Harmonic Reaction Inductive Folded Dipole Antenna for Direct Connection With Rectifier Diodes

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ABSTRACT In this paper, we present a harmonic reaction inductive folded dipole antenna (FDA) for a highly efficient rectenna which is close to the fundamental limitation on efficiency. To remove lossy RF circuit components of the rectifier, the proposed antenna topology integrates circuit functionalities for highly efficient rectification, such as impedance transformation to high-impedance, impedance matching, DC blocking, and harmonic reaction. The proposed antenna is connected directly to rectifier diodes. Thus, the rectification efficiency can be improved toward the fundamental limitation restricted by the performance of the rectifier diode. In experimental investigations of the 2.4 GHz band antenna, the antenna radiation efficiency is 99.2%, and the degradation due to integrated circuit functionalities is negligibly small. The 2.4 GHz band bridge rectifier achieves a rectification efficiency of 91.1% at an input power of 30 dBm. This clarifies the effectiveness of the efficiency improvement with the proposed direct connection topology between the proposed FDA and bridge diode.

INDEX TERMS Bridge rectifiers, harmonic reaction, inductive high-impedance folded dipole antennas, rectennas.

I. INTRODUCTION Microwave power transfer (MPT) can wirelessly transfer electric power to distant devices, and widespread social implementation of this technology is expected. Since the 1960s, solar power satellite systems have been studied [1]–[4]. The system collects solar power in a geostationary orbit and transfers it to Earth using MPT. In addition, MPT systems have been studied for commercial-based utilizations, such as transferring electric power to buildings or unmanned aerial vehicles (UAVs), such as drones and airships [5]–[7].

For enlarging MPT systems, it is important to realize high-power transfer systems with high transmission efficiency. Thus, a rectenna that is a receiving component of the MPT system must be a high-power operation as watt-class with high efficiency [3], [4].

The rectenna is consisting of a receiving antenna and an RF rectifier. For receiving antennas, dipole antennas or patch antennas have been used for watt-class rectennas [7]–[10]. There are several topologies for watt-class rectifiers [6]–[16]. Most rectennas employ a single-shunt rectifier that consists of a diode and a low-pass filter (LPF) for harmonic reaction, and it operates as a full-wave rectification [6]–[8], [11], [12]. In common cases, antennas and single-shunt rectifiers are independently optimized to the 50 Ω interface and are connected to the integrated rectenna. Another topology is the bridge rectifier. In the 1960s, a bridge rectifier was investigated for high-power MPT systems [9]. After this report, there have been fewer reports on high-power rectification with bridge rectifiers. In the 2010s, we reported high-power bridge rectifiers again with a focus on their possibilities for monolithic integration and high efficiency [13]–[16]. In these studies, we demonstrated an improvement in the rectification efficiency with a high-impedance RF source.
The rectification efficiency can be improved because of the high-voltage and low-current operation of the diode.

To realize a high-impedance RF source, we proposed a high-power rectenna with a high-impedance folded dipole antenna (FDA) [14]. Furthermore, an L-type LPF with the functionalities of impedance matching and the odd-order harmonic reaction is connected between a bridge diode and a high-impedance FDA to improve the rectification efficiency. The reported 2.4 GHz band rectenna with the FDA with an antenna impedance of 470 $\Omega$ achieved a rectification efficiency of 80.0% at an input power of 26.2 dBm with commercial Si Schottky barrier diodes (SBDs). However, owing to the insertion loss of the L-type LPF, the rectification efficiency decreases from the fundamental limitation of rectification efficiency, which is restricted by the bridge diode performance. In the past, there were some discussions on the rectenna topology with the FDA [17]–[20]. The above results with FDAs were investigated for low-power operations less than 1 mW, such as RF-IDs or energy harvesting. In these cases, there are few discussions on the harmonic reaction for rectification efficiency improvement, due to low harmonics’ generation of rectifier diodes in the low power operation.

This paper presents a harmonic reaction inductive high-impedance FDA for a highly efficient high-power rectenna as watt-class. The proposed antenna has circuit functionalities, such as impedance transformation, impedance matching, third-order harmonic reaction, and DC blocking. This harmonic reaction inductive high-impedance FDA is directly connected to the bridge diode. To improve the rectification efficiency, the lossy circuit components are removed. To further improve the efficiency, the rectenna employs GaAs SBDs. In the following descriptions, the configuration, design procedure, and experimental investigations are discussed to clarify the effectiveness of the proposed antenna topology.

This study is an extension of a previous work [21], and we present additional discussions on the proposed antenna, as follows: i) The detailed antenna design, including its procedure, antenna radiation efficiencies, and antenna radiation patterns under the step-by-step implementation of circuit functionalities, ii) degradation of the antenna radiation efficiency versus the matching susceptance of the bridge diode, and iii) degradation of the rectification efficiency due to insufficient harmonic reaction characteristics of the antenna.

Furthermore, we discussed our previous study on a 5.8 GHz band rectenna with a short stub connected high-impedance dipole antenna [22]. The dipole antenna realizes the required admittance with a short stub that interferes with the radiation pattern. The proposed FDA can realize the required admittance without additional components, such as a short stub.

Discussions of this paper are organized as follows. In Section II, the configuration of the rectenna with harmonic reaction inductive high-impedance FDA is described. Furthermore, the functionality of the third-harmonic reaction on the feeder is presented. Sections III and IV show the rectenna design procedure and the experimental results of the prototype rectenna, respectively.

II. CONFIGURATION OF PROPOSED ANTENNA FOR HIGHLY EFFICIENT RECTENNA OPERATION

Fig. 1 shows the configuration of the rectenna consisting of a harmonic reaction inductive high-impedance FDA and a bridge diode. Harmonic reaction feeders (HRFs) and bridge diode are fabricated on the surface side of the substrate. On the reverse side, an inductive high-impedance FDA is connected to the DC output port of the bridge diode. The proposed antenna topology covers the above circuit functionalities for highly efficient implementation.

Fig. 2 shows a functional circuit diagram of the rectenna with the proposed FDA. The proposed FDA includes the functionalities of impedance transformation, impedance matching, third-order harmonic reaction, and DC blocking, as the front end of the bridge diode. The proposed antenna topology covers the above circuit functionalities for highly efficient implementation.

Fig. 3(a) shows the RF equivalent circuit schematics of the rectenna with the proposed FDA. The admittance $Y_{\text{ant}}$ of the proposed antenna is represented by the admittance $Y_{\text{fda}}$.
of the inductive high-impedance FDA and impedance $Z_{\text{feed}}$ of the HRFs as follows:

$$\frac{1}{Y_{\text{ant}}} = \frac{1}{Y_{\text{fda}}} + 2Z_{\text{feed}}.$$  

(1)

The HRFs are designed to be short at the fundamental frequency $f_0$ and open at $3f_0$ for the third-order harmonic reaction. The details of the HRF are discussed below. Thus, the proposed antenna admittance $Y_{\text{ant}}$ is given as

$$Y_{\text{ant}} = Y_{\text{fda}} \text{ at } f_0$$

$$= 0 \text{ at } 3f_0.$$  

(2)

The admittance $Y_{\text{rect}}$ of the bridge rectifier is represented by a resistance $R_{\text{rect}}$ and a capacitance $C_{\text{rect}}$, and $Y_{\text{ant}}$ is designed to be the conjugate admittance of $Y_{\text{rect}}$ at $f_0$ as follows:

$$Y_{\text{rect}} = \frac{1}{R_{\text{rect}}} + j\omega C_{\text{rect}}$$

$$= Y_{\text{ant}}^* = Y_{\text{fda}}^* \text{ at } f_0.$$  

(3)

The admittance $Y_{\text{fda}}$ of the inductive high-impedance FDA is represented by an admittance $Y_{\text{rad}}$ of the radiation function and a susceptance $B_{tr}$ of the short stub function as follows:

$$Y_{\text{fda}} = Y_{\text{rad}} + jB_{tr},$$

$$Y_{\text{rad}} = \left[n(R_s + jX_s)\right]^{-1} \approx \left(nR_s\right)^{-1} \text{ at } f_0,$$

$$B_{tr} = -\left(Y_t/2\right)\cot\theta_t,$$  

(4)

where $n$ is the impedance transformation ratio of the transformer. $Y_t$ and $\theta_t$ are the characteristic admittance and electrical length of the short stub constructed with two elements of the FDA, respectively. $\theta_t$ is obtained from the length $S$, as shown in Fig. 1. Fig. 3(b) shows the admittance $Y_{\text{fda}}$ behavior versus length $S$ of the short stub. The impedance transforming ratio $n$ is tuned using the ratio of the element widths of the FDA. In Fig. 3(b), $nR_s$ was designed to be 300. Thus, the susceptance $B_{tr}$ is tuned with the length $S$. With shortening $S$, $Y_{\text{fda}}$ indicates the inductive susceptance $B_{tr}$, maintaining the antenna conductance $1/(nR_s)$, as shown in the figure. $Y_{\text{fda}}$ is designed to be the conjugate admittance $Y_{\text{rect}}$ of the bridge rectifier. Thus, the design goal of the antenna admittance is given by (3) and (4), as follows:

$$R_a \equiv nR_s = R_{\text{rect}}, \quad Y_t \cot\theta_t = 4\pi f_0 C_{\text{rect}}.$$  

(5)

The antenna resistance $R_a$ is designed based on the rectenna characteristics of the maximum input power and rectification efficiency, as discussed in Section III. The inductive high-impedance FDA can integrate circuits’ functionalities of impedance transformation and impedance matching, as shown in Fig. 2.

Fig. 4(a) shows the RF equivalent circuit schematics of the HRF connected between the inductive high-impedance FDA and bridge rectifier. The HRF consists of a planar inductor $L_f$ and transmission lines $T_1$, $T_2$, and $T_3$, as shown in the figure. The transmission lines $T_1$, $T_2$, and $T_3$ are configured with a strip conductor on the surface side and an element conductor of the FDA on the reverse side, and $L_f$ is configured with the short stub on the surface side, as shown in Fig. 1.
As already described, the input impedance $Z_{\text{feed}}$ of the HRF is designed to be short at $f_0$ and open at $3f_0$. In addition, the HRF is opened at the DC. Therefore, the HRF implements the circuits’ functionalities of the third-order harmonic reaction and DC blocking, as shown in Fig. 2. As shown in Fig. 4(a), $Z_{\text{feed}}$ is derived as follows:

$$\frac{1}{Z_{\text{feed}}} = 1/\beta + 1/\beta_d, \quad Z_{\text{c}} = \frac{Z_1 + jZ_2 \tan \theta_2}{Z_2 + jZ_3 \tan \theta_2}, \quad Z_{\beta} = -jZ_3 \cot \theta_3, \quad Z_{\beta_d} = j\omega L_{\beta_d} + Z_{\beta_d}, \quad Z_{\text{d}} = -jZ_4 \cot \theta_1,$$

where $Z_1$, $Z_2$, and $Z_3$ are the characteristic impedances, and $\theta_1$, $\theta_2$, and $\theta_3$ are the electrical lengths of the transmission lines T1, T2, and T3, respectively. Fig. 4(b) shows the impedance locus of each point inside the HRF at $f_0$ and $3f_0$. $Z_c$ is designed to be short at $f_0$ and inductive at $3f_0$. $Z_d$ is parallel-connected with $Z_4$, which is the capacitive impedance of the open stub T3. At $f_0$, $Z_{\text{feed}}$ is short, as indicated by $Z_c$. At $3f_0$, $Z_d$ is designed to be in parallel resonance with $Z_c$, and $Z_{\text{feed}}$ becomes open. As a result, the HRF has the functionality of a third-order harmonic reaction. In addition, the HRF has the functionality of DC blocking because of the open-stub configuration on the FDA.

As mentioned in this section, circuit functionalities at the front end of the bridge diode can be implemented in the proposed antenna topology.

### III. DESIGN OF RECTENNA WITH PROPOSED FDA

This section describes the design procedure based on [22] of the 2.4 GHz band 1 W rectenna with the proposed FDA.

#### A. GAAS SBD MODEL

Fig. 5 shows the characteristics of the GaAs SBD for the bridge diode. Fig. 5(a) and (b) show the DC characteristics, and junction capacitance, respectively. The SPICE diode model parameters listed in Table 1 are extracted from the measured characteristics. The simulated results with the extracted model are in good agreement with the measured results. The SPICE diode model is employed in the following simulations using the harmonic-balance method.

#### B. ANTENNA PARAMETERS

An antenna admittance $Y_{\text{ant}}$ with a resistance $R_a$ and a matching susceptance $B_m$, as shown in Fig. 6, will be optimized for the 2.4 GHz band 1 W bridge rectifier. In the optimization, we assume that there are no circuit losses in the passive circuits to predict the fundamental limitation on the rectification efficiency, which is restricted by the performance of the bridge diode.

Fig. 7 shows the simulated rectifier characteristics, which depend on the antenna resistance $R_a$. Fig. 7(a) shows the rectification efficiency $\eta_{\text{rec}}$, (b) maximum input power $P_{\text{in}}$, (c) optimized DC load resistance $R_{\text{L}}$, and (d) optimized matching susceptance $B_m$. Rectification efficiency $\eta_{\text{rec}}$ is derived from $P_{\text{dc}}/P_{\text{in}}$, and it is a fundamental limitation restricted by the performance of the bridge diodes because of the no circuit loss assumption. $R_{\text{L}}$ and $B_m$ shown in Fig. 7(c) and (d) are optimized to maximize the rectification efficiency for each $R_a$. Rectification efficiency $\eta_{\text{rec}}$ is improved with the increased antenna resistance $R_a$ owing to the lower RF current operation of the rectifier diodes. Further, the maximum input power is decreased because the higher RF voltage $V_s$ with higher $R_a$ causes a breakdown of the rectifier diodes in the lower input power $P_{\text{in}}$. As shown in the results, a rectification efficiency $\eta_{\text{rec}}$ of 93.3% at a $P_{\text{in}}$ of 33.0 dBm is obtained with $R_a$ of 300 $\Omega$. At this $R_a$, the optimized $B_m$ is 4.1 mS, and the optimized $R_{\text{L}}$ is 380 $\Omega$. Thus, the required antenna admittance $Y_{\text{ant}}$ of the FDA is 3.3 $+j4.1$ mS at 2.4 GHz.

#### C. HARMONIC REACTION INDUCTIVE HIGH-IMPEDANCE FDA

In this section, the detailed design procedure of the harmonic reaction inductive high-impedance FDA is described.
The circuit functionalities are implemented in the proposed antenna in a step-by-step manner. Fig. 8 shows the dimensions of the FDAs in three cases: (a) a high-impedance FDA (Case 1), (b) an inductive high-impedance FDA with DC blocking feeders (DCFs) (Case 2), and (c) a harmonic reaction inductive high-impedance FDA (Case 3). The physical dimensions of the FDA designed for each case are listed in Table 2. Fig. 9 shows the simulated antenna performance of FDA in each case. We focus on the antenna admittance $Y_{\text{ant}}$, reflection coefficient $\Gamma_{\text{ant}}$ at $3f_0$ for the third-order harmonic reaction, antenna gain at an azimuth angle of $90^\circ$, and antenna radiation efficiency $\eta_{\text{ant}}$. The results are summarized in Table 3.

In Case 1, the functionality of the impedance transform is implemented by the FDA. The antenna resistance $R_a$ of 326 Ω is obtained with the ratio of the element widths $W_{\text{ele1}}/W_{\text{ele2}}$ of 2. The simulated radiation efficiency $\eta_{\text{ant}}$ is 100%. The FDA can implement the functionality of impedance transform without additional loss.

In Case 2, the inductive high-impedance FDA with DC blocking feeders (DCFs) is designed for comparison with the proposed topology of Case 3. The differentiation of each case is the functionality of the third-order harmonic reaction. In Case 2, the DCFs are added only for DC blocking. The DCFs are configured with the strip conductor on the surface side and the element conductor of the FDA on the reverse side, as in the HRF of Case 3. The widths of the strip conductors are designed by overlapping with the FDA. It is designed as a quarter-wavelength transmission line. To maintain $R_a$ under the addition of the DCFs, the antenna element length $H_{\text{ele}}$ of 55 mm is aligned. For further additional functionality of the impedance matching, the length $S$ of the short points is shortened from 24.5 mm in Case 1, to 13 mm to obtain conjugate matching with the
rectifier. Simultaneously, we need to focus on the degradation of the antenna radiation efficiency $\eta_{\text{ant}}$ owing to the shortened $S$ of the FDA for impedance matching. Fig. 10 shows the simulated FDA characteristics versus length $S$. As shown in Fig. 10, the required $B_m$ of 4.1 mS indicated in Fig. 7(d) is obtained with an $S$ of 13.0 mm. The simulated $\eta_{\text{ant}}$ is 99.4%. Thus, the efficiency degradation is 0.6%, which is the same as the matching loss of 0.26 dB. This implies that the low-loss implementation of the impedance matching functionality can be obtained with the inductive high-impedance FDA.

In Case 3, the harmonic reaction inductive high-impedance FDA is designed. To integrate the functionality of the third-order harmonic reaction into the FDA of Case 2, the HRFs are used instead of the DCFs. The widths of the transmission lines T1 and T2 are designed based on overlapping with the FDA. Their lengths and inductor $L_f$ are designed to be $Z_c$ of short at $f_0$ and inductive at $3f_0$. The open stub T3 is designed to be $Z_{\text{feed}}$ open at $3f_0$. As a result, the designed $Z_{\text{feed}}$ is 0.02 $-j13.9$ $\Omega$ at $f_0$, and 3.9 $+j6.6$ k$\Omega$ at $3f_0$. After the implementation of the HRF with the FDA, $Y_{\text{ant}}$ at $f_0$ is shifted from the matching condition. Therefore, the dimensions of the overall harmonic reaction inductive high-impedance FDA are readjusted, as indicated in Table 2. The simulated $\eta_{\text{ant}}$ is 99.2%, and the efficiency degradation is 0.8% from the FDA of Case 1. In addition, we need to focus on an insufficient issue regarding the open condition of the HRF at $3f_0$. Table 3 shows that the antenna reflection coefficient $|\Gamma_{\text{ant}}|$ at $3f_0$ is 0.77, which indicates the loss component for $3f_0$ recovery to DC. The influence of an insufficient $\Gamma_{\text{ant}}$ at $3f_0$ on the rectification efficiency is shown in Fig. 11, which is a source-pull characteristic at $3f_0$. With $|\Gamma_{\text{ant}}|$ of 0.77, and an arg $\Gamma_{\text{ant}}$ of 3.3° at $3f_0$, the estimated degradation of the rectification efficiency is 0.8%. Thus, an overall efficiency degradation of 1.6% is estimated in the antenna design. This is the loss of 0.07 dB for the implementation of the circuits’
TABLE 3. Design results of FDAs in three cases.

|     | $R_a$ at $f_0$ (Ω) | $B_a$ at $f_0$ (mS) | $|\Gamma_{\text{ant}}|$ arg $\Gamma_{\text{ant}}$ at $3f_0$ | Gain at 90° (dB) | $\eta_{\text{rec}}$ (%) |
|-----|-------------------|-------------------|------------------------|----------------|-----------------|
| Case 1 | 326              | -                 | -                      | 2.2            | 100             |
| Case 2 | 298              | 4.0               | 0.79, -163°              | 2.1            | 99.4            |
| Case 3 | 301              | 4.3               | 0.77, 3.3°              | 2.2            | 99.2            |

$\Gamma_{\text{ant}} = (1/300 - Y_{\text{ant}})/(1/300 + Y_{\text{ant}})$

D. SIMULATION OF OVERALL RECTENNA

Fig. 12 shows the circuit schematics of the overall rectenna simulation, and Fig. 13 shows the simulated performances of the bridge rectifier shown in Fig. 12. In the simulation, the antenna admittance $Y_{\text{ant}}$ employs the simulated values of the FDAs in Cases 2 and 3. Fig. 13 (a) and (b) indicate the rectification efficiency $\eta_{\text{rec}}$ and DC output voltage $V_{\text{dc}}$, respectively. In addition to the simulated results of Case 2 and Case 3, the simulated results with the ideal circuit blocks of Fig. 6 are added as Ideal in the figures. A simulated rectification efficiency of 91.7% at 32.5 dBm is obtained with the proposed antenna topology of Case 3. We have an efficiency improvement of 4.4% from Case 2, which is the effect of the third-order harmonic reaction. Furthermore, the rectenna with the FDA in Case 2, which excludes the third-order harmonic reaction, is evaluated to confirm the effectiveness of the third-order harmonic reaction.

Fig. 13 shows the measured and simulated antenna admittances $Y_{\text{ant}}$ of the harmonic reaction inductive high-impedance FDA. The extended S-parameter method [24] is employed for the admittance measurements of the proposed antenna. The measured $\Gamma_{\text{ant}}$ at $3f_0$ shifts from the simulated value. The estimated rectification efficiency degradation is 1.7%, which is higher than the simulated value of 0.8%, as shown in Fig. 11.

Fig. 15 shows the measurement setup for rectification efficiency $\eta_{\text{rec}}$ of the rectifier. The distance between the transmitting antenna and rectenna is 0.5$\lambda_0$, that is a near-field condition. The reference antenna that is the same configuration as the antenna for the rectenna is employed for highly accurate measurement of the input power $P_{in}$ to the rectifier, as shown in Fig. 16(a). The reference antenna is the FDA in Case 1, which has the same simulated antenna gain as the FDA used in the rectenna. The reference antenna is connected to a $\lambda_0/4$ impedance transformer to match reverse, and it is connected to the bridge diode through the via-holes. DC chokes are also implemented on the same side.

IV. EXPERIMENTAL EVALUATION

A photograph of the 2.4 GHz band rectenna with the harmonic reaction inductive high-impedance FDA is shown in Fig. 14. Megtron 7 [23] is used as the substrate, and four packaged GaAs SBDs of the bridge diode are mounted on its surface. The smoothing capacitor is mounted on its surface.
50 Ω. \( P_{in} \) is obtained after correction with the loss of the \( \lambda_0/4 \) impedance transformer. The DC output power \( P_{dc} \) of the bridge rectifier is measured using the setup shown in Fig. 16(b). The propagation condition of the radio wave is the same as that shown in Fig. 16(a). The prototyped rectennas are placed at the same position as the reference antenna. The rectification efficiency \( \eta_{rec} \) obtained by \( P_{dc}/P_{in} \) is defined as the efficiency of the bridge rectifier, which excludes the internal loss of the antenna.

Fig. 17 shows the measured and simulated rectification efficiencies \( \eta_{rec} \) and output voltages \( V_{dc} \) of the 2.4 GHz band bridge rectifiers with the FDA of Case 2 and Case 3. In the measurements, the input power \( P_{in} \) is controlled to be lower output voltage \( V_{dc} \) than the breakdown voltage of 27 V. In addition, the load resistance \( R_L \) is optimized to obtain the highest rectification efficiency. Both the measured and simulated maximum rectification efficiencies are in good agreement. With the prototype rectenna and the proposed antenna topology in Case 3, the measured rectification efficiency \( \eta_{rec} \) is 91.1% at an input power \( P_{in} \) of 32 dBm. In comparison to the rectenna with the FDA in Case 2, an efficiency improvement of 7.1% is obtained. The effectiveness of the proposed antenna topology with the HRF is confirmed to improve the rectification efficiency.

Fig. 18 shows the azimuth pattern of the measured and simulated antenna gains of the harmonic reaction inductive high-impedance FDA. The measurement setup is the same as that shown in Fig. 16(b). The antenna gain is calculated from the difference between the received power of a standard
dipole antenna and the input power $P_{in}$ of the rectenna. The standard dipole antenna is placed at the same position as that of the rectenna, as shown in Fig. 16(b). The input power of the rectenna is estimated from the measured $V_{dc}$ versus the input power $P_{in}$, as shown in Fig. 17(b). The measured antenna gain is 2.4 dBi at an azimuth of 90°, which is in good agreement with the simulated gain within 0.2 dB.

Fig. 19 shows the reported maximum rectification efficiencies of 2.4 GHz band rectifiers in previous studies. The bridge rectifier in our study achieved the highest rectification efficiency of 91.1% in the 2.4 GHz band 1 Watt class rectifiers.

V. CONCLUSION

In this study, we developed a harmonic reaction inductive high-impedance FDA for a highly efficient high-power rectenna. The harmonic reaction inductive high-impedance FDA has circuit functionalities, such as impedance transformation, impedance matching, third-order harmonic reaction, and DC blocking, with less additional loss. The 2.4 GHz band bridge rectifier with the proposed FDA achieved a rectification efficiency of 91.1% with an input power of 32 dBm. This efficiency is close to the fundamental limitation of 93.3%, which is restricted by the performance of the rectifier diode. Compared with the FDA, which excludes the harmonic reaction, a rectification efficiency improvement of 7.1% was obtained in the experimental investigation. The effectiveness of the proposed harmonic reaction inductive high-impedance FDA is confirmed through simulations and experimental investigations.

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