Overview of Electrically Conductive and Active Shielding for Wireless Power Transfer with a Polyphase Wireless Electric Vehicle Charging Study

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***Abstract*—The development and deployment of wireless power transfer (WPT) is increasing across industries including applications in healthcare, sensing and telecommunications, and electric vehicle charging due to its increased mobility and convenience. An important aspect of wireless power transfer is shielding to limit the intensity of electromagnetic fields (EMF) within external regions to protect users and nearby technology. Within this paper, the classifications and recent developments in shielding technologies are reviewed with discussion on potential benefits and drawbacks towards application for wireless charging of electric vehicles (EV). Additionally, a design study is proposed and simulated in 3D FEA for a novel active shield to substantially reduce magnetic field emissions of a high-power, high-frequency rotating-field 3-phase electromagnetic coupler for quickly charging electric vehicles. The active shield, designed to reduce Z-axis emissions, was found to be highly effective, reducing maximum EMF emissions by 83% in aligned static operation and by 50% with lateral misalignment. Active shielding was also found to strongly mitigate the impact of lateral misalignment at each studied partial alignment.**

***Index Terms*—Wireless power transfer, electromagnetic field (EMF) emissions, shielding effectiveness, inductive charging, electric vehicle.**

I. INTRODUCTION

Wireless power transfer (WPT) is an increasingly prevalent technology deployed in numerous industries, including healthcare and communications, for the charging of electric devices due to its increased mobility and convenience where wired connections are inconvenient, hazardous, or not possible. Inductive coupling, the most popular method of application, generates a large field for loose mutual coupling to transfer energy across a gap between the transmitter and receiver. Methods of directional electromagnetic field restriction are necessary for high power levels and large gaps between couplers to protect users and nearby devices from potential harm. Multiple standards exist for maximum allowed field depending on the applications ranging from general healthcare electromagnetic field exposure and wireless power transfer to electric vehicles [1].

High power wireless charging has been proposed and demonstrated (>100kW) to minimize EV charging time to near parity with combustion propulsion and for applications ranging from space-limited/urban charging, autonomous vehicle charging, and in-route in-motion charging [2]. Due to the large airgaps for electric vehicle charging, typically greater than 150mm, significant electromagnetic field (EMF) emissions may permeate the vehicle if not compensated with effective shielding [3]. For wireless electric vehicle charging EMF limitations, the ICNIRP 2010 standard and SAEJ2954 vehicle regulations, defining a maximum field strength of 27μTrms at 0.8m radially and from the center of the receiver coil, are the most popular targets for field compliance [1], [4], [5]. Shielding topologies previously proposed including those shown in Fig.1 include passive, dissipation of stray EMF through a material like in [6]; active, excited cancellation with conductive coils similar to [7]; and reactive, stray EMF induced cancellation of magnetic fields such as in [8].

In this paper, shielding classifications and a summary of methods previously proposed in the literature will be discussed for limiting magnetic field emissions below ICNIRP 2010 specified limits. Additionally, a design study is proposed and simulated in 3D FEA for a novel active shielding application to a 3-phase rotating field coupler pair for charging electric vehicles.

II. CLASSIFICATIONS AND REVIEW OF WPT SHIELDING

To transfer power inductively, a strong loosely coupled field is developed which may result in a large area-of-effect including regions outside of the operational area. The applied wireless power transfer shielding varies depending on the size of the airgap and intensity of the field, size and weight constraints of the charging system, and the relative positioning of the transmitter and receiver to one another. Active and passive shielding types, with examples shown in Fig.1, are the main classifications of shields depending on whether the conductive material is actively excited or passively dissipates stray EMF respectively.

An example WPT schematic is shown in Fig. 2 for wireless charging of an EV including the transmitter/receiver coil pair, a resonant compensation bank, a high-frequency inverter, and a vehicle-side rectifier with the vehicle's battery operating as a load. Ferrite plates are typically used to guide flux, increasing

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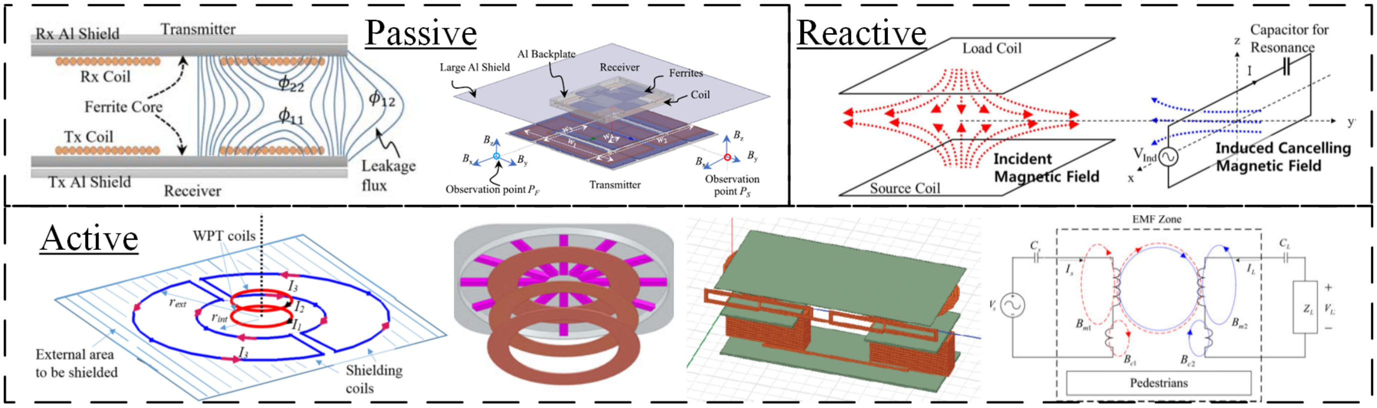


Fig. 1. Shielding coils for wireless power transfer ranging from passive to reactive to active cancellation. Examples graphics included from left to right, top to bottom are from: Mohammad *et al.*(2020), Mohammad *et al.* (2019), Kim *et al.* (2014); Cruciani *et al.* (2019), Tejada *et al.* (2017), Jiao *et al.* (2021), and Choi *et al.* (2013) respectively.

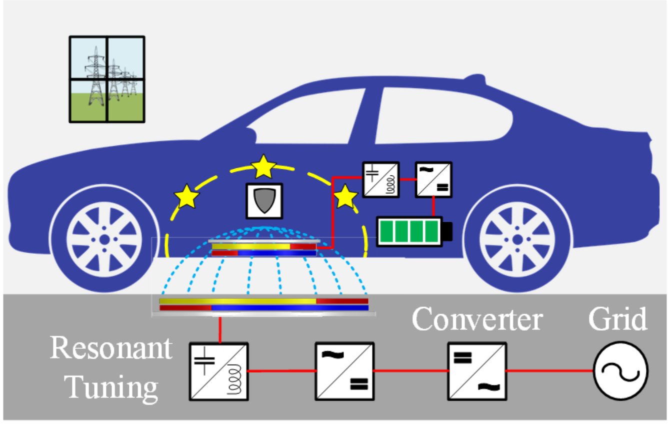


Fig. 2. Example application of wireless charging for electric vehicles using inductive coil coupling. Shielding is necessary to limit EMF within the dashed yellow boundary to restrict potential negative effects.

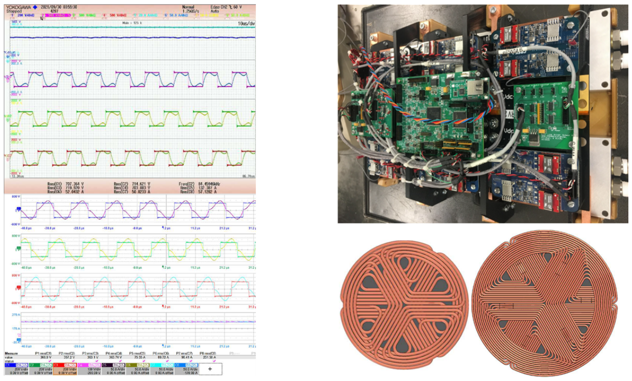

(a) (b)

Fig. 3. The proposed shielding design is for an existing set of rotating-field 3-phase coils with examples shown here with voltage and current waveforms from a previous experimental benchmark (a) and example power electronics and coil geometry of the prototype which currently employs conventional ferrite shielding (b) [2].

coupling between the transmitter and receiver coils [3]. The resonant compensation bank consists of reactive components enabling continuous operation regardless of switch conduction state, cancellation of coil-related self-inductance, and zero voltage switching (ZVS) operation [2]. The transmitter coil is driven by the output of an AC inverter at frequencies between 79-90kHz to induce a large magnetic field for loose mutual coupling across a large airgap. The induced current is rectified and bucked/boosted for delivery to the EV battery.

A. Passive Shielding

Passive shielding uses a conductive material selected to dissipate stray EMF. Metal plates of materials such as aluminum are commonly used for passive shielding with optimization having previously been proposed to maximize effectiveness and minimize losses [6]. Aluminum plates are the recommended shielding in SAEJ2954 standards for wireless electric vehicle charging to effectively limit EMF exposure to the driver at any position. Active US patents for passive shielding include EMF attenuation using a deployable grounding rod and using metallic ink [9] and the application of slots to cancel eddy currents in metal sheet shields [10].

Magnetic materials such as ferrite, typically used to guide flux during power transmission, have been proposed for the dual purpose of electromagnetic shielding in active US patents and papers including [9], [11]–[15]. A previous study has found that passive conductive aluminum shields are insufficient for bipolar transmitter/receiver pairs due to their unique flux distribution with ferrite shields proposed for effective shielding [16]. "Wing-type" ferrite shielding has also been proposed and developed previously to reduce EMF passively with minimal additional weight [17]. The main loss in magnetic materials shielding, including ferrites, is heat-producing hysteresis loss which can be reduced with geometric optimization [13], [18].

To restrict emissions effectively, passive shields are typically larger and thicker than alternatives at a similar power and frequency and have been found to be less effective at cancelling leakage field across a wide area [19]. Field cancellation offered by passive shielding can reduce system efficiency due to core loss and eddy current at high frequencies and result in substantial heating at high power levels but is suitable for dynamic and static charging.

B. Active Shielding

Active shielding employs electrically conductive coils powered either in series with the transmitting or receiving coils or through a separate circuit by auxiliary power electronics. The geometry of active shielding coils depends on the application environment, transmitter/receiver coil geometry, and intended utilization with examples varying between transversal coils, circumscribed coils, and planar adjacent coils [19], [20]. US patents for active shielding include the usage of a secondary element to mitigate electromagnetic radiation emissions [21], alteration of the control consecutive wireless transmitters to reduce combined EMF [22], and a separate converter unit designed to partially oppose field in the vehicle [9].

Utilization of active controlled flux cancellation has been studied to remove ferromagnetic material to reduce the weight and cost of the coil pair in other papers such as [19], [23]–[25]. Geometries for active shielding vary from circumscribed coils like in [26], [27], transversal coils similar to that proposed in [28], [29], and planar adjacent coils to protect nearby lanes [30]. Current excitation varies from paper to paper with some connecting the cancellation coil in series [19], [31], to those using separately excited and controlled cancellation [32].

While current can be controlled in the active shield to compensate for variation, this controllability requires an additional power source for operation, higher current is needed at misaligned conditions, and must consider the impact on power transfer [1], [20]. Additionally, active shielding introduces an extra layer of vulnerability as interruption of power could result in EMF levels exceeding safe limits.

C. Hybrid Shielding

Hybrid combinations of active and passive shielding have appeared throughout the literature including conductive and magnetic shielding, active and conductive shielding, and more advanced combinations. Efforts to combine active and passive shielding focus on minimizing weight, volumetric envelope, and impacts on efficiency while suppressing EMF below the specified limits [13]. Some past work has deployed active and passive shielding in the same design to utilize the benefits of both to ensure necessary EMF mitigation in the front and sides of the vehicle [33].

A popular hybrid combining active and passive methods is reactive shielding which uses stray field emissions to power a circuit containing the cancellation coils within the MHz frequency band. Geometries reported in literature vary from Litz wire to planar conductors [34] with some which self-tune their resonant behavior [35]. Active US patents for reactive shielding include the usage of induced current in a shield structure to cancel EMF that doesn't contribute to power transmission [36]. Efforts are ongoing to reduce overall efficiency degradation for reactive shields while considering field attenuation capability [13], [37], [38]. While this method does not suffer from the significant development of power electronics and associated efficiency of active shielding, it is dependent on the orientation of coils relative to one another, which may restrict utilization to stationary charging with very precise positioning.

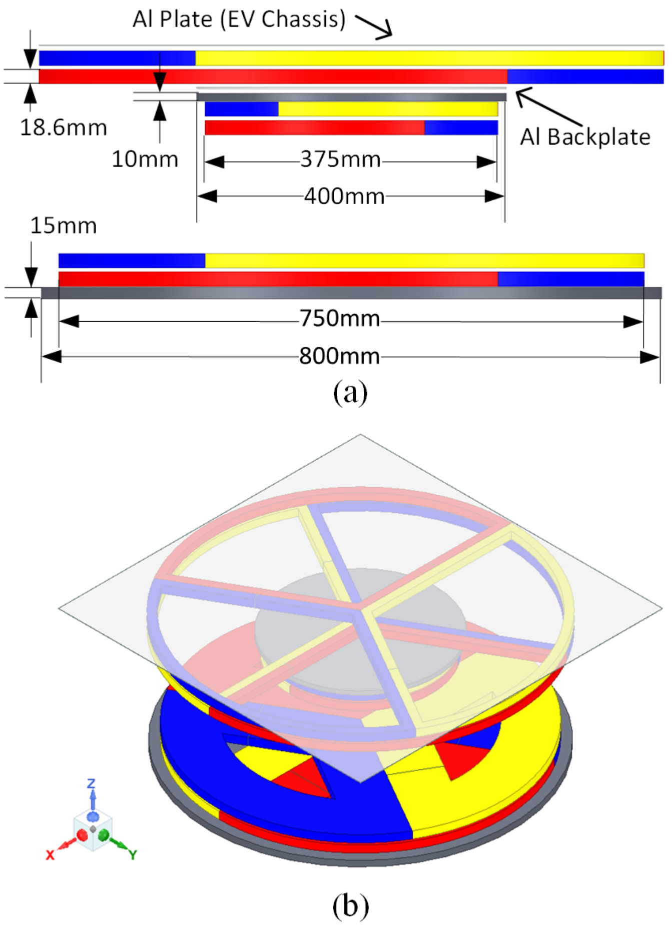
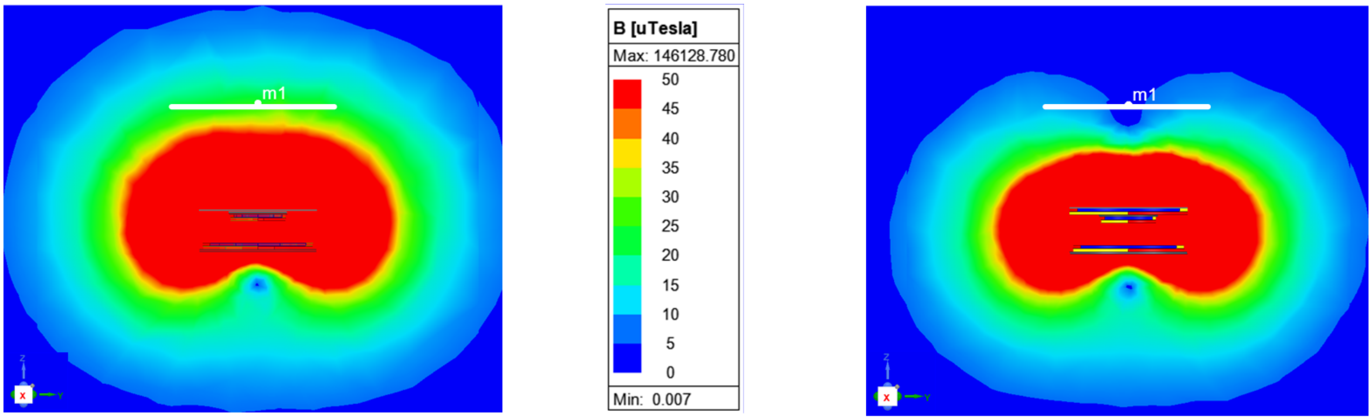


Fig. 4. A cross-sectional view (a) and 3D FEA model (b) of the polyphase coupler pair including active shielding on the secondary side and an aluminum plate resembling the vehicle chassis.

D. Challenges and Limitations

Vehicle-side shielding is necessary to avoid high power loss in the chassis and attenuate stray magnetic field from effecting the interior. EMF intensity increases with the square root of the power level and varies with alignment, requiring the development and deployment of varying shield technologies depending on the application environment [1]. The dosimetry of EMF throughout passenger cars has been investigated in multiple prior papers including [39], [40]. One recent paper investigated the potential impact on implanted pacemakers and found that they were resilient to the exposure resulting from dynamic wireless car charging [41].

Constraints on shielding for EV charging include the available volumetric envelope, the gravimetric allowance, and ef-



(a) (b)

Fig. 5. Example rotating field 3-phase WPT coil FEA results on the X-Z plane for the basic type with aluminum shielding (a) and with an operational series-connected active shield (b). The white line indicates the plane where B-field intensity is compared, 0.8m above the bottom of the secondary coil.

ficiency reduction to minimize the impact of WPT-associated systems on the EV's driving range. The ideal target for such systems is to reduce weight and size of shielding on the secondary side as much as possible while constraining EMF below safe standards.

III. DESIGN STUDY FOR A 3-PHASE ROTATING FIELD ULTRA-FAST CHARGERS

An active shield was designed and simulated in ANSYS Maxwell 3D finite element analysis (FEA) [42], [43] for 100kW rotating field polyphase coils, illustrated in Fig.4, to evaluate suitability for reducing stray EMF emissions while minimizing the impact on electric vehicle design. Polyphase coils have been shown to have a more uniform magnetic field distribution, deliver constant power, and have a higher power density compared with single phase bipolar alternatives [2]. A previous study of polyphase coil shielding focused on passive magnetic shielding, requiring two layers of magnetic shield to suppress EMF under maximum misaligned conditions [14].

Active shielding may allow for a smaller form factor than passive magnetic alternatives, depending on the impact on system performance. Using experimental voltage and current waveforms from a benchmark, shown in Fig.3(a), a rotating field polyphase coil pair, with geometry and power electronics shown in Fig.3(b), was simulated. The performance of the modeled polyphase couplers matched the mutual inductance reported in [2] at 1.2μH for 100kW operation with 250A in the primary, 160A in the secondary, and a 150mm airgap. The active shield was designed to specifically reduce maximum B-field intensity 0.8m above the bottom of the secondary receiver below 27μTrms in compliance with ICNIRP 2010 limits.

A conventionally shielded variant was also implemented and simulated using the suggested recommendations from SAEJ2954 including a 0.8m by 0.8m by 0.1mm aluminum plate to reduce emissions at 0.8m on the side planes or X and Y axis [16]. Following SAEJ2954, both designs also included two plates of ferrite on the bottom and top of the transmitter and receiver coils respectively to focus flux between the coil pairs and a thin large aluminum plate above the receiver ferrite to represent the EV chassis. Dimensions are shown labelled on the 2D view of Fig.4(a) and the 3D view is shown in Fig.4(b). Simulations were ran to attempt ferrite-less operation in efforts to reduce cost and weight using the active shielding but performance dropped 50% from 1.2 to 0.6μH.

IV. RESULTS AND DISCUSSION

Multiple parametric studies were performed varying active coil geometry including outer diameter and rotational angle assuming a series connection with the secondary and single turn throughout. An outer diameter of 800mm was selected to minimize B-field emissions as much as possible while remaining within the maximum area from SAEJ2954. Contrary to conventional WPT coils, the rotating polyphase coil field necessitates an active coil whose field also rotates accordingly. The angle of rotation for the active coil relative to the secondary was swept to reveal that the best angle was, as expected, that which matches the primary's rotation.

The magnetic flux density distribution in the XZ plane for the initial configuration with aluminum shielding is depicted in Fig.5(a) for a phase of 0 degrees. Application of the proposed active shielding, with resulting B-field in the XZ plane in Fig.5(b), reduces emissions at the target plane from a peak of 23μT to 4μT at a phase angle of 0. The modification of the flux density distribution indicates effective shielding capability for the stationary case with maximum alignment. Additionally, the aluminum plate used in the conventional passive shielding was removed in the active variant without reducing effective shielding in the Z-axis.

The maximum B-field intensity across all phases is shown in Fig.6 for 4 variants of the polyphase coupler coils at varying distance of the XY observation plane. While the aluminum shield variant performs best at distances from 300 to 400mm from the secondary receiver, the active shield reduces B field emissions below the ICNIRP 2010 limits, indicated by the gray dotted line, as early as 600mm. If the limits were to shift to 54μT at 500mm displacement, indicated on Figure 6

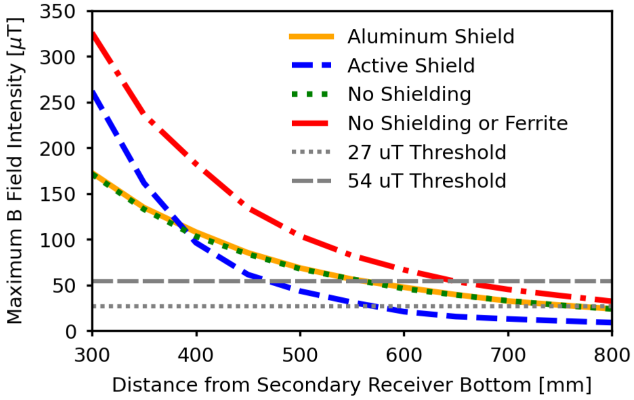


Fig. 6. Maximum B-field intensity recorded on an observation plane swept from 300 to 800mm from the bottom of the secondary receiver. The gray dotted line is the maximum limit for the ICNIRP 2010 standard on EMF emissions and the gray dashed line is twice that limit.

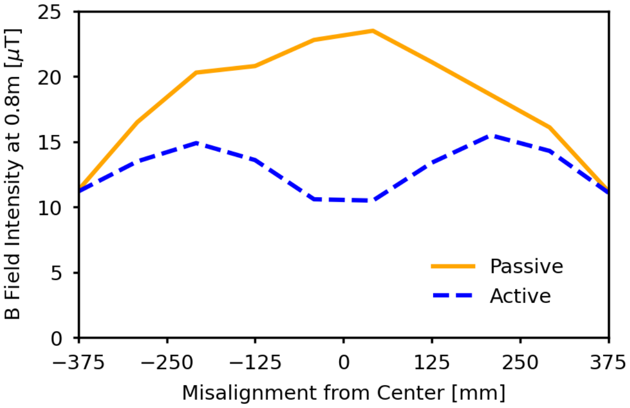


Fig. 7. Maximum B-field intensity at 0.8m from the bottom of the secondary considering misalignment in the Y-axis. Power is scaled depending on misalignment assuming LCC-S compensation.

with the gray dashed line, the active shield would be the only successful solution. This suggests that the size and weight of the active shield can be reduced further while maintaining sufficient shielding, reducing vehicle-side impact.

A study of misalignment was also performed by varying alignment across the Y-axis from maximum alignment/centered position with results shown in Fig. 7. Following the behavior of a WPT system compensated with an LCC-S configuration, power through the coil is reduced relative to the percentage of misalignment from the center position. Comparing the maximum B-field intensity at 0.8m Z-axis displacement, the single peak associated with the passive shield variant is reduced to two peaks at half of the magnitude. Significant reduction in B-field intensity at all studied positions of partial alignment suggest that the employed active shielding can greatly mitigate the expected impact of lateral misalignment.

V. CONCLUSION

This paper reviews the principal ideas and technologies proposed for EMF shielding of inductively coupled wireless power transfer in a variety of disciplines including the definitions of passive, active, and hybrid type shields. A survey of the recent literature in wireless power transfer is presented alongside some of the challenges and limitations in design application. An example is given for electric vehicle charging including application-specific challenges and limitations.

A design study is introduced proposing and simulating novel active shielding for a high-power 3-phase rotating field wireless charging of electric vehicles. The proposed active shield reduces maximum EMF emissions in the Z-axis by 83% in static operation and by 50% with lateral misalignment compared to a passive aluminum shielding recommended by the SAEJ2954. The impact of lateral misalignment is also greatly mitigated by active shielding as the B field intensity is reduced at all studied partial alignments. Future work may extend the active shield effectiveness to the front and side planes or reduce overall size while maintaining shielding capability.

ACKNOWLEDGMENT

This work was supported by the National Science Foundation (NSF) Graduate Research Fellowship under Grant No. 1839289. Any findings and conclusions expressed herein are those of the authors and do not necessarily reflect the views of the NSF. The support of ANSYS Inc., and University of Kentucky the L. Stanley Pigman Chair in Power endowment is also gratefully acknowledged.

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