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Investigation in wireless power transmission for UAV charging

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Abstract

This paper proposes application of wireless power transfer for charging of electric-powered Unmanned Air Vehicles (UAV)s. Multi-rotor systems, such as quadrotors, are light-weight and easy to operate. They are available in different sizes and with the wide range of capabilities. The main limitation of electric-powered UAVs is their range and endurance, due the limited battery capacity. Increasing battery system size is not a viable solution as its weight becomes a limiting factor. Supercapacitors are not an option, because of their low energy density. An alternative is to recharge UAV on the job, using wireless energy transfer (WET). WET was originally investigated by Nikola Tesla in the beginning of the 20th century. His patents are now common ground for any power transmission technology research, both wired and wireless. Investigations in resonance-based wireless energy transfer promise efficient wireless power transmission over several meters. This offers an ability to recharge moving vehicles, such as cars, trains and UAVs, wirelessly. For example, this technology can be applied to extend the range of UAVs used for the inspection of power transmission lines and towers. Presented project investigate capabilities and limitations of the wireless power transmission, for particular UAV application, i.e. for the infrastructure inspections.

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Keywords: Wireless power transfer; UAV; power lines; quadrotor

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1. Introduction

The use of rotary wing UAVs, with single, or multiple rotors, has gained significant interest in the past few years in various applications. Multi-rotor UAVs of various sizes and capabilities are commercially available. These platforms are stable and easy to use but, applications are restricted by their electric power supply based on the batteries. Although battery technology has improved in terms of power density, specific weight and durability, batteries subsystem remains a critical, heavy item on an UAV. Supercapacitors might be the part of the future hybrid battery / supercapacitors UAVs' energy supply system, but not at this stage of the development.

WET research on larger scale could lead to a new concept of charging moving vehicles and UAVs remotely. Principles of wireless power transfer were first investigated by Nikola Tesla (10 July 1856 – 7 January 1943) and patented in 1900 [1]. A hundred year later this was followed by number of patents based on Tesla's principles [2],[3],[4].

Wireless Power Consortium has developed Qi inductive power standard for the power transfer over distances of up to 4cm. Mobile devices, like small home appliances are placed on the top of the power transmission pad and charging is performed by the use of resonant inductive coupling.

Nomenclature

A	surface area
$\boldsymbol{B}$	flux density
$\boldsymbol{H}$	magnetic field
$\boldsymbol{i}$	electric current
μ	permeability
μ_0	free space permeability
μ_r	relative permeability
$\boldsymbol{r}$	radius
Φ	magnetic flux
e	induced electromotive force
D, d	distance
L	inductivity
C	capacity
ε	permittivity
ε_0	vacuum permittivity
ε_r	relative permittivity
P_m	Power in magnetic field
W_m	Energy in Magnetic field

The resonant inductive coupling technique pioneered by Tesla has recently become a central concept in modern wireless power development, and is being widely used in short range wireless transmission systems like mobile phone charging pads. Possible applications in automotive engineering were considered in [5], while interesting experimental results were presented in [6]. Wireless power transmission could range from *mW*, like in the case of biomedical implants applications, up to the *kW* range that could be used for the electrical vehicles charging [7].

Every wireless communication is wireless power transfer as well. The amount of power received is too small for the mechanical work, but we already have solutions that use wireless transferred energy to power communication devices [8]. There is an intensive research in the integration of the wireless energy transfer with the wireless communications, known as simultaneous wireless information and power transfer (SWIPT) [9].

We are now trying to go one step forward. Our idea is to investigate applications of UAVs for the infrastructure inspection while energy will be gathered from the green sources, or the power transmission infrastructure elements. It could include building infrastructure inspection, agriculture areas monitoring, water processing plants observing, or power distribution line inspection. Data can be processed on the UAV or sent to the monitoring center using 4G communications. Depending on the infrastructure and environment monitored, power could be harvested from green sources like solar, wind, thermal or from some physical field energy. Finally, we may have WET going in both directions. Resonant wireless power transfer from UAV to ground sensors is presented in [10]. A comprehensive review of the microwave power transmission (MPT) is given in [11] highlighting that it is suitable to energize lightweight mobile crafts. MPT is also considered to remotely power airplanes, ground vehicles and naval ships. One of the main problems is the antenna size needed for the practical amount of energy collection. The other, prospective, application area is the energy transfer of the space solar power (SSP), collected by satellites positioned in geosynchronous orbit, which is 36 800 km above the Earth.

Our concept of powering UAV, while inspecting high voltage power lines, is based on energy harvesting from the power line generated electromagnetic field, at the close vicinity of the conducting wires. The entire power line is acting as an extremely long antenna as shown in Fig.1.

UAV motion planning is an important component in energy savings. Sampling based approach is one of the efficient solutions already presented in the literature [12]. Finally, when the questions of power supply and motion planning are answered, we can concentrate on the inspection requirements and methodology. A research on auto-tracking algorithm for power line inspection, based on the application of unmanned aerial vehicle is presented recently [13]. More on automatic system for overhead power line inspection using UAV is given in [14].

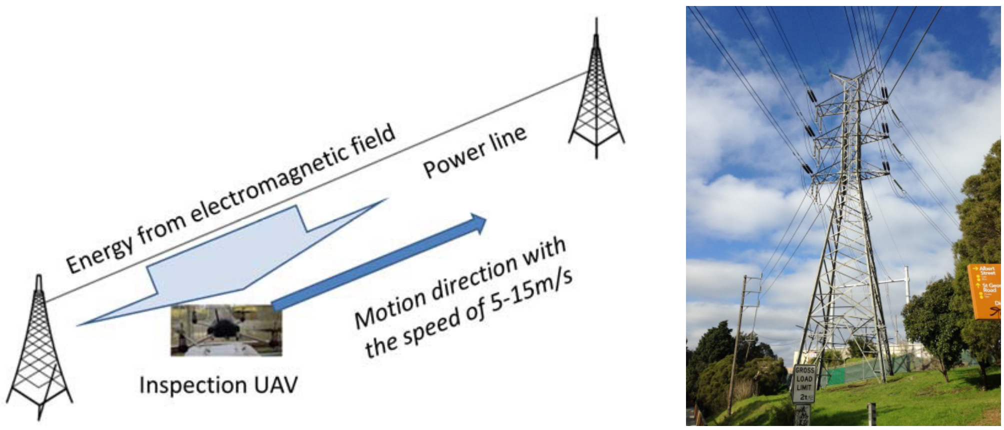

Fig. 1. Concept of powering UAV while inspecting high voltage power lines.

2. Electromagnetic induction

Current flow, ***i***, through the wire creates magnetic field, ***H***, around that wire, as presented in the Fig. 2 (a). Generated field has a circular shape. Magnetic field direction depends on the direction of current flow and can be determined by the use of Ampere's Rule as shown in Figure 2 (b). It is also known as Right-Hand Rule.

Fig. 2. (a) Current, ***i***, radius, ***r***, and Magnetic field, ***H***, vectors. (b) Ampere's Law known as Right Hand Rule.

Expression for the magnetic field intensity, H, generated around the conductor, through which electrical current i is flowing, is given by equation (1):

$$H = \frac{i}{2\pi r} \tag{1}$$

Magnetic field, as a special state of the space, can be expressed using magnetic flux lines. The density of those lines corresponds to the magnetic field intensity. Magnetic flux density, B, also depends on the material around conductor as given by equation (2), where μ is a constant called *permeability* of the medium. It has two components: relative permeability μ_r which specifies medium magnetic characteristics, and free space permeability μ_0 with the value given by equation (2). We assume that in the air we have the same μ_0, while in the ferromagnetic materials we have extremely high values of μ_r. [15]

$$\boldsymbol{B} = \mu\boldsymbol{H}, \quad \mu = \mu_r\mu_0, \quad \mu_0 = 4\pi 10^{-7}\left[\frac{H}{m}\right]; \quad where \quad \mu_r = \{1 - 3 * 10^5\} \tag{2}$$

From the equation (1) we can see that the field is proportional to the current intensity and inverse proportional to the distance from the conductor. Magnetic flux density distribution in the space, i.e. distance distribution, around the conductor, for different current values is shown in the Fig. 3.

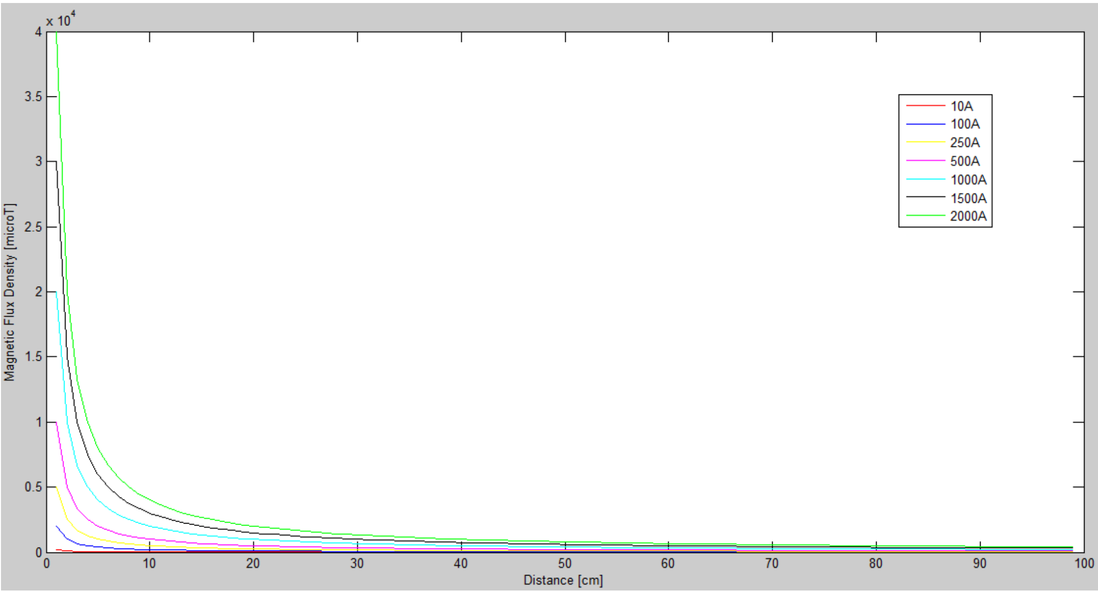

Fig. 3. Magnetic field distribution along the distance from the conductor, for different current values.

Magnetic flux is a product of flux density and the surface area, $\boldsymbol{A}$, covered by a conductor contour, as given by equation (3).

$$\emptyset = \boldsymbol{BA} = \mu\boldsymbol{HA} \tag{3}$$

Electromagnetic induction is the process of electromotive force creation. Faraday's law of electromagnetic induction states that a time-varying flux, $d\Phi$, generates an induced electromotive force, EMF or e, as per equation (4), where an imaginary surface area A is bounded by a conductor wire, as shown in the Fig. 4.

$$e = -\frac{d\emptyset}{dt} = -\frac{d(\boldsymbol{BA})}{dt} = -\frac{d(\mu\boldsymbol{HA})}{dt} \tag{4}$$

Induced electromotive force could also be expressed as in equation (5).

$$e = -\frac{d\emptyset}{dt} = -\frac{d}{dt}\int_S \boldsymbol{B}d\boldsymbol{A} \tag{5}$$

This expression incorporates flux changes as result of contour area changes, $d\boldsymbol{A}$, and flux density, $\boldsymbol{B}$ changes.

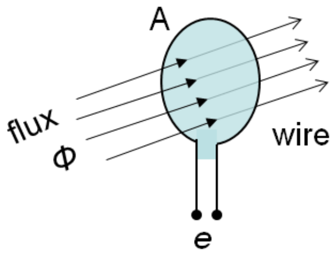

Fig. 4. Electromagnetic induction in a wire contour.

3. Wireless power transfer options

Wireless power transmission (WPT) is a collective term that refers to a number of different technologies for transmitting power by the means of physical fields. With electromagnetic field, we mainly talk about near-field inductive WPT and far-field WPT. Microwave power transfer (MPT) is far-field WPT used for the large amount of power transfer between two locations.

A wireless power system consists of a transmitter device connected to a source of power such as mains power lines, which converts the electrical power to a time-varying electromagnetic field, and one or more receiver devices which receive the field power and convert it back electric power, consumed by an electrical load. On the transmitter side the input power is converted to an oscillating electromagnetic field by an antenna device. A similar antenna or coupling device, on the receiver side converts the oscillating fields to an electric current. Global system structure is shown in Fig. 5.

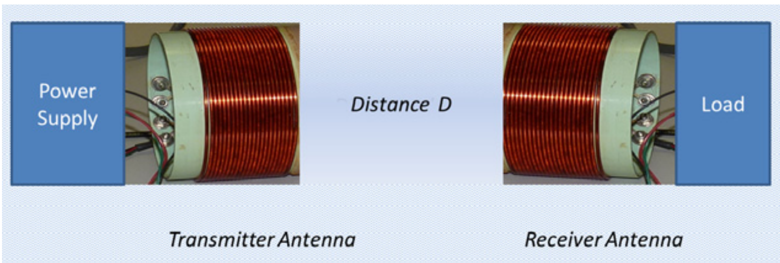

Fig. 5. Wireless power transfer transmitter and receiver.

Near-field region means that the area is within about *1* wavelength (λ) of the antenna. In this region the oscillating electric and magnetic fields are separate and power can be transferred via electric fields, by capacitive coupling, i.e. electrostatic induction, between metal electrodes, or via magnetic fields by inductive coupling, electromagnetic induction, between coils of wire. These fields are not radiative, meaning the energy stays within a short distance of the transmitter. The range of these fields is short, and depends on the size and shape of the antenna devices, which are usually coils of wire.

Resonance, in the case of resonant inductive coupling, can significantly increase the coupling between the antennas, allowing efficient transmission at larger distances, although the fields still decrease as per equation (1). The range of near-field devices is conventionally divided into two categories:

- Short range - up to about one antenna diameter: $D_{range} \leqslant D_{ant}$. This is the range over which *ordinary* ***non-resonant*** *capacitive or inductive coupling* can transfer practical amounts of power.
- Mid-range - up to 10 times the antenna diameter: $D_{range} \leqslant 10\ D_{ant}$. This is the range over *which* ***resonant*** *capacitive or inductive coupling* can transfer practical amounts of power.

3.1. Inductive coupling

Electrical transformer basically performs a simple form of wireless power transmission. Primary and secondary transformer's coils are not directly electrically connected. They are parts of separate electrical circuits. Energy transfer takes place through the process of mutual induction. Mobile phone and electric toothbrush battery chargers use this principle for charging. Induction cookers, also, use this method. The main problem here is the short range of operability. The receiver must be directly adjacent to the transmitter. Common uses of resonance-enhanced induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad (the transmitter circuit) and the receiver module (embedded in the load) to maximize energy transfer efficiency. Battery-powered devices fitted with a special receiver module can then be charged simply by placing them on a wireless charging pad.

2.1.2 Capacitive coupling

In capacitive coupling with electrostatic induction, power is transmitted by electric field between electrodes such as metal plates. The transmitter and receiver electrodes form a capacitor. An alternating voltage generated by the transmitter is applied to the transmitting plate, and the oscillating electric field induces an alternating potential on the receiver plate by electrostatic induction which causes an alternating current to flow in the load circuit. The amount of power transferred increases with the frequency and the capacitance between the plates. It is proportional to the total surface area, ΣA of the elementary plates areas A, positioned against each other from both sides of the capacitor and inversely proportional to the plates distance d, as shown in the Fig. 6.

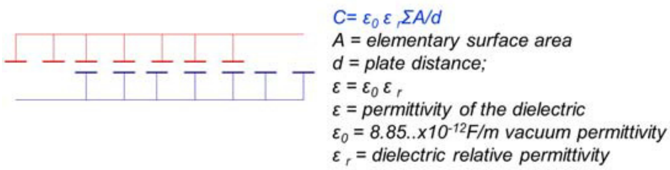

Fig. 6. A variable capacitor with metal plates.

Capacitive coupling has only been used practically in a few low power applications, because the high voltages on the electrodes are required in order to transmit useful power.

2.1.3 Magnetodynamic coupling

In this method, power is transmitted between two rotating armature, one in the transmitter and one in the receiver, which rotate synchronously, coupled together by a magnetic field generated by permanent magnets on the armatures. The transmitter armature is turned either by, or as, the rotor of an electric motor, and its magnetic field exerts torque on the receiver armature, turning it. The magnetic field acts like a mechanical coupling between the armatures. The receiver armature produces power to drive the load, either by turning a separate electric generator or by using the receiver armature itself as the rotor in a generator. This device has been proposed as an alternative to inductive power transfer for noncontact charging of electric vehicles. A rotating armature embedded in a garage floor or curb would turn a receiver armature in the underside of the vehicle to charge its batteries. Two energy conversions, electrical to mechanical and to electrical again, make the system less efficient than electrical systems like inductive coupling.

4. Energy in magnetic field

As it is shown in [15] the power P_m, absorbed by a magnetic field, during its establishment is given by the equation (6):

$$P_m = \int \mathbf{H} \frac{\partial \mathbf{B}}{\partial t} dV \tag{6}$$

In this power equation, apart from vector $\boldsymbol{H}$ and the partial derivative of the vector $\boldsymbol{B}$, $\partial\boldsymbol{B}/\partial t$ we have elementary, i.e. differential volume, dV. When we multiply equation (6) by dt the power expression becomes energy expression as given in the equation (7). This is the incremental energy absorbed by the magnetic field when the flux density, $\boldsymbol{B}$, is increased for the amount of $d\boldsymbol{B}$.

$$dW_m = \int_V \mathbf{H} d\mathbf{B} dV \tag{7}$$

Now, by integrating this over the considered space volume, we can derive the expression for the total energy absorbed by a stationary magnetic field. It is given by equation (8):

$$W_m = \int_V dV \int_{B_0}^{B_F} \mathbf{H} d\mathbf{B} \tag{8}$$

The second integral upper limit B_F represents final value of the magnetic flux density, while the lower limit B_0, represents initial value before the current is established. Now, if we take the first derivative, over dV, of the expression for energy, equation (8), we have energy density of the magnetic field. It is given by equation (9).

$$\frac{dW_m}{dV} = \int \mathbf{H} d\mathbf{B} \tag{9}$$

The equations above are applicable for all environments around the conductors. Having in mind equation (2), which establishes linear relationship between vectors **B** and **H,** in vacuum, the air and magnetic materials, we could simplify previous expression and derive new density equation (10).

$$\frac{dW_m}{dV} = \mu \int_0^H H dH = \frac{\mu}{2} H^2 = \frac{\mu}{2} \mathbf{BH} \tag{10}$$

If we now plug in equation (1) into equation (10) we will have energy density, in the air, as a function of electrical current through the conductor, as given by equation (11).

$$\frac{dW_m}{dV} = \frac{\mu}{2}H^2 = \mu_0 \frac{i^2}{2(2\pi r)^2} \qquad [\frac{J}{m^3}] \tag{11}$$

To get some impression of the energy in the magnetic field, we calculated energy density for the particular value of electrical current as, *i=1500A*, at the distance *r=0.2m* from the conductor. Energy density is $0.179\ J/m^3$. Following all of this, our next research objective is to establish how much of the field energy, as given by previous equations and calculations, could be extracted and used to power UAVs. Energy can only be extracted if we have flux changes, as given by equations (4) and (5). Our source of energy is AC current going through transmission lines, with the frequency of *50* or *60Hz* depending of the standards in the given country. In addition to that we have change of flux caused by the UAVs traveling along the lines. We have only considered magnetic field caused by the current through single line. In reality we have *3, 6* or more transmission wires. Interference can decrease, or increase the value of the resultant magnetic field and it depends on the considered point location *(x, y, z)* in space around conductors. It will be matter for a more comprehensive theoretical and practical investigation, in the near future.

5. Experiments

In the process if our investigation we have conducted few experiments with the models of real power distribution systems. In one of the experiments, as a power distribution line, an AC power cable was used. It was carrying current of *i=10A.* That was out transmitter, as explained in the Fig. 5. For the receiver we have selected a coil of copper wire, with the solenoid diameter of *59mm*, length of *107mm* and the number of turns *250*. Inductivity of the coil is measured and it has value of *L=1.41-1.39mH* in the frequency range of *50-10kHz*. Lab setup is given in the Fig. 7 and measurement results could be seen on the Fig. 8.

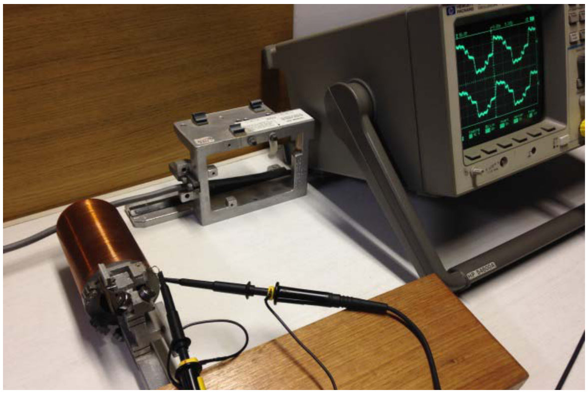

Fig. 7. Lab setup for EMF testing.

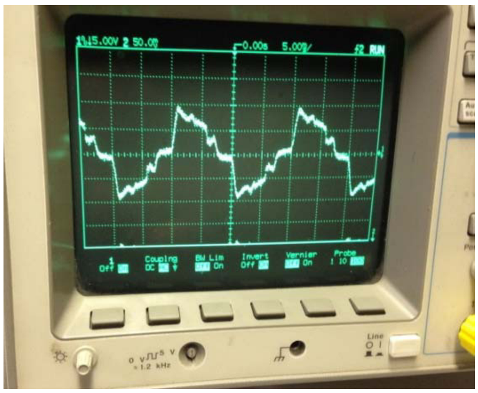

Fig. 8. EMF test measurements.

Measurements were conducted from the distance of *2cm* from the conductor wire. The frequency of the signal source was *50Hz*, normal AC power load frequency. Measurements, as shown in the Fig. 8 bring sinusoidal induced voltage with the amplitude of around *10V*. This result is obtained using transmitter line with the voltage of *240V,* current of *10A* and frequency of *50Hz*. If we scale this findings, using equations (4) and (1), to the level of voltages and current that could be found on the transmission lines, reasonable amount of power will be available for a quadrotor, as shown on the Fig. 9, to recharge while travelling along the long power distribution lines. Voltages on those lines range from the *115kV* to *1200kV*, while current goes from few hundreds of *Ampere* up to *1500A,* or even *2000A*. In such cases distances from the transmission lines could be greater than just few *cm* as in our experiments.

To get some impression of energy requirements, let us consider an available drone battery of *5200mAh*. Drone, like one shown in Fig.9, consumes *750-900mA* in normal operation, while flying at the speed of *10m/s.* That corresponds to *36km/h*. If we assume an average consumption of *800mA*, that will give us total of *6.5 flying hours*.

Following that travelled *Path* is *234km*. If we use a circular antenna, similar to our experimental coil, but with the diameter of *0.2m*, the total space volume covered by drone receiver will be *Volume = Path*Antenna surface.* Since we know energy density in a stationary magnetic field, as shown above, we could calculate total energy available on the path. That will give us *1315 J.* This is just a simple estimate.

Now, we need to convert our battery capacity into the corresponding energy. If battery voltage is *12V*, then energy stored is equal to *5200mAh*12V=224,640J.* This is well above our energy in the stationary magnetic field, but we do not base our expectations on that source. We will investigate how much energy could be extracted from the changing magnetic flux as per equation (5). Finally, application of that equation is the only way to extract any energy from the field.

Fig. 9. A quadrotor for the power line inspection investigations.

6. Inspection of Power Lines

Our interest is in UAVs' applications for power line inspection. Power lines are a critical infrastructure subsystem in the supply of power to homes, hospitals, industry, etc. It needs regular inspection, maintenance and repair. This is a significant task since power lines can run for long distances, through rough and remote terrain, forests, and on high altitudes.

Power line inspection involves examining the pylons and their high voltage insulators. Even the connecting screw must be intact. This process is increasingly being performed by helicopters. Typically the smallest team is made up of an observer using dedicated equipment and a pilot. The inspection frequency depends on transmission line size. The helicopter usually hovers at a horizontal distance close enough for observation, and not too far from the ground. This means that the noise produced by the inspection limits the hours the helicopter can fly, due to noise abatement laws and disturbance to livestock. Electricity providers in many countries commission the service of manned helicopter companies to conduct power line inspections, check for cracks and corrosion, wash insulators, and detect thermography problems and clear vegetation around towers and power lines.

Using manned helicopters is an expensive and risky operation. Utility operators are looking for alternative ways for conducting routine inspections. Several different systems have been proposed to replace manned inspection. Some of them are quite innovative, for example robots that move along the line. For a complete survey of the power lines and towers, remotely controlled UAV are sometimes used, that fly along the length of the tower and takes infra-red, optical images, or both. The main problem is that this remains expensive for the many *km* of power lines and hundreds of towers that have to be inspected.

7. Conclusion

The real benefits for the overhead power line inspections come from UAV operations that can be done routinely and autonomously. A complete system that is reliable and effective does not exist yet, but enabling technologies are already developed. One of the main disadvantages of electric quadrotors is the need for the battery system recharging when functioning on the long distances. Applying concept presented here we could recharge the quadrotor on the job.

Future investigations and experiments should deal with the process of extracting power from the transmission system model. If that proves successful, the next step will be to scale the system up, to the real dimensions and the real high voltages on the electrical power distribution lines. In our model voltage is *240V* and the currant is just *10A*. Distribution voltages may go up to *1200kV* and the current up to *2000A*. In the real system absorbed power might be enough for the continuous UAVs' operation, but even that is not critical. We could have non inspection intervals, of any duration, that could be used for the additional charging. During the charging periods energy could be harvested based on solar collected power, or by wired based charging, from power lines, to speed up the process. For the full independency of the system, on possibly faulty power lines, photovoltaic solar cells could be placed along the infrastructure. Obviously there is large number of research questions for the future investigations.

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