Unmanned Aerial Vehicles in Power Systems: Technologies, Use-Cases, Outlooks, and Challenges

Farrokh Aminifar, *Senior Member*, *IEEE* and Farnoosh Rahmatian, *Fellow, IEEE*

***Abstract*—Electricity service interruptions, even as short as a few seconds, are no longer socially or economically acceptable. Yet the operation and control of the existing power grid infrastructure is complicated by an ever-increasing number of severe natural disasters, deliberate/accidental incidents, and vandalism. In many parts of the world, the reliability and resilience of infrastructures that are interdependent and geographically dispersed are being improved using unmanned aerial vehicles (UAVs), commonly referred to as drones. This paper assesses various aspects of UAV applications in electricity networks, of value as deployment of UAVs continues to grow. We provide thorough discussions and elaborate on: 1) the emergence of UAVs including their development processes and milestones, 2) UAV technology types, characteristics, and benefits to various applications, 3) a wide range of power system UAV use cases ranging from condition monitoring and well-being inspection of power system components, laser technology-enabled 3-D mapping, post-disaster damage assessment and functioning, to supporting operation and maintenance tasks, 4) opportunities and future insights for UAV applications including autonomous functioning, networked UAVs, real-time condition-based maintenance, cost-effective meter reading, collection of nontechnical loss testimonial data, future demand analysis, and mining discovery supports, and 5) technical, regulatory, and socioeconomic challenges of vast UAV deployment.**

***Index Terms*— Unmanned Aerial Vehicle (UAV), Condition Monitoring, Field Assessment, Aerial Reconnaissance.**

I. Introduction

THE ELECTRICITY network is a very large-scale and widely-distributed system that is highly interdependent with other large infrastructure systems (i.e., natural gas, telecommunication, water and wastewater, and transportation). Power grids are being stressed by severe loading conditions caused by rising electrification of infrastructure (for example, increasing use of electric vehicles) as well as overall growth in world population and electricity usage. Any prolonged electricity interruptions can have a widespread effect on other systems, including disruptions in internet and security equipment, traffic and street lights, pumping stations and public transportation, home appliances and tall building elevators, large industrial equipment and hospital devices, water supply and natural gas delivery network, etc. [1].

F. Aminifar is with the Electrical and Computer Engineering Department, Illinois Institute of Technology, Chicago, IL 60616 USA (E-mail: faminifa@iit.edu). F. Rahmatian is with NuGrid Power Corp., Vancouver, BC, Canada (frahmatian@nugridpower.com).

Climate changes are expected to intensify the number and severity of natural disasters, with a direct impact on interdependent infrastructures [2],[3]. The advent of the smart grid and the integration of sensor/actuator data infrastructure with that of the power grid has enabled additional improvements in power system resilience, reliability, economics, security and sustainability while seeing increased exposure to cyber and physical attacks [4]. Accordingly, electric power engineers are confronting an intricate dilemma for enhancing operation and planning of the power system.

Unmanned aerial vehicle (UAV) technology promises to address some of these challenges. A UAV (commonly known as a drone) is an unmanned vehicle or aircraft without a human pilot. The unmanned aircraft system (UAS) includes UAV technology and a ground-based control system providing communication. UAV missions include various degrees of autonomy; they are controlled either by a remote human operator or by an onboard autonomous computer [5]. In practice, terms for UAVs, UASs, and drones are often used interchangeably. Here, we use UAV to describe the vehicle including its control, communication, and interfacing accessories.

Aside from the first unmanned explosive balloon made in 1849 [6], UAV technology in its current form was made available in 1907, advanced predominantly during the World War II [7]. Like many other notable technologies, its development was driven by military application. As consumer technologies advanced in the 21st century, UAV became a viable option for civil, commercial, and entertainment purposes. Fig. 1 illustrate important milestones in the emergence and evolution of UAV technology [8].

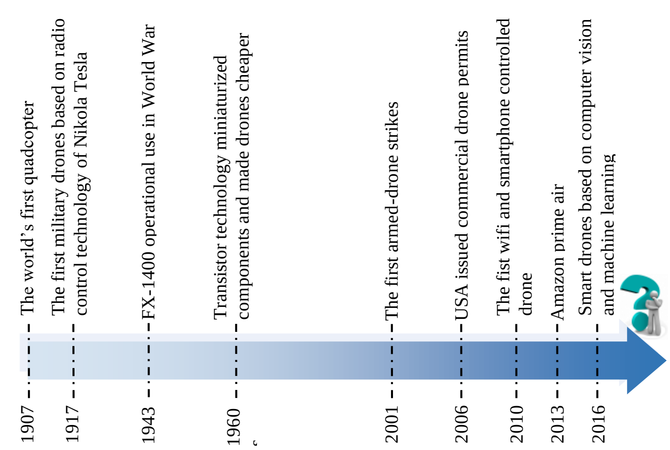

Fig. 1. Key milestones in the UAV evolution.

Most ground based field operations pose no major risk to humans, but UAV technology adds another dimension, enabling individual missions to be accomplished in inaccessible situations. UAV systems can survey hazardous situations or deliver aids/tools/goods in hard-to-reach areas. Integrating global position systems (GPS) (or its counterparts) with UAV technology was a major milestone enabling UAV location to be precisely identified improving its navigation and control functions accordingly [9]. In addition, a UAV's geographical information is managed by a geographic information system (GIS), enabling various legacy applications that have been developed for GIS platforms [10]. Synergies between UAV and GIS technology benefit both; for example, GIS databases can be updated dynamically using the unprecedented flexibility and maneuvering capabilities of UAV.

UAVs are much cheaper to produce than crewed aircrafts because of their very small and light body. Lower weight can also substantially lessen the UAV's operation cost [11]. In addition, unmanned flights make the UAV's crash incidents much more tolerable, both financially and socially. These advantages have simplified reliable UAV design and manufacture, and encouraged use for previously impossible tasks. UAVs also have a relatively long-life span, often exceeding 10 years, with minor maintenance requirements, procedures and expenses [12]. Their affordable purchase price and low operation cost favorably impact benefit-to-cost ratio, a key decision criterion in civil and commercial applications. Key technical challenges of UAVs include risk of midair collisions, cyberattacks, virus contamination, communication disruptions and vehicle crashes, not to mention limited travel range and inability to refuel midair. Non-technical concerns for widespread deployment of UAVs include lack of sufficient and clear legislative and regulatory mandates, the chance of ground crowd injuries, privacy invasions, security violations, and potential misuse by individuals [13],[14].

Virtually all types of large infrastructure benefit from UAV applications, including critical advances for first responders, i.e. police forces and firefighters. Still, the Association for Unmanned Vehicle Systems International (AUVSI) declared that due to the high operating costs of manned aircraft, fewer than 3% of law enforcement units have aviation assets to support their daily operations [11]. UAVs could enable a paradigm shift by introducing advanced camera technology, computer vision, image processing, and machine learning. UAV can effectively enhance a first responder's situation awareness and expedite their decision-making processes by initiating prompt, broad, and precise surveillance and search. Additionally, UAVs can benefit emergency/disaster management including pre-event inspections, during-event interactions, post-event rescues, damage evaluations and service restoration. Thermal imaging devices mounted on UAVs can be tailored to monitor forest wildfires, enabling early detection of fire threats in dense and vast forests. In disaster areas, larger UAVs can deliver sizable and very critical loads to increase survival rates for local inhabitants.

A UAV's aerial reconnaissance and patrolling functions can support detection of illicit trafficking and smuggling across borders. In these cases, a UAV's photography and recording capabilities become decisive for collecting evidence at crime scenes. Ironically, there is also potential for traffickers to exploit UAV technologies [15] for their own benefit.

A UAV's image processing capabilities enable wildlife preservation as well as conservation of ecosystems that support human lives [16]. They are helpful with constant monitoring of fauna, particularly tracking of animal movements and counts on a long-term basis. It is important that an animal's natural lifestyle and habitats are not distorted by UAV missions.

UAV technology is increasingly used in the agriculture industry to make quick and credible crop management decisions [17]. In the farming industry, UAVs can identify deficits in crops, irrigation and soil, so that timely action can be taken. UAVs can also help predict harvests using farm data analytics. Pattern recognition and imaging methods can be applied to UAV farm data to distinguish healthy and unhealthy crops and farm products. UAV data analytics used for harvest optimization, are one of the most fundamental ways to advance agricultural technology. In addition to monitoring, agricultural UAVs can also facilitate aerial seeding and pesticide spraying, in fact these two duties can be fully transferred to UAVs. However, UAVs can also collect proprietary data on competitors in unregulated areas, posing ethical concerns and requiring strict regulations [18].

UAV technology can be used in the large infrastructures to inspect devices remotely, enabling preventive maintenance and real-time hardware setting adjustments. On-board high-resolution and thermal cameras along with other mission-oriented sensors enable a UAV to perform precise inspections of power distribution and transmission lines, telecommunication towers, railroads, roadways, oil and gas pipelines and platforms, piers, sky-scrapers, bridges, mines, wind-turbines and storage tanks. Compared to traditional inspections, these inspections are cost effective and avoid risks of injury/death to on-site crew [19]. An ever-expanding list of commercial UAV applications is outlined in [20].

This paper explores UAV applications in electric power systems and in the electric utility industry as a whole. In Section II, it outlines UAV technologies and types. Current use-cases and field experiences are presented in Section III. Section IV explores future opportunities and challenges in the path to the vast deployment of UAV in the electricity industry.

II. UAV Technologies

UAV technologies can be classified by various criteria including by application, structural design type, intelligence and autonomy class, size and weight, payload capacity, powering type, endurance, flight altitude and range, hovering capability, take-off and landing direction or launching mechanism. They can be used for military, civil, commercial or entertainment purposes [21]. Commonly tailored for public safety and logistics, civil applications include police surveillance, delivery of health care supplies, environment protection, forest/wildlife monitoring, disaster prediction/tracking, law enforcement and aerial border patrol. Commercial UAVs are usually driven by private parties with economic objectives, such as crop management, shipping and delivery, entertainment and infrastructure inspection, to name a few. This commercial class of UAVs has the steepest market growth and employment opportunities [22]. In the US alone, the commercial UAV market has escalated from $40 million in 2012 to about $1 billion in 2017, and is predicted to account for $31-$46 billion of the country's GDP by 2026 [23]. The entertainment industry uses UAVs for fun/hubby/recreation purposes, including recent racing events [24].

UAVs are categorized into large, medium, small and miniature size classes. Large-size UAVs can carry heavy goods and/or cover very large geographic areas [25]. Medium-size UAVs are for reconnaissance or gathering data. Small-size UAVs have by far the widest application, used by commercial entities, government sectors, professional photographers and hobbyists. Miniature-size UAVs are only a few centimeters wide, sometimes even smaller; they are used in special military missions, spy undertakings and rescue missions (especially during extreme events like tornados and earthquakes).

As shown in Fig. 2, the structural design of a UAV can be fixed-wing, multi-rotor, single-rotor or fixed-wing hybrid [26]. The fixed-wing UAV has an airplane-like design and can be powered by either gas or electric engine. It is expensive but possesses the most mature technology and highest energy efficiency. Fixed-wing UAVs are usually large or medium size and fly with high endurance/speed; however they cannot hover so they take off and land horizontally, requiring more space. Fixed wing units have limited flying flexibility and maneuverability, so steering them requires professional training. Although most fixed-wing UAVs usually are military class, they are occasionally employed in civil or communication applications requiring long and fast flights. They are viable for niche applications like aerial mapping or long-distance inspection of infrastructure, like power transmission lines.

The multi-rotor UAV has gained attention recently in civil, commercial, and entertainment applications. Its frame might have two (bicopters), three (tricopters), four (quadcopters), six (hexacopters), or eight (octocopters) arms and motors [27]. Quadcopters are the most popular, broadly used for a range of applications. The more arms/engines the Quadcopter has, the more degree of freedom is granted for its control at the expense of lower energy efficiency. Multi-rotor UAVs are all electrical and usually manufactured in medium or small sizes. They are the easiest and cheapest type of UAV, requiring no special training. Multi-rotor UAVs have a great controllability feature, hover with least vibration, and can take off and land vertically. However, multi-rotor UAVs are less energy-efficient because they lack wings (must defy gravity using only small rotating propellers). Multi-rotor UAVs also have limited flight endurance, speed and payload capacity, deterring their use for commercial applications where crafts must carry heavy goods or travel long distances. Although the multi-rotor UAV applications are becoming widespread, its technology is still developing, particularly in terms of energy efficiency.

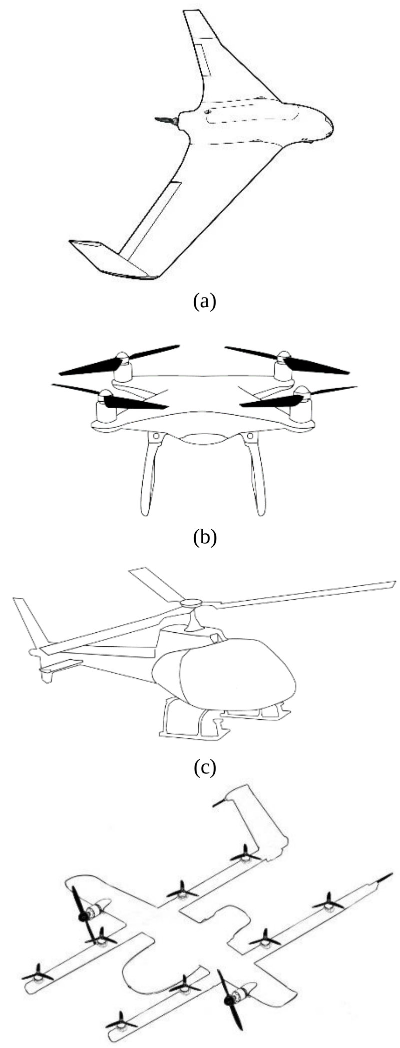

Fig. 2. UAV structural variations, (a) fixed-wing, (b) multi-rotor, (c) single-rotor, and (d) fixed-wing hybrid.

The single-rotor UAV, commonly referred to as a heli-drone, has a helicopter-like design which can be powered by gas engine, and is manufactured mostly in large sizes. It stands somewhere between fixed-wing and multi-rotor UAVs in terms of efficiency, endurance, speed, payload capacity and price. It takes off and lands vertically and can effectively hover, but is not as stable as a multi-rotor UAV. The single-rotor UAV's major disadvantage is its long rotating blades, which preclude commercial and entertainment use. By contrast, multi-rotor UAVs have adopted very small propellers which are protected by guards or even cages.

The fixed-wing hybrid UAV represents a new generation of UAV, combining the fast forward-moving capability of fixed-wing UAVs with the hovering feature of multi-rotor UAVs; however, the hybrid is not perfect in either category. Fixed-wing hybrid UAVs are still in early development stage, so current designs are very expensive to implement. With upcoming development, this UAV type has the potential for novel usages in an expanding number of application domains.

Fig. 3. pictorially compares three classes of fixed-wing, single-rotor, and multi-rotor UAV technologies in terms of various criteria. Clearly, fixed-wing and multi-rotor UAVs are quite disparate and single-rotor UAVs lie between them.

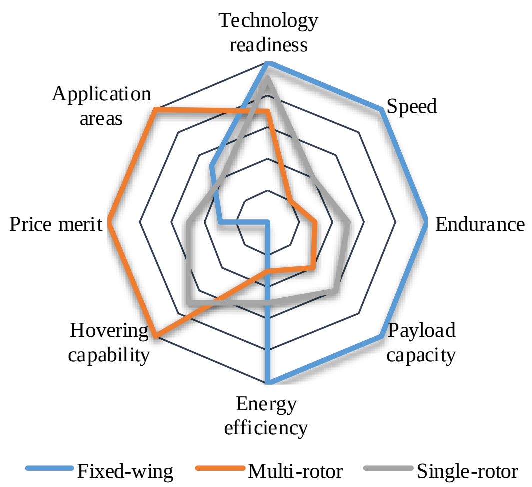

Fig. 3. Comparison of fixed-wing, multi-rotor, and single-rotor UAVs.

III. USE CASES AND EXPERIENCES

The Federal Aviation Administration (FAA) in the U.S. passed small UAS rule (part 107) in 2016, which includes a set of rules for operating a UAV commercially [28]. Since then, companies and utilities have deployed many commercial UAV applications. Electric utilities envision a wide range of UAV applications to avoid hazardous conditions for crew working on electric power systems. In this section, we review power system applications supported by real-world experiences and use-cases. The more novice applications and development are introduced in Section IV.

A. *UAVs for Aerial Inspection*

A short browse through existing literature reveals that a common UAV application is the inspection of power plants, substations, overhead transmission/distribution lines, and other capital-intensive assets. These assets are expected to be in-service for several decades and it is imperative to perform routine inspections and maintenance in order to prolong their lives. Not only must power utilities consider asset management to ensure operability of these critical assets, they must also consider system security. They must monitor for acts of vandalism, accidental and deliberate physical attacks, and harsh environmental conditions (such as ice and snowstorms, excessive heat, lightening, and contamination). Power lines are extended over unprotected private or public terrains, making them especially vulnerable to adverse externalities.

The inspection of power line equipment has routinely been executed by linemen, bucket trucks, and more recently by crewed aircrafts. Such inspections have traditionally been difficult, hazardous, and costly for electric utilities because the equipment is positioned high above the ground and occasionally passes through dense or hard-to-reach terrains. It is estimated that such inspections would cost \$6-8 billion annually for the U.S. power companies [29]. UAVs can cut down this cost considerably, offering fast and safe alternatives for power line inspections. UAV technology is more flexible, particularly in dense urban or inaccessible areas, and able to capture much higher quality photos and videos from any angle. It can also run over hot transmission lines and perform its functions while the lights remain on. These UAV benefits also apply to inspections of power plant equipment such as boilers and cooling towers, as well as to substation components such as transformers and CTs/CVTs. The investment rate of return on UAVs is extremely high, given their low investment/running costs and significant savings from reducing costly crewed operations.

In the electric utility industry, ComEd and Xcel Energy were the first two utilities granted by the FAA to use UAVs [30],[31]. These UAV operations involved beyond visual line of sight (BVLOS) application, meaning that UAVs fly several miles away (beyond the operator's visual line of sight). At present, energy companies are using UAVs for high-fidelity inspections of transmission line power equipment including towers, poles, insulators, conductors, guard wires, and accessories [32]-[39]. In addition, UVAs can enable early detection of sagging spans, leaning poles, broken or slack stay wires, broken or chipped insulators, and discolorations due to corrosion [40]. Infrared cameras can use thermal imaging to inspect power lines and substations, revealing incipient insulator or splice failures as well as loose connections due to local temperature increases [40]. Ultraviolet cameras mounted on UAVs can also detect abnormal corona discharges around insulators, fittings, and conductor surfaces [41],[42].

As large industrial complexes with huge structures, power plants can also benefit from UAV capabilities [43],[44]. High-resolution UAV imaging and 3-D modeling can easily carry out early detection of physical damages to cooling towers [45]. Leakage is a major deficiency in large boiler structures, which can be detected immediately and fixed using gas sensors and thermal imaging [46]. Firing ducts, catalysts, silencers, tube panels, stack dampers, baffles, and heat recovery steam generators are other components which benefit from continuous inspection by UAVs [44].

Wind turbines and photovoltaic solar farms are another power system asset needing constant health inspections. UAV enable regular or thermal inspections of wind turbine blades to take place even while rotating, which is extremely essential to avoid life-threatening accidents such as subsurface defects in composite materials [47]. This type of UAV inspection is attractive for offshore wind farms that have poor accessibility mainly due to maritime weather conditions [48]. Not only do large PV farms require precise monitoring equipment to detect deficiencies in the design and the operation of PV panels, they also require routine cleaning of PV panels. A UAV's thermal imaging feature can identify defective panels to be examined further by technical crews [49]. In addition to utility benefits, engineering and construction corporations also use UAV technology for project management and quality assurance purposes.

B. UAVs for 3-D Mapping

Light detection and ranging (LiDAR) is a laser technology on UAVs that is used for remote distance measurements, substantially speeding up 3-D mapping and modeling of structures. Using numerous overlapped photos of physical phenomena captured by LiDAR-equipped, GPS-equipped and GIS-connected UAVs yields unprecedented 3-D mapping capability. These exciting advances in mapping science, commonly referred to as photogrammetry [50], provide power companies with 3-D maps and models of power transmission and distribution lines, associated corridors, and any objects in their path [51]. In particular, this UAV technology is helpful (in fact, essential) to monitor high-voltage lines right-of-way and tree encroachment custody [52]. It provides the necessary time and performance data to facilitate the construction and installation of large towers. This UAV technology also verifies as-builts and confirms payments for outsourced maintenance or construction jobs [53].

C. UAVs for Post-Disaster Management

Power companies are revisiting post-disaster management and strategies in the face of recent hurricanes, extensive flooding, heavy snowfalls, record-high temperatures, record-setting droughts, and wildfires [53]. These extreme events are recognized as high-impact and rare (HR) events that can affect many power system components simultaneously. Accordingly, modeling and analyses of consequences (referred to as resilience assessment), is completely different from traditional power system reliability evaluation (that assumes only a limited number of components on forced outage) [3]. *Resilience* is defined as the infrastructure's ability to reduce the magnitude and/or duration of disruptive HR events. The effectiveness of a resilient infrastructure or enterprise depends on its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive HR event [54].

The resilience analysis of any infrastructure, such as electric power system, has three principal stages of pre-, during-, and post-event, as depicted in Fig. 4. They are also called ex-ante, real-time, and ex-post. The first stage, referred to as *avoidance stage*, mainly focuses on system robustness in a given state. This state promotes maintaining system services using proactive operational maneuvers before the event occurs [55]-[57]. During the event, known as *survival stage*, responses to the event (both system responses and operator responses are modeled and studied). At this stage, UAV aerial imagery is extremely helpful, particularly if the event proceeds slowly, as happened during the California wildfires in 2019 [58]. At the end of the second stage, system performance inevitably degrades to some extent, hopefully not too much. The last stage, known as *recovery stage*, begins right after the extreme event is cleared and includes both damage assessment and service restoration. Damage assessment benefits significantly from UAVs.

Damage assessment is inherently a time-consuming process due to the geographical dispersion of electrical networks. This process can take much longer in an extreme event since there might be numerous broken components and access roads could be cracked. UAV aerial inspection of the suspected damage area enables the repair crew to quickly determine the size and severity of damage, as well as estimated repair requirements, especially any needs for spare equipment [59]. With that information, repair equipment can be dispatched optimally and promptly to save lives. It is worth noting that despite the short period of time that UAVs have been used commercially, there have been numerous reports of their use in successful post-event damage assessments [60],[61].

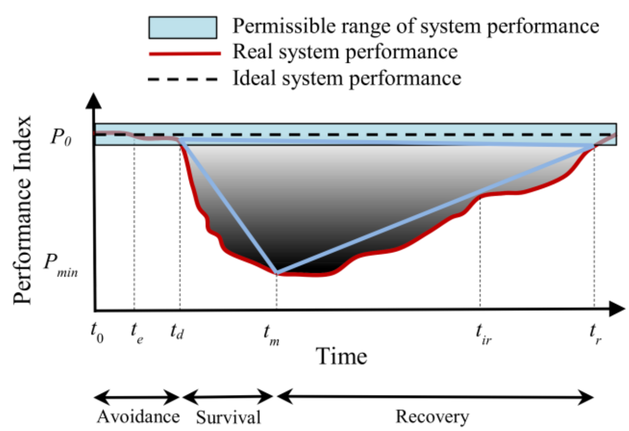

Fig. 4. Three stages of resilience study modeling [3].

D. UAVs for Operation and Maintenance Support

A specific class of commercial UAVs, referred to as heavy lifting drones, is designed to lift, carry and drop weights, ranging from a few kilograms to hundreds of kilograms [62]. These UAVs are capable of performing major tasks (beyond photography, videography or other types of data collection), enabling a wide spectrum of new applications.

Electric power system outages are relatively more frequent in winter. Snow accumulation and ice coating make power lines heavier than specified by design criteria. Irreversible sagging spans, tower leaning, pole downfall, insulator mechanical failure, and insulator snow-bridged electrical flashover are among adverse consequences of snowstorms. UAVs armed with fire-spewing guns can effectively save the most critical sections of damaged equipment [63].

Trash (such as kites or nets) tangled in power line conductors and towers is cumbersome, dangerous, and costly for electric power companies to remove. The flamethrower UAV has been deployed in such incidents to burn the trash and clear rubbish from the line [64],[65].

Crews periodically wash and clean power line insulators, particularly insulators associated with lines extending over air-polluted areas; otherwise, these locations are at risk of a flashover that could result in power outages and damaged electrical equipment. To reduce equipment downtime, insulators are washed while the line is energized. This process, referred to as hot/live line insulator washing, is a sensitive maneuvering process that UAVs can perform more efficiently, safely and inexpensively [66]. In addition, line construction companies can use UAVs to string line conductors more easily, a task that has been cumbersome for decades [67].

Finally, UAVs have evolved in applications that periodically clean solar panels/mirrors and wash wind turbine blades. Solar mirrors/panels, especially those located in dry, dusty deserts and air-polluted regions, require regular cleaning to maintain their nominal efficiency. UAV technology meets this need perfectly [68], outperforming legacy robots in several ways. A UAV does not need to be shifted from one row to the next manually, nor does it contact the delicate surface of mirrors/panels using wheels or suction cups [69]. UAVs are currently the easiest and cheapest alterative for solar mirror/panel cleaning. For wind turbines, factors such as snow, ice, pollution, humidity, dust, and insects can deteriorate performance and/or period of useful life. Maintenance of wind turbine blades and other parts is a routine procedure which can be done effectively by giant UAVs [70].

IV. Outlooks and Perspectives for UAVs

It is a common practice to indicate the status of emerging technologies on the Gartner's hype cycle to represent the maturity, adoption, and social application/adaptation of technologies [71]. Specific to the UAV technology, different assessment reports have reached a consensus that UAV technology has already surpassed the *technology trigger* phase and is more or less at the *peak of inflated expectations* stage, as depicted in Fig. 5 [72],[73]. This phase is recognized by mass media commentaries, technology publication blasts, proliferation of suppliers, and expansion of activities beyond those evident in the *early adopters* phase. Many UAV success stories and opportunities are broadcasted daily, also accompanied by scores of experiments failed due to unresolved challenges.

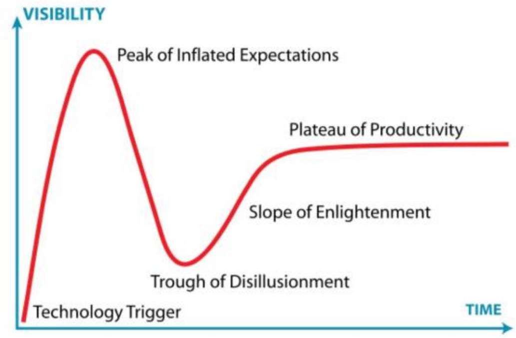

Fig. 5. Five-phase Gartner's hype cycle [71].

In this section, we discuss the opportunities and challenges of implementing UAV technology.

A. UAV Opportunities and Future Insights

One of the most groundbreaking technologies of the UAV world is the application of machine learning (e.g., artificial intelligence) for empowering UAVs to run autonomously [23]. An autonomous UAV flies based on pre-specified schedules or triggering conditions, without interference from a human pilot. Attractive for repeated and periodical surveillance missions such as power line inspection, the real value of using UAVs to inspect power lines will fully unfold when data analytic tools are employed to interpret and gain practical insights from UAV-captured data. A UAV with embedded intelligence and analytics will no longer be used simply as a camera for transmitting pictures and videos; it can perceive its surroundings, enabling it to map areas, track objects, and provide analytical feedback in real time [74].

Practically, machine learning techniques require a huge amount of input data, not always available via manual inspection routines, but made possible by UAV deployments. An intelligent machine supported by a large volume of data enables "finding the needle in a haystack" [53]. With automated inspection and image processing tools, the level of scrutiny can even identify a broken strand within hundreds of miles of a conductor [75]. Machine learning applications in soft computing assemblies are expected to change the landscape of UAV applications in the foreseeable future.

Complicated tasks require multi-agent settings. Networked UAVs, an eminent notion in 5G cellular networks [76], includes several interfacing UAVs that share information and increase redundancy to improve overall efficiency and reliability of the mission.

The hierarchical design of data flow and processing is a critical subject for the optimal operation of geographically-dispersed systems. When UAVs are equipped with processing power, it is a matter of choice in the hierarchical design to compromise the balance of raw and processed data flows. The two extreme ends of the decision are represented by cloud computing and fog (edge) computing applications. The former has a central processing architecture, though not necessarily a single center, which transfers the data with no initial processing stage. Cloud data management supports flexible and wide data accessibility that might be of interest in specific applications. However, fog computing relies on the computational power available at data sources (i.e., network edges) and transfers the processed data. Any decision point between the two extremes might be appropriate, enabling benefits from both computing architectures, optimized for the given circumstance. Applied properly and effectively, this process for adaptive design can yield various opportunities for networked UAVs.

The periodic maintenance approach is criticized for neglecting certain remedial actions as they surface in real time. Necessary maintenance might not take place at the required time, resulting in higher operation and maintenance costs. Condition-based maintenance (or its counterpart which is labeled the reliability-centered maintenance [77],[78]) was introduced as a viable substitute in real-time operation. Condition-based maintenance involves real-time inspection of components that are a bottleneck in optimal system operation. UAV technology will vastly increase proliferation of conditions-based maintenance activities by facilitating real-time inspection of components [53]. Likewise, reliability-centered maintenance and asset management procedures can benefit from UAV deployment.

Automatic meter reading (using an inexpensive mobile or drive-by technology) is the wireless reading of meters, using a short-range RF receiver/transmitter by a computer-equipped vehicle that traverses a neighborhood [79]. Although automatic meter reading saves labor expenses for individual meter readings, a simple UAV equipped with a computer and antenna is even more cost-effective to further automate the meter reading routine, keeping the metering infrastructure untouched [80],[81]. UAV can also offer shorter reading periods and identify any deliberate or inadvertent anomalies in end-user metering. In this regard, non-technical loss is the electric energy consumed by customers but not paid for, primarily due to energy theft [82]. Meter tampering, meter bypassing, and un-metered supply are the common types of non-technical loss. In the latter case, an end user connects two wires directly to the overhead grid with no meter (and no protection device) in the middle. As UAVs become more precise and more nimble, testimonial data collected by aerial inspections would be sufficient for court convictions in such cases.

Extensive planning stages and processes enable reliable and robust operation of electric power grids in expanding constrained geographic regions and overburdened cities. UAV 3-D mapping, spatial analysis, and visualization are fundamental ingredients that can streamline infrastructure expansion. UAV technology can be critical to identify necessary constituents and estimate growing electricity demand, both basic inputs to electricity planning studies.

Environmental protection can be managed using pollution metering, along with necessary precautions to enforce forest and wildlife conservations. Similarly, large industrial complexes such as power plants require routine inspection of exhausted/leaked gases into the environment and of wastewater released into rivers and lakes. UAVs equipped with specific gas or liquid sensors (for example, measuring NO_x or methane level) enable practical reduction of environmental footprint [83].

Due to high conductivity, certain minerals such as copper and aluminum are considered essential materials to manufacture various electrical devices. Over time, mining companies have had to look harder and dig deeper to find new deposits of these minerals. UAV aerial photography and mapping aided this work, enabling mining companies to explore large geographic areas and quickly identify the places where new resources and reserves can be developed [84].

B. Challenges of UAV Technology Implementation

Considering the worldwide perspectives on UAV technology, the first and foremost inhibitor of extensive UAV deployment is the lack of regulatory structures, registration settings, and legislation for the provision of training certificates that will reinforce civil and commercial use. In the U.S., pressure from public and private sectors convinced the FFA to release UAV non-military application rules and further ease those restrictions over the time. The ever-expanding market for UAV technology was under the spotlight, which was not the case in many other countries where regulations have yet to address many UAV applications. More waivers and more BVLOS flying permits will be needed in order to proliferate the widespread applications of UAV technology. It is envisioned that global investment in UAV technology will increase in response to economic forces and public acceptance [23].

New regulations should help reassure the public about dependability, affordability, durability, safety, and effectiveness of this new technology for various private and public applications [85]. A UAV is a fragile mechanical/electrical device which should be handled with extra care; those tailored for civil and commercial uses are still expensive and can be damaged easily by novice UAV operators [86]. Lack of regulatory knowledge can also lead to misuse, so civil and commercial UAV operators should be trained, tested, and certified by legal entities. Also, UAV training and testing facilities must be easily accessible at reasonable cost. Training programs should include hands-on field sessions, in addition to online access to basic instructions and related regulations.

UAVs flying in enormous numbers can entail a high safety risk. UAVs can tumble to the ground from high altitudes when a battery is depleted, adverse weather is encountered, or a UAV crashes into an obstacle. Telemetry to indicate a battery's state-of-charge, ambient temperature and humidity, and nearby objects can reduce safety risk. In such cases, alarm sensors can notify operators of any breach of security limits in order to prevent UAV incidents. In addition, the introduction of sensors enabling flying UAVs to avoid objects can avert air collisions and accidents [27]. Human error is also a major source of UAV risk which can be averted to a great extent by mandating a two-pilot team [53]. In summary, reliability of UAVs require processes and technological improvements on many fronts.

A UAV is an unmanned and sophisticated vehicle, exposed to all kinds of incidents that could lead it to harm or be harmed. Considering the embedded physical and technological risks in launching a UAV, it is imperative that the insurance industry be included as a stakeholder in UAV technology development [87], [88].

Flying endurance limits the usefulness of some UAVs, especially multi-rotor UAVs. Battery technology and other powering alternatives such as hydrogen fuel cells are still challenging technical issues to be resolved [89]. At the same time, components (especially electrical motors), must continue to become more energy efficient. In multi-rotor UAVs, energy is mainly consumed to overcome gravity in order to hover; weight is therefore pivotal for power source sizing and flight endurance. In addition to electrical motors, a UAV uses various sensors with different functionalities. Technological advancements will hopefully be made possible by industry R&D departments focused on lighter and lower-powered sensors. These developments will gradually lighten the aircraft, increase payload capacity, enhance UAV price merit, and lead to more widespread usage.

The value of harnessing big databases for understandable, noticeable, and actionable knowledge is already recognized. Although this achievement is recognized in academia and R&D centers, industrial companies and government agencies must employ data scientists to fully realize these benefits. Other challenges on the way to full realization of UAV advantages are employee training and the evolution of workflows to incorporate new inspection data-oriented stages [53]. In some situations, workers may be reluctant toward UAV advancements, fearing future job loss. Leadership should revise workflows/portfolios and ensure employees understand their role in those new workflows. New technologies, especially automation of procedures and tasks, initially elicit unemployment fears, however new and larger job opportunities often emerge.

Beyond the regulatory and technical challenges discussed above, broad deployment of UAVs brings other difficult issues. The combination of remote control and long-range communications enable deniability when an offensive action has taken place by a UAV. UAVs can be close to us with no way to recognize their owner. They can easily hurt power system components which are mainly mounted outside and interruptible by a short circuit (easily made by a small piece of steel). At present, the tools to trace, track, and disable a suspected UAV are very poor [90]. The challenge gets even worse as the number and variety of flying UAVs grows, meaning vast use of UAVs can be a real security threat. Extensive regulatory and technical advancements are needed to navigate and alleviate these concerns.

Fig. 6 summarizes this paper, showing characteristics of various UAVs, including opportunities and challenges faced by common use cases.

V. Summary and Conclusion

With increased development and interest in various UAV types and their potential, electric power systems are among the industries standing to benefit from UAV technology. This paper briefly reviewed the history and technology of UAVs, and reported experiences and use-cases in electric utilities. Finally, the paper explored future opportunities and insights as well as challenges ahead. As discussed, UAVs can offer a significant paradigm shift for aerial inspection, 3-D mapping, post-disaster management, and field operations. Further opportunities include autonomous operation by machine learning techniques, micro-inspection by image processing tools, networked UAVs with higher performance and efficiency, mixed cloud/edge computation benefits, proactive condition-based maintenance, periodical wireless meter reading, pollution footprint assurance, expansion planning load estimation, and enhanced mining exploration. However, technical and non-technical challenges have slowed UAV deployment. Regulatory issues, low public acceptance and reliance, limited training and testing facilities, reliability concerns, insurance considerations, power and sensor technological needs, the need to revisit workflows, and security concerns are among challenges which were examined. This paper aimed to convey the opportunity to apply advancements in UAV technology to power engineering. It was concluded that intensive R&D efforts are necessary to address certain challenges and to proliferate the applications of UAV in the foreseeable future.

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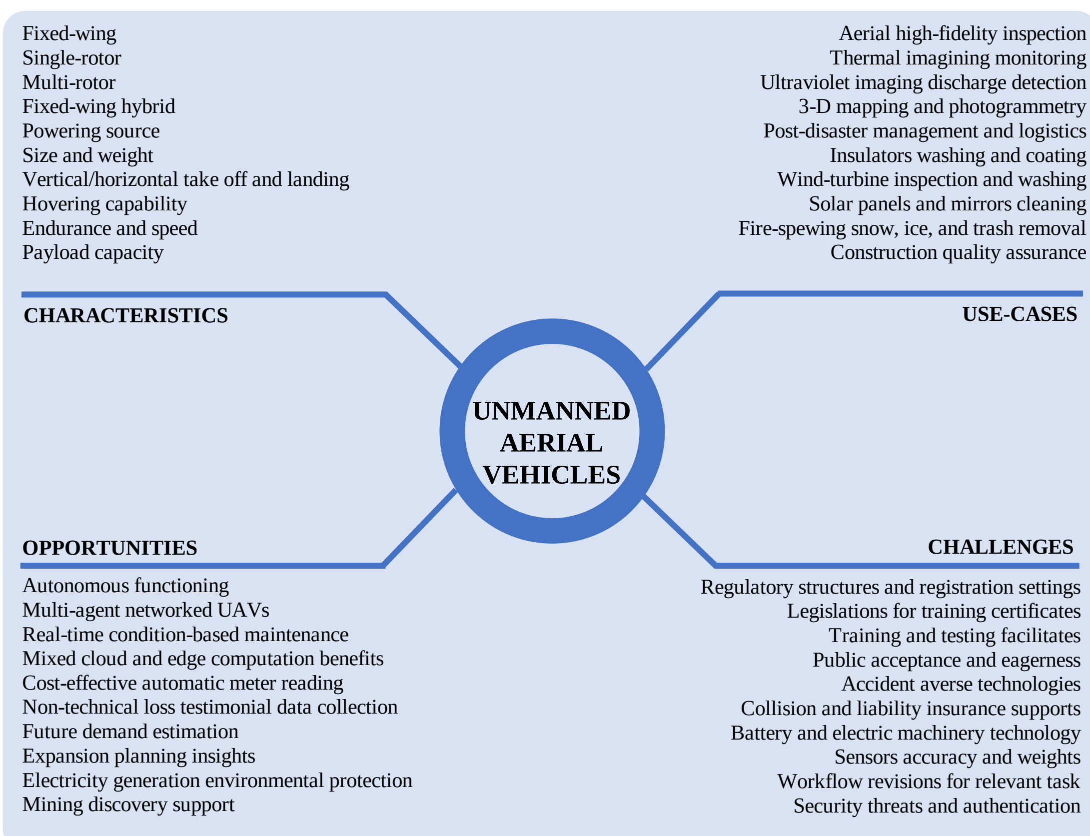

Fig. 6. Summary of opportunities and challenges for types of UAVs in various use cases.

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