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Equivalent Circuit to Overcome Thévenin Limit for Receiving Lossy Dipole Antennas Motivated by the Poynting Streamline Analysis

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ABSTRACT In classical antenna theory, the Thévenin equivalent circuit is a commonly used tool to analyze the characteristics of receiving antennas. However, when dealing with a lossy antenna that is near a large load impedance, this circuit has limitations in determining the loss and scattered powers. To overcome this limitation, this work models and analyzes the antenna directly as a receiver and visualizes the flow of field energy around the antenna through generating streamlines of the Poynting vector field. Motivated by the Poynting streamline analysis, a new equivalent circuit for receiving lossy electric and magnetic dipole antennas is introduced in response to an incident plane wave, which addresses the shortcomings of the traditional Thévenin equivalent circuits.

INDEX TERMS Equivalent circuits, antenna loss, scattered power, Poynting streamline method, receiving antennas.

I. INTRODUCTION

FROM classical antenna theory, the equivalent circuit of a receiving antenna when responding to an incident plane wave is traditionally based on Thévenin's theorem, utilizing a series RLC circuit [1]. However, it is important to note that Thévenin's theorem is applicable only for evaluating currents, voltages, and power external to the sub-circuit replaced by the Thévenin equivalent circuit [2]. Consequently, the conventional Thévenin equivalent circuit possesses inherent limitations when analyzing receiving antennas with losses, making it challenging to accurately predict dissipated and scattered powers [3], [4], [5]. For instance, employing the Thévenin equivalent circuit implies that a receiving open-circuited lossy antenna would exhibit zero power dissipation and scattering due to the absence of current. However, these results are inconsistent with observations derived from full-wave models of receiving lossy antennas [5], [6].

The limitations of the Thévenin equivalent circuit model for receiving antennas were first identified in 2002 [7], sparking a lively debate on the accuracy of the equivalent circuit in describing receiving efficiency and scattered power. Love argued that the traditional model led to a paradox in which the receiving efficiency of any antenna could not exceed 50% [4], [8]. Collin addressed this paradox and explained that the real part of the internal impedance in the equivalent circuit represented the antenna's re-radiated field but not the total scattered power [3].

Numerous studies have confirmed the limitations of the Thévenin equivalent circuit model. In 2005, Andersen et al. conducted a study on the absorption efficiency of receiving antennas under matched load conditions, revealing a theoretical absorption efficiency range of 0% to 100% [9]. Best and Kaanta employed numerical analysis in 2009 to accurately calculate scattering and absorption powers, further affirming the limitations of traditional equivalent circuits in predicting energy consumption solely at the load [5].

To address these limitations, scholars have made continuous efforts to improve and modify the equivalent circuit model. Love proposed an enhanced model that incorporates both voltage and current sources for representing receiving antennas [8]. Geyi introduced an alternative equivalent circuit considering the coupling between transmitting and receiving antennas, providing a physical definition for the source and emphasizing the effectiveness of the traditional model in such scenarios [10]. Bray presented an improved equivalent model using passive distributed transformers and a perturbation method to predict absorption, loss, and scattering properties of receiving wire antennas [11]. Huang et al. proposed a constant power source model in 2021, assuming a constant and independent power capture by the antenna regardless of the load [12].

To date, there is no well accepted equivalent circuit model that effectively captures the characteristics of receiving antennas, particularly when it comes to losses and scattering properties of lossy antennas. This absence of consensus may stem from the absence of a direct method to model and comprehend the underlying physics of receiving antennas and establish a robust connection with the equivalent circuit. Additionally, there is a need for comprehensive validation to ensure the accuracy and reliability of the proposed equivalent circuit models.

The Poynting streamline approach is a possible method for modeling the response of a receiving antenna to an incident plane wave. This approach involves using the streamlines of the Poynting vector field to visualize the energy flow of the incident electromagnetic waves around the antenna. By tracing the distribution of energy from the far-field to the near-field region of the antenna, it becomes possible to clearly visualize the power available at the antenna load in a two-dimensional geometry. Similarly, the dissipated power can be represented in another two-dimensional geometry, where the energy from the field is absorbed and dissipated by the lossy materials of the antenna. Changes to the absorbed power resulting from variations in the antenna load impedance can be demonstrated by modifying the Poynting streamlines absorbed by the antenna. As a result, the Poynting streamline method provides a straightforward approach to comprehend the physical characteristics of the receiving antenna and can assist in the development of a new equivalent circuit.

The Poynting streamlines method was first introduced in the 1970s [13], [14], and has been used for receiving dipole antenna analysis [6], [15], [16], [17], reflector antenna study [18], superdirectivity antenna design [19], [20], [21], [22], mutual coupling analysis of array antennas [23], [24], and antenna gain improvement design [25]. In this paper, we use the Poynting streamlines analysis technique to analyze the characteristics of the receiving lossy dipole antenna under different load conditions and correlate it to the equivalent circuit. One can gain a clear understanding of the limitations of the traditional Thévenin equivalent circuit by examining the distribution of Poynting streamlines near open-circuited receiving lossy antennas. A new equivalent circuit model inspired by this method is proposed to overcome the limitations of the traditional Thévenin equivalent circuit in the analysis of a receiving lossy dipole antenna. A comparison between the traditional Thévenin equivalent circuit, the new equivalent circuit, and the full-wave method reveal that the proposed new equivalent circuit accurately predicts the absorbed powers by the antenna load and lossy

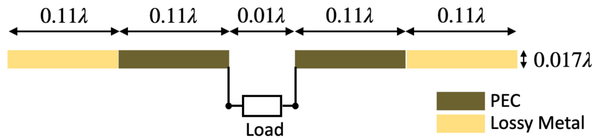


FIGURE 1. Receiving lossy dipole antenna dimension.

materials, as well as the scattered power of the receiving antenna. This verification of accuracy successfully addresses the limitations of the traditional Thévenin equivalent circuit when dealing with receiving lossy dipole and loop antennas under plane wave incidence. As a potential application, it can operate as a theoretical circuit model to more accurately investigate the scattering field under varying antenna load conditions, with the aim of minimizing the Radar Cross Section (RCS) of the receiving antennas [26].

II. POYNTING STREAMLINE ANALYSIS

A. RECEIVING LOSSY DIPOLE ANTENNA MODEL

Lossy dipole antennas are usually modeled by lossy materials. However, it may be difficult to distinguish the power difference between the lossy and lossless parts of the antenna. In order to clearly find the difference in the influence of the distribution of Poynting streamlines near the lossy and lossless parts of the dipole antenna, half the length of the arm is made of the perfect electrical conductor (PEC), and the other half of the length is made of lossy metal with a limited conductivity [6]. The dimensions and material properties of the receiving lossy dipole antenna are described in Fig. 1, where the antenna arm has a length of 0.22λ and a diameter of 0.017λ. The conductivity of the lossy metal is set to 15 S/m and the operating frequency of the dipole antenna is 1 GHz. The two arms are connected by a load with a gap distance of 0.01λ.

The load impedance Z_{load} is given by

$$Z_{\text{load}} = R_{\text{load}} + jX_{\text{load}}. \tag{1}$$

The antenna impedance Z_{ant} is given by

$$Z_{\text{ant}} = R_{\text{rad}} + R_{\text{loss}} + jX_{\text{ant}}, \tag{2}$$

where R_{rad} is the antenna radiation resistance and R_{loss} is the antenna loss resistance. Based on a full-wave model, the calculated R_{rad}, R_{loss}, and X_{ant} for the lossy antenna is 63.7 Ω, 49.8 Ω, and −37.6 Ω, respectively.

B. POYNTING STREAMLINE DISTRIBUTION

The streamlines of Poynting vector field are calculated by a full-wave model using the Finite Element Method (FEM) solver in HFSS from Ansys Inc. As shown in Fig. 2, a plane wave along the -z direction is incident on the receiving lossless and lossy dipole antennas under different load conditions. The incident field strength is 1 V/m and the polarization of the plane wave is linear and parallel to the dipole antenna. Streamlines terminated by the antenna load are marked in red, and streamlines terminated by the lossy

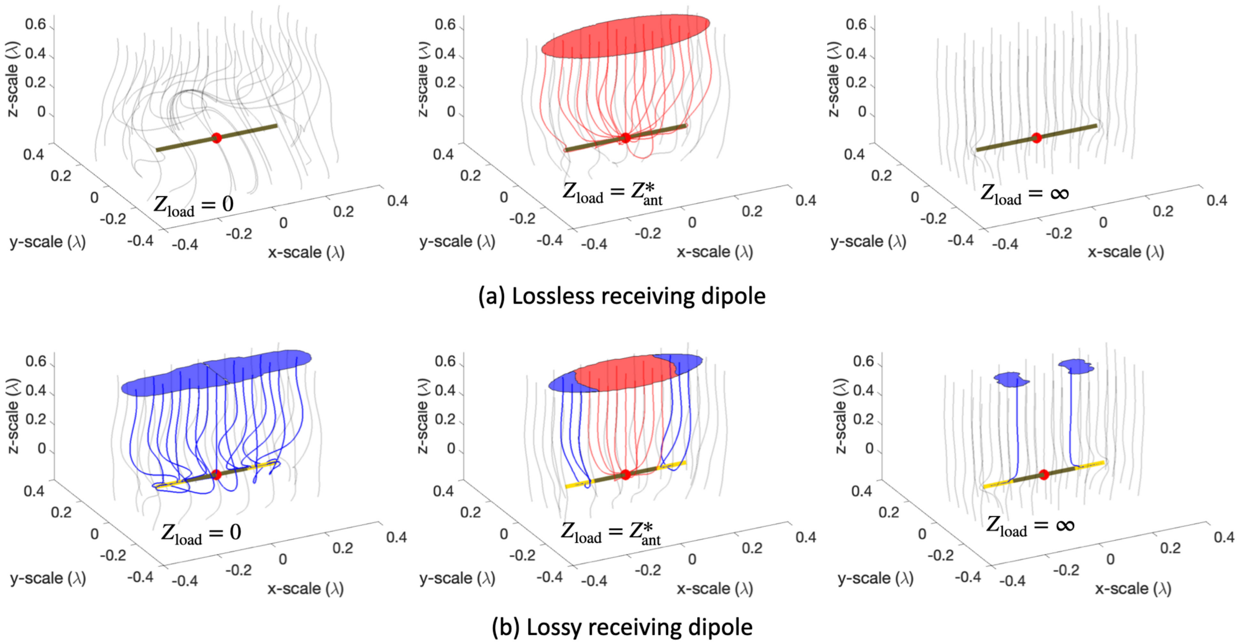


FIGURE 2. Poynting streamline distribution of lossless and lossy dipole antennas under different load conditions [6].

metal of the dipole arm are marked in blue. Other streamlines that went past the antenna are marked in gray.

In the plots of the distribution of Poynting streamlines, A_{load} is defined as the red-shaped region in the antenna's far-field region where the Poynting streamlines are terminated by the antenna load. Similarly, A_{loss} is defined as the blue-shaped region in which the Poynting streamlines are terminated by the lossy metal of the antenna. Since A_{load} and A_{loss} are defined in the far-field region of the antenna, the electromagnetic energy within these regions is evenly distributed. Therefore, $P_{\text{load,st}}$ defined as the power absorbed by the antenna load can be calculated by the following equation

$$P_{\text{load,st}} = A_{\text{load}} P_{\text{inc}}, \tag{3}$$

where P_{inc} represents the power density of the incident plane wave. Similarly, the power dissipated on the lossy metal of the antenna can be calculated as

$$P_{\text{loss,st}} = A_{\text{loss}} P_{\text{inc}}. \tag{4}$$

As the antenna impedance varies from 0 to infinity, the distribution of Poynting streamlines changes. At an impedance of 0 (i.e., a short circuit), no Poynting streamlines are absorbed by the load in a lossless receiving dipole antenna. The maximum bending of the Poynting streamlines indicates that the most scattered power is absorbed by the receiving antenna. However, in a receiving lossy dipole antenna, the absorption of Poynting streamlines by the lossy metal is represented by the blue shape area, which maximizes the loss power, $P_{\text{loss,st}}$. When the load impedance matches the antenna impedance conjugate, the red Poynting streamlines absorbed by the antenna load are maximized, resulting in the highest field energy absorbed by the antenna load. At infinite load impedance, the antenna becomes an open circuit.

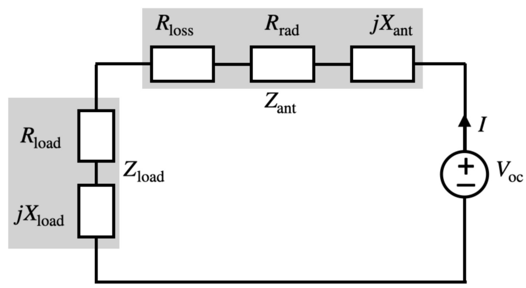


FIGURE 3. Traditional Thévenin equivalent circuit for a receiving antenna.

In both lossless and receiving lossy dipole antennas, no Poynting streamlines are absorbed by the load. For a receiving lossy dipole antenna, the number of dissipated Poynting streamlines in the lossy metal is close to the minimum, with the least bending indicating the minimum scattered power absorbed by the receiving antenna.

III. TRADITIONAL CIRCUIT LIMITATIONS

A. THÉVENIN EQUIVALENT CIRCUIT

The Thévenin equivalent circuit is the most commonly used circuit model for analyzing the receiving antenna [1], and has a good agreement with the load power when the antenna is under different load conditions [5]. The block diagram is shown in Fig. 3, where a constant voltage source V_{oc} is used, and the antenna impedance Z_{ant} is connected in series with the load impedance Z_{load}. The current I is determined by

$$I = \frac{V_{\text{oc}}}{Z_{\text{load}} + Z_{\text{ant}}}. \tag{5}$$

The power delivered to the antenna load is given by

$$P_{\text{load}} = \frac{1}{2} |I|^2 R_{\text{load}}. \tag{6}$$

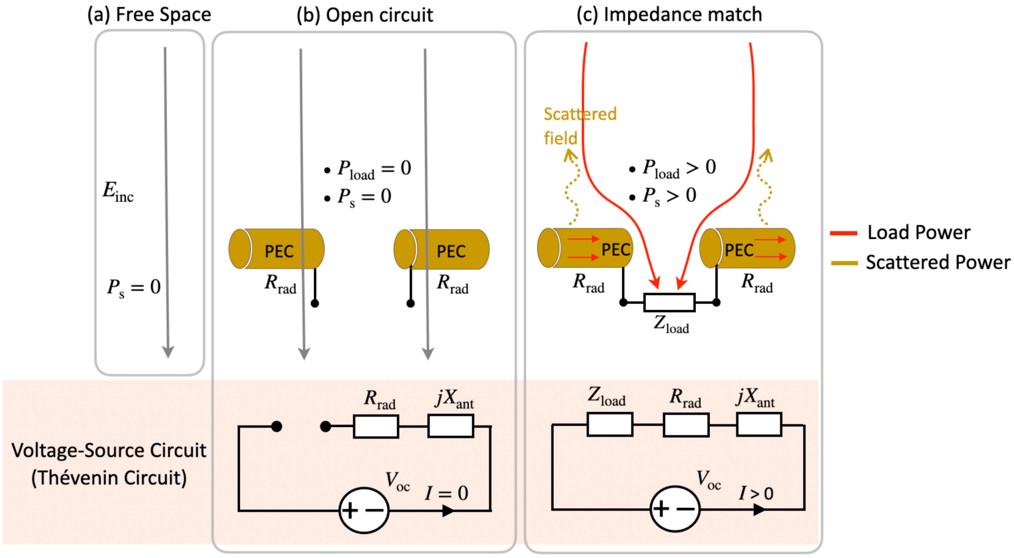


FIGURE 4. Correlations between Poynting streamlines distribution and Thévenin equivalent circuit for lossless receiving dipole antenna.

The dissipated power on the antenna's lossy material is

$$P_{loss} = \frac{1}{2}|I|^2 R_{loss}, \tag{7}$$

and the total scattered power by the receiving antenna is

$$P_s = \frac{1}{2}|I|^2 R_{rad}. \tag{8}$$

When the antenna impedance Z_{ant} is the complex conjugate of Z_{load}, the V_{oc} in the Thévenin equivalent circuit can be calculated from the received power by the antenna load $P^{match}_{load,st}$ using the Poynting streamline method by

$$V_{oc} = (Z_{load} + Z^*_{ant}) I_{match} \tag{9}$$
$$= 2R_{load} I_{match}, \tag{10}$$

where I_{match} represents the current in matched circuit and is given by

$$I_{match} = \sqrt{\frac{2P^{match}_{load,st}}{R_{load}}} \tag{11}$$
$$= \sqrt{\frac{2A^{match}_{load,st} P_{inc}}{R_{load}}}. \tag{12}$$

$A^{match}_{load,st}$ represents the red area in Fig. 2, where the field energy in this area is absorbed by the antenna load.

B. CORRELATIONS TO POYNTING STREAMLINES

The correlation between the Poynting streamline distribution and the Thévenin equivalent circuit for a lossless receiving dipole antenna is illustrated in Fig. 4. In Fig. 4(a), a straight Poynting streamline indicates that there is no scattered field power, P_s. Fig. 4(b) depicts the open-circuited lossless receiving dipole antenna, which behaves as a minimum scattering antenna [27], where the scattered field power is close to zero. The straight Poynting streamlines in this figure represent close to zero load power P_{load} and scattered power P_s. These outcomes can be approximately predicted using the conventional Thévenin equivalent circuit with a constant voltage source [5]. As Z_{load} is infinite, the current I becomes zero, resulting in zero P_{load} and P_s.

However, when the load impedance matches the antenna impedance conjugately, the presence of a PEC structure in Fig. 4(c) generates a scattered field due to the induced current on the PEC arms at the resonant frequency. The bending of the Poynting streamlines is a result of the scattered field power radiated from the PEC arms since the Poynting streamline is calculated from the total field, E_{total}, given by $E_{total} = E_{inc} + E_s$. As a result, the Poynting streamlines are bent and terminated by the antenna load. The absorbed field power by the antenna load and the scattered field power can be calculated from the traditional Thévenin equivalent circuit using (6) and (8), respectively [5].

C. LIMITATIONS

The Thévenin equivalent circuit provides a simple way to model and analyze the characteristics of a receiving antenna. However, as pointed out in many works [3], [4], [5], it is inaccurate to handle the loss and scattered powers for receiving lossy antennas when the antenna is close to an open circuit.

The special case of an open-circuit receiving lossy antenna is particularly interesting. When the antenna is an open circuit, from (5), the current I is zero, resulting in zero loss and scattered powers. According to (5), the current I is zero, resulting in zero loss and scattered powers. However, this contradicts the powers calculated from the Poynting streamline distribution of the open-circuit lossy dipole antenna depicted in Fig. 2(b). When the antenna is open-circuited, some blue Poynting streamlines are absorbed and dissipated by the lossy metals, leading to non-zero loss power. Furthermore, when the antenna is open-circuited, some of the Poynting streamlines are bent and concentrated

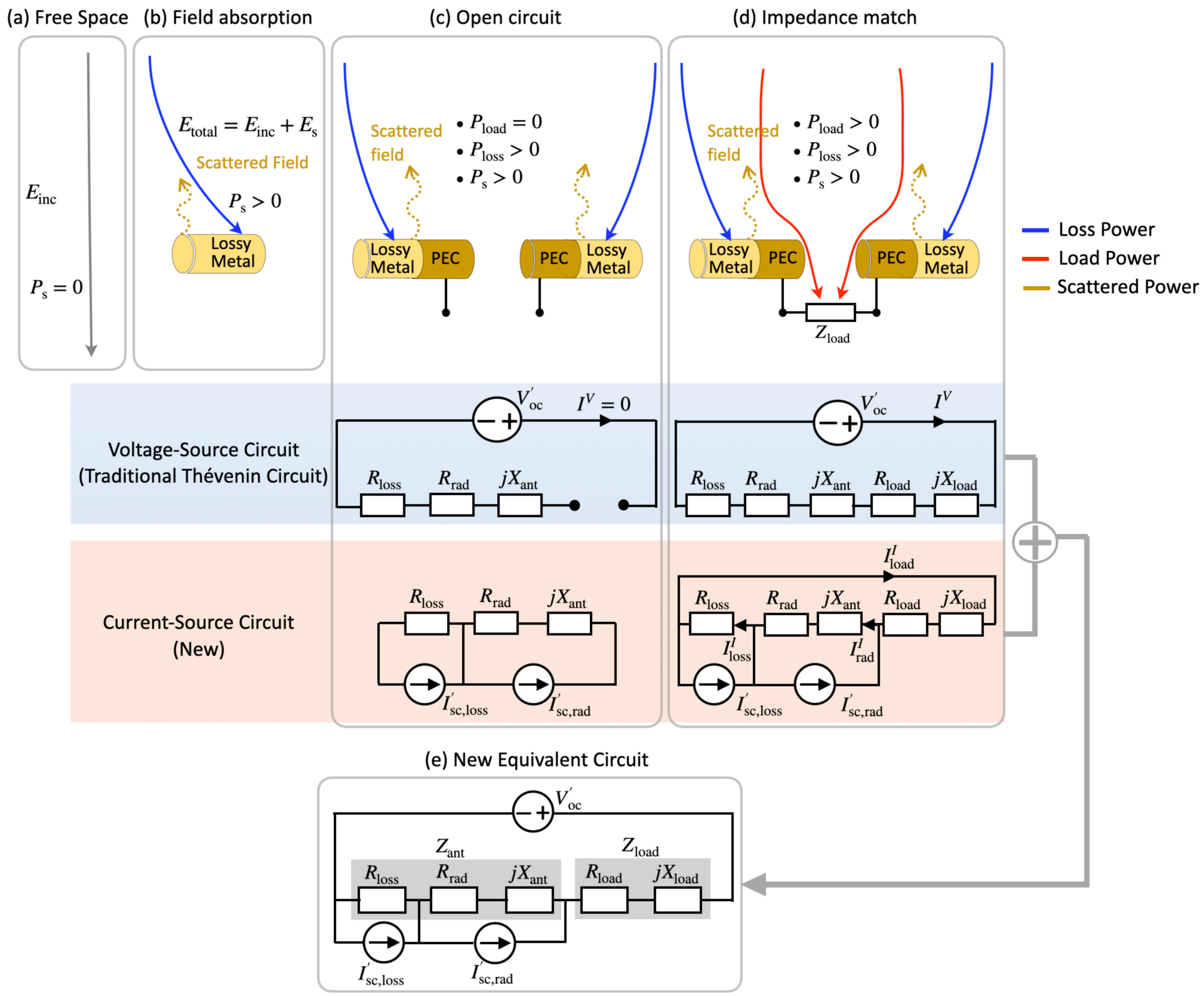


FIGURE 5. Derivation of a new equivalent circuit from the Poynting streamline distribution for receiving lossy dipole antenna.

on the lossy metals. The bending of the Poynting streamlines near the antenna indicates that the scattered power for the open-circuited lossy antenna is non-zero, since the Poynting streamlines are calculated from the total field, which is the sum of the incident and scattered fields. This result contradicts the zero scattered power calculated from the Thévenin equivalent circuit in (8).

IV. NEW EQUIVALENT CIRCUIT

The Poynting streamline method offers an intuitive approach to visualizing and comprehending the energy flow around a receiving antenna. The distribution of Poynting streamlines, as shown in Fig. 2, provides a clear depiction of the powers absorbed and scattered by each physical component of the antenna under various load conditions, which can be easily correlated with corresponding circuit elements in an equivalent circuit. Furthermore, this physical representation offers a straightforward means of understanding the limitations of the Thévenin equivalent circuit when the antenna is open-circuited. In this section, we will develop a new equivalent circuit model based on the insights gained from the Poynting streamline analysis of the receiving lossy dipole antenna. Since this work focuses on receiving dipole antenna, the scattered power from parasitic elements or other scattering objects within the antenna's structure is not considered in the proposed new equivalent circuit analysis [5].

A. DERIVATION FROM POYNTING STREAMLINES

In Fig. 5, a new equivalent circuit is derived based on the Poynting streamline distribution of a receiving lossy dipole antenna. The lossy metal is treated as an absorber. Compared with Fig. 5(a), the bending and absorption of the Poynting streamlines in Fig. 5(b) are attributed to the scattered field radiated from the lossy metal.

For an open-circuited lossy dipole antenna in Fig. 5(c), the bending and absorption of the Poynting streamlines by the lossy metal can be contributed to the scattered field from the dipole arms, resulting in a non-zero current through R_{rad} and R_{loss}. However, the traditional Thévenin equivalent circuit that uses a voltage source cannot account for this effect, as the current I^V on R_{rad} and R_{loss} is zero, leading to zero radiated and loss powers. To address this issue, the new equivalent circuit introduces additional current sources across R_{rad} and R_{loss} to account for non-zero radiated and loss powers. Since the current distribution across the PEC and lossy metals are different, two independent current sources $I'_{\text{sc,loss}}$ for R_{loss} and $I'_{\text{sc,rad}}$ for R_{rad} and X_{ant} are included in the new equivalent circuit. To avoid constant current across R_{rad} and R_{loss} as Z_{load} changes, the current sources are used in the new equivalent circuit rather than the voltage sources.

Fig. 5(d) demonstrates that when the antenna is impedance matched, the Poynting streamlines are bent and absorbed by the antenna load and lossy metals due to the scattered field, resulting in non-zero load and loss powers. The current and voltage across the circuit elements are contributed by both the voltage source of the traditional Thévenin equivalent circuit and the current source of the newly added equivalent circuit.

Fig. 5(e) presents a new equivalent circuit is motivated by the Poynting streamline distribution. Since the two types of constant sources are included in the equivalent circuit in Fig. 5(c) and (d), respectively, the new equivalent circuit in Fig. 5(e) can be considered as a superposition of voltage-source and current-source equivalent circuits. The voltage-source equivalent circuit is identical to the traditional Thévenin equivalent circuit, except for the value of voltage source V'_{oc}. The current-source equivalent circuit is utilized to address the issue of zero loss and scattered powers encountered when using the traditional open-circuited Thévenin equivalent circuit. When the antenna is short-circuited, the current through the lossy metal or R_{loss} is maximized and results in maximum power loss, so the number of the dissipated Poynting streamlines in the lossy metal is maximized in Fig. 2(b) left. When the antenna is open-circuited, the current through the lossy metal or R_{loss} is minimal, equal to the $I'_{\text{sc,loss}}$, resulting in minimum power loss. Thus, the number of dissipated Poynting streamlines in the lossy metal is minimized in Fig. 2(b) right. The next section will provide solutions for the antenna load, loss, and scattered powers in the new equivalent circuit.

B. ANALYSIS

1) CURRENT-SOURCE EQUIVALENT CIRCUIT

When the antenna is open-circuited, the current in the voltage-source circuit becomes zero, and the loss and scattered powers can be calculated from the current-source circuit. The current source $I'_{\text{sc,loss}}$ and $I'_{\text{sc,rad}}$ can be calculated from the open-circuited current-source circuit by

$$I'_{\text{sc,loss}} = \sqrt{\frac{2P^{\text{oc}}_{\text{loss}}}{R_{\text{loss}}}}e^{j\theta_{\text{sc,loss}}}, \tag{13}$$

and

$$I'_{\text{sc,rad}} = \sqrt{\frac{2P^{\text{oc}}_{\text{s}}}{R_{\text{rad}}}}e^{j\theta_{\text{sc,rad}}}, \tag{14}$$

where the loss power $P^{\text{oc}}_{\text{loss}}$ and the scattered power P^{oc}_{s} can be calculated from (26) and (27).

The voltage source V_{oc} is usually related to the electric field and the current source is usually related to the magnetic field. In the near-field region of the antenna, since there is a 90° phase difference between the electric field and the magnetic field, the phase angle of the current sources $\theta_{\text{sc,loss}}$ and $\theta_{\text{sc,rad}}$ are set to 90°.

In the current-source equivalent circuit, the current passing Z_{load} is given by

$$I^{\text{I}}_{\text{load}} = -\frac{I'_{\text{sc,loss}}R_{\text{loss}} + I'_{\text{sc,rad}}(R_{\text{rad}} + jX_{\text{A}})}{Z_{\text{load}} + Z_{\text{ant}}}. \tag{15}$$

The current in the R_{loss} is given by

$$I^{\text{I}}_{\text{loss}} = I'_{\text{sc,loss}} + I^{\text{I}}_{\text{load}}, \tag{16}$$

and the current in the R_{rad} is given by

$$I^{\text{I}}_{\text{rad}} = I'_{\text{sc,rad}} + I^{\text{I}}_{\text{load}}. \tag{17}$$

2) VOLTAGE-SOURCE EQUIVALENT CIRCUIT

The total current in the antenna loss resistance R_{loss} is the sum of the current in the voltage-source circuit and the current-source circuit. When the antenna impedance is the complex conjugate of the load impedance, the absolute value of the total current can be calculated from the loss power $P^{\text{match}}_{\text{loss,st}}$ by

$$I_{\text{loss,match}} = I^{\text{I}}_{\text{loss,match}} + I^{\text{V}}_{\text{match}} \tag{18}$$

$$= \sqrt{\frac{2P^{\text{match}}_{\text{loss,st}}}{R_{\text{loss}}}}e^{j\theta_{\text{loss,match}}}. \tag{19}$$

The current $I^{\text{V}}_{\text{match}}$ in the matched voltage-source circuit can be calculated from (15), (16), (18), and (19). The voltage source V'_{oc} can be given by

$$V'_{\text{oc}} = I^{\text{V}}_{\text{match}}Z_{\text{ant}}, \tag{20}$$

and the current I^{V} in the voltage-source circuit is given by

$$I^{\text{V}} = \frac{V'_{\text{oc}}}{Z_{\text{ant}} + Z_{\text{load}}}. \tag{21}$$

3) SUPERPOSITION

The total load current is the sum of the load current I^{V} in the voltage-source circuit and the current I^{I} in the current-source circuit. The total load power P'_{load} in the new equivalent circuit can be calculated by

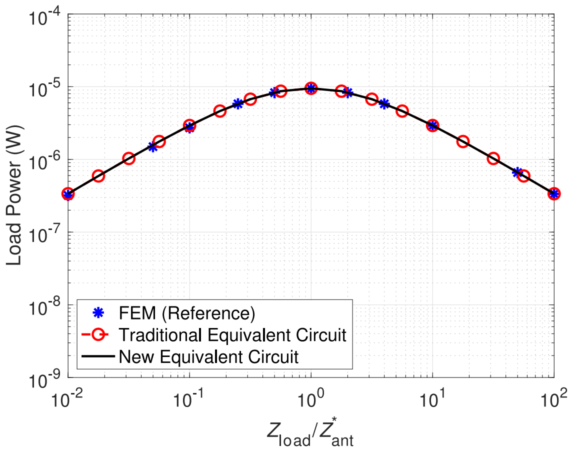
$$P'_{\text{load}} = \frac{1}{2}\left|I^{\text{V}} + I^{\text{I}}_{\text{load}}\right|^2 R_{\text{load}} \tag{22}$$

Similarly, the total loss power P'_{loss} and scattered power P'_{s} are given by

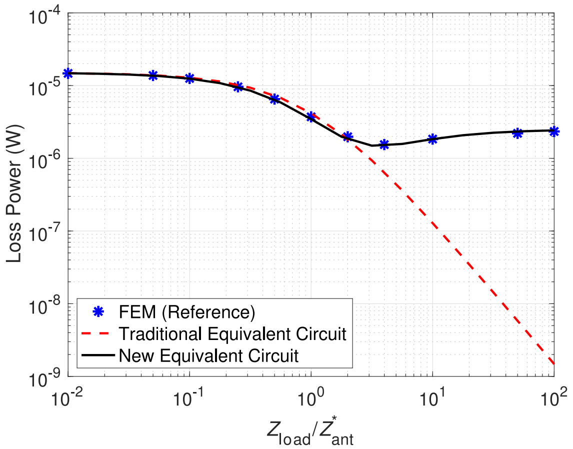
$$P'_{\text{loss}} = \frac{1}{2}\left|I^{\text{V}} + I^{\text{I}}_{\text{loss}}\right|^2 R_{\text{loss}}, \tag{23}$$

and

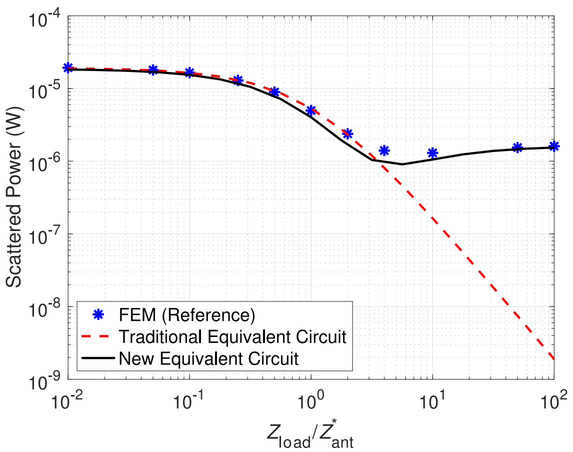
$$P'_{\text{s}} = \frac{1}{2}\left|I^{\text{V}} + I^{\text{I}}_{\text{rad}}\right|^2 R_{\text{rad}}. \tag{24}$$



(a) Load power



(b) Loss power



(c) Scattered power

FIGURE 6. Comparison of load power, loss power, and scattered power calculated from FEM(reference), traditional Thévenin equivalent circuit, and new equivalent circuit for receiving lossy dipole antenna.

V. VERIFICATION

Through the above analysis, we find that inspired by the Poynting streamline method, a new equivalent circuit is proposed to address the limitations of the traditional

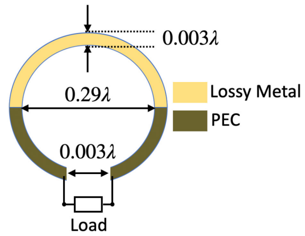


FIGURE 7. Receiving lossy loop antenna dimension.

Thévenin equivalent circuit in dealing with the loss and scattered powers of the receiving dipole antennas. In this section, the accuracy of the proposed new equivalent circuit is verified. The traditional Thévenin equivalent circuit can accurately calculate the load power of the antenna under different load conditions [5].

A. REFERENCE RESULTS USING FULL-WAVE ANALYSIS

To compare the results of the proposed equivalent circuit with a full-wave model, we calculate the antenna load power, loss power, and scattered power of the receiving lossy antenna using FEM. The absorbed power by the antenna load can be calculated from the surface integral of the inward flowing flux of the Poynting vector of the total field $\boldsymbol{E}_t$ and $\boldsymbol{H}_t$ through the surface surrounding the receiving antenna load by

$$P_{\text{load,FEM}} = -\frac{1}{2} \oiint_{S_{\text{load}}} \text{Re}\left(\boldsymbol{E}_t \times \boldsymbol{H}_t^*\right) \cdot \hat{\boldsymbol{n}} dS, \tag{25}$$

and the loss power can be calculated from the surface integral through the surfaces surrounding the lossy metals of the receiving antenna by

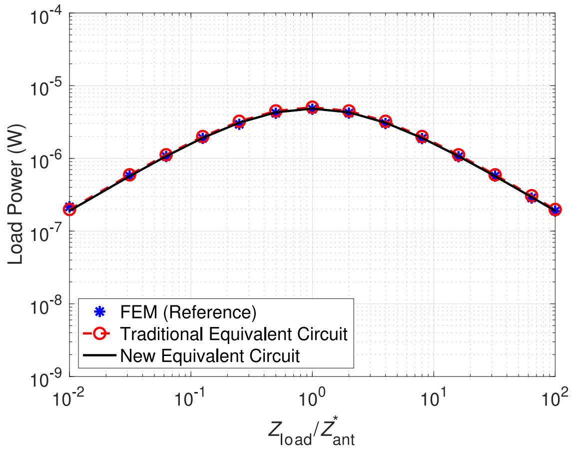
$$P_{\text{loss,FEM}} = -\frac{1}{2} \oiint_{S_{\text{loss}}} \text{Re}\left(\boldsymbol{E}_t \times \boldsymbol{H}_t^*\right) \cdot \hat{\boldsymbol{n}} dS. \tag{26}$$

The scattered power by the receiving antenna including the re-radiation and structural or residual scattering components [28] can be calculated from the scattered field $\boldsymbol{E}_{sc}$ and $\boldsymbol{H}_{sc}$ through the surface surrounding the receiving antenna by

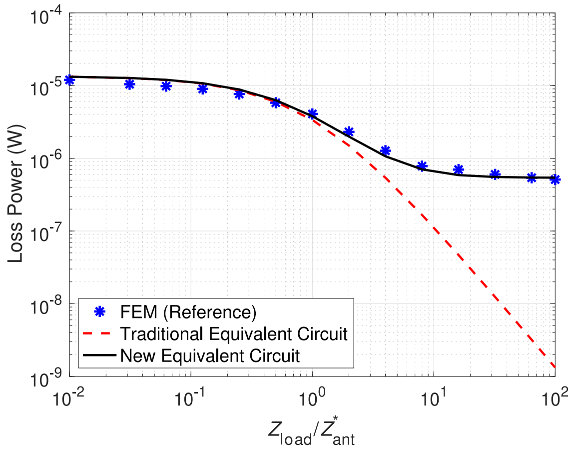
$$P_{\text{s,FEM}} = -\frac{1}{2} \oiint_{S_{\text{sc}}} \text{Re}\left(\boldsymbol{E}_{sc} \times \boldsymbol{H}_{sc}^*\right) \cdot \hat{\boldsymbol{n}} dS. \tag{27}$$

B. RECEIVING LOSSY DIPOLE ANTENNA

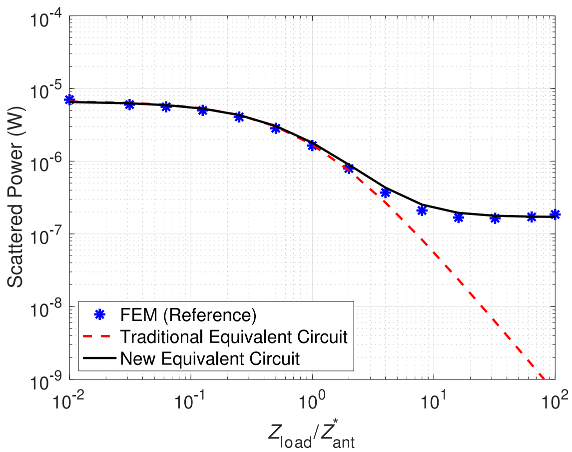
Fig. 6 compares the load power, loss power, and scatter power of a lossy dipole antenna under different load conditions in Fig. 1. The load impedance of the antenna ranges from $0.01Z_{\text{ant}}$ to $100Z_{\text{ant}}$. Three different methods are used: the FEM in (25), (26), and (27), the traditional Thévenin equivalent circuit in (6), (7), and (8), and the new equivalent circuit from (22), (23) to (24). $\theta_{\text{loss,match}}$ sets to 15° using the least mean square method to make P'_{load} in (22) approximately equal to P_{load} in (6). The load power shows good agreement among the three methods, but for the loss and scatter powers, the traditional Thévenin equivalent circuit deviates significantly from the FEM results when the



(a) Load power



(b) Loss power



(c) Scattered power

FIGURE 8. Comparison of load power, loss power, and scattered power calculated from FEM (reference), traditional Thévenin equivalent circuit, and new equivalent circuit for receiving lossy loop antenna.

antenna is close to an open circuit. On the other hand, the new equivalent circuit is approximately in good agreement with the FEM results, which confirms its accuracy. For the comparison of the scattered power, the new equivalent circuit results are slightly lower than the FEM results when Z_{load} is close to Z^*_{ant}. One possible reason is that the voltage and current sources are approximated to be constant and are independent of the change in the load impedance, which might be slightly different from the FEM results using a real antenna model.

C. RECEIVING LOSSY LOOP ANTENNA

Furthermore, the accuracy of the proposed equivalent circuit is confirmed with a receiving lossy loop antenna. The dimensions and material properties of the loop antenna are shown in Fig. 7. Specifically, the loop antenna has a diameter of 0.29λ and a width of 0.003λ, and the conductivity of the lossy metal is set to 15 S/m. The loop antenna operates at a frequency of 1 GHz and feeds the loop antenna with a load that has a gap distance of 0.003λ. Fig. 8 compares the load power, loss power, and scatter power of a receiving lossy loop antenna under different load conditions. The load impedance of the antenna ranges from $0.01Z_{\text{ant}}$ to $100Z_{\text{ant}}$. Similar to the receiving lossy dipole antenna, the load power shows good agreement among the three methods, but for the loss and scattered powers, the new equivalent circuit is in good agreement with the FEM results compared with the traditional Thévenin equivalent circuit.

Based on the results presented above, it is evident that the traditional Thévenin equivalent circuit is not effective in accurately predicting the loss and scattered powers when the antenna is near an open circuit. However, the excellent agreement observed for the load power, loss power, and scattered power obtained through Poynting streamline analysis confirms the high level of accuracy provided by the proposed new equivalent circuit model.

VI. CONCLUSION

The analysis and comprehension of the behavior of receiving lossy antennas have benefited from the utilization of the Poynting streamline method. By examining the distribution of the Poynting streamlines in the vicinity of the receiving antenna, it becomes possible to visualize the absorption of field power by the antenna load and the dissipation of power in the antenna's lossy material. Drawing inspiration from the Poynting streamline method, a novel equivalent circuit has been proposed to address the limitations of traditional Thévenin equivalent circuits in accurately determining the loss and scattered powers for the dipole and loop antennas. The proposed circuit model demonstrates excellent agreement with respect to load power, loss power, and scattered powers, thereby confirming its accuracy.

As of now, to the best of our knowledge, a universally validated equivalent circuit model encompassing all types of antennas has yet to be established. This could be attributed in part to the considerable variation in scattered power across different antenna types, particularly when subjected to varying impedance-matching conditions and antenna structures [9]. Consequently, a longstanding discourse surrounding the circuit model for receiving antennas has persisted over recent decades [3], [4], [5], [7], [8], [12], [28], [29]. We hold the expectation that adopting the Poynting streamline method to formulate a fresh equivalent circuit of the dipole antennas in this work could present an innovative avenue for advancing the understanding of antenna reception properties. This, in turn, might facilitate the development of a more generalized circuit model catering to a broad spectrum of antenna types in future investigations.

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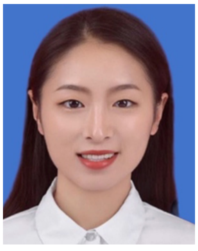

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