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Improvement of Pulse Shape by Reducing Ripple Using Coaxial Cable

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***Abstract* — Even though pulse shape in rectangular form is desirable for most applications, pulse generated from coaxial cable has ripple and is not in desired rectangular shape. This study is to improve the pulse shape generated from coaxial cable to be rectangular shape. Coaxial cables with difference dielectric materials are studied for generation 100 ns pulse. The study has been carried out by state space representation method and MATLAB simulation for pulse forming network of Type-B which has same characteristics of coaxial cable. Ripple can be reduced to 2% to 3% increasing the inductance values next load higher than characteristics inductance of coaxial cable.**

***Keywords*—Characteristic impedance, Coaxial cable, Dielectric constant, Pulse forming network, Ripple**

I. INTRODUCTION

Coaxial cables are the interconnection pulse from one end to another. It is surrounded by a copper mesh. The inner dielectric separates the core and the shielding wire apart. Coaxial cable conducts electrical signal using an inner conductor normally a solid copper, stranded copper surrounded by an insulating layer (dielectric) and all enclosed by a shield [1]. Fourth years afterwards (in 1884), the first coaxial cables were made by an electrical engineering company named siemens. The function of dielectric material in the coaxial cable is to maintain the spacing between the shield and the centre conductor. Lower-loss cables are achieved by using dielectric materials with insulating properties. Generally, like any transmission line, the coaxial cable has four parameters: capacitance resistance, conductance and inductance in lossy transmission line. In lossless line, it has capacitance and inductance [2].

Common dielectric materials: air spaced supports a lower dielectric constant than rubber, silicon and water while allowing for a small diameter cable size. A practical way of getting rectangular pulse shape of width few microsecond or nano second is with help pulse forming line (PFL). Pulse forming network can be used actual transmission line or cable but a set of capacitors or inductors are arranged in a specific way [3]. The coaxial cable is charged from dc power supply through an appropriate load.

The pulse width is twice the time taken by electromagnetic wave to travel the length of coaxial cable in dielectric medium between the coaxial cable conductor [4]. Each cable has a capacitance between the centre and outer conductor proportional to the length of the element. Magnetic fields are produced by current flow along the centre conductor. Each differential element has a series inductance. The rise time of the output waveform generated by using coaxial cable is very fast such as nanosecond [5]. The output of the half of charging voltage is obtained when the termination impedance is at 31.63 Ω which equal the characteristic impedance of coaxial cable as [6, 7]. Pulse forming network consisting of identical inductance and capacitance values connected in cascades by ladder system are generally used [8]. The pulse forming network of coaxial cable can be generated low front rising time pulse with several hundreds of nanoseconds in duration. The effect of the component parameters to the rising time, falling time, the overshoot, the undershoot, ripple and effective width of the output pulse is studied [9].

II. MATHEMATICAL MODELLING

A. Characteristic Impedance of Coaxial Cable

Figure 1 illustrates a coaxial cable where the mechanical properties as the dielectric material, the length and the ratio of inner and outer conductors are resented to

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get the characteristics inductance and capacitance of the cable.

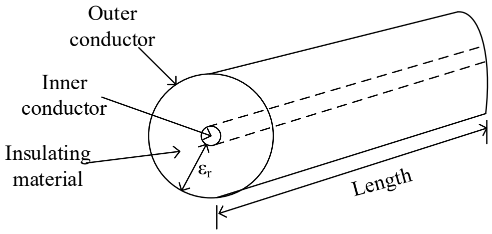

Fig. 1. Mechanical design of coaxial cable.

The analytical equations of capacitance and inductance values for coaxial cable [1, 2].

$$C_n = \frac{2\pi\varepsilon}{\ln(D/d)} \times l \qquad (F) \tag{1}$$

$$L_n = \frac{\mu}{2\pi} \ln\left(\frac{D}{d}\right) \times l \qquad (H) \tag{2}$$

The characteristic impedance of coaxial cable can be found the following equation.

$$Z_0 = \sqrt{\frac{L}{C}} \qquad (\Omega) \tag{3}$$

, where D is the outer conductor (mm), d is the inner conductor (mm), l is the length of the coaxial cable (m), Ɛ is the dielectric constant of insulation shield. C is the capability of the coaxial cable to carry a charge (F), L is the series inductance (H). The inductance and capacitance values can be found by applied Eqs. (1) and (2) of using mechanical parameters of coaxial cables.

B. State Space Method for Pulse Forming Network of Type-B

At first, calculate the ABCD matrix using Kirchhoff's Law and state space form to Simulink in MATLAB to model the system. The characteristic of the pulse forming network voltage fed is used to simulate based on the inductor currents and the capacitor voltages are applied.

$$\dot{x}(t) = A\,x(t) + B\,u(t) \tag{4}$$

$$y(t) = C\,x(t) + D\,u(t) \tag{5}$$

, where x is called the state vector, y is called the output vector, u is called the input vector, A is the n × n state matrix, B is the n × 1 input matrix, C is the 1 × n output matrix, D is the feedback through matrix and n state variables for number of inductance and capacitance values.

The mathematical model for the LC pairs circuit can be formulated as Kirchhoff's voltage law and Kirchhoff's current law.

Type-B pulse forming network with nth section is shown in Fig. 2.

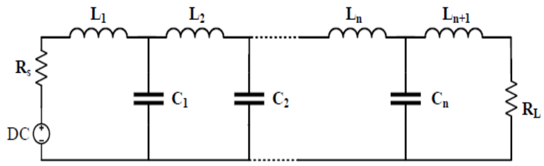

Fig. 2. Simple pulse forming network with n[th] section.

$$\dot{x}(t) = \frac{d}{dt}\begin{bmatrix} i_1(t) \\ i_2(t) \\ i_3(t) \\ i_4(t) \\ V_1(t) \\ V_2(t) \\ V_3(t) \end{bmatrix}, \quad x(t) = \begin{bmatrix} i_1(t) \\ i_2(t) \\ i_3(t) \\ i_4(t) \\ V_1(t) \\ V_2(t) \\ V_3(t) \end{bmatrix}$$

$$A = \begin{bmatrix}
\frac{-R_s}{L_1} & 0 & . & . & . & 0 & \frac{-1}{L_1} & 0 & 0 & 0 & . \\
0 & 0 & . & . & . & 0 & \frac{1}{L_2} & \frac{-1}{L_2} & 0 & 0 & . \\
. & . & . & . & . & 0 & 0 & 0 & . & . & . \\
. & . & . & . & . & . & . & . & \frac{1}{L_{n-1}} & \frac{-1}{L_{n-1}} & . \\
. & . & . & . & . & . & . & . & . & \frac{1}{L_n} & \frac{-1}{L_n} \\
. & . & . & . & . & \frac{-R_1}{L_{n+1}} & . & . & . & . & \frac{1}{L_{n+1}} \\
\frac{1}{C_1} & \frac{-1}{C_1} & 0 & . & . & . & . & . & . & . & 0 \\
0 & \frac{1}{C_2} & \frac{-1}{C_2} & . & . & . & . & . & . & . & 0 \\
0 & 0 & . & . & . & . & . & . & . & . & . \\
. & . & \frac{1}{C_{n-1}} & \frac{-1}{C_{n-1}} & 0 & 0 & . & . & . & . & . \\
. & . & . & \frac{1}{C_n} & \frac{-1}{C_n} & 0 & . & . & . & . & .
\end{bmatrix}$$

The constant A matrix is varied for each section, but the other B, C, D constant matrices are not varied.

C. Pulse Shape Improvement

The pulse characteristics of coaxial cable are (i) rise time, (ii) fall time, (iii) pulse magnitude, (iv) pulse width, (v) overshoot and (vi) ripple in Fig. 3 and Fig. 4. A better flat-top can be obtained by approximating smoother pulses. When output pulse produces from coaxial cable, the pulse shape is not smoothed and the leading edge is distorted called ripple and overshoot original pulse shape in Fig. 4.

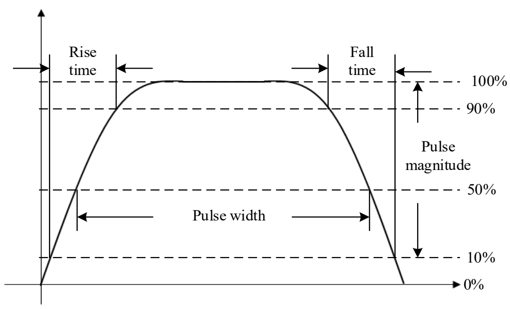

Fig. 3. Pulse characteristic of output pulse shape.

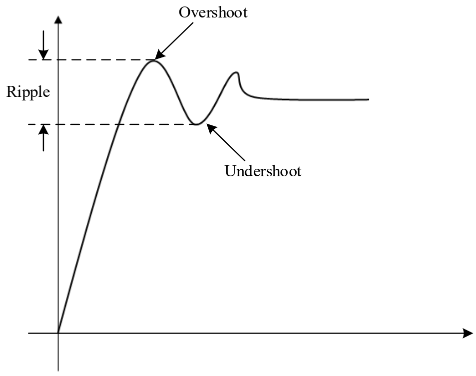

Fig. 4. Pulse ripple of output pulse shape.

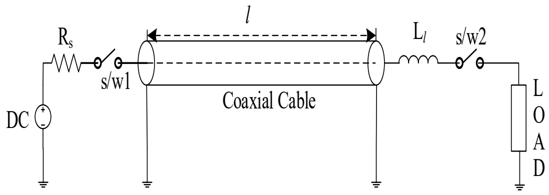

Fig. 5. Generation of output pulse shape from coaxial cable.

To solve this problem, a series inductor will be connected to the outgoing of coaxial cable as shown in Fig. 5. The pulse shape can be smoothed by increasing the inductance value of next series inductor 1, 2 and 3 times the characteristic inductance of coaxial cable. When the ripple and overshoot percentages at the leading edge of output pulse are reduced, the rise time and fall time of output pulse are slightly wider than the normal pulse shape.

III. PULSE GENERATED BY COAXIAL CABLE

When producing the output pulse shape from coaxial cable, the desired pulse shape can be found from the inductance and capacitance values of the coaxial cable. The inner conductor of a coaxial cable can be charged and discharged energy as in series inductance, and the insulating material between the inner and outer conductors can be charged and discharged as the capacitance.

The needed capacitance (C) and inductance (L) for desired pulse (100 ns) can be calculated on matched load and arranged numbers of section.

$$\tau = 2\,n\sqrt{LC} \tag{6}$$

The values of inductance and capacitance for each section based on desired pulse and desired load are:

$$L = \tau\, Z / (2\, n) \tag{7}$$

$$C = \tau / (2\, n\, Z) \tag{8}$$

, where τ is desired pulse (100 ns), Z_0 is (31.62 Ω) on matched load, n is the number of sections, Z_0 is characteristic impedance. First, we will find the needed inductance and capacitance 100ns pulse capacitance for 100ns pulse generating by using Eqs. (7) and (8). To get the desired 100 ns pulse, consider the number of LC pairs on the coaxial cable. The inductance (L) and capacitance (C) are the electrical properties of the coaxial cable.

When we use the dielectric materials (air, rubber, silicon and water), the needed lengths and the inner and outer diameter ratios are shown in Table I. When considering the number of sections to produce the output pulse for desired 100 ns pulse and load 31.62 Ω, the needed inductance (L) and capacitance (C) are 1.6 µH and 1.6 nF for one section, 0.8 µH and 0.8 nF for two sections and 0.4 µH and 0.4 nF for the three sections so on.

Table I: Coaxial cable length and diameter ratio for dielectric constant material.

Dielectric Materials (ε_r)	Length (m)	D/d
Air (1)	15.2	1.7
Rubber (7)	8.76	2.5
Silicon (11.68)	6.78	3.3
Water (55.5)	2.04	54.6

The inductance (L) and capacitance (C) values are the respectively. As the mechanical designs of coaxial cable, the inner and outer diameter ratios (D/d), the dielectric constant (ε_r) and length of coaxial cable can be calculated by using Equations (1) and (2) from the searchable inductance and capacitance values.

Coaxial cables with different dielectric constant, length and ratio of inner and outer diameters for desired 100 ns pulse are shown in Table I. This observation is that the length and the ratio of inner and outer diameter of coaxial cable are varied due to the dielectric constant of insulation materials.

The small value of dielectric constant air Eq. (1) is obtained the length (15.2 m) and the smaller diameter ratio for desired pulse. When the dielectric constants are large, as water (55.5), it can be obtained the short length but the ratio of diameter (D/d) are very large. In order to investigate the characteristic of the pulse forming networking for coaxial cable, the inner and outer diameter ratio are the same 1.7 and the length of coaxial cable are 1 m and 2 m for each dielectric material. The rise time is determined by the rise time of the last mesh in the network close to the load.
In mathematically, rise time is:

$$t_r = \frac{\pi - f}{\omega_n \sqrt{1-\zeta^2}} \tag{9}$$

The needed frequency for pulse width 100 ns is 5 MHz for period.

$$\text{Ripple}\ (\%) = e^{-\zeta\pi / \sqrt{1-\zeta^2}} \times 100\ \% \qquad (10)$$

, where ζ is the damping ratio depends on capacitance, inductance and load resistance. Rise time and ripple percentage of output pulse shape can be calculated the inductance and capacitance values and matched load of desired pulse [10].

Table II: Parameters of needed inductance and capacitance values for same diameter ratios and short lengths.

Dielectric constant	Length (m)	D/d ratio	No of LC pairs	L (µH)	C (nF)
Air	1	1.7	15	0.106	0.105
Rubber	1	1.7	6	0.106	0.73
Silicon	1	1.7	5	0.106	1.22

Table II shows the inductance and capacitance values for required LC pairs of various dielectric constants. The two switches are used to control the charging and discharging of coaxial cables, the output pulse voltage obtained across load is rectangular shape with pulse voltage. The output pulse waveform was obtained for a charging voltage of 1 V. When Switch 1 is closed at 0.1 µs while Switch 2 closing time is delay at 0.2 µs, the pulse duration 100 ns is achieved.

IV. SIMULATION RESULTS AND DISCUSSION

A. Simulation Model for Output Pulse Shape from Coaxial Cable

A typical circuit diagram for a coaxial cable used in pulse forming network is presented in Fig. 6. The coaxial cable transmission lines are charged by the supply voltage. The time of Switch-1 is discharged from the supply voltage at 0.1 µs. All energy stored in the pulse forming network represent coaxial cable is discharged at Switch-2 towards the load when Switch-2 is closed at 0.2 µs. The output voltage is half of the charging voltage. The state space representation and MATLAB simulation are used to analysis the response of the circuit for the result of output pulse shape. The magnitude of pulse duration, pulse rise time, pulse fall time, percentage of overshoot, undershoot and ripple are researched by MATLAB Simulink.

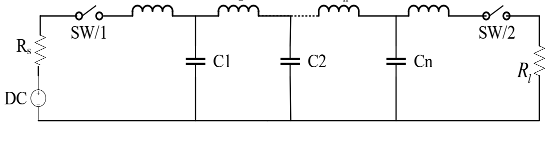

Fig. 6. Circuit diagram of pulse forming network for n^{th} section.

B. Before Pulse Shaping Improvement

The output pulse shape is evident by overshoot and ripple near the beginning of the pulse and the oscillations. The simulation of the pulse forming network for coaxial cable of the output voltage, pulse width, ripple, overshoot was tested with insulation of air, rubber, silicon and water. The desired output pulse has for duration of 100 ns having rising time and falling time better than around 10 ns in dielectric constant (air). When the same diameter ratio 1.7 and the length 1 m are considered.

Table III: Comparison of theoretical and simulation results for normal condition.

Dielectric Materials	Theoretical Results			Simulation Results		
	Air	Rubber	Silicon	Air	Rubber	Silicon
Rise time (ns)	8	21.2	27.4	9.73	19.8	23.5
Ripple (%)	16	16	16	12	13	12
Pulse width (ns)	100	105	114	99	95	101
Pulse mag (V)	0.5	0.5	0.5	0.42	0.45	0.44

Table III shows the theoretical results and simulation results of small diameter ratio and short length (1 m) condition of 100 ns. At normal condition, the rise time are more narrows in air than other dielectric materials in both simulation and theoretical results. The ripple percentage of simulation results is smaller than the theoretical results. When the dielectric constants are more and more large, the rise time of pulse shape are more and more wide.

The normal voltage of the output pulse for a matched load is 0.5 V at half of the charging voltage, but the ripple percentage will present at 16%. The inductance and capacitance ratios are 1 in air, 7 in rubber, 11.5 in silicon and 54.5 in water, respectively. The characteristic impedance will be varied with depend on dielectric constant.

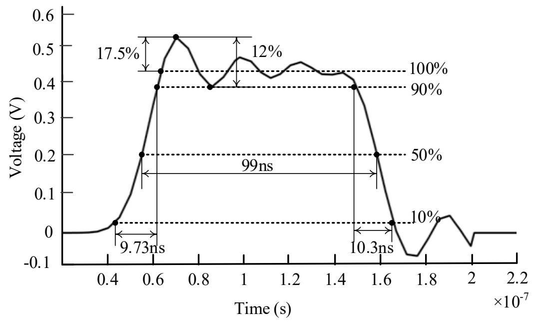

Fig. 7. Simulation results for output pulse of ε r (air).

For the diameter ratio 1.7 and length (1 m), the simulation of pulse forming network for coaxial cable at dielectric constant air in Fig. 7 is composed of 15 sections of inductance and capacitance values series and parallel network. The capacitance and inductance values of each section are 0.106 µH and 0.105 nF in dielectric constant for air. The charging voltage is 1 V. The amplitude of the output pulse is about 0.5 V at half of the charging voltage. It can be found that the pulse duration is approximately 99 ns with the rising time is 9.73 ns and falling time is 10.3 ns.

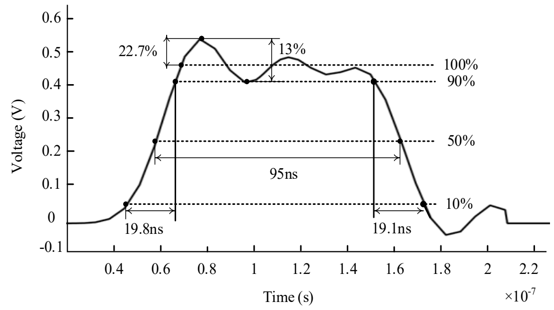

Fig. 8. Simulation results for output pulse of ε_r (rubber).

Figure 8 shows the output pulse with the dielectric constant of rubber, the number of sections 6 and the inductance and capacitance values of 0.106 µH and 1.22 nF to get a pulse width of 100 ns. The amplitude the characteristic impedance of the coaxial cable is kept 12 Ω. The observation is that the pulse duration is 95 ns with the rising time of 10% to 90% is 19.8 ns and falling time of 90% to 10% is 19.1 ns.

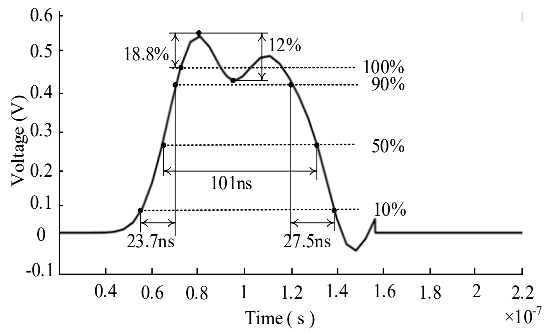

Fig. 9. Simulation results for output pulse of ε_r (Silicon).

Figure 9 is the simulation results for output pulse characteristic of dielectric constant (silicon). The measured output voltage amplitude across a characteristic impedance (9 Ω) is approximately half of the pulse forming network of charging voltage in dielectric constant (silicon). The number of sections is 5 and the inductance and capacitance values of 0.106 µH and 1.22 nF for each section are needed to get a pulse width of 100 ns.The amplitude the characteristic impedance of the coaxial cable is kept 12 Ω. The observation is that the pulse duration is 95 ns with the rising time is 19.8 ns and falling time is 19.1 ns.

C. After Pulse Shaping Improvement

Figure 10 shows the output voltage waveform of the pulse forming network of coaxial cable for ripple and overshoot reducing. To eliminate the distorting pulse shape, the inductance values of the last location are increased series location at the outgoing of the coaxial cable.

At first, the series inductances of the last location are increased 100% (or) 2 times of the normal condition. The rise time was observed between 15 ns and 20 ns. The ripple percentage can be eliminated 7% and overshoot is 11% of normal pulse shape.

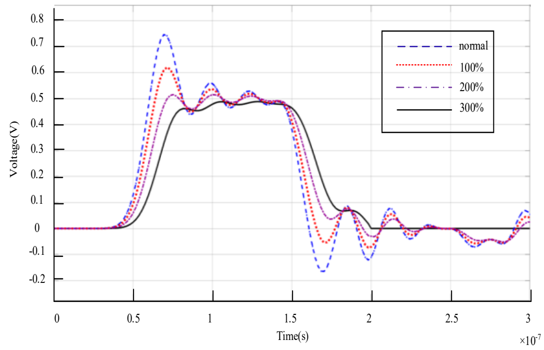

Fig. 10. Simulation results for output pulse of reducing ripple and overshoot.

When the inductance of 200% (or) 3 times are increased, the rise time is around 20 ns, the ripple percentage is decreased until 4%. The pulse shape has been smoothed by increasing the inductance value of 300% with overshoot percentage of 2% and ripple of 2%. But pulse rise time is longer than around 25 ns of normal pulse shape. The characteristic impedance is 31.62 Ω at ε_r (1), 12 Ω at ε_r (7), 9.32 Ω at ε_r (11.68) and 4.27 Ω at ε_r (55.5) slightly small respectively.

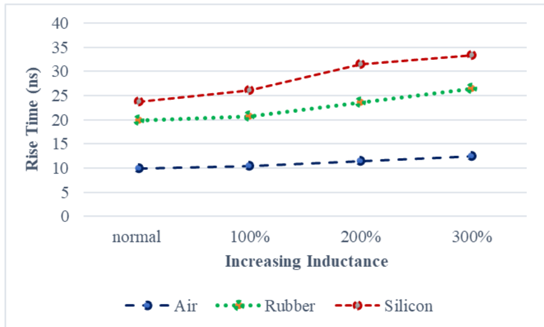

Fig. 11. Comparison for rise time of output pulse with different dielectric materials.

Figure 11 shows the comparison of rising time of output pulse with different dielectric materials. This condition is that the rising time is the most in silicon and the least in air. As the inductance of the outgoing section of the coaxial cable is increased as 100% (0.108 µH) in air, 10% to 90% of frontal rising time of the pulse (tr) are increased to about as (10.5 ns). In rubber, the rising time is about (18 ns) and in silicon is (26.1 ns). As the inductance of the outgoing section of the coaxial cable is increased as 200% (0.21 µH) in air, 10% to 90% frontal rising time of the pulse (tr) are increased about as (11.5 ns). In rubber, the rising time is about (23.5 ns) and in silicon is (31.5 ns).

Figure 12 shows the comparison of fall time of output pulse with different dielectric materials. When reducing ripple percentage and overshoot percentage, fall time in rubber and silicon significantly higher but air is not much significant.

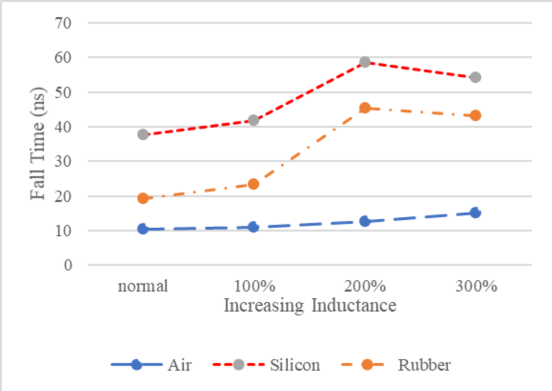

Fig. 12. Comparison for fall time of output pulse with different dielectric materials.

As the inductance of the outgoing section of the coaxial cable is increased as 100% (0.108 µH) in air, 90% to 10% frontal rising time of the pulse (t_f) are increased to about as (11.02 ns). In rubber, the rising time is about (23.4 ns) and in silicon is (30.7 ns). As the inductance of the outgoing section of the coaxial cable is increased as 200% (0.21 µH) in air, 90% to 10% frontal rising time of the pulse (t_f) are increased about as (12.5 ns). In rubber, the rising time is about (45.47ns) and in silicon is (45 ns).

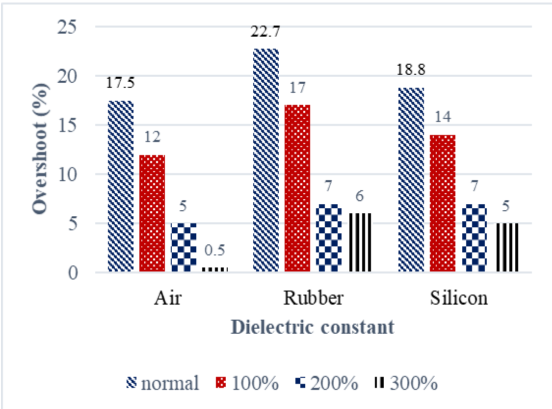

Fig. 13. Comparison for overshoot of output pulse in increasing the outgoing of inductance with different dielectric materials.

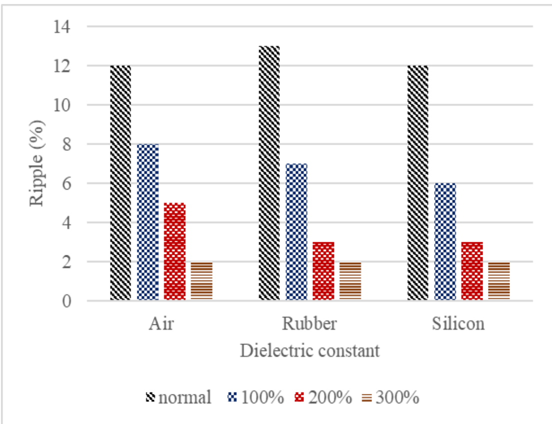

Fig. 14. Comparison for ripple of output pulse in increasing the inductance percentage of outgoing of coaxial cable with different dielectric materials.

Figure 13 and Fig. 14 are the comparison of reducing overshoot and ripple percentages due to the increasing the inductance of outgoing of coaxial cable with 100%, 200% and 300% level. The overshoot percentage is the most in rubber at normal condition as the percentage of outgoing inductance increases, the overshoot and ripple percentages can be reduced.

The series inductance of the last location is increased 100% (or) 2 times of normal condition. The ripple percentage can be eliminated 8% and overshoot is 12% of normal pulse shape in air. When the inductance of 200% (or) 3 times are increased, the ripple percentage is decreased until 5% and overshoot is 5%. The pulse shape has been smoothed by increasing the inductance value 300% with overshoot percentage of 0.5% and ripple of 2%.

The series inductance of the last location is increased 100% (or) 2 times of the normal condition. The ripple can be eliminated 7% and overshoot 17% of normal pulse shape in Rubber. When the inductance of 200% (or) 3 times are increased, the ripple percentage is decreased until 3% and overshoot of 7%.

The pulse shape has been smoothed by increasing the inductance value 300% with overshoot percentage of 5% and ripple of 2%. Of these, dielectric constant (air) can be reduced to a minimum overshoot and ripple percentages, but the rise and fall times are slightly increased.

The pulse shape has been smoothed by increasing the inductance value 300% with overshoot percentage of 5% and ripple of 2%. The ripple percentage can be reduced the same at 2% of all dielectric materials at the increasing inductance is 300%.

The difference characteristic of normal conditions and pulse shaping improvement. When the inductances of the outgoing of coaxial cable are increased until 300%, ripple percentage can be reduced to 2% of all the dielectric constants of insulation shield. The pulse rise times are the smallest in air of three dielectric constant materials.

V. CONCLUSION

The inductances of the outgoing of coaxial cable are maintained 200% to 300% larger, depending on the pulse shaping requirement. The rectangular pulse shape of desired 100 ns has been developed by using coaxial cable transmission lines depend on pulse forming network of Type- B. The rising time is reduced than by using dielectric constant with shorter length and smaller ratio of inner and outer diameters. The good flat top can be produced by increasing the inductance of the outing end of the coaxial cable. In dielectric constant air, the rise time and fall time are the shortest the other dielectric constants. The desired pulse shape for 100 ns by altering the dielectric constant for coaxial cable has been simulated by MATLAB. In this study, when the constant value of insulation shield of coaxial cable is small, it has better pulse shape for output pulse.

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