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ON IMPROVING POWER SUPPLY FLEXIBILITY

Ekpa T. K. [1*], *Sani S.*[2], *Hasssan A. S.*[3] *and Kalyankolo Z.*[4]

[1, 3,4]**Department of Electrical, Telecommunications & Computer Engineering, KIU-Uganda.**
[2]**Department of Mathematics, University of Eswatini-Eswatini.**

Abstract

The increasing variability of loads on power supply systems has led to even stricter flexibility requirements. This work reviews wireless power technologies for power supply system flexibility. Principally, methodologies for improving flexibility issues in wireless power supply systems are discussed with respect to coil structure and design strategies. Again, models for wireless power systems are discussed in view of evolving coil designs. Finally, a methodology for addressing limitations in existing models is proposed.

Keywords: Wireless Power Transfer, Alignment Sensitivity, Power Supply Flexibility, Magnetic Circuit

1.0 Introduction:

Energy is needed for human society to accomplish necessary functions. The preferred form of energy distribution worldwide is an electric power supply system [1]. An important feature of a power supply system is that the load location and magnitude vary with time [2]. Consequently, a power supply system needs to accommodate these changes for a better quality of user experience. Unfortunately, conventional approaches dealing with flexibility requirements in mobile devices use storage resources that require significant financial expenditure for implementation. Additionally, conventional approaches seem weak on changing load location and alignment which are enhancing co-ordinates for better user experience. For instance, using the conventional power supply system entails plugging a mobile phone when its battery runs down. During the recharging process, the phone is effectively tethered to a fixed location. This results in user inconvenience during maximum requirement times leading to a frustrating user experience.

Wireless power technologies offer several methods of improving power supply flexibility via the elimination of fixed tether of wired systems for a more inherent flexibility. Unfortunately, these methodologies further still have several limitations. First, wireless power transfer (WPT) systems are typically designed for smart devices in order to utilize the advanced communication and control capabilities of smart devices. However, most mobile phones in use are non-smartphones [3]. Moreover, problems such as higher power consumption of smartphones, dependency syndrome and the overall higher cost of using a smart phones have been identified as key factors in a trend towards increasing non-smartphone usage by Jardim [3] and Lin [4]. Thus wireless power systems need to accommodate non-smartphones which can neither easily regulate their instantaneous power demands nor accurately report their positioning and orientation relative to the power source. Consequently, there is an increased supply side burden to ensure system flexibility resulting in increasingly complicated coil designs to mitigate flexibility issues in wireless power systems. Subsequent sections discuss existing wireless power designs under three classes according to coil structure and overall design strategy.

2.0 Impedance Matching Methods.

Impedance matching was introduced in a prototype wireless power system for strong coupling between sources and loads to enhance power transfer by Cannon *et al*[5]. Unfortunately, changes in the load magnitude changes the resonant frequency and results in a loss of matching in the system.A study by Kim *et al* [6] also noted the effect of changing load magnitude on the resonant frequency. Thus, suggesting that impedance matching method degrades system flexibility over load magnitude without significant gains in flexibility over location and alignment. Liu and Wang applied impedance matching to a wireless power system for two devices, it was noted that changing loads negatively impact on the efficiency regulation [7]. An RF adaptive frequency control was proposed to maintain impedance matching.

Corresponding Author**:** Ekpa T.K., Email: ekpa.theophilus@stud.kia.ac.ug, Tel: +2347085715798

Zhang *et al*placed a relay coil between transmitter (Tx) and receiver (Rx) to improve flexibility over displacement [8]. However, the problems of impedance matching persisted in addition to variable positioning of the relay. Kim *et al*implemented switchable impedance networks to maintain impedance matching over varying load magnitude [9]. Although, this design demonstrated a stronger flexibility performance over load magnitude, the flexibility performance over load location and alignment was weak; see figure 1.Lee *et al* used a Tx reflector and a switchable capacitance to control impedance matching [10]. This method further strengthened flexibility performance over varying load magnitude and location but could not improve performance over alignment. An alternative design byKim *et al* maintained impedance matching by changing the operating frequency with respect to load location [11]. Unfortunately, health and safety concerns on high power fields operating at high frequency limit the application of the design.

Remark 1. *Impedance matching methods increase the susceptibility of power supply system flexibility to changes in load magnitude.*

Evidently, impedance matched wireless power supply systems are threatened by significantloss in efficiencies via loss of impedance matching. As such, impedance tracking components are required at additional costs and increasingly complicated design amidst weak flexibility performance over location and alignment.

3.0 Multiple coil methods

Fukushima *et al* designed a wireless power supply system with phase shifted power supplies applied to two Tx coils with an additional coil for reflected power suppression. The need for a symmetrical arrangement of the coils resulted in a weak performance over load alignment [12].Waters *et al* used two adjacent coils fed by phase shifted power inputs for short range power transfer [13]. The resulting field had alternating regions of maximum power which were controlled to coincide with the load location. As a drawback, this method required a separate radio feedback with its attendant cost of materials and increased design complexity.

Hu *et al*set up three adjacent coils as a pyramid design (figure 2) [14]. This design was less sensitive to changing alignment as demonstrated by an efficiency regulation of 25% over alignment. Again, the design could not improve flexibility over load location despite having a relatively bulky Tx design. A design by Kallel*et al* reduced the size of the Tx by using a matrix of flat coils [15]. Unfortunately, the flat shape degraded the flexibility performance over alignment as seen from a demonstrated efficiency regulation of 41.4%; see figure 3. In addition, the method required a feedback for auto-tuning which complicates the design.

Wang *et al* experimented with a flat anisotropic matrix of meta-material [16] and was able to improve the peak efficiency of the system but had no impact on the overall efficiency regulation. Nguyen *et al*used a meta-material array behind the Tx to concentrate the magnetic field [17]. The system demonstrated a relatively stronger flexibility performance than the system of Wang *et al* over changing load location although it also experienced degraded performance over changing load alignment. Zhang *et al* developed a system with two spaced Tx coils which produced a quasi-uniform field between them [18]. A major limitation of the system is that the load location is restricted to the region between Tx coils. Fu *et al* identified an additional problem of cross coupling between individual coils of multiple coiledTx which negatively affects system performance [19]. Unfortunately, designs to minimize cross coupling require additional compensation circuits at a cost.

Remark 2. *Multiple coil methods fail to enhance flexibility of wireless power supply systems over location.*

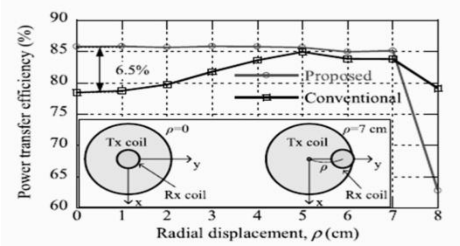

Figure 1: Comparison of power transfer efficiencies; [9]

Figure 2: Fabricated model of misalignment insensitive WPT system; [14]

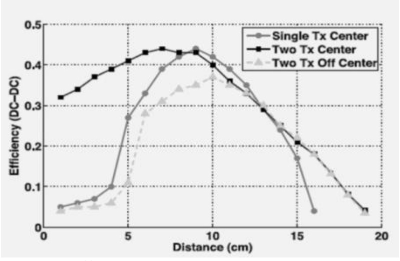

Figure 3: Efficiency versus distance comparisons with auto-tuning enabled; [15]

Figure 4: SCMR with two orthogonal loops each (connected) and embedded; [20]

Although multiple coil methods improve flexibility over alignment, they do not enhance flexibility performance over load location. Furthermore, the need for phase shifted or tuned power supplies and compensation circuits complicate system design and increases costs of construction. Alternatively, compound coil structures may better address flexibility issues over changing load location.

4. Compound coil structures:

Jonah *et al* introduced the orthogonal two-loop coil structure for Tx and Rx [20]; figure 4. This method achieved an efficiency regulation of 21% over four coordinates of alignment and displacement (see figure 6). However, an efficiency regulation of 91% over yaw rotation and *z*-displacement resulted in an overall weak flexibility performance. Daerhan*et al*presented a modified orthogonal three-loop coil with a resulting efficiency regulation of 6% over six coordinates of alignment and displacement [21]; (figures 5 and 7). The flexibility performance in this case was a remarkable improvement over previous methods. However, orthogonal loop coil structures are volumetric and bulky contributing to inefficient use of space on mobile devices.

Ekpa employed a spherical dipole coil as Tx and a flat rectangular dipole coil as Rx [22]. The system had an efficiency regulation of 10% over azimuthal displacement though, flexibility performance over axial displacement was poor at an efficiency regulation of 49%. John proposed a design based on parametric oscillation with a Tx comprising an array of circular coils linked by a helical tertiary coil [23]. Unfortunately, design and analysis of the system is very complicated.Choi *et al*adopted tri-axial crossed dipole coils as shown in figure 8 [24]. The resulting design had a receiver voltage regulation of 13% over alignment. A major complication in the design is the difficulty in analyzing the complex field distribution of the Tx using conventional methods.

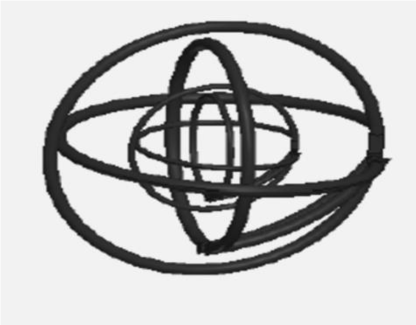

Figure 5: SCMR with three orthogonal loops; [21]

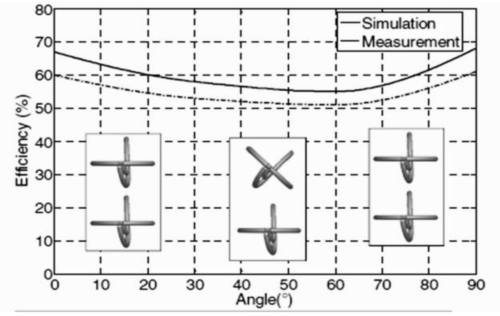

Figure 6: SCMR with two orthogonal loops with angular elevation misalignment; [24]

Remark 3. *Conventional wireless power models are not optimal for a straightforward discussion and analysis of compound coil structures.*

Complicated coil structures have unconventional geometries and symmetries. As a result, existing models for wireless systems do not adequately capture the peculiarities which arise from their unusual field distributions. For instance the coil structure of John produces a net field which is a superposition of a large number of individual fields from each coil of the circular array and the loops of the tertiary helix [23]. Conventional analysis of this coil would require a comprehensive study of its spatial geometry. Thus, there is a gap for broader discussions on simpler wireless power models for complicated coil structures.

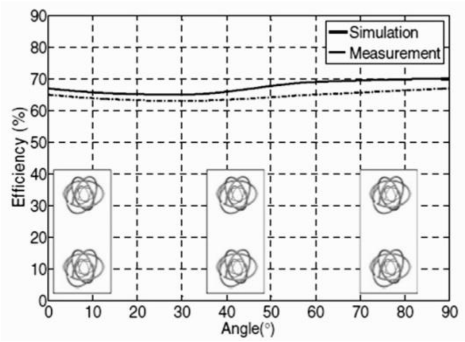

Figure 7: SCMR with three orthogonal loops with angular elevation misalignment angles; [21]

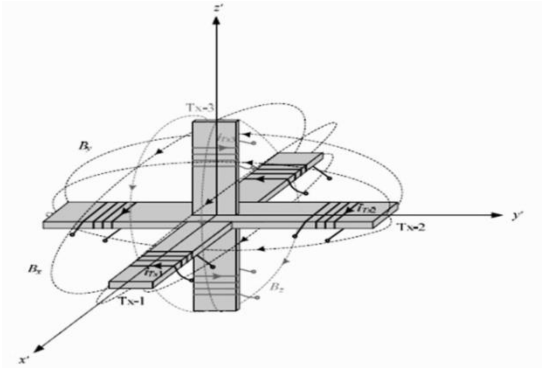

Figure 8: Three orthogonal dipole coils; [24]

5. Evolving WPT models with External Interferences:

The most common approach to modeling wireless power systems develops a transformer equivalent circuit for analysis discussed by Rim and Mi [25]. The physical properties of the coils are explicitly defined. However, this model is less accurate for compound coil systems at high frequency. Additionally, the transformer model does not consider external interferences on the wireless power system. Wireless power systems may be affected by ground plane interference where grounded ferromagnetic material within its operating space acts as a magnetic shield. This results in lower efficiencies and further degrades the flexibility performance by introducing unexpected loading on the wireless power system. Wireless power devices operate at frequencies typically in the KHz - MHz range. Interferences from large radio sources may induce significant sub-harmonics. Switching devices in large converter systems also produce non-characteristic interferences and sub-harmonics [26]. Sub-harmonics distort the sinusoid waveform which is the basic signal model for the transformer model resulting in inaccurate results for the system states. Systems designed based on the transformer model will thus show deviations between modelled and measured performance. Therefore, external interferences from high frequency circuits may significantly distort performance of wireless power systems.

Another approach represents the wireless power system as ann-port network of coupled resonators governed by a scattering matrix [27] and[28]. The use of s-parameters leads to more accurate derivations of power transfer and system efficiency at high frequency. However, the scattering matrix model does not provide information on the internal states of the wireless power supply system. Voltage and current waves cannot be simultaneously determined in the system. Therefore, one cannot evaluate power levels at internal points using the scattering matrix.

As a result, the level of compliance of the wireless power space with safety standards cannot be determined. Also, the scattering matrix model fails to capture external interferences on the wireless power system. The scattering matrix is a model for linear circuits, external interferences such as sub-harmonics are inherently non-linear. Consequently, such effects are not accurately represented in the s-matrix. We also note that a wireless power system for multiple devices is a network of cross-interacting nodes which may be operating at different frequencies. This leads to a large multi-port s-matrix in which case, analysis may require complicated techniques such as the MC procedure presented by Heuermann [29].

Conjecture 1. *Amodel of wireless power systems operating under external interferences may not exist in the literature.*

Wireless power systems are subject to external interferences which impact on their performances. Proper modelling of these systems requires an inclusion of interferences to accurately evaluate performance. A possible approach to incorporating interference in a model is to evaluate its electrical characteristics and then input additional loads in the transformer model. The governing voltage equations are given in this case are similar to that given by Rim and Mi[25]

$$v_1 = L_{l1}\dot{i}_1 + v_m \tag{1}$$

$$v_2 = nv_m - L_{l2}\dot{i}_2 \tag{2}$$

Where $v_m = L_m(\dot{i}_1 - n\dot{i}_2) = L_m\dot{i}_m$

Given measured coupled interference L_i, with coupling ratio k, this model can be extended in the form

$$v_1 = L_{l1}\dot{i}_1 + v_m + v_{mi} \tag{3}$$

$$v_2 = (nv_m + kv_{mi}) - L_{l2}\dot{i}_2 \tag{4}$$

Where $v_{mi} = L_i(\dot{i}_1 + n\dot{i}_2 - k\dot{i}_i)$

However, the challenges of the transformer model persist here. Moreover, the distinct coupling regime external interferences pose another challenge. Aggregation of many interference sources spread through the WPT space will increase the complexity of this model.The scattering matrix model may be extended in a similar manner as the transformer model.Given the electrical characteristics of an interference source, one can model this source as an additional port on the scattering matrix. The system amplitude equations of the scattering matrix model are given by Bodrov and Sul[27] as

$$V_1 = \sqrt{Z_0}(s_{+1} + s_{-1}),\ V_2 = \sqrt{Z_0}(s_{+2} + s_{-2}), \dots, V_n = \sqrt{Z_0}(s_{+n} + s_{-n}) \tag{5}$$

$$I_1 = \frac{1}{\sqrt{Z_0}}(s_{+1} - s_{-1}),\ I_2 = \frac{1}{\sqrt{Z_0}}(s_{+2} - s_{-2}), \dots,\ I_n = \frac{1}{\sqrt{Z_0}}(s_{+n} - s_{-n}) \tag{6}$$

Where s_+ and s_- denote incident and reflected waves. The scattering matrix for an *n*-port network is given by

$$S = \begin{matrix} s_{11} & \cdots & s_{1n} \\ \vdots & \ddots & \vdots \\ s_{m1} & \cdots & s_{mn} \end{matrix}, \tag{7}$$

Where $s_{mn} = \frac{V_{0m}^-}{V_{0n}^+}$

The wave amplitudes V_{0i}^- and V_{0i}^+ of interference sources can be introduced into the s-matrix. Unfortunately, the s-matrix is frequency dependent, and s-parameters are defined at a given frequency therefore, the introduction of sub-harmonic interferences may further complicate analysis. Furthermore, interference ports do not terminate in matched loads, thus the scattering parameter is the phasor quotient of the incident and exiting wave in the form $S_m = \frac{V_{0n}^-}{V_{0n}^+}$ which is more difficult to measure. For more on the discussion of multiple port scattering matrices, see the work of Stiles [30].

An alternative methodology may evaluate the magnetic properties of interference effects within a desired wireless power space. This may be actualized by measuring ambient fields in the location where the wireless power system will be deployed. Additionally, coupling to ferromagnetic planes may be measured over a suitable length of time to obtain an interference profile. The measurements of magneto motive force (mmf) and complex magnetic impedance for interference effects can be incorporated into thepower-invariant magnetic circuit model of Dominguez [31]. The system is a cascade of tow lossy gyrators between the electrical and magnetic domains such that

$$\sum_{input} VI = \sum F\dot{\emptyset} + \sum_{output} VI + P_{Lm} + P_{Le} \qquad (8)$$

Where P_{Lm} and P_{Le} are losses in the electrical and magnetic domains respectively.
In this regard, one can explicitly define ambient interferences within the magnetic domain by measuredmmf, F_i andcoupled impedanceZ_μ, the magnetic domain term becomes

$$\sum F\dot{\emptyset} = \sum F_m \dot{\emptyset_m} - \left(\dot{\emptyset_m}^2 Z_\mu + F_i \dot{\emptyset_m}\right) \qquad (9)$$

One can then apply energy methods or circuit theory to determine the power interactions due to external interference. The resulting analysis will expectedly retain the simplicity of circuit analysis while enhancing accuracy in representing the performance of WPT systems. Additionally, the analysis may be applied for all coil structures since the coil is characterized only by its mmf and gyrated impedance. This methodology may provide two way advantages. We can design wireless power systems with knowledge of interferences and their influence on system flexibility. Conversely, negative powers in the magnetic domain may also provide information on the interference which the wireless power system presents to radio networks. This may be of greater significance in WPT systems operating in the vicinity of low power wireless communication networks.

6. Conclusions and Future Work:

Compound coil structures demonstrate the best flexibility performance although difficulties in analysis persist. There is need for better approaches which analyze and improve flexibility issues in wireless power supply systems with simplicity. One approach may consider the wireless power supply system as a power transfer process through a magnetic circuit. By applying the formulation of the magnetic circuit by Dominguez [31], one can represent such a wireless power supply system as a network of complex reluctances and mmf sources.
In this regard, coupled interferences can be modeled successfully as series reluctances and mmf sources within the magnetic circuit. The resulting analysis is simple and applicable for any coil structure. Furthermore, such magnetic circuit design for wireless power systems ensures flexibility under interference conditions. The complex coupled differential equations arising out of the magnetic circuit design can be analyzed by the simple Langrangian energy methods. The dimensions of the Tx may be manipulated to ensure that load devices receive power with a high flexibility.

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