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ANALYSIS OF NEAR-FIELD WIRELESS POWER TRANSMISSION FOR FRACTIONATED SPACECRAFT APPLICATIONS

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The modular design of a fractionated spacecraft is intended to avoid drawbacks inherent to monolithic designs such as subsystem failure, expensive designs, underestimated costs, expensive launches and over-complex systems. Since the power systems represent one of the main mass and volume drivers of spacecraft, one of the key technologies required for truly fractionated architectures is the ability to distribute power wirelessly between spacecraft depending on the respective power needs over time. Investigations on the subsystem aspects of radiative wireless power transmission have been published, including the use of both, laser and microwave frequencies. Near-field wireless power transmission has so far been quickly discarded, mainly due to its apparent limited range. The present paper intends to contribute to this discussion by investigating a method of increasing the range near-field power transmission, which might be sufficient for its use within fractionated spacecraft applications.

I. INTRODUCTION

With the increasing maturation of the space sector, spacecraft have tended to increase in mass, complexity and performance. Modern telecommunication satellites typically have power levels up to 20kW, masses at launch of more than 5 tons and an increasing number of more and more sophisticated transponders. In July 2009, Arianespace has launched Terrestar-1, with a mass of 7 tons the largest and most powerful telecommunication satellite. Added complexity has also added cost in a non-linear manner. As Brown notes in his 2006 paper on fractionated space architectures, the complexity and the cost of an engineering system scale exponentially with respect to the system's capability. This is because the assured delivery of capabilities necessitates making the system robust to various uncertainties, failure modes, and the mechanisms to addressing these, which themselves grow with the system's complexity. Brown used the term "cost-complexity death spiral" for this relation.[1]

In parallel, advances in miniaturisation and electronics have led to the emergence of a new niche market in space: nanosats, standardised, simple, less powerful, relatively cheap and small spacecraft.[4]

I.1 Fractionated Spacecraft

The concept of fractionated spacecraft, tries to combine the benefits of standardised small spacecraft (e.g. robustness, flexibility and cost) with the capabilities of larger platforms.

Results from first system assessments promised fractionated space systems a higher value return on investment than for traditional monolithic systems. Such fractionated systems seemed more appropriate for value-centric engineering, rapid initial operational capabilities due to staged deployment, flexibility to changing threats or needs and even lower launch costs due to more launch vehicle options.

Key to the concept of fractionated spacecraft is the modular design. Since the first engineering proposal of fractionated spacecraft in 1984 by Molette, Cougnet et al [3], the concept has been matured mainly after 2005, when the US Defense Advanced Research Projects Agency started to conduct some highly publicised studies on the concept. These aimed at developing the concept with the purpose of creating a new paradigm in space systems, essentially for defence mission purposes.[1][2][6][7]

One of the key drivers from the US Department of Defence (DoD) point of view has been the consistency of US DoD space programmes running over budget and over time. A 2009 report by the US Government Accountability Office (GAO) concluded that current weapon systems development programs are overrunning 42% in development cost and 25% in production cost, and are reaching initial operating capability, on average, 22 months behind schedule [8]. Fractionated spacecraft offered indications that this new approach might enable to address the delays and overruns associated with complexity management of space related defence acquisition programmes.

Common to most fractionated spacecraft concepts is the separation of key power subsystem functions such as generation of power, energy storage and power distribution, from the payload, the unit that performs the actual tasks, and which is therefore liberated from traditional constraints such as sun-pointing and cycling in and out of eclipses. Respectively, these functions are centrally performed by some external, power providing spacecraft, which offers also to be conceptually simpler since its design no longer needs to take into account requirements coming from the different payloads.

Recently, Nag et al. concentrated on robust options to implement the requirements of fractionated spacecraft to maintain formation flight among its physically distinct elements while at the same time being capable of collision avoidance. A robust and simple distributed autonomous control based on equilibrium shaping was developed to demonstrate the capability of the fractionated spacecraft to perform collision avoidance manoeuvres in the event of directed or random threats, and to return to its original configuration after the threat has passed away.[10]

Although substantial analysis has been performed related to system studies and market / manufacturing oriented assessments, these have not yet converged into a solid technical concept.

Since the power systems represent one of the main mass and volume drivers of spacecraft, one of the key technologies required for truly fractionated architectures is the ability to distribute power wirelessly between spacecraft depending on the respective power needs over time.

I.2 Wireless Power Transmission

Wireless power transmission has been studied and experimented with since the first experiments by N. Tesla end of the 19^{th} century and the first successful laboratory scale demonstrations during the 1960s by Brown et al. [11]-[14][19]. In principle, the physics wireless power transfer is similar to those of wireless communication though while efficiency is key to the first, the signal-to-noise ratio is the key parameter for the second. First intended applications for power transmission included the provision of energy from ground to helicopters, balloons and other air platforms.[15][19] Especially the US Raytheon Company pushed the technology since 1958. Triggered by the prospect of the cavity magnetron developed first in Great Britain and then in the US during World War II and able to efficiently generate hundreds of kilowatts of power at a wavelength of about 10 cm, the studies and experiments focused on microwave-powered aircraft that could stay on station at high altitudes for long periods of time and function as communication or surveillance platforms.[13][19] With the publication of the first engineering paper on the concept of space solar power from space by P. Glaser in 1968, and especially the onset in 1977 of the large US DoE-NASA work on space solar power, the attention shifted to the use of microwaves for very long distance wireless power transmission applications.[16][17][18][19]

Notable key experiments demonstrating the technical viability of wireless power transmission via microwave and its constant improvements over the last 50 years include

- In 1963, an experiment at Raython's lab showed to US Air Force officials the transmission of 400 W of CW power (generated by a magnetron), converted at the receiving antenna into 100 W of dc power to drive a motor attached to a fan.
- In November 1964, Brown demonstrated a 10h continuous, wireless powered helicopter flight, based on a newly developed rectenna for the receiving part, generating up to 270W.
- Supported by a small NASA contract involving directly W. von Braun, in September 1970, the first overall efficiency measurement was done, reaching a surprising overall dc to dc efficiency of 26%.
- In 1975, the overall system efficiency was increased in a test in the Raytheon Laboratory to 54% with a total power output of 495W.
- In the same year, the first large-scale, long-distance experiment was conducted by Raython under JPL contract at the Venus Site of the JPL Goldstone Facility. The distance between transmitting and receiving antennae was 1.6km. Over 30 kW of dc power was obtained from the GaAs diode rectenna arrary with a ratio of dc output to incident microwave power of 0.84. Part of dc output was used to light light-bulbs. [17][20] Later, a single rectenna element operating a 6W RF input, developed by Bill Brown demonstrated 91.4% efficiency.[21]
- Japanese experiments conducted by Kaya and Matsumoto in 1980s and 1990s, demonstrating wireless power transmission in the ionosphere, from a car to a small plane in flight as well as to a balloon.
- The first successful test of the retro-directive passive antenna system from space to ground by Kaya et al in 2006,[22] as well as the first successful test of an end-to-end system, powered by solar photovoltaic panels from Mt. Haleakea at Maui Island to the 120km distant Mt. Mauna Lea in the big island of Hawaii.[23][25]

I.3 WPT and fractionated spacecraft

In principle, each module of a fractionated spacecraft could have its own, independent power system based on photovoltaic panels. This approach however adds mass to the overall system and complexity to the design, since each fractionated spacecraft then needs to comply with both, power system requirements (orientation with respect to sun, eclipse cycles etc) as well as payload requirements. A different approach is therefore based on mother/resource and daughter/payload spacecraft, where the mother spacecraft generates the electricity required for all daughter spacecraft, to which it is then transmitted wirelessly when needed and as much as needed.

This approach has for example been analysed by Jamnejad and Silva, including the type of transmitting antennas (reflectors/phased arrays), the mechanisms of redirecting and/or refocusing the single or multiple beams in the near to mid-field regions of the transmitting antenna, as well as feasibility ranges for efficient and robust performance.[24] Their analysis is based on some assumptions concerning size constraints for both the resource as well as the payload spacecraft. Emitting antenna diameters for the resource spacecraft have been limited to a rather generous maximum of 50m, while the receiving antenna diameter were constrained to 1m diameter. Based on these limitations and well-documented relations between frequency, apertures and distances, combinations of frequencies and distances were derived, considered as potentially suitable to fractionated spacecraft. Given that microwave beams can be generated with higher efficiency at lower frequencies (over 80% at 2.45GHz, compared to less than 30% at 61.25GHz and falling further with even higher frequencies), but on the other hand higher frequencies allow smaller emitting and transmitting antenna diameters and thus masses, there is no generally optimal design point even based on such simplified assumptions, which ignore other parameters such as beam quality.

Based on an overview of options, Jamnejad and Silva selected defocussing phase arrays, reflector systems and reflectarrays as well as an embedded rectenna architecture for recommended further investigations for fractionated spacecraft applications. [24] According to the authors, beam shaping can be used to optimize the transmission efficiency while minimizing the interference and power spill-over through side-lobes. Jamnejad and Silva furthermore conclude that several technology areas required further maturation, including efficient rectenna diodes, phased array antennas, high breakdown/low loss transmit filters, phase shifters, and retro-directive systems. [24]

Another system level assessment of wireless power transmission for an application similar to fractionated spacecraft has been published by Lafleur and Saleh, who assessed this concept in the frame of small satellites, by using a parametric model of spacecraft design variables. They simplified the system to two spacecraft only, ignored all pointing losses, assumed no storage needs and thus continuous power and no interruptions. Lafleur and Saleh concluded that the design space for power beaming is severely constrained, requiring high transmission frequencies and large antenna diameters, and stringent proximity distance. Their overall parameters were in the order of 1m diameter for both transmitting and receiving antennas, using 33 GHz frequency and requiring distances in the order of 100 m. Especially due to the constraint of same size, small receiving and emitting antennas, since both mounted on small spacecraft, the conclusions were rather unfavourable for such a use of wireless power transmission via microwaves since each small spacecraft would be required to nevertheless generate 90% of its power need from an onboard power source.[27]

Turner et al studied a new innovative concept for transferring power within a fractionated system, based the use of a resource spacecraft that distributes high-intensity beams of unconverted concentrated sunlight to high-temperature compact receivers on receiving spacecraft, which use heat engines to generate power from heat stored in receiver reservoirs, providing routine and contingency energy storage. Turner concludes that the power transfer efficiency would be around 25%, substantially higher than those Turner assumes for microwave (3%) or active optical (4%) schemes.[26]

However, another form of wireless power, which has not been analysed previously for fractionated spacecraft is near-field wireless power.

II. NEAR FIELD WIRELESS POWER

Near fields [28][29] can be seen as the reactive field surrounding any electrically charged object. In the static case, these fields are simply the electro-static fields, while in the non-static case they form time varying electric and magnetic fields, which are out of phase close to the object (closer than λ), and can be used to induce current in near-by objects.

In contrast to the far-field waves, near-fields represent zero energy flow according to the Poynting vector due to the 90 degree phase difference between the electric and magnetic fields [31]. This gives near-fields an advantage in efficiency as they do not radiate energy away from the source [28].

In general, the emitted fields of an antenna, which make up the field in the far-field region, can be made small if the antenna is much smaller than the wavelength. This can be achieved easily with a coil made of a few turns. Such a coil is a poor radiator, and the primary field emitted from this will be a near-field [30]. If then a similar coil is placed in the vicinity of the first, the two will couple via magnetic induction, and energy will be transferred from one to the other. This effect is greatly enhanced if the system is made to resonate.

Although the concept of magnetic induction between conductors has been around since Faraday it has seen only recent interest for the application of wirelessly powering implantable medical devices [31][32][33] Previous work in this area concentrated on calculating the coupling between the coils and enhancing it through changing the shape [31]. However, poor efficiencies will be achieved unless the systems is made to resonate.

This was shown recently by Karalis et al [34] who demonstrated that medium power levels (~50W) can be transmitted over distances of approximately 2m at the right frequencies.

Other recent work has demonstrated power transfer to multiple receiver coils using one transmitter [35][36][37].

We analyse this form of wireless power transfer analytically in the form of magnetically coupled coil resonators and asses its applicability to fractionated spacecraft.

III. NEAR-FIELD WIRELESS POWER FOR FRACTIONATED SPACECRAFT

III.1 System structure

In order to assess the potential of using near-field wireless power for fractionated spacecraft in principle several requirements need to be defined:

1. the distance over which power can be transferred efficiently
2. the flexibility to adapt to different formation configurations
3. the possibility to supply power to more than one element of the fractionated spacecraft
4. the possibility to vary power levels according to needs

Fractionated spacecraft can impose further constraints related to mass and size of the power transmission modules on the system. To simplify the requirements for this first assessment points 2 to 4, have been temporarily neglected, all coils are assumed to be perfectly axially aligned and of the same size. As the limiting factor in near-field wireless power transfer is the short range [34], the present assessment focuses on increasing the distance of power transfer.

For this first assessment, coils of 0.5m radius (which might be considered as a reasonable assumption and fully in line with the size considerations taken as basis for wireless power transmission to small spacecraft as well as fractionated spacecraft [24]) and three turns each, operating in the fundamental mode, have been chosen. A wire thickness of 2mm radius for the coils was chosen. The coils are assumed to have a self-inductance of 1nF. The inductance of the coils was calculated using $L = N^2 R\mu \cdot \left[\ln(8R/a) - 2\right]$ where N is the number of turns, R is the radius of the coil, μ is the permeability and a is the wire thickness.

III.2 Methodology

Systems of coupled resonators can be analysed using lumped element models and Kirchoffs circuit laws, where the effect of the coupled fields is modelled using mutual impedances. A lumped element circuit model of a group of m coupled resonators is shown in figure 1, where the elements enclosed by a dashed line constitute a two-port network.

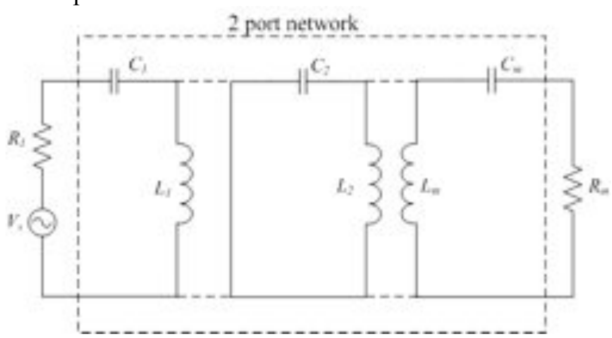

Fig. 1: Lumped element model circuit diagram of coupled series LC resonators.

To achieve near-field wireless power transfer coil resonators are used as they are easy to analyse and the capacitive coupling between them can be neglected.

Using Kirchoff's voltage law, the following equations for the set of m magnetically coupled series LC resonators shown in figure 1 can be written [38].

$$
\begin{aligned}
V_s &= I_1\left(R_1 + i\left[\omega L_1 - \frac{1}{\omega C_1}\right]\right) - i\omega M_{12} I_2 \\
&\quad \ldots - i\omega M_{1n} I_n \\
0 &= I_2\left(R_2 + i\left[\omega L_2 - \frac{1}{\omega C_2}\right]\right) - i\omega M_{21} I_1 \\
&\quad \ldots - i\omega M_{2n} I_n \\
&\ \ \vdots \\
0 &= I_m\left(R_m + i\left[\omega L_m - \frac{1}{\omega C_m}\right]\right) - i\omega M_{m2} I_2 \\
&\quad \ldots - i\omega M_{mn} I_n
\end{aligned} \qquad [1]
$$

Where I_n is the current in the nth circuit, M_{mn} is the mutual inductance between the mth and nth circuits, L_m and C_m are the inductance and capacitance of the mth circuits respectively, V_s is the voltage of the source, ω is the angular frequency and R_m is the resistance of the mth

circuit. The output and load impedance is contained within R_1 and R_n respectively.
These equations can be collected into a matrix form as

$$\begin{bmatrix} V_S \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix} \cdot \begin{bmatrix} Z_1 & -X_{L12} & \cdots & -X_{L1n} \\ -X_{L21} & Z_2 & \cdots & -X_{L2n} \\ \vdots & \vdots & \vdots & \vdots \\ -X_{Lm1} & -X_{Lm2} & \cdots & Z_m \end{bmatrix} \quad [2]$$

or

$$[V] = [I] \cdot [Z]. \quad [3]$$

Where $X_{Lmn} = i\omega M_{mn}$ is the inductive reactance due to the mutual inductance, M.

The mutual inductance was calculated using Neumanns formula [30]

$$M = \frac{\mu}{4\pi} \oint\oint \frac{dl_p \cdot dl_q}{R_{pq}} \quad \text{for } p \neq q, \quad [4]$$

Where dl_p and dl_q are the pth and qth line elements of the coils and R_{pq} is the distance between them. The planar distance between the coils D, is a function of R and hence the mutual inductance.

The power transfer can be found by solving the equations [1] simultaneously for the current in the mth circuit. Using network analysis, a transfer function of the network shown in figure 1 can be defined.

$$S_{21} = \frac{2 I_m \sqrt{R_1 R_m}}{V_s}. \quad [5]$$

An inspection of equation [4] shows that to maximise power transfer, the current in the mth circuit must be maximised. However, I_m is a function of M_{mn}, R_1 and R_m. To maximise power transfer, the sizes of R_1 and R_m must be matched to the impedances of the coils. In the current analysis, R_1 and R_m are assumed to be 50 ohm. The impedances of the coil resonators are not matched to these loads. However, the object of this study is to show how the range of wireless power transfer can be extended, which is unaffected by these parameters, not to determine the absolute values of power transfer as these will depend strongly on the architecture of the fractionated spacecraft.

III.3 Results

The magnitude of S_{21} was calculated for systems of 2, 3, 4 and 5 aligned, identical and equally spaced coils, without the presence of extraneous objects. Figure 2 shows the magnitude of S_{21} as a function of the distance between the coils, D, and the frequency, f. The total distance between the coil connected to the source and the coil connected to the load, D_{TOT}, is then $D_{TOT} = D \cdot (m-1)$.

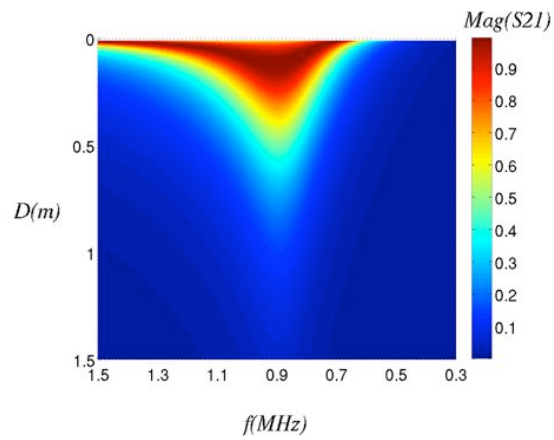

Fig. 2: Power transfer, $|S_{21}|$ between two coils as a function of distance, D and frequency, f.

Figure 2 shows that at a distance between coils equal to the coil radius, D=0.5m, $|S_{21}|$=0.452, while at a distance equal to twice the coil radius, D=1m, $|S_{21}|$=0.134. The distance of maximum power transfer can be increased in several ways, such as increasing the coil size or the number of turns. However, the effect of these parameters is left for future work while this study focuses on the effect of placing other identical, but unloaded, resonators in-between the transmitting and receiving coils in order to extend the total distance of power transfer through a type of "power-hopping".

Figure 3 shows the effect of adding an unloaded identical unloaded resonator into the middle of the transmitting and receiving coils, so that each coil is separated by a distance D.

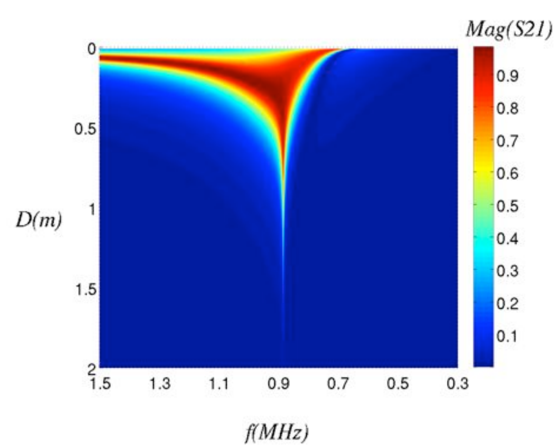

Fig. 3: Power transfer, $|S_{21}|$ between three equally spaced coils as a function of distance, D and frequency, f.

Figure 3 shows that at D=0.5m, $|S_{21}|$=0.891, while at D=0.75m, $|S_{21}|$=0.415. By comparing figures 2 and 3 it can be seen that by adding a unloaded coil in between the transmitting and receiving coils $|S_{21}|$ has increased from 0.452 to 0.891 at D=0.5m coil separation while the total distance of the power transfer, D_{TOT}, has increased from 0.5m to 1m.

Figures 4 and 5 show the effect of two and three coil resonators in-between the transmitting and receiving coils respectively.

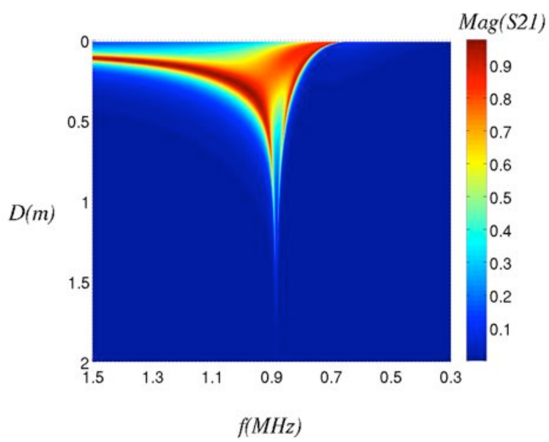

Fig. 4: Power transfer, $|S_{21}|$ between four equally spaced coils as a function of distance, D and frequency, f.

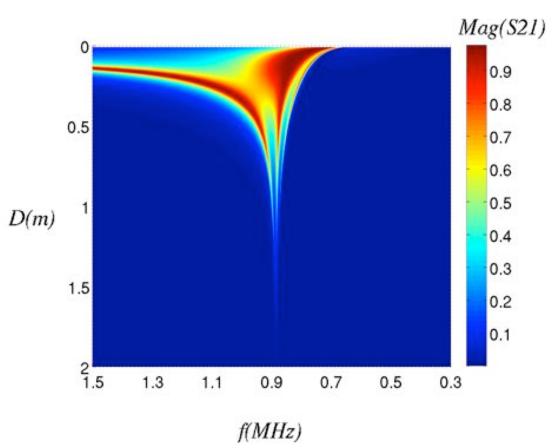

Fig. 5: Power transfer, $|S_{21}|$ between five equally spaced coils as a function of distance, D and frequency, f.

Figures 4 and 5 show that $|S_{21}|$ at D=0.75m is 0.456 and 0.668 respectively. Figures 3, 4 and 5 show that at D=0.75m moderate increases in $|S_{21}|$ can be achieved while D_{TOT}, increases from 1.5m to 2.25m to 3m respectively. This shows that adding extra unloaded coils in between the transmitting and receiving coils is an effective way of increasing the total distance of power transfer with little loss.

Figures 4 and 5 show a frequency splitting of the primary resonant mode. To understand this effect it must be remembered that the coupling between non-adjacent coils is negligible. It should also be noted that the quality factors of the unloaded coils are much larger than those connected to loads. This means they store a greater fraction of the total energy of the system and hence coupling directly associated with those coils will have a larger effect on the efficiency of power transfer.

The splitting of the resonant mode in figures 4 and 5 is due to the mutual coupling between adjacent coils. The mutual coupling can, both, increase and decrease the stored energy [36], hence decrease and increase the resonant frequency respectively.

In figure 4 there are two major peaks apparent in $|S_{21}|$. These two solutions correspond to the two effects present in the coupling of two adjacent coils, which are raising and lowering the resonant frequency.

In the case of five coupled coils, there are three unloaded coils, which, between them create four effects of raising and lowering the resonant frequency. However, two of these effects are the same, resulting in just three different effects. These can be seen as peaks in $|S_{21}|$ in figure 5.

The three peaks shown in figure 5 represent a lowering of the total quality factor of the system. The presence of more than one peak in $|S_{21}|$ means that field lines are not coupling so as to create the same effect. Rather they are coupling so as so to create effects, which are optimal at different frequencies and hence not acting in union.

If the coupled field lines can be made to act in union (couple to the correct places on adjacent loops) at one single frequency, then the distance of maximum power transfer can be increased significantly. This may be achieved by altering the shape of the coils or operating at different modes.

Therefore, in order to extend the distance over which maximum power transfer can be achieved when using the power hoping method described above, the cross-coupling between adjacent coils needs to be engineered in such a way as to always create the desired coupling.

V. CONCLUSION

Simple systems of 2, 3, 4 and 5 resonant inductively coupled coils of 0.5m radii and three turns have been analysed using Kirchoffs laws. The effect of adding unloaded resonators in-between the transmitting and receiving coils, power-hopping, has been analysed. It was shown that the total distance of power transfer can be increased by approximately linearly with the number of unloaded resonator added and thus in principle, without any optimisation and by just using simple 3 turn coals, near-field wireless power transfer can in principle be extended beyond the usual limits. This does not yet allow concluding that near field wireless power transmission might be suitable to fractionated spacecraft but encourages further work in this direction.

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