The Feasibility of Self-Resonant Structures in Wireless Power Transfer Applications

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***Abstract*—The efficiency and range of wireless power transfer (WPT) is dependent on the Q of the resonant coils. The multilayer self-resonant structure (MSRS) has been shown to have Q more than $6\times$ conventional coils. This structure has an integrated capacitance, which limits the minimum achievable size and frequency. In this paper, we explore the minimum feasible resonant frequency and the maximum power level without dielectric breakdown that can be achieved using the MSRS given a size constraint. This analysis is applied to two case studies; one for consumer electronics and one for electric vehicles. The example MSRS for electric vehicles has a diameter of 20 cm and height of 5 cm. If a 100 kHz resonant frequency is selected, the MSRS can achieve an output power of 10 kW at a range of 20 cm with an input voltage of 500 V.**

I. Introduction

The range and efficiency of a resonant inductive WPT system is limited by the quality factor Q of the resonant coils and the magnetic coupling factor k between the coils [1]. The magnetic coupling factor is determined by the geometry of the coils, and the spacing between them, so the potential improvement of k is limited. Therefore, improving the Q of resonant coils is instrumental in improving the range and efficiency of WPT systems.

Conventional resonant wireless power transfer coils consist of loops of wire placed on a ferrite core and connected to a ceramic or film capacitor. In the kHz frequency range, high-performance coils are made from litz wire. Litz wire shares the current between many thin isolated strands of wire that are twisted together, which effectively reduces proximity-effect power loss. However, proximity effect can still dominate loss, leading some designs to use very fine litz strands, which are very expensive [2]. Moreover, connections between the litz wire and the capacitors are problematic. Terminating litz wire with a large number of strands is difficult, and the benefit of the litz wire extends only to that point—connections between the capacitors and the litz wire are then solid conductors which are not effectively utilized, and can have eddy-current losses induced by the field of the coil [3]. Furthermore, although ceramic or film capacitors can use foil or metalized film conductors much thinner than a skin depth, eddy currents can be induced in them depending on their orientation and proximity to the magnetic field produced by the coil. They can also suffer from proximity-effect losses arising from the current flow to them and in them. At MHz frequencies, proximity loss in litz wire is very high because strand diameters are too large compared to the skin depth δ. Thinner strands would reduce loss, but are very difficult to manufacture [2]. Coils can be made with solid wire but skin effect results in poor utilization of the conductor. For example, the skin depth of copper at 6.78 MHz is 25 µm, so current flows in only a small fraction of a mm-scale conductor.

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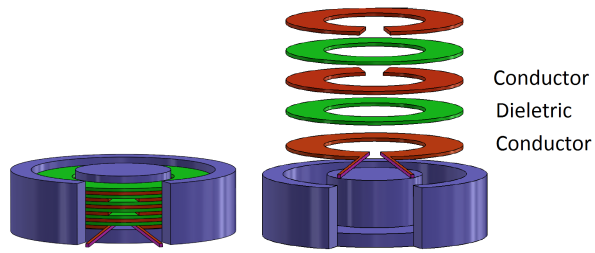

Fig. 1. Self-resonant structure, shown with exaggerated layer thickness for clarity. In practice, layer thicknesses is on the order of 10 µm and many layers are used. [4]

The multilayer self-resonant structure (MSRS), discussed in [3]–[6], is a high-Q alternative to conventional WPT coils that can be constructed using low-cost materials. The structure comprises a stack of C shaped conductive layers with alternating orientations that are separated by a dielectric and placed in a magnetic core (see Fig. 1). This structure significantly reduces winding loss compared to conventional WPT coils due to: equal current sharing between many thin foil layers which reduces the impact of proximity effect; alignment of foil layer parallel to the magnetic field which reduces eddy currents; and inductive coupling of the layers which eliminates terminations in the high-current path. This structure has been demonstrated with a Q of 1173 for a diameter of 6.6 cm [5], a 6x improvement over similarly sized coils in the literature. These experimental results highlight the MSRS's ability to increase the range and efficiency of inductive WPT.

The MSRS can be used to achieve a high-Q resonant structure making it desirable for many different WPT applications; however, the inductance of the structure is fixed, so the resonant frequency ω_0 is limited by the integrated capacitance. The capacitance of the structure is determined by both the size of the structure and the properties of the winding materials. In order to comply with some standards, such as Qi, low-frequency operation (below 200 kHz) is required, but achieving low resonant frequencies can be challenging. For example, consider the prototype developed in [4]. This

6.78 MHz MSRS prototype had a diameter of 6.6 cm, and the winding was constructed using PTFE dielectric with a thickness of 12.5 µm, and copper with a thickness of 12.5 µm. Achieving a resonant frequency of 200 kHz at this size and with these materials would require a winding height of 19 cm. A thinner dielectric could, in principle, be used to achieve a 200 kHz resonant frequency with a more practical height. For example, 180 nm PTFE dielectric would make 200 kHz possible with a 2 mm winding height. However, such a thin dielectric presents challenges regarding both manufacturing and dielectric breakdown, which would limit the power handling capability to under 5 W at a wireless range of 66 mm.

This paper explores the feasible range of resonant frequencies that can be achieved using the MSRS given a size constraint, and the power handling capabilities of these structures as limited by dielectric breakdown. First in Section II, we provide some general background on the MSRS. Next, in Section III, we explore the impact of MSRS size, height, conductor thickness, dielectric thickness, and dielectric permittivity on the minimum achievable resonant frequency. In Section IV, we present a lumped impedance model of two coupled MSRSs in order to calculate an analytical expression for the maximum power handling capability without dielectric breakdown. Finally in Section V, we discuss potential construction methods for the MSRS, and use the analysis in this paper to explore the space of achievable designs for two case studies. This paper is not intended to aid in the design of MSRSs, but instead is a first-order analysis that bounds the achievable application space; the design of high-Q MSRSs is discussed in [3]–[5].

II. Background on the Multi-layer Self-Resonant Structure

The multilayer self-resonant structure (MSRS) is a parallel resonator that is constructed from alternating C-shaped thin conductive layers and washer-shaped dielectric layers that are stacked into a magnetic core (see Fig. 1) [3]–[5]. A section is two C-shaped foil layers separated by a low-loss dielectric. The C-shaped conductors within a section have opposite orientations, which results in two overlapping areas and forms two capacitors. As current flows through a section it passes through both capacitors, and creates an inductive current loop. This results in a parallel LC resonator in which the inductance L is equivalent to a single turn around the magnetic core and the capacitance is the series combination of two section-half capacitances C_{sh} [3]. This section-half capacitance can be expressed in terms of the angle of overlap of the layers in radians θ, the inner radius of the coil r_1, the outer radius r_2, the permittivity of the dielectric ε_d, and the dielectric thickness t_d

$$C_{sh} = \varepsilon_d \left(\frac{\theta}{2\pi}\right)\left(\frac{\pi\left(r_2^2 - r_1^2\right)}{t_d}\right) = \frac{\varepsilon_d \theta (r_2^2 - r_1^2)}{2t_d}. \quad (1)$$

A more complete description and diagram of the section-half capacitance can be found in [3], [5].

The self-resonant structure is constructed from many sections that are separated from each other by a low-loss dielectric layer. Excluding the first layer, each section is excited by inductive coupling so no terminations are needed in the resonating high-current path. The strong coupling effectively puts all of the sections in parallel. Each section has a capacitance $\frac{C_{sh}}{2}$, and there is additional capacitance between a section and the layers above and below it. Therefore, a structure with m sections has a capacitance C_s of $C_s = mC_{sh}$, and a resonant frequency $\omega_0 = (C_s L)^{-0.5} = (mC_{sh}L)^{-0.5}$.

III. Achievable Resonant Frequency

This section examines how the size, winding height, and winding materials impact the minimum achievable resonant frequency of a size-constrained MSRS. The capacitance C_s of a MSRS is integrated into the winding, so a size constraint limits the resonant capacitance, and therefore the range of achievable resonant frequencies. The minimum achievable resonant frequency $\omega_{0,min}$ is calculated from an equation describing the height of the winding. The height of a MSRS winding h_w is

$$h_w = 2m(t_d + t_c) = \frac{4t_d}{L\omega_0^2 \varepsilon_d \theta (r_2^2 - r_1^2)}\left(t_d + t_c\right), \quad (2)$$

where t_c is the conductor thickness, t_d is the dielectric thickness, ε_d is the permittivity of the dielectric. The minimum achievable resonant frequency $\omega_{0,min}$ is found by solving (2) for ω_0, and is

$$\omega_{0,min} = \sqrt{\frac{4t_d}{Lh_w \varepsilon_d \theta (r_2^2 - r_1^2)}\left(t_d + t_c\right)}. \quad (3)$$

A. Impact of MSRS Size

The minimum achievable resonant frequency is highly dependent on the size of the structure. A structure with a larger size will have both a larger inductance and section-half capacitance, and therefore have a smaller $\omega_{0,min}$. The relationship between the achievable $\omega_{0,min}$ and the size of the structure is understood by considering a scaling factor ϵ, which scales all linear dimensions of a baseline magnetic core. We consider a baseline structure with an inductance L_0, core diameter of d_{c_0}, outer winding radius r_{2_0} and inner winding radius r_{1_0}. For this analysis, the winding materials are constant with scaling, so t_d and t_c are independent of ϵ.

The inductance of the scaled structure L is $L = \epsilon L_0$, as discussed in [7]. Given that $L \propto \epsilon$, and h_w, r_2, and r_1 are proportional to ϵ, $\omega_{0,min}$ is

$$\omega_{0,min} = \sqrt{\frac{4\left(\frac{t_d}{\varepsilon_d}\right)\left(t_d + t_c\right)}{(\epsilon L_0)(\epsilon h_w)\theta\left(\left(\epsilon\, r_{2_0}\right)^2 - \left(\epsilon\, r_{1_0}\right)^2\right)}}. \quad (4)$$

Therefore, $\omega_{0,min} \propto \epsilon^{-2}$, which highlights the challenge of creating small and low-frequency MSRSs. The impact of MSRS winding size and other design parameters on (3) is summarized in Table I.

B. Impact of the Winding Height

A constraint on the winding height limits the number of sections, and therefore the range of resonant frequencies that can be acheived. This phenomenon is highlighted by $\omega_{0,min} \propto h_w^{-0.5}$. It should be noted that the inductance of a MSRS changes slightly with the height of the winding; however, this is not included in our analysis. To demonstrate the impact of this assumption, a finite element analysis is used to calculate the inductance as a function of the fill factor with a fixed core height. For a pot core shape with a height of 16.2 mm and a diameter of 66 mm the the inductance value is within 20% of the nominal inductance value, which is the inductance with half of the winding window filled.

C. Impact of Winding Material Selection

The materials used to construct the winding of a MSRS impact the achievable resonant frequency. The impact of t_c, t_d, and ε_d on $\omega_{0,min}$ highlight the constraints imposed by material selection, $\omega_{0,min} \propto \sqrt{(t_d/\varepsilon_d)\,(t_d + t_c)}$. The impact of each variable on $\omega_{0,min}$ is described below. It should be noted that the fabrication processes and materials limit the achievable t_c, t_d, and ε_d. These limits are not considered in this section, but are discussed in Section V-A.

1) Dielectric Permittivity: The minimum achievable resonant frequency $\omega_{0,min}$ is inversely proportional to the square root of dielectric permittivity ε_d ($\omega_{0,min} \propto {\varepsilon_d}^{-0.5}$). Therefore, independent of t_c and t_d, selecting a dielectric material with a large ε_d increases the viable frequency range. It should be noted that in general dielectric materials with a large ε_d have a low quality factor Q_d, which is an upper bound on the Q of the MSRS.

2) Dielectric Thickness: Depending on the relative thickness of the materials ($t_d >> t_c$ or $t_d << t_c$), the impact of changing the dielectric thickness varies. If the thickness of the dielectric is greater than the thickness of the conductor ($t_d >> t_c$), then $\omega_{0,min} \approx t_d$. If the thickness of the dielectric is small compared to the thickness of the conductor ($t_d << t_c$), then $\omega_{0,min} \approx {t_d}^{0.5}$. Therefore, reducing the dielectric thickness is at least as effective at reducing $\omega_{0,min}$ as is increasing ε_d, and can be much more effective. Reducing t_d can be very beneficial in the design of size constrained MSRSs, but it should be noted that t_d limits the breakdown voltage of the dielectric, and could be the limiting factor in the power handling capability of the MSRS. This is discussed further in Section IV.

3) Conductor Thickness: The impact of conductor thickness on feasible frequency range also depends on the relative thickness of the materials. If the thickness of the conductor is much thicker than the thickness of the dielectric ($t_c >> t_d$), then $\omega_{0,min} \approx \sqrt{t_c}$, and if the thickness of the conductors is much smaller than the thickness of the dielectric ($t_c << t_d$), then the thickness of the conductor does not impact $\omega_{0,min}$. The conductor thickness can be reduced to decrease the size of a MSRS; however, the conductor thickness has a large impact on Q [3], [5] and a relatively small impact on $\omega_{0,min}$.

TABLE I
HOW MINIMUM ACHIEVABLE RESONANT FREQUENCY $\omega_{0,min}$ SCALES WITH MSRS PARAMETERS.

	Constraint	
Property	$t_d \gg t_c$	$t_d \ll t_c$
Size	ϵ^{-2}	ϵ^{-2}
Winding Height	${h_w}^{-0.5}$	${h_w}^{-0.5}$
Dieletric Permittivity	${\varepsilon_d}^{-0.5}$	${\varepsilon_d}^{-0.5}$
Dielectric Thickness	t_d	$t_d^{0.5}$
Conductor Thickness	t_c^0	$t_c^{0.5}$

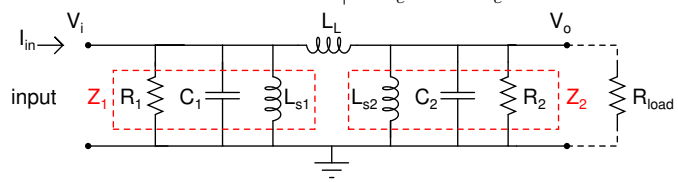

Fig. 2. A lumped element model of two coupled MSRSs. A load resistor R_{load} is shown, but is not inherent to the structure.

IV. POWER HANDLING

According to section III-C, minimizing the dielectric thickness t_d is key for reducing the size, thickness, and resonant frequency of MSRSs; however, utilizing thin dielectric layers decreases the dieletric breakdown voltage and therefore the power handling capabilities of the MSRS. In this section, we investigate how dielectric breakdown limits the power handling capability of the MSRS. It should be noted that the power handling of the MSRS is not necessarily limited by the dielectric breakdown voltage limit, and instead could be limited by other factors (e.g. health and safety concerns or temperature rise). The impact of temperature on the power handling capabilities of MSRSs is discussed in [6]. Therefore, analyzing the impact of dielectric breakdown voltage illuminates the limitations of thin dielectric layers by highlighting in-feasible MSRS designs, but does not guarantee a feasible design.

The maximum power that can be handled without dielectric breakdown P_{max}, can be derived from a lumped element model of two coupled MSRSs. The lumped element model, presented in Fig. 2, is constructed from a model of a single MSRS, which is the parallel combination of an equivalent inductor, capacitor, and resistor. The send structure has an impedance Z_1, which is $Z_1 = C_1||R_1||L_{s1}$, and the receive structure has an impedance Z_2, which is $Z_2 = C_2||R_2||L_{s2}$. This analysis assumes the system is operated at resonance, so the impedance of the inductor and the capacitor cancel each other such that $Z_1 = R_1$ and $Z_2 = R_2$. The magnetic coupling between the MSRS is modeled using a π transformer model. The load is modeled with a resistor R_{load}, and its value can be selected in order to maximize the efficiency of power transfer.

The optimal load resistance is dependent on the distance between the coils, R_1, and R_2, and can be found by minimizing the loss fraction with respect to R_{load}. The loss fraction λ is the ratio of the power lost to the output power. The output power is $P_o = V_{o,RMS}^2/R_{load}$ and the power lost $P_L = V_{in,}^2/R_1 + V_{o,RMS}^2/R_2$. We de-

fine a factor $F_{io} = V_i/V_o$, that is the ratio of V_i to V_o, where $F_{io} = j\omega L_L/Z_2 + j\omega L_L/R_{load} + 1$; therefore,

$$\lambda = \frac{||F_{io}||^2 R_{load}}{R_1} + \frac{R_{load}}{R_2}. \tag{5}$$

The optimal load resistance $R_{load,opt}$ is computed by solving $\frac{d\lambda}{dR_{load}} = 0$ for R_{load}, and is

$$R_{load,opt} = \sqrt{\frac{1}{\frac{1}{(\omega L_L)^2} + \frac{R_1}{R_2(\omega L_L)^2} + \frac{1}{R_2^2}}}. \tag{6}$$

Using $R_{load,opt}$, we compute the voltage across the dielectric in both the send and receive structure. The factor $F_{io} > 1$, so the input voltage is always larger than the output voltage. Thus, if the send and the receive structures are identical (as assumed in this paper), the dielectric breakdown would occur in the send structure. For an output power P_o, the maximum voltage across the dielectric of the receive structure is $V_o = \sqrt{\frac{P_o R_{load,opt}}{2}}$, and the maximum voltage across the dielectric of the send structure is

$$V_i \quad = F_{io}\sqrt{\frac{P_o R_{load,opt}}{2}}. \tag{7}$$

We assume that the breakdown voltage is $V_{bd} = E_{bd}/t_d$, where t_d is the thickness of the dielectric and E_{bd} is the dielectric strength of the material. So, the maximum power handling of a MSRS without breaking down the dielectric material P_{max} occurs when $V_i = V_{bd}$, which results in

$$P_{max} = \left(\frac{E_{bd}}{F_{io} t_d}\right)^2 \frac{2}{R_{load,opt}}. \tag{8}$$

The maximum power, as limited by dielectric breakdown, is impacted by many factors including design considerations of the MSRS (e.g size, height, and resonant frequency) and WPT system parameters (e.g. wireless range). The impact of these factors will be explored for two case studies in Section V.

V. Results

The analysis in Section III and IV outlines the achievable resonant frequency and power handling without dielectric breakdown of MSRSs. We apply this analysis to two case studies; one for a consumer electronic device, and one for an electric vehicle. These results both highlight the range of feasible designs for these two examples, and provide an example of how to apply the analysis presented in this work.

The achievable resonant frequency and power handling capabilities of the MSRS are significantly impacted by the thickness of the winding materials (t_d, t_c) and the electrical properties of the dielectric (ε_d, E_{bd}). In Section V-A, we discuss a few processes which could be used to create the winding of the MSRS, and some of the dielectrics associated with each process. In Sections V-B and V-C, we calculate the range of achievable resonant frequencies and P_{max} for MSRS designed for the two case studies.

A. Possible Winding Materials

The available materials for constructing the MSRS are dependent on the manufacturing process. To date, the MSRS has been constructed by stacking foil and polymer films, but there are other potential methods including low-temperature co-fired ceramics (LTCC) and thin-film deposition. In this Section, we discuss some of the dielectric materials that can be used with these construction processes, listed in Table III.

1) Stacking Films: Stacking foil and polymer films is a method which has been used to manufacture MSRS in [3]–[5]. The dielectric layers were constructed from either PTFE or polypropylene. Both of these materials have a relatively low dielectric constant (≈ 2), but are extremely low loss materials ($Q_d \geq 5000$) [8]. Another possible polymer film dielectric material is polyimide. It has significantly higher loss ($Q_d = 660$), but has a E_{bd} of 200 $\mathrm{V/\mu m}$, which is approximately $10\times$ larger than PTFE and polypropylene [8], [9]. We have found freestanding dielectric films available with thicknesses as low as 6 μm, but thinner dielectric film layers may be possible.

2) Low-temperature Co-Fired Ceramics: Low-temperature co-fired ceramic materials (LTCC) could be used to create the layers of the MSRS. The range of material properties that can be achieved using this method are explored by investigating the suite of products offered by ElectroScience, which offers a large number of dielectric pastes. ESL4113 is the lowest loss dielectric paste with $Q_d = 200$, which is $3\times$ less than polyimide and at-least $20\times$ less than PTFE, but it has a dielectric constant between 90–130, which is more than $25\times$ larger than the dielectric constant of the reported polymer films. The highest energy density dielectric paste is ESL4212-C. It has a dielectric constant of $12,000 \pm 1,500$, which is nearly $3000\times$ larger than the dielectric constant of the reported polymer films; however, it has a $Q_d = 33$, which makes it impossible to use in the construction of a high-Q MSRS [10].

3) Deposition: Deposition of dielectric material (e.g. alumina) and conductive layers could be used to produce dielectric layers more than an order of magnitude thinner than stacking films or LTCC. Alumina has a dielectric constant around 10, which is more than $3\times$ larger than the reported polymer films, and it has $Q_d = 1400$, which suggest that it can be used to create a high-Q MSRS [11].

B. Case Study I: MSRS for Consumer Devices

The frequency range and power handling of a MSRS that could fit into some consumer devices (e.g. laptop) is calculated using the theory discussed in this paper. We consider a pot core half, as in [4]. It has a diameter of 66 mm and a height of 3.5 mm, which constrains the winding to have a height of $h_w = 1.5$ mm, an inner winding radius of $r_1 = 14$ mm, and an outer winding radius of $r_2 = 27$ mm. The send and receive coil are identical.

The input voltage required to achieve a desired output power P_o is calculated based on the analysis in Section IV, and requires element values for the model in Fig. 2. The values of the elements are calculated based on a finite element simulation that models the inductors. The inductance values are a function of the wireless range x. The capacitors C_1 and C_2 are $C = \frac{1}{L_s \omega_0^2}$, so the impedance of the parallel combination of L_s and C is infinite. The values of C_1 and

TABLE II

POTENTIAL DIELECTRIC MATERIALS FOR CONSTRUCTING THE MSRS. THE PRESENTED DATA IS INTENDED TO PROVIDE A FIRST-ORDER ESTIMATE OF DIELECTRIC PERFORMANCE THAT CAN BE USED TO COMPUTE THE RANGE OF FEASIBLE DESIGNS OF MSRSS.

Construction Process	**Material**	**Material Properties** E_{bd}	$\frac{\varepsilon_d}{\epsilon_0}$	Q_d	**Minimum** t_d
Polymer Films	PTFE	19.7 V/µm [8]	2.1 [8]	> 5000 [12]	6 µm
	Polypropylene	23.6 V/µm [8]	2.3 [8]	5000 [13]	6 µm
	Polyimide	≈ 200 V/µm [9]	3.4 [9]	666 [9]	6 µm
LTCC	ESL4113	12 V/µm [10]	110 ± 20 [10]	200 [10]	35–50 µm [10]
	ESL4117	20 V/µm [10]	300 ± 30 [10]	150 [10]	35–50 µm [10]
	ESL4212	4 V/µm [10]	$12,000 \pm 1,500$ [10]	33 [10]	35–50 µm [10]
Deposition	Alumina	13.4 V/µm [8]	9.34 or 11.54 [8]	1428 [11]	n/a

TABLE III

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	Polyimide	≈ 200 V/µm [9]	3.4 [9]	666 [9]	6 µm
LTCC	ESL4212	4 V/µm [10]	$12,000 \pm 1,500$ [10]	33 [10]	35–50 µm [10]
Deposition	Alumina	13.4 V/µm [8]	9.34 or 11.54 [8]	1428 [11]	≪ 1µm

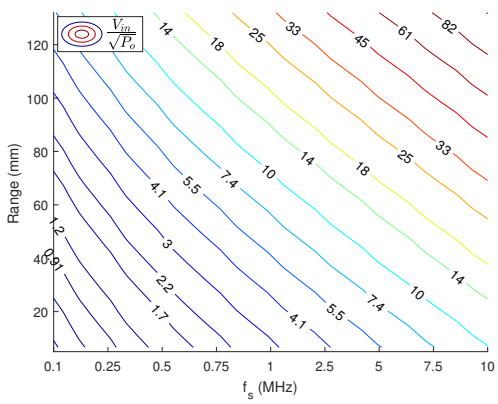

Fig. 3. The ratio $V_i/\sqrt{P_o}$ is plotted over a range of operating frequencies and wireless distances for the MSRS described in Case Study I. The maximum voltage in the MSRS can be calculated for an arbitrary power level by multiplying the plotted values by $\sqrt{P_o}$. The Q used to create this plot was 500.

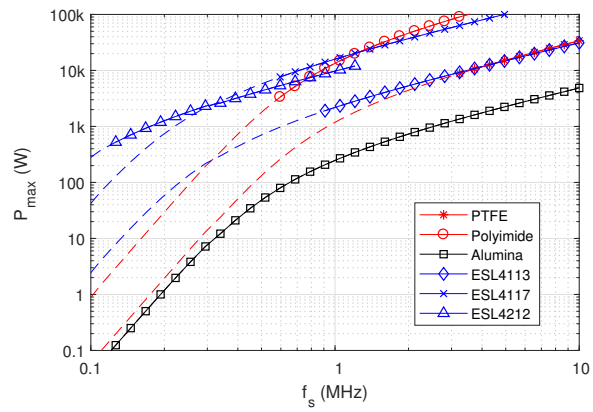

Fig. 4. The maximum achievable power without dielectric breakdown P_{max} is plotted as a function of resonant frequency for Case Study I. Very large values of P_{max} are not necessarily achievable in practice, but instead are an indication that dielectric breakdown is not a limiting factor. The optimal conductor thickness is used and the Q is assumed to be the Q of the dielectric Q_d. If the required dielectric thickness is less than the minimum available (listed in Table III), then P_{max} is plotted without any markers.

C_2 change depending on the desired resonant frequency, and to accommodate changes in L_s due to varying the wireless range. The resistors R_1 and R_2 are computed from the Q of the MSRS $R = Q\omega_0 L$, where L is the inductance of an uncoupled MSRS. We are making the simplifying assumption that Q is independent of frequency and range, which is not necessarily true, but allows the input voltage to be plotted without a specific MSRS design. Finally, the optimal load resistance is calculated from (6). From (7), it can be shown that at a specific wireless range and frequency the ratio $V_i/\sqrt{P_o}$ is constant. Therefore, the ratio $V_i/\sqrt{P_o}$ can be used to compare the input voltage at various operating conditions, and easily allows the maximum voltage to be calculated for an arbitrary power level. $V_i/\sqrt{P_o}$ is plotted as a function of wireless range and frequency in Fig. 3.

Both the wireless range and operating frequency impact the maximum voltage in the MSRS. As shown in Fig. 3, at long range and high frequency, $V_i/\sqrt{P_o}$ is large, so a large electric field must be sustained without breaking down the dielectric material.

The maximum voltage limits the range of operating frequencies and the achievable output power without dielectric breakdown P_{max}. For Case Study I, P_{max}, calculated by (8), is plotted in Fig. 4 based on the dielectric properties reported in Table III, the winding height, and the optimal conductor thickness. The conductor thickness is chosen to optimize Q, as discussed in [3]. The Q of the MSRS is assumed to be the Q of the dielectric Q_d. The P_{max} increases with the Q of the MSRS, so Q_d provides an upper bound on the achievable Q, and therefore power handling. In practice, the Q of the MSRS will be less than Q_d, so P_{max} will also decrease. Fig 4 assumes that the wireless range is 6.6 cm, or equivalent to the diameter of the MSRS. As shown in Fig. 3, decreasing the wireless range decreases $V_i/\sqrt{P_o}$, so at ranges less than 6.6 cm even more power could be handled.

For Case Study I, all of the dielectrics can be used to

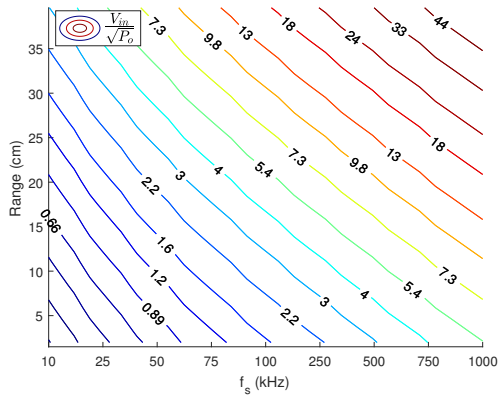

Fig. 5. Similar to Fig. 3 except $V_i/\sqrt{P_o}$ is plotted over a range of operating frequencies and wireless distances for the MSRS described in Case Study II.

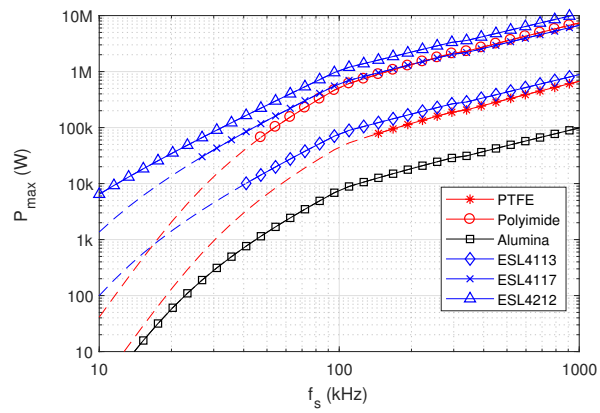

Fig. 6. Similar to Fig. 4 except P_{max} is plotted as a function of resonant frequency for Case Study II.

construct MSRSs that can handle a large amount of power ($P_{max} > 1$ kW) at frequencies above 3 MHz. At these frequencies, the power handling will not be limited by the breakdown of the dielectric, but instead by a thermal constraint. Reducing the resonant frequency reduces $V_i/\sqrt{P_o}$, so a smaller electric field needs to be supported; however, a larger capacitance is needed to achieve a lower resonant frequency, so the electric field must be maintained across a smaller distance. Therefore, although $V_i/\sqrt{P_o}$ decreases with frequency, the maximum achievable output power without breakdown is less at lower frequencies. ESL4212 can be used to create low-frequency MSRS, but the Q_d is 33, which makes it impossible to create a high-Q MSRS. Alumina can be used to construct a high-Q MSRS at a resonant frequency of approximately 300 kHz, and can handle 8 W at this frequency. For this case study, even if very thin PTFE and alumina were used, it would be challenging to meet the Qi standard of $\omega_0 < 200$ kHz, because P_{max} would be less than 2 W. However, if very thin polyimide dielectric was used, a relatively high-Q MSRS with power handling above 80 W could be created with a resonant frequency of 200 kHz.

C. Case Study II: MSRS for Electric Vehicles

In Case Study II, the frequency range and power handling of MSRSs that could be used to recharge electric vehicles is explored. For this example, the core has a diameter of 20 cm, a height of 5 cm, an available winding height of $h_w = 3$ cm, an inner winding radius of $r_1 = 43$ mm, and an outer winding radius of $r_2 = 82$ mm. The input voltage required to achieve a desired output voltage is calculated in a similar manner as Case Study I. $V_i/\sqrt{P_o}$ is plotted versus both frequency and wireless range in Fig. 5. For Case Study II, an input voltage of 500 V is required to achieve an output power of 10 kW for a 100 kHz MSRS operated at a wireless range of 20 cm.

The maximum achievable power without dielectric breakdown P_{max} is calculated for many dielectric materials and plotted in Fig. 6. The assumptions include: the Q of the MSRS is the Q of the dielectric $Q = Q_d$, the range is $x = 20$ cm, and the conductor thickness is chosen to maximize Q (presented in [3]). The highest Q dielectric, PTFE, can achieve a minimum frequency of 145 kHz, and can handle 79 kW without breaking down the dielectric. ESL4113 dielectric paste can achieve a resonant frequency as low as 40 kHz, and can handle more than 10 kW at that frequency. Alumina can achieve resonant frequencies below 10 kHz, but P_{max} due to dielectric breakdown is less than 1 kW below 40 kHz. For this case study, high-Q ($Q > 500$) MSRSs that can handle a significant amount of power can be created at frequencies as low as 50 kHz. Lower resonant frequencies can be achieved with alumina, but the power handling is limited (e.g. 1 kW at 40 kHz). Higher power levels could be handled at low-frequencies if thinner polymer films or dielectric pastes could be used.

VI. Conclusion and Future Work

The high-efficiency and long-range WPT achievable with the multilayer self-resonant structure (MSRS) makes it desirable for many WPT applications. The capacitance of the MSRS is integrated into its winding, which adds an additional design constraint compared to conventional coils. This paper provides analytical tools for exploring the achievable resonant frequencies and power handling capabilities due to dielectric breakdown of MSRS. This analysis is applied to two case studies; one for consumer electronics and one for electric vehicles. These examples highlight the large range of achievable frequencies that can be achieved with the MSRS and the large power handling capabilities of the structure, which makes the high-Q MSRS suitable for many WPT applications.

References

[1] E. Waffenschmidt and T. Staring, "Limitation of inductive power transfer for consumer applications," in *13th European Conf. on Power Electr. and Apps.* IEEE, 2009, pp. 1–10.

[2] C. R. Sullivan, "Cost-constrained selection of strand diameter and number in a litz-wire transformer winding," *IEEE Trans. on Power Electr.*, vol. 16, no. 2, pp. 281–288, 2001.

[3] C. R. Sullivan and L. Beghou, "Design methodology for a high-Q self-resonant coil for medical and wireless-power applications," in *14th Workshop on Control and Modeling for Power Electr. (COMPEL).* IEEE, 2013, pp. 1–8.

[4] A. L. F. Stein, P. A. Kyaw, J. Feldman-Stein, and C. R. Sullivan, "Thin self-resonant structures with a high-Q for wireless power transfer," in *Applied Power Electr. Conf. and Exposition (APEC).* IEEE, 2018.

[5] A. L. F. Stein, P. A. Kyaw, and C. R. Sullivan, "High-Q self-resonant structure for wireless power transfer," in *Applied Power Electr. Conf. and Exposition (APEC)*. IEEE, 2017.

[6] P. A. Kyaw, A. L. F. Stein, and C. R. Sullivan, "Power handling capability of self-resonant structures for wireless power transfer," in *IEEE PELS Workshop on Emerging Technologies: Wireless Power (WoW)*, 2018 in press, pp. 1–6.

[7] A. L. F. Stein, P. A. Kyaw, and C. R. Sullivan, "Figure of merit for resonant wireless power transfer," in *Workshop on Control and Modeling for Power Electr. (COMPEL)*. IEEE, 2014, pp. 1–7.

[8] W. Haynes, *CRC Handbook of Chemistry and Physics, 97th Edition*. CRC Press, 2016.

[9] "Dupont kapton summary of properties," http://www.dupont.com/content/dam/dupont/products-and-services/membranes-and-films/polyimde-films/documents/DEC-Kapton-summary-of-properties.pdf, accessed: 4-16-2018.

[10] "Electroscience thick-film materials and ceramics tapes," http://www.electroscience.com/, accessed: 4-16-2018.

[11] "Aluminum oxide, Al_2O_3 ceramic properties," http://accuratus.com/alumox.html, accessed: 4-16-2018.

[12] H. W. Starkweather Jr, P. Avakian, R. Matheson Jr, J. J. Fontanella, and M. C. Wintersgill, "Low-temperature dielectric behavior of polymers and copolymers of tetrafluoroethylene," *Macromolecules*, vol. 24, no. 13, pp. 3853–3856, 1991.

[13] R. Deshpande, *Capacitors*. Mc Graw Hill, 2015.