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Characteristic of Current Diffusion on Double-Plate Conductor for Smaller Resistive Load

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Abstract

Power transmission line is one of the pivotal parts of a power system. It connects power generation house with the consumer even in the long distances. Research on current diffusion on the conductor is inevitable to maximize the power dispatch on transmission line. The main purpose of this study is to recognize the behaviors and characteristics of current diffusion in double-plates conductor for further development in the future. The research outcomes would be very useful, particularly in the transmission line study. In this paper, study will be focused on the characteristic of current diffusion in conductor due to its variation impedance value of load particularly when resistive load is smaller than the conductor impedance (Z_o). This research is conducted by experimental test and carried out through extensive simulation using MATLAB and Visual Basic Program in MS. Excel. Poynting theory is employed as a validation approach. The simulation and experiment results show that if R_L is smaller than the line impedance Zo, deficiency current establish will occur where the electromagnetic energy is not sufficient for the load.

Keywords: Conductor; current diffusion; impedance

1. Introduction

Power transmission is one of the important parts of power system delivery due to its role in connecting power house to the loads centereven in very long distances [1]. One of the pivotal things on power transmission that should be taken into consideration is how to maximize the power delivery on the conductor through the current diffusion study on transmission line.

Research on current diffusion on conductor can be divided into two where the first case is investigation on impacts of current diffusion on conductor for resistive value larger than transmission line impedance, this study has been carried out in prior research in [2]. In this study, the second case of current diffusion on conductor is studied where the study is focused on the impacts of current diffusion on conductor for resistive value smaller than the transmission line impedance. The study of current diffusion could not be separated with the theory of energy storage where the storage process can be done in form of magnetic field and electric field processes. The energy storage that performed through magnetic field generally applied to inductor (L) which storing energy in Joule. The energy capacity is depending on the value of L and the current flow on it. The formula can be stated as follow:

$$W_m = \int_0^t P_L dt = \int_0^I LI \frac{dI}{dt} = \int_0^I LI \quad dI = \frac{1}{2} LI^2 \text{ (J)} \qquad (1)$$

The formula above becomes the fundamental of superconductor development where the coil is placed in the very extreme low temperature (cryogenic state). This superconducting coil could store energy in very high efficiency [3], applied in wind turbine generators [4-6], and in micro hydro [7, 8]. Meanwhile, energy storage that performed from electrical field normally occurs due to the difference capacitance among some parts including the difference on their voltages. The energy content that stored can be formulated as follow [9]:

$$W = \frac{1}{2C} Q^2 = \frac{1}{2} QV = \frac{1}{2} CV^2 \text{ (J)} \qquad (2)$$

It can be concluded from eq. (1) and (2), that electromagnetic energy can be determined by the flowing current in conductor while electrostatic energy is influenced by potential (V) at plates.

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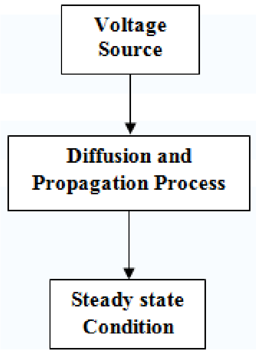

Figure 1. Process diagram of diffusion and propagation in a conductor

1.1. Poynting theory

John Henry Poynting (1852-1914) is the first person who introduced Poynting Vector as can be determined with the following equation [10]:

$$P = E \times H \ (\frac{W}{m^2}) \tag{3}$$

where:

E = Electric Field (V/m)
H = Magnetic Field (A/m)

Poynting theory allows the wave propagation of power flow to be easily calculated. The power flow can be calculated based on multiplication vector of the perpendicular of *E* and *H* (according to the "Right Hand Rule").

1.2. Parallel plate voltage at transmission line

In this paper, research is focused on the diffusion and propagation process of current flow in a conductor after connected to a voltage source as illustrated in Fig. 1, where load is applied in condition of smaller than line impedance.

When voltage is applied at the first point of the conductor with two identical plates, a magnetic field will across the conductor in V/m and simultaneously, there is a current flow (I_D) in the conductor. According to the "Right Hand Rule", when a current flow in the conductor, it will generate a magnetic field (H) where the direction is dictated by the current flow. The movement of magnetic field, H is determined by I_D and current velocity (*v*) which can be determined according to the equation (4):

$$v = \frac{1}{\sqrt{\varepsilon\mu}} \ (\frac{m}{s}) \tag{4}$$

When magnetic field moves, a back electric field simultaneously will be appeared in opposite direction, limiting the velocity of magnetic field movement itself. This phenomenon can be written in the following equation:

$$E_B = -Bv \tag{5}$$

$$V_B = E_B \times g = -B \times g \times v \quad \text{(V)} \tag{6}$$

where: g is distance between plates conductors (m)

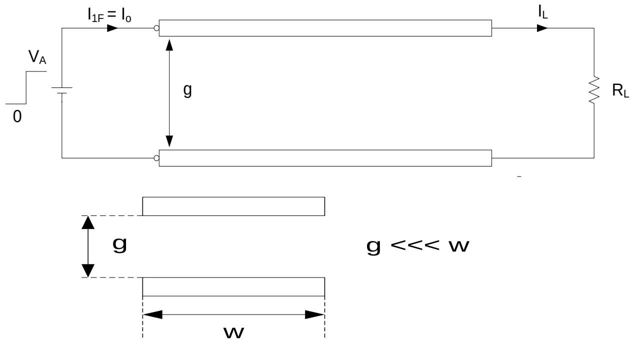

Figure 2. Conductor configuration with identical plates

Figure 2 is the equivalent circuit represents the experiment test for current diffusion at conductors with parallel plates where distance between plates (*g*) is very small compared to the wide (*w*).

2. Research Methodology

This research is conducted by experimental test and carried out through extensive simulation using MATLAB and Visual Basic Program in MS. Excel. Poynting theory is employed as a validation approach. In this paper, a smaller resistive load than the line impedance is employed. The value of resistive load is 5x smaller than the line impedance. However, for comprehensive study an equal value of resistive load and line impedance is formerly conducted.

3. Results and Discussion

3.1. Current characteristic in line

When wave front reach the load, there are three form of energies produced, electric field (*E*) which generates electrostatic; magnetic field resultant (*H*) which generates mechanical energy; and sustainable power that is determined by $V_A \times I_o$.

3.1.1. R_L Equal with line impedance (Z_0)

Discussion on R_L equal with the line impedance (Z_0) has been provided in the prior paper in [2]. If the value of R_L is equal with Z_0, the value of I_0 will bring a small negative V_A (ohmic voltage drop) from source to the load as illustrated in Fig. 3.

From Fig. 4, it can be seen that the magnitude of voltage along the conductor has the same value as simulated with MATLAB in the case of R_L=Z_0. Meanwhile, the V_{fr}–forward and V_b-backward calculated using Excel Visual Basic is listed in Table 1.

3.1.2. R_L Smaller Than Line Impedance (Z_0)

The propagation process will show a different response when R_L is smaller than Z_0. There will be a current deficiency where electromagnetic value is too small for the load. The propagation diffusion process can be seen in Fig. 5.

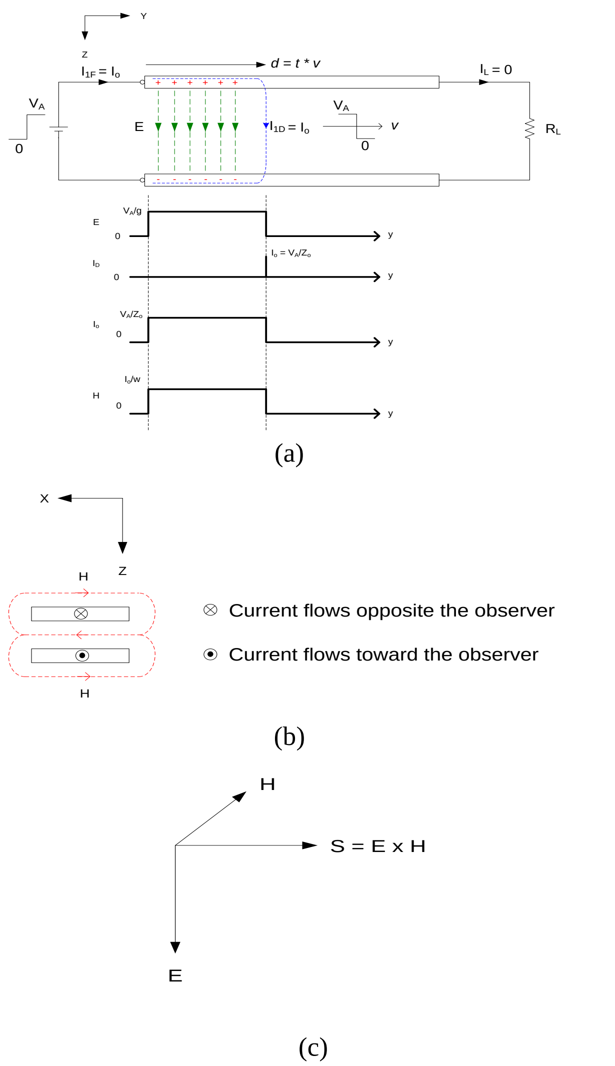

Figure 3.Process of diffusion and propagation in a conductor;
(a) Equivalent Circuit (b) Magnetic Field and (c) Poynting Vector [2]

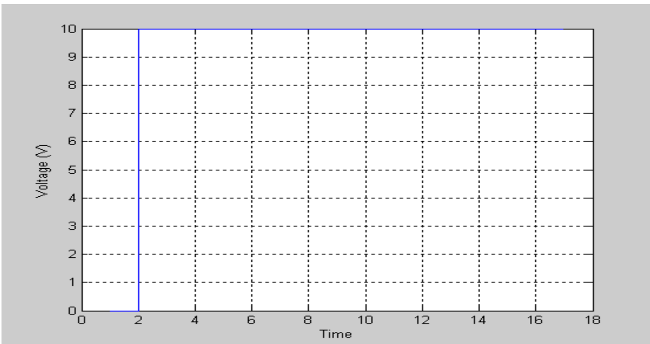

Figure 4. Matlab plot for $R_L = Z_o$

Table 1. V_{fr}–forward and V_b-backward for R_L=Zo [2]

V_A	**:**	**10**	**V**		
Z_o	**:**	**10**	**Ohm**		
R_L	**:**	**10**	**Ohm**		
V_{fr} (V)	**I_{fr} (A)**	**I_e (A)**	**ΔV (V)**	**V_b (V)**	**I_b (A)**
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1
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10	1	0	0	10	1
10	1	0	0	10	1
10	1	0	0	10	1

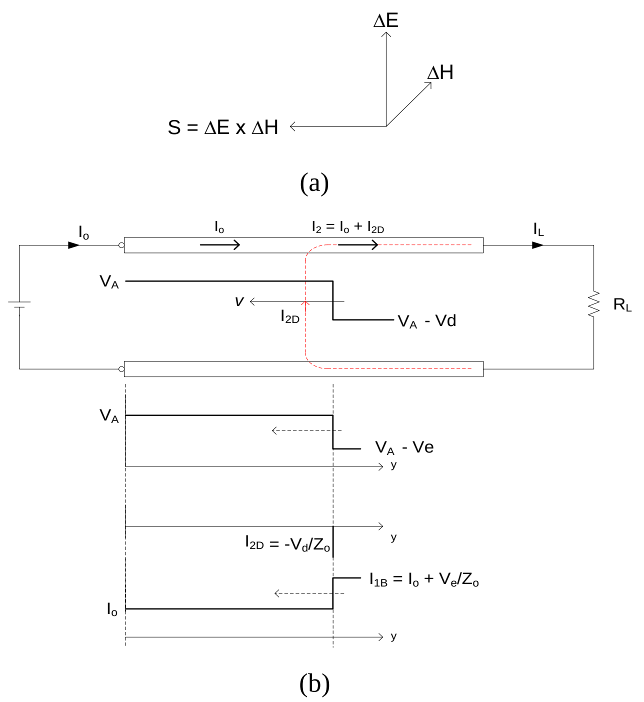

Figure 5. Process diffusion of propagation of first backward wave for R_L<Zo, (a) Poynting Vector (b) Equivalent Circuit [2]

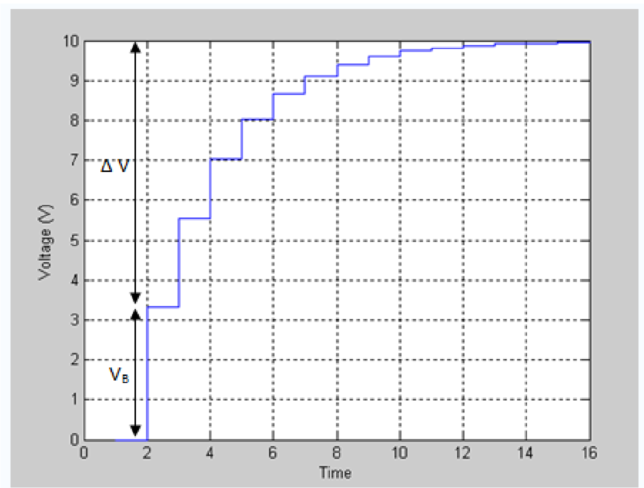

Figure 6. Matlab plot for R_L < Zo

As can be seen in Fig. 6, from time to time the V backward becomes larger until the transition of the voltage propagation reach the same value with V_A. The equation to determine the V-backward and ΔV can be stated as follow:

1st Forward

$$V_{1F} = V_A \text{ and } I_{1F} = \frac{V_A}{R_L} \tag{7}$$

1st Backward

$$V_{1B} = V_A + \Delta V_1 \text{ and } I_{1B} = I_{1F} - \frac{\Delta V_1}{Z_o} \tag{8}$$

Nth transition

$$V_{nF} = V_A,\, I_{nF} = I_{(n-1)B} + \frac{\Delta V_{(n-1)}}{Z_o},\, I_{nd} = \frac{\Delta V_n}{R_L} - I_{nF}$$

,

$$\Delta V_n = -I_{nd}(Z_o // R_L), \tag{9}$$

$$V_{nB} = V_{nF} + \Delta V_n, \tag{10}$$

$$I_{nB} = I_{nF} - \frac{\Delta V_n}{Z_o} \tag{11}$$

3.2. Laboratory experiment

In this experiment, parallel plate conductors are used and sourced with 2V, this value is selected because if the input voltage larger than noise it will influence the voltage characteristic of the load.

As shown in Fig. 7, there is a time delay between V_{in} and V_{out}. This is occur due to propagation wave that move forward toward the load required certain time where its velocity depends on conductivity, permeability and physical properties of the conductor. In this research, time delay has reach about 100 ns.

To calculate the load impedance, a simple circuit is assembled as shown in Fig. 8 to measure the current flow (I_0).

By calculating the voltage value between R_1 = 1 Ohm, we could obtain the measured current by V_{R1}= I_o x R_1 or can be written V_{R1}= I_o. As shown in Fig. 9, the initial voltage value is 2 V and the measured current is 165 mA, therefore the line impedance is:

$$Z_0 = \frac{V_A}{I_0} = \frac{2}{0.165} = 12.12 \approx 12 \text{ Ohm}$$

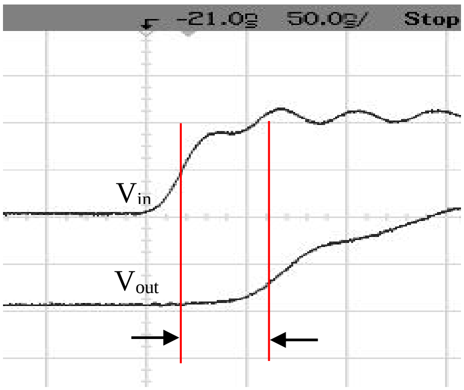

Figure 7. V_{in} versus V_{out}

Figure 8. A simple circuit to measure the current flow in conductor

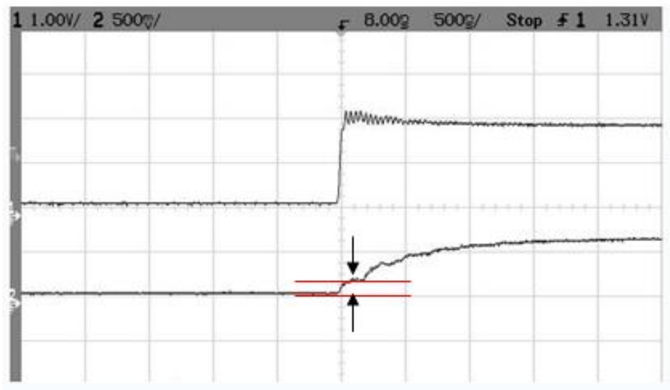

Figure 9. V_{in} and current flow (I_o)

The next measurement is to investigate the current diffusion characteristic in conductor when the R_L is smaller than the line impedance (Zo). The comparison between calculation and measurement can be seen in Figs. 6 and 9.

It can be concluded from simulation and laboratory measurement that if R_L is smaller than the line impedance Zo, deficiency current establish will occur where the electromagnetic energy is not sufficient for the load. As a result, the load voltage become smaller than V_A which in turn reduce the $-V_d$ that is propagated back toward the source with current displacement of I_{D2}=-V_d/Zo. By using the n^{th} transition equation, it is clearly shown that voltage backward increased gradually from time to time until matching the voltage source V_A.

Table 2. Forward and backward voltage for R_L=*Zo/5* (computed using VB-Excel)

V_A :	10	Volt			
Z_o :	10	Ohm			
R_l :	2	Ohm			
V_{Fr} (V)	**I_{fr} (A)**	**I_d (A)**	**ΔV (V)**	**V_b (V)**	**I_b (A)**
10	1	4	-6.66667	3.333333	1.666667
10	2.333333	2.666667	-4.44444	5.555556	2.777778
10	3.222222	1.777778	-2.96296	7.037037	3.518519
10	3.814815	1.185185	-1.97531	8.024691	4.012346
10	4.209877	0.790123	-1.31687	8.683128	4.341564
10	4.473251	0.526749	-0.87791	9.122085	4.561043
10	4.648834	0.351166	-0.58528	9.414723	4.707362
10	4.765889	0.234111	-0.39018	9.609816	4.804908
10	4.843926	0.156074	-0.26012	9.739877	4.869939
10	4.895951	0.104049	-0.17342	9.826585	4.913292
10	4.930634	0.069366	-0.11561	9.88439	4.942195
10	4.953756	0.046244	-0.07707	9.922927	4.961463
10	4.969171	0.030829	-0.05138	9.948618	4.974309
10	4.979447	0.020553	-0.03425	9.965745	4.982873
10	4.986298	0.013702	-0.02284	9.977163	4.988582

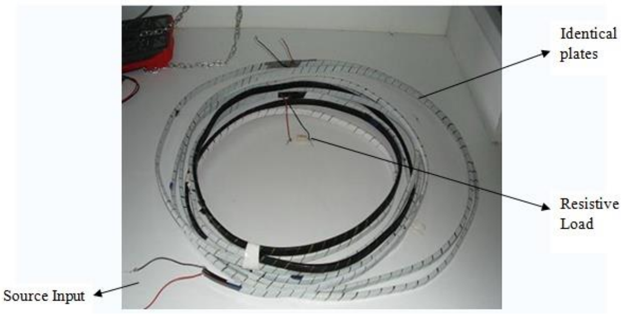

Figure 10. Experiment circuit set up for current diffusion study [2]

For study validation, the experimental set up is conducted as shown in Fig. 10. Using oscilloscope, the wave propagation diffusion of the experiment is measured as depicted in Figs. 7 and 9. The experiment set up as shown in Fig. 10 consists of identical plates where resistor terminals is designed to allow measurement conducted at the middle and the end of the identical plates.

4. Conclusion

Study of current diffusion characteristic in a conductor involves several parameters including propagation velocity of the current flow. The propagation is influenced by permeability, conductivity and the physical properties of the conductor. If the initial voltage is given, there will be an electric field (E) that related to current wave front I_D. Meanwhile, the magnetic field (H) that is also depending on I_D, will generate back electrostatic (E_b) which limit the electromagnetic velocity. The comparison value between R_L and Z_0 will determine the diffusion and propagation characteristic in the system. It can be drawn a conclusion from simulation and laboratory measurement that if R_L is smaller than the line impedance Z_0, deficiency current establish will occur where the electromagnetic energy is not sufficient for the load. As a result, the load voltage become smaller than V_A which in turn reduce the $-V_d$ that is propagated back toward the source with current displacement of $I_{D2}=-V_d/Zo$. By using the n^{th} transition equation, it is clearly shown that voltage backward increased gradually from time to time until matching the voltage source $V_{A.}$

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