UAV-Assisted Fault Location in Power Distribution Systems: An Optimization Approach

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***Abstract*—Improvement of reliability indices and decreasing the energy not supplied (ENS) are two main purposes of the power distribution systems' operator. Installation of visual or remote fault indicators (FIs) can significantly contribute in achieving these aims. However, installation of these types of FIs in the areas with limited or no communication coverage is not practical. This paper presents a novel conceptual structure for application of unmanned aerial vehicles (UAVs) in distribution systems. In the proposed framework, UAV-based FIs (UFIs) which are installed in the non-coverage areas, communicate with the UAVs and send their signals to them, when a fault occurs in downstream. We formulate an optimization problem to find the optimal number of UFIs and UAVs as well as their locations, taking both communication and investment constraints into consideration. To evaluate the effectiveness of the presented framework, simulation results are presented and discussed for bus 6 of the IEEE-RBTS (RBTS6).**

***Index Terms*—Power distribution systems, Unmanned aerial vehicle (UAV), Fault indicator (FI).**

NOMENCLATURE

$\boldsymbol{A}$	UFIs to UAVs assignment matrix.
c	Speed of light.
$C_{\ell k}^{FI}$	Cost of k type FI installation at candidate point ℓ (\$).
C_j^{UAV}	Cost of j-th UAV installation (\$).
$d_{i,j}$	Euclidian distance between UAV j-th and UFI i-th.
$EOCost$	Expected outage cost to consumer (\$).
f_c	Carrier frequency.
F	Objective function.
F_e	Economic part of objective function (\$).
$FICost$	Maintenance and investment cost of FIs (\$).
$FIMC_{\ell k,n}$	Maintenance cost of k type FI at point ℓ and at year n (\$).
F_r	Reliability-based part of objective function.
$g_{i,j}$	Ground-to-air channel between UFI i-th and UAV j-th.
$IC^s(r_{(x,y),t})$	Interruption cost of load type of s located at point (x,y) due to outage time t (\$).
$Id_{\ell k}$	Duration of interruption of load point ℓ due to outage of equipment k (h/f).
$\bar{L}_{i,j}$	Path loss average for the channel between UAV j-th and UFI i-th.
$Load_{n,(x,y)}^s$	Demand of load type of s located at point (x,y) at year n (kW).
nFI_k	Number of available k type FIs.
n_ℓ	Number of customer at load point ℓ.
$nUAV$	Number of available UAVs.
$nUFI$	Number of available UFIs.
$nyear$	Horizon of the planning (year).
P_i	Transmit power at UFI i-th.
$Pr_{i,j}^{\mathsf{LoS}}$	LoS probability of UFI i-th and UAV j-th.
$Pr_{i,j}^{\mathsf{NLoS}}$	NLoS probability of UFI i-th and UAV j-th.
PWF	Present worth factor.
$r_{i,j}$	Received signal at UAV j-th from UFI i-th transmission
s_i	Data symbol of UFI i-th.
$SNR_{i,j}$	Received SNR at UAV j-th from UFI i-th transmission
$UMC_{j,n}$	Maintenance cost of UAV j-th at year n (\$).
$UAVCost$	Maintenance and investment cost of UAVs (\$).
(x,y,h)	3-D Cartesian coordinate.
z_j	Additive white Gaussian noise at UAV j-th.
α	Path loss exponent.
α_e	Weighting factor of F_e in objective function.
α_r	Weighting factor of F_r in objective function.
β	Constant parameter whose value depends on the carrier frequency and environment type.
γ_t	Predetermined SNR threshold.
η_1	Path loss coefficient corresponding to the LoS.
η_2	Path loss coefficient corresponding to the NLoS.
η_{inf}	Inflation rate.
η_{int}	Interest rate.
$\theta_{i,j}$	Elevation angle of UAV j-th with regard to UFI i-th.
λ_k	Failure rate of equipment k.
ξ	Constant parameter whose value depends on the carrier frequency and environment type.
σ_j^2	Noise variance at UAV j-th.
φ_j	$0/1$ variable which is equal to 1 if UAV j-th installed.
$\psi_{\ell,k}$	$0/1$ variable which is equal to 1 if a k type FI installed at candidate point ℓ.
Λ_{Bus}	Set of buses.
Λ_{FI}	Set of FI types including RFIs and UFIs.

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Λ_{Line}	Set of lines.
Λ_{LP}	Set of load points.
Λ_{LT}	Set of load types.
Λ_{Trans}	Set of transformers.
Λ_{UAV}	Set of UAVs.
Λ_{UFI}	Set of UFIs.
Λ_{xy-c}	Set of candidate locations for FIs installation.

I. INTRODUCTION

Distribution systems are an important part of power systems which play key roles in distribution of power to the customers in the medium or low voltages [1], [2]. Occurrence of faults in these systems can directly affect energy not supplied (ENS) and dissatisfaction of the customers, as well as decreasing the reliability indices [3]. Installation of fault indicators (FIs) in the distribution systems can significantly reduce the ENS and also increase the reliability indices [4], [5]. The FIs are able to indicate the fault occurred at their downsides and can be categorized into 1) visual FIs (VFIs) which flash due to occurrence of downside fault and must to be checked via the repair crews and 2) remote FIs (RFIs) which send the alert to the control center or repair crews [6]. The authors in [7], have studied the effects of FIs installation on the reliability indices and shown that the numbers and locations of FIs significantly affect these indices. The impacts of using automated circuit breakers and a fault detector located beside each breaker on ENS have been investigated in [4]. In [5], two algorithms for FI placement are presented and their effects on system average interruption duration index (SAIDI), average service unavailability index (ASUI), and ENS are studied. A multistage distribution expansion planning problem has been presented in [8], considering installation of FIs and presence of vehicle to grid (V2G) in smart grids. The authors in [9], have formulated a mixed integer linear programming (MILP) method to optimize the type, number, and location of automation devices and FIs in presence of distributed generations (DGs). A mixed integer nonlinear programming (MINLP) problem has been formulated in [10] to optimize the types, locations, and automation levels of protection devices including FIs in distribution companies (DisCos).

All above-mentioned literatures [4]–[10] and the other similar works have used VFIs and RFIs in the power distribution systems. Deploying VFIs in the distribution system that crosses mountainous or forest areas is not practical, since such areas are likely impassable to wheeled vehicles in spots. In addition, RFIs cannot be used in such areas due to poor or lack of network coverage. Therefore, design of distribution systems that deal with this problem is of paramount importance and is the main aim of this paper.

Recently, the use of unmanned aerial vehicles (UAVs) has been attracted significant interest to provide reliable, robust, and cost-effective communications in civilian and military envisioned usages. Among several, two main applications of UAV-assisted communications are UAV-aided ubiquitous coverage and UAV-aided information dissemination and data collection [11]. In the former, UAVs are employed to provide seamless wireless connectivity in areas without infrastructure coverage such as battlefields, disaster scenes, mountainous, and inaccessible areas, or areas with severe shadowing conditions. In the latter, UAVs are utilized to collect or disseminate information from or to widely distributed wireless devices such as sensors, especially in the remote areas. In these applications, UAVs are generally stationarily and their positions are pre-adjusted. This motivates us to utilize UAVs in distribution systems to overcome the connectivity problem in non-coverage or inaccessible distribution systems.

UAVs have been applied in some other parts of power systems. Some researchers have applied the UAVs for monitoring, inspection, and sensing of the power transmission lines [12]–[17]. The authors in [12] have reviewed the application of UAVs for emergency or routine high-voltage transmission lines inspection. Moreover, the authors in [13] have proposed a framework for damage assessment of power transmission networks with the aid of UAVs. More specifically, it optimizes the location of UAVs and their paths while considering minimization of operating cost and assessment time. A detail review on remote sensing approaches including UAVs application to survey the power lines is presented in [14]. A multi-platform system for power line inspection by UAVs in presence of different communication systems has been presented in [15]. Automatic meter reading is another application of UAVs in power systems which has been studied in [18], [19]. Some predicted/expected applications of UAVs in electric utility construction are reported in [16], [17] and concluded as: inspections of members, poles, or structure conditions, inspections of energized lines, thermal imaging of electric equipment, and detection of corona.

To the best of our knowledge, however, none of the previous works, have taken advantage of UAVs to enhance the performance of the distribution systems that cross mountainous or forest areas with limited or no communication coverage. Accordingly, the main focus of this paper is to study FI installation in UAV-assisted distribution systems, wherein the installation of conventional FIs (VFIs and RFIs) is not practical in some regions.

The main contributions of this work are summarized as follows:

- A new conceptual structure for UAV applications in power distribution systems is proposed. In particular, we present a novel UAV-based framework for optimal installation of FIs in a distribution system, while considering economic and reliability issues into account. The proposed method optimizes 1) number of utilized UAVs, 2) flight destinations of UAVs during the occurrence of faults, and 3) number and locations of UAV-based FIs (UFIs)[1] and conventional FIs.
- The proposed optimization framework considers the communication constraints as well as investment constraints of UAVs, UFIs, and conventional FIs. Our findings reveal that utilizing UAVs in power distribution systems significantly reduces the expected outage cost to consumers and improves the reliability indices by about 34.2%.

[1]In this work, FIs with the ability of communicating with UAVs are termed as UFIs.

- Interestingly, we show that increasing the number of utilized UAVs does not necessarily improves the objective function. However, as the quality of service (QoS) requirement of the power distribution system is increased, the optimal number of UAVs increases.

Current literature on applications of UAVs in the transmission systems [12]–[15] are largely limited to the lines inspection. However, there is a large scope for research on UAV-aided solutions to prepare communication platform or locate the faults in the network. In this paper, we propose a new framework for applying multiple UAVs in distribution systems to provide a wireless connectivity and facilitate the location-finding process of faults in the feeders that have limited/no communication coverage. It is worthwhile to mention that using single or multiple-UAV systems mainly depends on the application scenarios. For instance, for UAV-aided wireless coverage, we have to use multi UAVs above the coverage areas to provide real-time communications with ground [20], [21]. However, for delay-tolerant applications, it is adequate to use a single UAV to fly over the coverage zone to transmit and/or receive information from the ground [11]. Nevertheless, using one single UAV to cover whole region in large distribution systems may increase the interruption time and the risk to lose all the information about the system. In addition, since in these systems UAV flight route is generally too long, single-UAV deployment may require a much larger battery size and high investment cost.

The rest of the paper is organized as follows: Section II presents the system model and main assumptions. Section III describes the problem formulation and computational considerations. Section IV introduces a case study. Numerical results are reported and discussed in Section V. Finally, Section VI concludes the paper and summarizes the key findings.

II. System Model

Consider a distribution system that crosses mountainous or forest areas. In these type of areas, there are some zones with limited or no communication coverage. In such cases, using the remote access FIs is impossible. For example, in a forest area which is a highly scattering environment or in a mountainous area with severe obstacles, the conventional terrestrial channel quality between RFIs and repair crews is very weak. Fig. 1 shows an example of such areas. As shown in Fig. 1, some parts of feeder 4 (dashed-line zone) has no wireless coverage and/or are difficult to transit. Hence, installation of remote or visual FIs in this zone is not possible. A novel UAV-based approach is presented in this paper to overcome this problem and provide seamless wireless connectivity to FIs. In particular, we propose to install UAV stations and UFIs with the ability of communicating with UAVs in these areas. During the occurrence of the fault in a feeder and power interruption, installed instruments at the UAV stations detect the zero voltage of the feeder and then order the UAVs to move into their predetermined locations. On the other hand, UFIs with the ability of communicating with UAVs are installed in this zone. These UFIs start transmitting signals to the UAVs, once a fault occurs in their downstreams.

When UAVs receive information signals from the UFIs, they transmit the collected information to distribution system's operator. The proposed approach assists the operator or repair crews to make a correct decision and reduce the time needed to look for the fault location. Fig. 2 illustrates a conceptual layout of the proposed approach. Fig. 2(a) shows a UAV station. At the beginning, UAVs are located at their stations. Capacitive voltage detectors (CVDs) are installed on the feeder. CVDs are not used for protection or measurement purposes but they are used for indication of the voltage [22]. The CVDs send the status of the voltage (0/1) to the voltage indicating system (VSI). In case of occurrence of fault, VSI detects the issue and sends the flight order to UAV. Then, the UAV will move to its predetermined position, hovering there to provide services to UFIs. After receiving signal from the UFI(s), UAV will send the information to the operator/repair crews and then return back to its station and start charging from the installed photovoltaic panel and its related battery[2]. Fig. 2(b) depicts the signal communications between UFIs and UAVs (green lines) and between UAVs and operator/repair crews (red lines). It is worthwhile to mention that compared with the traditional *RFIs-to-control center* (*ground-to-ground*) links, *UFIs-to-UAVs* (*ground-to-air*) links generally have higher gains as a result of the short-range line-of-sight (LoS) communication links [8]–[10]. Particularly, it is more likely that the terrestrial *RFIs-to-control center* channels suffer from multipath fading due to the diffraction, reflection, and scattering by mountains, obstacles, tress, etc. [11]. In the proposed approach, placement of the UFIs and UAVs are vital and need to be optimized. Also, the need for reliable communications between UFIs and UAVs imposes some communication constraints to the optimization problem which are based on the channel model and will be presented in Subsection II-A. Moreover, optimal UFIs placement, which reduces the time needed to search for the fault location and improves the reliability indices, is presented in Section III.

We also assume that UFIs communicates with UAVs via a frequency-division multiple access (FDMA) scheme [23], which allows multiple UFIs transmissions without interference constraint. In addition, a three-dimensional (3-D) Cartesian coordinate system is considered, where the horizon coordinate of i-th UFI and the location of j-th UAV are given by (x_i, y_i) and (x_j, y_j, h_j), respectively.

A. Channel and Signal Model

To have a realistic propagation, for the *UFI-to-UAV* channels we consider a statistical model from [23]–[26]. In the statistical channel model the probability that a *ground-to-air* link experiences in LoS propagation depends on the type of the environment, the height of the UAV, and the elevation angle at the UFI. In the following, we model the *ground-to-air* channel between UFI i-th and UAV j-th. Other *ground-to-air* channels can be easily derived with appropriate changes of indices. The

[2]If after a specific time, UAV does not receive any signal form the UFIs, it returns back to the station.

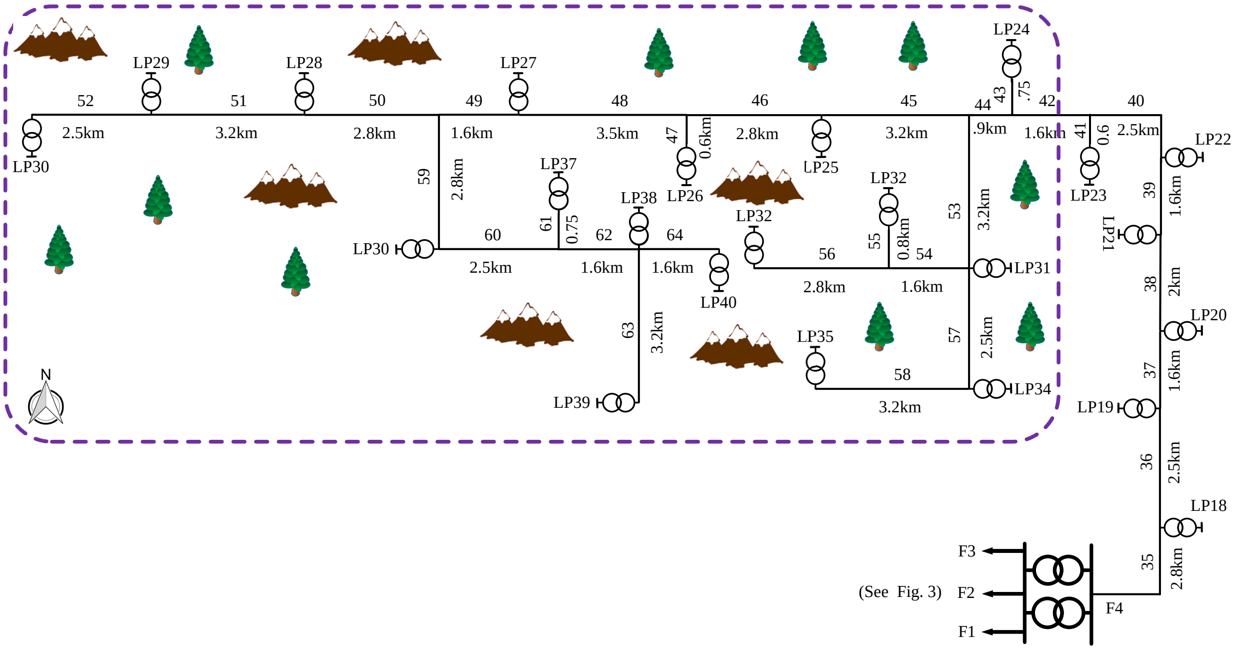


Fig. 1: The rural eara with limited/no communication coverage.

LoS probability is expressed as [24], [25]

$$Pr_{i,j}^{\mathsf{LoS}} = \frac{1}{1+\xi\exp(-\beta(\theta_{i,j}-\xi))}, \tag{1}$$

where $\theta_{i,j}$ is the elevation angle of UAV j-th with regard to UFI i-th, which is given by

$$\theta_{i,j} = \frac{180}{\pi}\sin^{-1}\left(\frac{h_j}{d_{i,j}}\right), \tag{2}$$

with

$$d_{i,j} = \sqrt{(x_i-x_j)^2+(y_i-y_j)^2+h_j^2}. \tag{3}$$

Furthermore, ξ and β are constant parameters whose values depend on the carrier frequency and environment type. Moreover, the non-LoS (NLoS) probability is $Pr_{i,j}^{\mathsf{NLoS}} = 1 - Pr_{i,j}^{\mathsf{LoS}}$. The path loss model for the LoS (NLoS) link between the ground transmitter UFI and UAV with the distance $d_{i,j}$ is given by $L_{i,j}^{\mathsf{LoS}} = \eta_1 B d_{i,j}^{\alpha}$ ($L_{i,j}^{\mathsf{NLoS}} = \eta_2 B d_{i,j}^{\alpha}$) where $B = \left(\frac{4\pi f_c}{c}\right)^{\alpha}$, α, f_c, and c denote the path loss exponent, carrier frequency, and the speed of light, respectively. Also, η_1 and η_2 ($1 < \eta_1 < \eta_2$) are the path loss coefficients corresponding to the LoS and NLoS cases depending on the environment, respectively, We adopt the path loss average considering both LoS and NLoS links for the channel between UAV j-th and UFI i-th as [26]

$$\bar{L}_{i,j} = B d_{i,j}^{\alpha}(Pr_{i,j}^{\mathsf{LoS}}\eta_1 + Pr_{i,j}^{\mathsf{NLoS}}\eta_2). \tag{4}$$

Now, assume that UFI i-th transmits data signal to the UAV j-th. Let P_i be the transmit power at UFI i-th. The received signal at UAV j-th, $r_{i,j}$, is given by

$$r_{i,j} = \sqrt{g_{i,j}}s_i + z_j, \tag{5}$$

where $g_{i,j} = \frac{1}{\bar{L}_{i,j}}$ denotes the *ground-to-air* channel between UFI i-th and UAV j-th. Further, s_i denotes the data symbol of the UFI i-th satisfying $\mathbb{E}\left\{|s_i|^2\right\} = P_i$ and z_j is the additive white Gaussian noise (AWGN) at UAV j-th with $\mathbb{E}\left\{z_j z_j^*\right\} = \sigma_j^2$, where $(\cdot)^*$ and $\mathbb{E}\{\cdot\}$ stand for conjugate and the expectation, respectively. Invoking (4) and (5), the resulting signal-to-noise ratio (SNR) expression at UAV j-th can be written as

$$\mathrm{SNR}_{i,j} = \frac{P_i((x_i-x_j)^2+(y_i-y_j)^2+h_j^2)^{\frac{-\alpha}{2}}}{B\sigma_j^2\left(\frac{\eta_1-\eta_2}{1+\xi\exp(-\beta(\theta_{i,j}-\xi))}+\eta_2\right)}, \tag{6}$$

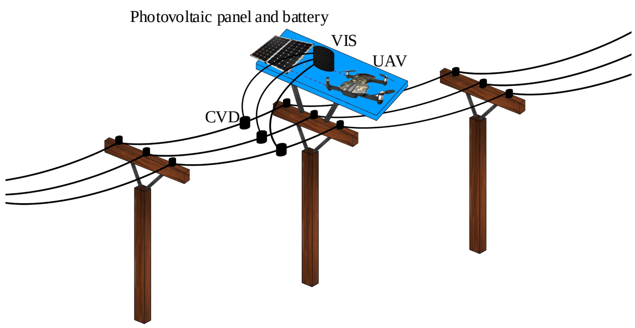
which is clearly a function of the UAV and UFI positions. Therefore, the optimal placement of the UAVs contributes to keep UAVs received SNR or the links quality above a certain predefined level.

III. Problem Formulation

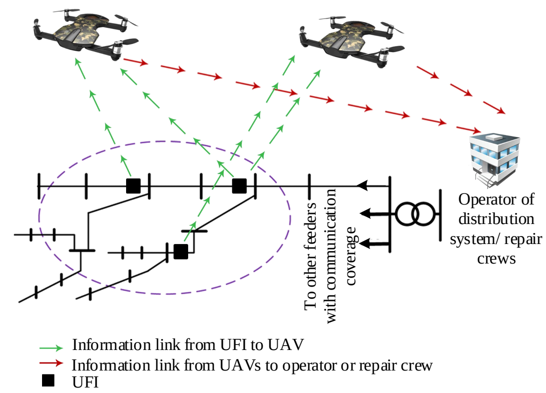
The aim of our work is to present an optimization framework for optimal placement of RFIs and UFIs in power distribution systems include rural and urban networks. Moreover, optimizing the number of utilized UAVs and their flight destinations, i.e., their 3D coordinates, is another key contribution of this work. The objective function of this optimization problem consists of two main components: economic (F_e) and reliability-based (F_r) components and is given by

$$\text{minimize} \quad \alpha_e F_e + \alpha_r F_r, \tag{7}$$

where α_e and α_r are weighting factors related to economic and reliability-based parts of the objective function, respectively. The economic part of (7) is given by



(a) UAV station



(b) UFI-UAV and UAV-operator links

Fig. 2: Proposed conceptual structure.

$$F_e = FICost + UAVCost + EOCost, \tag{8}$$

where

$$FICost = \sum_{\ell \in \Lambda_{xy-c}} \sum_{k \in \Lambda_{FI}} \psi_{\ell,k} \Big(C_{\ell k}^{FI} + \sum_{n=1}^{nyear} PWF^n . FIMC_{\ell k,n} \Big), \tag{9}$$

$$UAVCost = \sum_{j \in \Lambda_{UAV}} \varphi_j \left(C_j^{UAV} + \sum_{n=1}^{nyear} PWF^n . UMC_{j,n} \right), \tag{10}$$

$$PWF = \frac{1+\eta_{inf}}{1+\eta_{int}}, \tag{11}$$

and

$$EOCost = \sum_{n=1}^{nyear} \left(PWF^n . \sum_{(x,y) \in \Lambda_{LP}} \sum_{s \in \Lambda_{LT}} \sum_{k \in \{\Lambda_{Line} \cup \Lambda_{Trans} \cup \Lambda_{Bus}\}} Load_{n,(x,y)}^s . \lambda_k . IC^s(r_{(x,y),t}) \right). \tag{12}$$

As Eq. (8) indicates, economic part of the objective function consists of investment and maintenance cost of different kinds of FIs and UAVs (Eqs. (9)-(10)), as well as expected outage cost to consumers (Eq. (12)). Since the distribution system includes urban and rural networks, different types of customers (Λ_{LT} consists of residential, industrial, commercial, and farm types of loads) and different contingencies have been considered in (12) [6].

The second part of the objective function is the reliability-based part and can be consisted of reliability indices such as SAIDI, customer average interruption duration index (CAIDI), system average interruption frequency index (SAIFI), etc. Without loss of any generality, we have only considered SAIDI as the reliability-based part of the objective function. However, other indices can be easily considered in the objective function. Therefore, the reliability-based part of the objective function can be expressed as [6]

$$F_r = \frac{\sum_{\ell \in \Lambda_{LP}} \sum_{k \in \{\Lambda_{line} \cup \Lambda_{Trans} \cup \Lambda_{Bus}\}} \lambda_k . Id_{\ell k} . n_\ell}{\sum_{\ell \in \Lambda_{LP}} n_\ell}. \tag{13}$$

Decreasing the interruption durations via reducing the SAIDI will decrease other indices such as CAIDI. Consequently, by adding this part to the objective function, the interruption durations will reduce and customers of distribution systems benefit from this reduction.

The formulated objective function in Eqs. (7)-(13) is subjected to the following constraints:

The number of installed RFIs and UFIs, and utilized UAVs is limited by

$$\sum_{\ell \in \Lambda_{xy-c}} \psi_{\ell,k} \le nFI_k, \qquad \forall k \in \Lambda_{FI}, \tag{14}$$

and

$$\sum_{j \in \Lambda_{UAV}} \varphi_j \le nUAV, \tag{15}$$

respectively. The number of available RFIs, UFIs, and UAVs are the input variables of the optimization problem and are predetermined according to management decisions and credits allocation.

Before proceeding, let $\mathbf{A}$ be the $nUFI \times nUAV$ UFIs to UAVs assignment matrix, where each element a_{ij} being 1 if UFI i-th is assigned to UAV j-th, and 0 otherwise. We aim to deploy the most cost-effective number of UAVs such that each uncovered UFI is served by at least one UAV within its communication area. Thus, the constraint is given by

$$\sum_{j=1}^{nUAV} a_{ij} \ge 1, \qquad \forall i \in \Lambda_{UFI}. \tag{16}$$

Finally, in order to ensure the coverage requirements for all uncovered UFIs, the instantaneous received SNR from UFI i-th at its assigned UAV j-th should lay above a predetermined threshold γ_t. This constraint can be expressed as

$$\mathrm{SNR}_{i,j} \ge \gamma_t a_{ij}, \qquad \forall i \in \mathcal{L}. \tag{17}$$

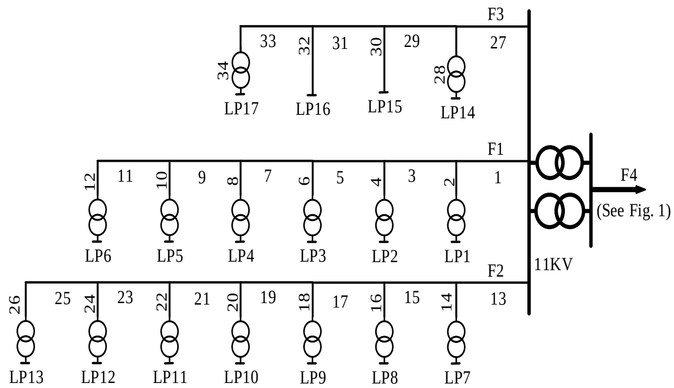


Fig. 3: Feeders 1, 2, and 3 of the test system located in the areas with acceptable communication coverage [32].

γ_t is determined according to the QoS requirement of control data in the considered distribution system. Invoking (6), the constraint in (17) can be written as

$$\frac{P_i((x_i - x_j)^2 + (y_i - y_j)^2 + h_j^2)^{\frac{-\alpha}{2}}}{B\sigma_j^2 \left(\frac{\eta_1 - \eta_2}{1+\xi \exp(-\beta(\theta_{i,j} - \xi))} + \eta_2\right)} \geq \gamma_t a_{ij}, \quad \forall i \in \Lambda_{UFI}. \tag{18}$$

It is worth mentioning that it would be interesting to investigate the UAV-assisted distribution systems which support high QoS requirement applications such as sending the image or video to the UAVs for inspection and other purposes. We set this aside for our future work. Moreover, we note that the main focus of this paper is to present a new conceptual structure for UAV applications in power distribution systems, and hence we have selected the simple single-objective approach. This approach is acceptable and widely used in the literature [27]–[29]. Another interesting approach to solve this problem is using multi-objective optimization method with two objective functions, i.e., $\min F(x) = \{F_e, F_r\}$. In this case, Pareto-optimal set of solutions will be achieved and final decision should be taken by analyst or modeler of the system [6].

The proposed optimization problem (Eqs. (7)-(18)) is an MINLP problem that can be solved by using different optimization methods. In this paper, we use the General Algebraic Modeling System (GAMS) software package [30]. Solver AlphaECP which is based on the extended cutting plane (ECP) method [31] has been selected to solve the optimization problem by GAMS.

IV. Case Study

In order to evaluate the proposed optimization framework, it is tested on a distribution system connected to bus 6 of the IEEE RBTS6 [32]. The selected test system is a typical urban/rural network including residential, commercial, small industrial, and agricultural loads. Fig.1 shows feeder 4 of this test system. As shown in Fig.1, it is assumed that some areas of this feeder cross mountainous or forest areas with no communication coverage (dashed-line), and hence installing the RFIs is impossible. Therefore, UFIs can be installed in these types of areas to communicate with UAVs and transmit the alarm signals to the system operator via UAVs. Without loss of any generality, we set the location of $LP30$ as the origin point, i.e., $(x_{LP30}, y_{LP30}, h_{LP30}) = (0.0.0)$. Note that, to avoid complexity in presentation of the case study, the height of the distribution system in the non-coverage zone has been set to a specific constant value and ups and downs of the ground have been neglected. The other feeders of the test system (F1, F2 and F3) are depicted in Fig. 3. These feeders are located in the areas with an acceptable communication coverage where installing the RFIs is possible. The values of lines data and failure rates of equipment are based on [32] and [33], and time for repairing the lines is assumed to be 3 hours. Manual switching time is set to 20 minutes. Installation cost of RFIs and UFIs are \$1000 [6], [34]. Note that RFIs and UFIs only cover their downstreams and do not recognize the faults at their upstreams. The investment cost of the UAV installation is set to \$2000 [13]. Inflation and interest rates are assumed to be 6% and 7%, respectively. Horizon of the planning problem is 10 years. Number of available RFIs, UFIs, and UAVs are 20, 15, and 6, respectively. Weighting factors related to economic and reliability-based parts of the objective function (α_e, α_r) are set to 0.7 and 0.3, respectively. The effects of changes in these weighting factors are discussed in Section V-A. Other data about the case study can be founded in [35].

TABLE I: Optimal locations of RFIs in feeders located in the areas with acceptable communication coverage.

Feeder	Optimal RFIs locations*
F1	1E-6B
F2	13E-19E
F3	27E-29B-29E-30B-32B-33B
F4	35E-36E-38B-38E-39E

* B: beginning of line, E: end of line.

TABLE II: Optimal locations of UFIs and optimal flight destinations of UAVs in the areas with limited or no communication coverage.

	UAV1	UAV2	UAV3
x (m)	9289	15893	5642
y (m)	1243	1991	614
h (m)	2179	4000	2372
Covered UFIs*	48E-49E-59B-62B	45B-45E-48B-53B-54E-57B	50E-51E

* B: beginning of line, E: end of line.

V. Simulation Results and Discussion

The proposed framework has been applied to RBTS6 and the optimization problem has been solved by GAMS software package [30] on a computer with 4 GB RAM and 1.73 GHz CPU. The average time for solving the proposed MINLP problem is about 640 seconds.

Table I reports the optimal locations for installation of RFIs in the feeders located in the areas with acceptable communication coverage. Also, Table II presents the optimal

TABLE III: Effect of application of the proposed method on each part of the objective function.

	$F_e(\$)$	F_r
Conventional method (RFI-assisted only)	119363.5	6.4488186
Proposed method (RFI and UFI-assisted)	97081.34	4.2378553
Improvement compared with conventional method	18.7%	34.2%

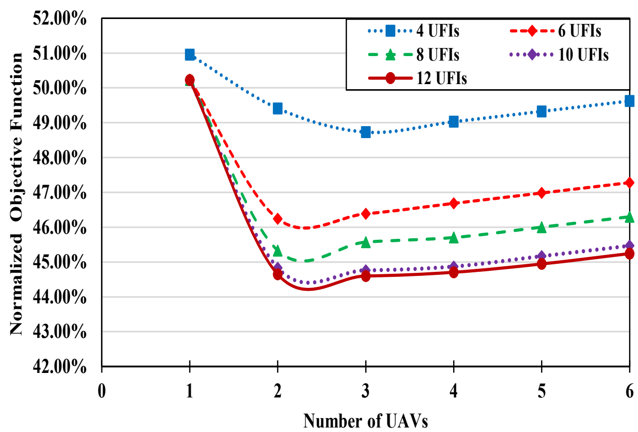


Fig. 4: Normalized objective function versus different number of utilized UAVs and for different numbers of UFIs.

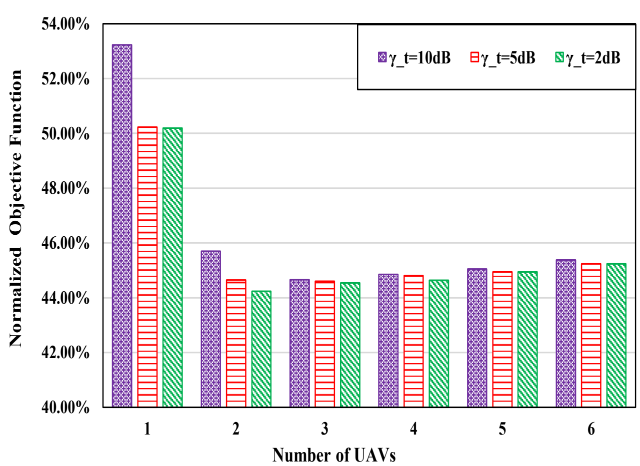


Fig. 5: Normalized objective function versus different number of utilized UAVs and for different values of γ_t.

locations of UFIs and optimal 3D coordinates of UAVs flight destinations in the areas with no communication coverage. Note that some parts of feeder 4 are located in the areas with coverage and installation of RFIs is practical over there (35E, 36E, 38B, 38E, and 39E). Twelve UFIs should be installed in the presented locations. Note that in Tables II and III, B and E represent the installation of UFIs at the beginning and end of each line, respectively. As shown in Table II, despite the possibility of installation six UAVs (number of available UAVs are assumed to be six), only three UAVs have been used. These UAVs ensure the communication coverage for all twelve installed UFIs. UAV1 covers four of twelve UFIs (which are installed in 48E, 49E, 59B, and 62B) while UAV2 and UAV3 cover two and six installed UFIs, respectively (please see the last row of Table II).

Table III compares the economic (F_e) and reliability-based (F_r) components of the objective function in presence or absence of UAVs and UFIs deployment. It is observed that utilizing UAVs in operation of the distribution systems significantly reduces the expected outage cost to consumers, around 18.7%, and improves the reliability indices, about 34.2%.

In order to study the effect of number of installed UAVs on the objective function, we have forced the optimization problem to use exactly 1 to 6 UAVs. Number of available UFIs in each of the above cases has been set to $4, 6, 8, 10$, and 12 UFIs, respectively. As shown in Fig. 4, increasing the number of utilized UAVs does not necessarily improve the objective function, e.g., despite of using 4, 5 or 6 UAVs and increment of the coverage for UFIs, the objective function increases in comparison with utilization of only 3 UAVs. Note that for the sake of transparency, we have shown the normalized objective functions in Figs. 4 and 5. The base value for the normalization is the value of the objective function in absence of FIs and UAVs.

Fig. 5 depicts the objective function versus UAV numbers for different QoS requirements, γ_t, in the considered system setup. As γ_t is increased, the optimal number of UAVs increases. For example, to guarantee $\gamma_t = 3$ dB, the optimal number of UAVs is 2, while it is 3 for $\gamma_t = 5$ dB. This is intuitive because a larger γ_t means that more information has to be transmitted to the control center. Moreover, it can be observed that our proposed scheme significantly reduces the objective function. The positive impact on the cost reduction is more pronounced in the case of the high QoS requirement.

A. Sensitivity Analysis

In the above presented results, α_e and α_r (weighting factors related to economic and reliability-based parts of the objective function in (7)) are set to 0.7 and 0.3, respectively. In order to analysis the sensitivity of the objective function to the weighting factors, these factors have been changed in a way that $\alpha_e + \alpha_r = 1$ and the obtained results are demonstrated in Figs. 6-9.

As shown in Fig. 6 increasing α_e (decreasing α_r) increases the contribution of the economic part to the objective function, and hence reduces the total cost of the system. The same behavior is observed in Fig. 7 for α_r and F_r; That is higher

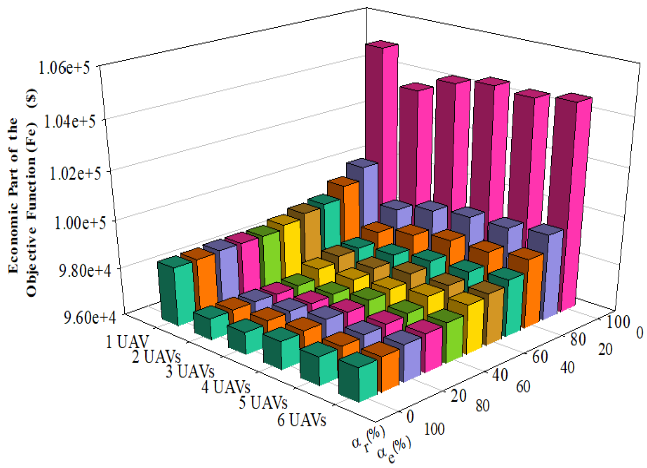


Fig. 6: Sensitivity analysis of the economic part of the objective function.

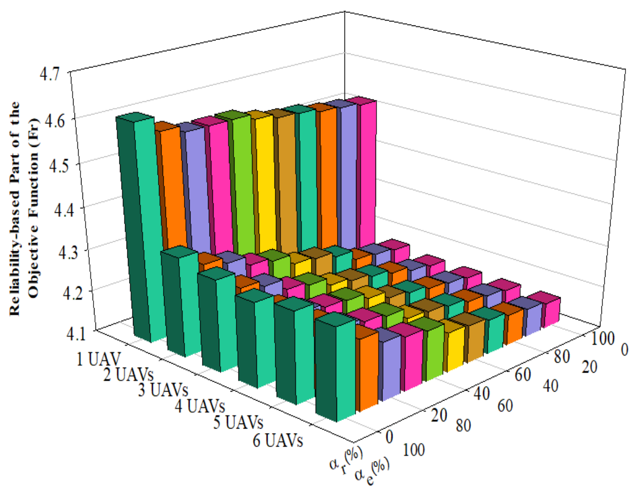


Fig. 7: Sensitivity analysis of the reliability-based part of the objective function.

α_r results lower F_r. Moreover, Fig. 8 reveals that for a system which values more on reliability, i.e., a system with larger α_r, the optimal numbers of UFIs and UAVs are higher.

Fig. 9 plots the normalized objective function of optimization problem (7) versus α_r and α_e for different number of UAVs. We see that the minimum value of the objective function is achieved when 3 UAVs have been utilized.

From Figs. 6, 7, and 9, it is evident that F_e, F_r, and the normalized objective functions with 1 UAV are much higher than those with multiple UAVs. The main reason is that in case of using more than 1 UAV, only the UAV cost (Eq. (10)) will be increased. However, installation of more than 1 UAV not only decreases the expected outage cost to consumer (Eq. (12)) but also decreases the interruption duration of load points due to outage of equipment ($Id_{\ell k}$ in Eq. (13)). Consequently, installation of more than 1 UAV decreases both the economic and reliability-based parts of the objective function and also the normalized objective function.

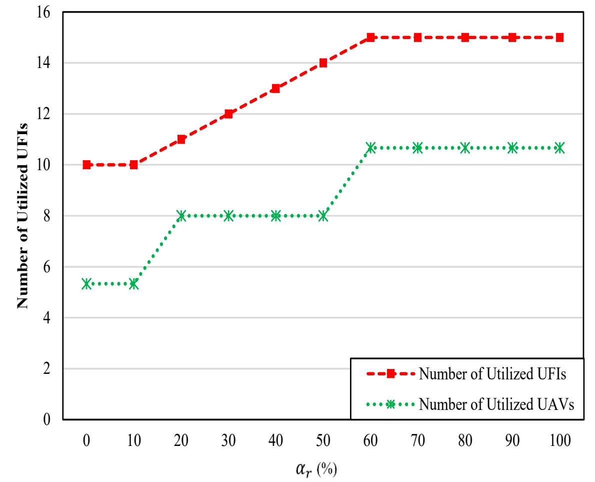


Fig. 8: The effect of increasing α_r on the number of utilized UFIs and UAVs.

VI. Conclusion

In this paper, we have presented a new framework for application of UAVs in the power distribution systems located in non-coverage areas for fast fault location. In the presented framework, RFIs are utilized in parts of the distribution systems which are located in the areas with reliable communication coverage, while UFIs and UAVs are utilized in non-coverage areas. To this end, an optimization framework has been formulated to find the optimal numbers and locations of RFIs and UFIs as well as the optimal numbers and flight destinations of utilized UAVs. The main capabilities of the proposed framework are concluded as follows:

- It minimizes the expected outage cost to consumer about 18.7% while improves the reliability indices of the distribution system about 34.2% (Eqs. 7-13, Table III).
- Both communication constraints and investment constraints are included in the optimization formulation (Eqs. 14-18).
- Our proposed framework is general as it can deal with different QoS requirements (Eq. 18 and Fig. 5).
- It determines the flight destination of UAVs in a way that full communication coverage is provided for the installed UFIs (Eqs. 16-18, Table II).

It would be interesting to extend this work to the UAV-aided power distribution systems with mobile UAVs and investigate joint optimal fly path planning and communication scheduling. Another potential future research direction would be to study the application of multi-objective optimization approach for solving the optimal RFIs and UFIs placement problem.

VII. Acknowledgement

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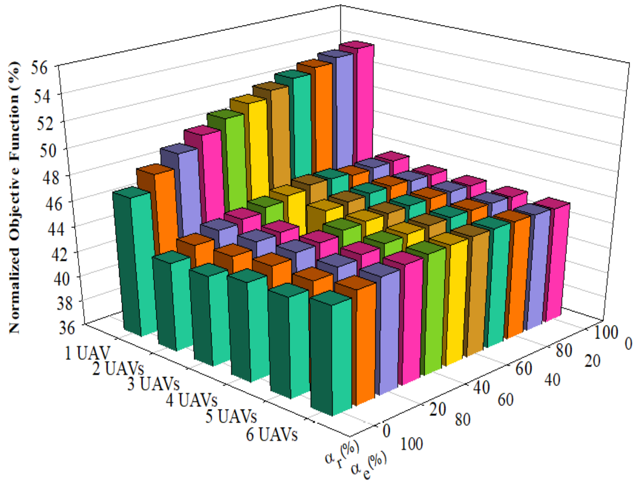

Fig. 9: Sensitivity analysis of the objective function.

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