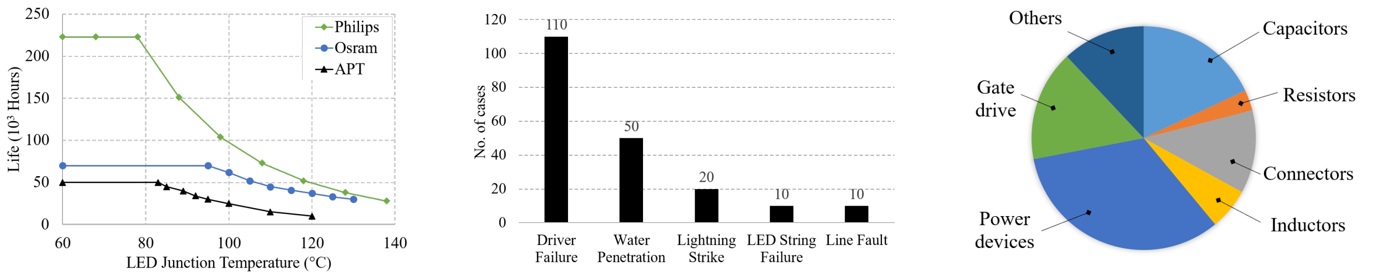
VI. Lighting Systems

As 4th generation lighting devices, Light Emitting Diodes (LEDs) have became popular quickly in many fields due to its benefits such as environmental friendliness, energy efficient, long life and high reliability [33]. In operation, LEDs convert electrical energy into visible light through a core light-emitting diode. Lighting systems in buildings are being upgraded to LED based systems considering the above-mentioned advantages.

In Singapore, the Housing & Development Board (HDB) as a part of *Roadmap to Better Living in HDB Towns*, is expanding sustainable living to existing HDB estates with the HDB Greenprint [34]. This model includes upgradation of lighting systems to energy efficient LED lightings and outdoor LED lightings with occupant sensing and control. Lighting is one of the major functions associated to safety, security and comfort of occupants in a building and hence it is important to understand failure causes and mechanisms associated with LED lights.

A. Failure Mechanisms and Statistics

Common failure modes for the LED devices include:



(a) LED lift time estimation [26]

(b) Failure statistics of LED [27]

(c) Failure in converters [28]

Fig. 5: Failure statistics of LED and power electronic converters

1) *Chip failure:* Large stresses due to heat, manufacturing defects and mechanical stress could leads to micro cracks on the LEDs. Device current could aggravate these micro cracks thereby increasing stresses on premature cracks till the point of complete failure.
2) *Encapsulation failure:* This type of failure is often caused by improper packaging design or production process. Problems in epoxy resin leads to decrease in the life of device. It will quickly deteriorate optical permeability, refractive index, expansion coefficient, hardness, permeability, and packing properties.
3) *Thermal stress failure:* High power LEDs generate a lot of heat and are often exposed to uncontrolled outdoor environments. An increase of LED's junction temperature accelerates the ageing of LEDs by altering the properties of epoxy resin material such that its thermal resistance increases. As a result, the heating surface between the chip and the package degrades, leading to encapsulation failure. C. Ding and T. Zhang in [26] provided comparison of lifetime reduction with increase in junction temperature for LEDs from three different manufacturers viz Philips, Osram and APT as shown in Fig. 5a. LEDs are said to be at end of life stage when the output luminous flux decay to $50\% - 70\%$ of its initial values. From Figure 5a, it is observed that service life of all LEDs decrease with an increase in junction temperature.
4) *Electrical over-stress failure:* High currents through the LEDs lead to device failures.

In [27], failure statistics of 200 LED Lamps are presented as shown in Fig. 5b. Among the presented cases, 55% of failures are resulted from LED driver failure and rest are of various causes.

B. Monitored Signals

With LED lighting gaining popularity, their condition monitoring techniques have also attracted attention. Several options have been researched and reported, for instance, a health monitoring and life prediction method is proposed based on LED's junction temperature, electrical parameters (such as reverse bias current) and life-time models for LED lighting system in [26]. The monitoring circuit can be designed and integrated into the LED driver making the whole system compact and cost effective.

VII. Power Converter Systems

One can see Power Electronic Converters (PEC) playing a major role in controlling different components of the building starting from motors in ACMV, lift, escalator and solar inverters, to drivers for LED lighting to solid-state breakers. As PECs perform such critical functions, their health has to be monitored similar to that of motors, transformers and LEDs to ensure continues operation.

An industrial survey from various manufacturers revealed that PECs operate at more than 80% load conditions (sometime overloaded) nearly half their life-time [28], [35]. Often, thermal capacity of PECs is over designed to ensure their reliability. Among the components of power converters, highest number of failures were caused by degradation of passive elements (capacitors, inductors, resistors and connectors) [35]. Research shows that aluminum electrolytic capacitors have lower operating life time especially at higher temperature and humidity, and account for over 50% of the LED driver failures. Failures in power devices account for nearly 1/3 of total failures in power converters as shown in Fig. 5c. For control of PEC, various states, for instance, output and/or input currents and voltages are sensed and feedback to the controllers, where control and protection algorithms are implemented. It is a general research direction at present to identify the faults in power converters using already sensed states.

VIII. Conclusion

In this paper, a detailed analysis of failure mechanisms and statistics of critical assets of the building based on their electrical components is presented. To provide a complete picture on the possibility of predictive and preventive maintenance for buildings, existing condition monitoring methods for these electrical equipment are discussed. Additionally, suitable electrical and mechanical signals are suggested for condition monitoring of these assets based on the presented statistics analysis.

1) Motor Current Signature Analysis (MCSA) and analysis of external magnetic fields are recommended and extensively researched for online condition monitoring of induction motor which is one of the crucial components of assets in the building.
2) Among the online condition monitoring techniques for transformers in buildings, dissolved hydrogen gas mon-

itoring, infrared thermography, vibration analysis and Partial discharge (PD) measurements are popular.

3) Power converters for motor drives, lighting and renewable energy conversion are equipped with sophisticated protection schemes that respond in few $10's$ of ns to μs for catastrophic failures such as short-circuit of devices and DC bus etc. Internal variables such as device temperature, leakage current, input current etc., are recommended for condition monitoring.

This will enable the building operators to identify potential failures of building equipment and their evolution in real-time, driving decisions on scheduling repair or replacement of components to minimize downtime and maximize resilience.

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