# Finite Element Analysis Modeling and Experimental Verification of Reflected Wave Phenomena in Variable Speed Machine Drive Cables

Han Xiong[1], Alex Louie[2], Rui Liu[3], Julia Zhang[4], Annette von Jouanne[5]

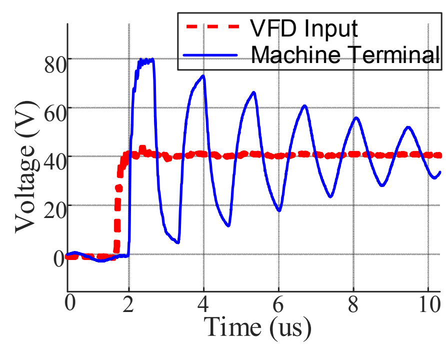
[1]School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA, xiongh@oregonstate.edu
[2]The Engineering Enterprise, Auburn, CA, USA, alex.louie@engent.com
[3]School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA, liur@oregonstate.edu
[4]School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA, zhangjul@eecs.oregonstate.edu
[5]School of Electrical Engineering and Computer Science, Oregon State University, Corvallis, OR, USA, avj@eecs.oregonstate.edu

***Abstract* - Modern variable frequency drives (VFDs) are employed in various industry applications. The machine windings may be subject to large overvoltage, called reflected wave phenomena (RWP), if long cables are used or fast voltage rise times are implemented in the VFD system. The overvoltage places high electrical stress on the machine terminal windings, in the long term resulting in the winding insulation degradation and eventually a complete insulation breakdown. Several methods were proposed to model the RWP overvoltage based on the transmission line theory to study how various factors affect the RWP. The accurate acquisition of the electrical characteristics of the cable for the RWP models however proved to be difficult. This work proposes to use a 2D finite element analysis (FEA) model to simulate the electrical characteristics of the power cable under test. The characteristics are then used to construct a two-port network in a circuit simulation of RWP. The accuracy of the modeling technique is experimentally verified by measuring the voltage overshoots using cables of different lengths and under different switching frequencies and duty cycles. The simulation results are found to closely match the experimental findings after adopting a compensation method.**

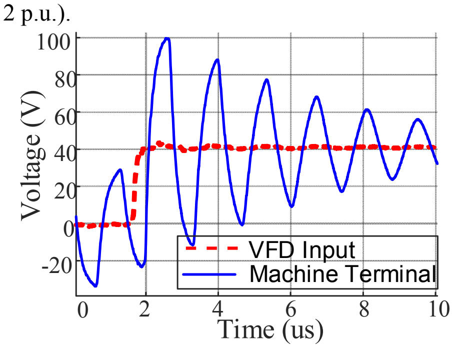
***Keywords—finite element analysis, reflected wave phenomenon, power cable, machine terminal overvoltage***

## I. Introduction

Variable frequency drives (VFDs), due to their capabilities of more flexible machine control and improved efficiency, have gained popularity in the electric machine system for various applications such as generation, propulsion, pumps, and compressors. The fast rise times associated with the power semiconductor devices in the VFDs, however, are well known to cause large overvoltage at the electric machine terminals, especially if long power cables are used [1]. Fig. 1 presents the experimentally measured results of the overvoltage. The dashed red curve represents the input voltage generated by the VFD system, and the solid blue curve represents the measured output voltage from the end of a 120-ft power cable connecting to the terminals of an electric machine. The magnitude of such overvoltage in one voltage pulse, as previous research has concluded, can reach a maximum of twice the DC bus voltage (2 p.u.) as shown in Fig. 1(a). In extreme cases where the previous overvoltage oscillation has not decayed fully at the arrival of the next voltage pulse, the next overvoltage has the possibility to reach up to four times the DC bus voltage (4 p.u.). Such scenario often is a result of low/high duty cycle or high switching frequency in the VFDs and is often referred to as double pulsing. Fig. 1(b) demonstrates an event of double pulsing where the overvoltage magnitude reaches more than twice the input voltage.




(a) Typical overvoltage in one voltage pulse due to RWP (less or equal to 2 p.u.).




(b) Typical overvoltage in double pulsing (greater than 2 p.u., less than 4 p.u.).

Fig. 1. Experimentally obtained results to demonstrate the possible RWP overvoltage.

Several methods have been proposed to mitigate the overvoltage including applying filters [2-3] or optimizing PWM strategy [4]. To guide practical applications, a table was created to help select the cable length for VFD-driven electric machine system to avoid the overvoltage [4]. With the emergence of wide bandgap (WBG) devices, however, the

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VFD systems will experience even faster rise time and higher switching frequency. This will not only aggravate the magnitude of the overvoltage due to RWP, but also initiate the occurrence of overvoltage at a shorter cable length. To take full advantage of the WBG device for a VFD system, an accurate and robust modeling technique of RWP is needed to avoid the overvoltage at the machine terminals.

Transmission line theory is the basis to most RWP modeling. Saunders used the transmission line theory to analytically derive the effect of voltage rise time [5]. Skibinski created a Simulink model incorporating frequency dependent skin and proximity effects [6]. Scott constructed a SPICE model to account for high frequency response in the power cables [7]. It is crucial to accurately obtain the electrical characteristics of the power cable, specifically *RLGC* parameters, to utilize the transmission line theory [8]. Using transmission line theory, the power cable can be modeled using four basic components, the resistance $R$, the inductance $L$, the conductance $G$, and the capacitance $C$ as shown in Fig. 2. The modeling methods mentioned above either adopted mathematical approaches to calculate the *RLGC* parameters [2, 3, 4], or used the network analyzer to conduct manual measurements [7]. The mathematically determined *RLGC* parameters were tested to have the possibility to be off by a large amount [4]. Using the network analyzer to manually measure the electrical properties of the cable will yield accurate results. The input voltage from the VFD, however, often has small voltage ripples of high frequency, and it requires the electrical properties of the cable to be swept over a wide frequency range to take into account the response for the high frequency voltage ripples. It is time-consuming to conduct such measurements.

This work proposes to use finite element analysis (FEA) to simulate the electrical characteristics of the power cables with respect to frequencies. With only the geometric information of the cable and the materials used, FEA can simulate the *RLGC* parameters of any cable with an autonomous frequency sweep. Tilea [10] performed the FEA modeling however the experimental verification was never implemented. The contributions of this work are to, 1) experimentally verify the accuracy of FEA cable model in a RWP circuit simulator using a commercially available power cable tested with a VFD system; and 2) propose a cable elongation compensation method for the RWP simulation model to improve its consistency with the experimental tests.

## II. Fundamentals of Reflcted Wave Phenomenon

The overvoltage on the machine terminals due to the use of VFD system was observed and investigated as early as the 1990s [6]. The theoretical analysis of the RWP using transmission line theory has been well investigated and documented since then [1-6]. In this section a simple example of reflected wave process in a lossless transmission line model with ideal pulse voltage input is introduced to introduce the basic process of a reflected voltage [1].

Fig. 2 demonstrates the components of a typical VFD system. As it is established that the power cable behaves like a transmission line for the pulses [2], a transmission line model is used to represent the power cable connecting the output of the inverter and the input of the motor in Fig. 2. The four parameters, $R_x$, $L_x$, $G_x$, and $C_x$ represent the resistance, inductance, conductance and capacitance per unit length of the power cable.

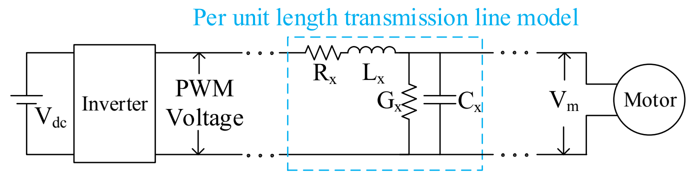



Fig. 2. Typical schematic of VFD system with the power cable represented by basic transmission line models in series.

To better demonstrate the voltage reflection process, Fig. 3 visually explains the overvoltage at the output of an open-circuited transmission line with an ideal voltage pulse source as input. The rise time of this ideal voltage source is zero. In the figure the time delay $t_d$ is the amount of time the waveform requires to travel down the length of the transmission line, $l$, where the velocity of the wave is found by $v = \frac{1}{\sqrt{L_x C_x}}$. The traveling voltage wave will get reflected at both ends of the transmission line, and the magnitude of the reflect wave is determined by the reflection coefficient. The reflection coefficient of the load side can be found by

$$\Gamma_L = \frac{Z_L - Z_0}{Z_L + Z_0} \tag{1}$$

where $Z_L$ is the load impedance, and $Z_0$ the characteristic

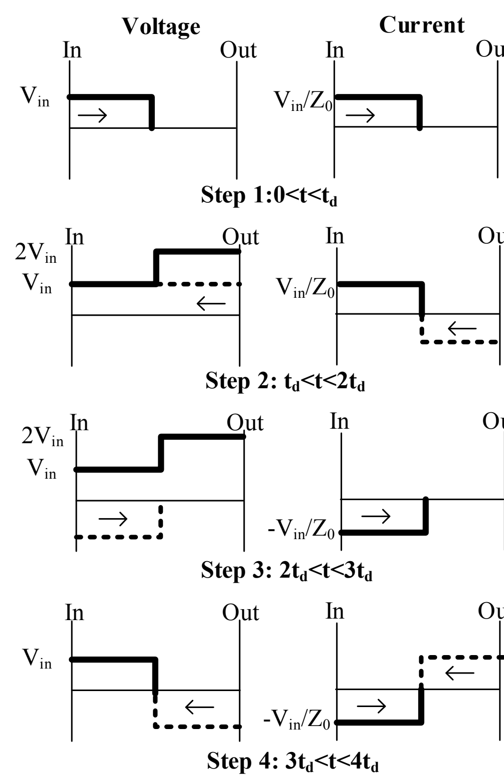



Fig. 3. Reflected wave process between ideal voltage input and output of a lossless transmission line with open circuit load.

impedance of the cable which is found by $Z_0 = \sqrt{\frac{L_x}{C_x}}$. The source side reflection coefficient, $\Gamma_S$, can be similarly found by using the source impedance, $Z_S$, in place of $Z_L$ in Eq. (1). In the example presented in Fig. 3 with open-circuited load and ideal input voltage, the circuit yields $\Gamma_L = 1$ and $\Gamma_s = -1$.

In the first step presented in Fig. 3, the pulsed voltage wave travels through the transmission line towards the output. The reflection process begins in step two. The load reflection coefficient, $\Gamma_L = 1$, means that a full reflection will occur. The reflected voltage waveform will travel back towards the input of the transmission line with an equal magnitude, resulting in a transmission line output voltage of 2 p.u. When the first reflected wave reached the input of the transmission line at step 3, the source reflection coefficient, $\Gamma_s = -1$, means the second reflected voltage waveform, traveling towards the output, will have an equal but opposite magnitude. The overall voltage on the transmission line is reduced from 2 p.u. back to 1 p.u. When this second reflected wave hits the transmission line output and is reflected once more time towards the input of the transmission line, the resultant voltage on the transmission line becomes zero. Once the third reflected wave reaches the input the process begins all over again.

Using the lossless transmission line model in Fig. 3, the voltage oscillation at the transmission line output will have a peak value of 2 p.u. and will not die down. Realistically however the shape and duration of the output waveform are strongly affected by lossy transmission line characteristics and pulse rise time.

## III. Reflected Wave Phenomenon Simulation

In order to properly evaluate the performance of RWP simulation, a commercially available cable is modeled using the FEA method in this section. The electrical characteristics of the cable then are exported to a circuit simulation in ANSYS to model the RWP.

### *A. FEA Modeling of Power Cable*

The power cable selected in this research for both the FEA simulation and experimental tests is the Belden 29501 multi-conductor 1000-V VFD cable. The most important factors in determining the transmission line characteristics of the power cable are the construction and the materials. A short sample of the Belden cable was broken down and measured for an accurate model of the cable construction. The electrical properties of the materials used in the cable were obtained from the manufacturer's datasheet. The cable was created in the FEA tool ANSYS Q3D as shown in Fig. 4, and the specifications used are summarized in Table I.

Table I. Belden 29501 Cable Specifications

| Cable Parameter | Dimension | Material |
|---|---|---|
| Conductor Strand | 0.0079 in | AWG30 Tinned Copper |
| Overall Conductor | 0.057 in | 41 Stranded Tinned Copper |
| Insulation Thickness | 0.056 in | XLPE(Phase Conductor) PVC(Ground Conductor) |
| Shield Thickness | 0.022 in | 100% Aluminum 85% Tinned Copper Braid |
| Jacket Thickness | 0.048 in | PVC |

Only phase A and B were excited in the cable model to be consistent with the experimental setup. The other conductors were floated. The cable was solved at a wide range of frequencies to accurately model the high frequency response due to both the fast rise time and the high oscillation frequency of the voltage wave. The *RLGC* parameters with respect to the frequencies were exported from ANSYS Q3D to ANSYS Simplorer. They were then used to compile a two-port network to represent the response of the power cable in the circuit.

### *B. Reflected Wave Phenomenon Simulation*

The RWP model created in circuit simulator ANSYS Simplorer can be seen in Fig. 5. The two-port network, compiled from the *RLGC* parameters in the FEA simulation results, represents the power cable response. The input of the cable was an ideal trapezoidal voltage source with adjustable rise time and switching frequency. The peak of the trapezoidal voltage source was 42 V to be consistent with the experimental VFD system presented in Section IV. The output was left as an open circuit to reduce the number of factors influencing the RWP analysis.

A summary of the simulation parameters is listed in Table II. The effect of three major factors on the RWP overvoltage were investigated in the simulation, and they are: 1) length of the power cable; 2) switching frequency of the input voltage; and 3) rise time of the input voltage. Fig. 6 gives the selective simulation results to demonstrate the effect of the above three factors on the overvoltage waveform at the output of the power cable.

In Fig. 6 the red dashed line is the voltage at the input of

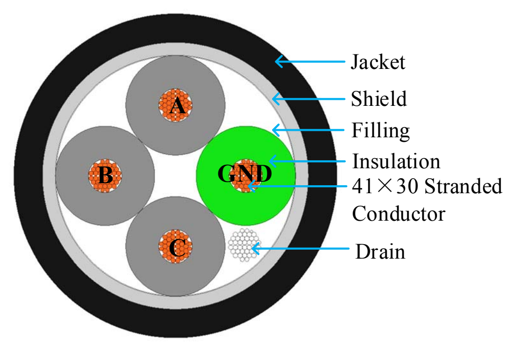



Fig. 4. Construction of the Belden 29501 cable in ANSYS Q3D.

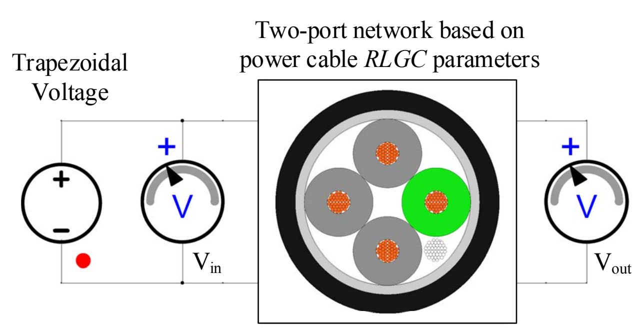



Fig. 5. FEA cable solution incorporated in ANSYS Simplorer circuit for RWP modeling.

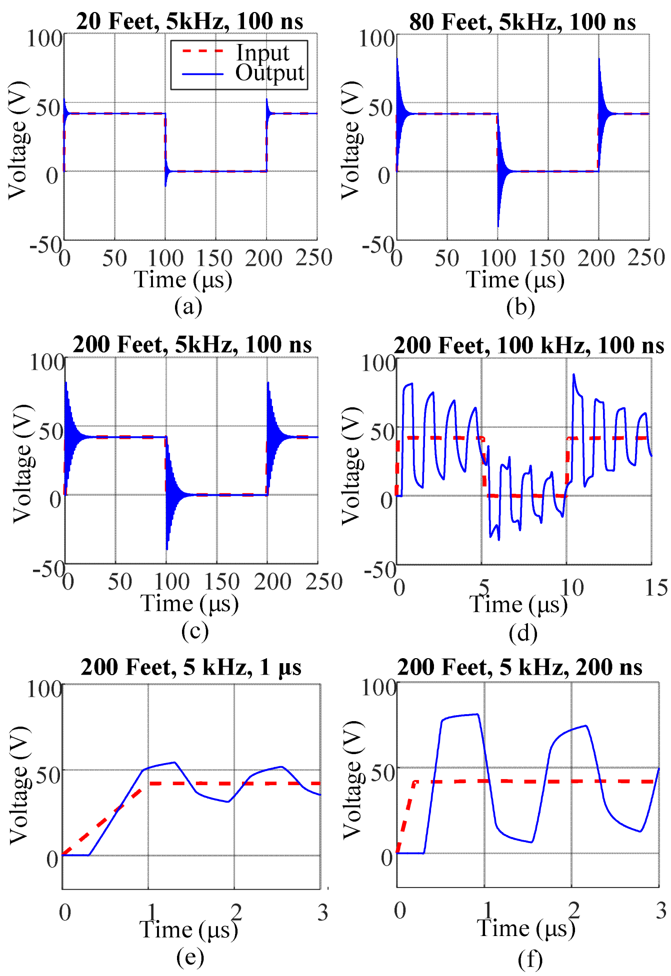



Fig. 6. Selective simulation results to demonstrate the effects

Table II. Reflected wave phenomenon simulation parameters.

| | | |
|---|---|---|
| **DC Bus Voltage** | 42 V | |
| **Cable Length** | 10 ft, 20 ft, 40 ft, 80 ft, 120 ft, 200 ft | |
| **Switching Frequency** | 5 kHz | 100 kHz |
| **Rise Time** | 100 ns, 200 ns, 300 ns ,1 µs | 50 ns, 100 ns |

the power cable, and the blue solid line is the voltage at the output. The title of each plot refers to the parameters (length of the power cable, switching frequency of the input voltage, and the rise time of the input voltage) applied in that simulation case. Observations made from the results in Fig. 6 are summarized here:

- A Longer cable length aggravates the overvoltage magnitude from the comparison of Fig. 6(a) and (b). In the simulation, a cable of 20 ft is too short to allow full voltage reflections. When the length is increased to 80 ft, however, the overvoltage peak jumps to 82 V (2 p.u.) in Fig. 6(b).
- A faster switching frequency, from comparing Fig. 6(c) and (d), increases the possibility of double pulsing, which potentially could result in an overvoltage peak of 164 V (4 p.u.). A faster switching frequency allows shorter time for the overvoltage oscillation to decay. When the oscillation does not fully die down on the arrival of the next pulse, double pulsing will occur. The overvoltage peak in a double pulsing event is determined by the magnitude and polarity of the instant voltage when the next pulse hits. It can be inferred that a very high or low duty cycle potentially can also induce double pulsing for the same reason. A longer cable, by increasing the overvoltage oscillation time, is another possible reason for the occurrence of double pulsing.
- A shorter voltage rise time allows a full reflection from the comparison in Fig. 6(e) and (f). It has been established that if the rise time is less than the cable time delay $t_d$, such as the 200 ns rise time in Fig. 6(f), then the voltage reflection at the output of the cable is determined primarily by the load reflection coefficient $\Gamma_L$ [1]. In the case of open circuit, the output will reach 2 p.u. If the rise time is longer than $t_d$, the voltage reflection will be proportional to the ratio of the time delay and rise time as well as $\Gamma_L$ [1].

The impacts of the three major factors on RWP overvoltage summarized from the simulation results are consistent with the analyses from the established theoretical method [1-5]. This RWP circuit model is further used to generate simulation results for verification by experimental tests.

## IV. Experimental Verification

### A. *Experimental Test Setup*

The experimental tests were conducted to observe and record the overvoltage at the cable output. A VFD system with a 42-V DC power supply was used for tests as shown in Fig. 7. The inverter board was controlled by a dSpace CP1104 I/O Controller, which was linked with Simulink and Control-Desk in real time. A Tektronix DPO 4034B 350 MHz oscilloscope with high voltage differential probes was used to measure both the input wave of the cable and the output voltage waveforms. Due to the limit of the inverter board, the voltage switching frequency has a maximum of 40 kHz, and the rise time of the voltage pulse is relatively steady at approximately 150 ns. The detailed parameters used in the tests are summarized in Table III.

### B. *RWP Experimental Test Results*

Selective experimental test results are presented in Fig. 8 to demonstrate the effects of the voltage switching frequency, the voltage duty cycle, and the power cable length. The dashed red line in Fig. 8 represents the measured input voltage of the power cable, and the blue solid line represented the measured output voltage. The title of each plot states the cable length, the switching frequency, and the duty cycle of the test.

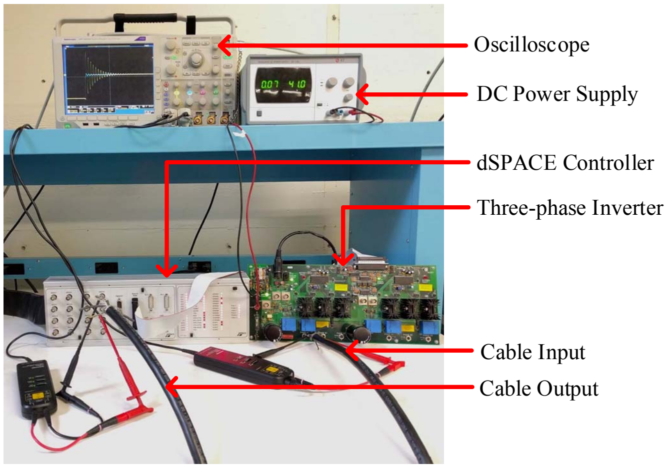



Fig. 7. Experimental test setup.

Table III. Belden 29501 Experimental Testing Parameters

| Parameters | Values | |
|---|---|---|
| DC Bus Voltage | 42 V | |
| Rise Time | 150 ns | |
| Switching Frequency | 5 kHz, 10 kHz, 20 kHz, 30 kHz, 40 kHz | |
| Duty Ratio | 50% | 90% |
| Cable Length | 10 ft, 20 ft, 40 ft, 80 ft, 120 ft, 200 ft | 120 ft, 200 ft |

In Fig. 8(a) and (b), a 200 ft cable was under test for two different switching frequencies, 5 kHz and 30 kHz. At 5 kHz, the voltage oscillation was barely decayed fully when the next voltage pulse hit. When the switching frequency was increased to 30 kHz, double pulsing occurred and the overvoltage peak exceeded 2 p.u. For the two tests conducted in Fig. 8(c) and (d), the duty cycle was increased. The voltage oscillation was barely decayed fully in Fig. 8(c). When the duty cycle was increased the time for the voltage oscillation to decay shortened. As a result double pulsing occurred in Fig. 8(d). The overvoltage peak, however, did not exceed 2 p.u. because at the moment the next voltage pulse hit, the instant voltage oscillated to the positive side. The combined effect was an overvoltage peak that was lower than 2 p.u. In Fig. 8(e) and (f) the length of the cable was increased from 20 ft to 80 ft. It was observed that increasing the length of the power cable aggravated the overvoltage at the output.

The effects of three factors (switching frequency, duty cycle, and cable length) were investigated using the experimental tests. It was summarized that: 1) increasing the cable length aggravates the overvoltage at the output of the power cable; 2) a very high or low duty cycle has the potential to induce double pulsing at the output; and 3) a higher switching frequency also can possibly induce double pulsing. It can be inferred that under certain conditions having a longer cable yields the possibility to induce double pulsing as well.

The summaries are consistent with the observations made from the simulation results presented in Section II. The

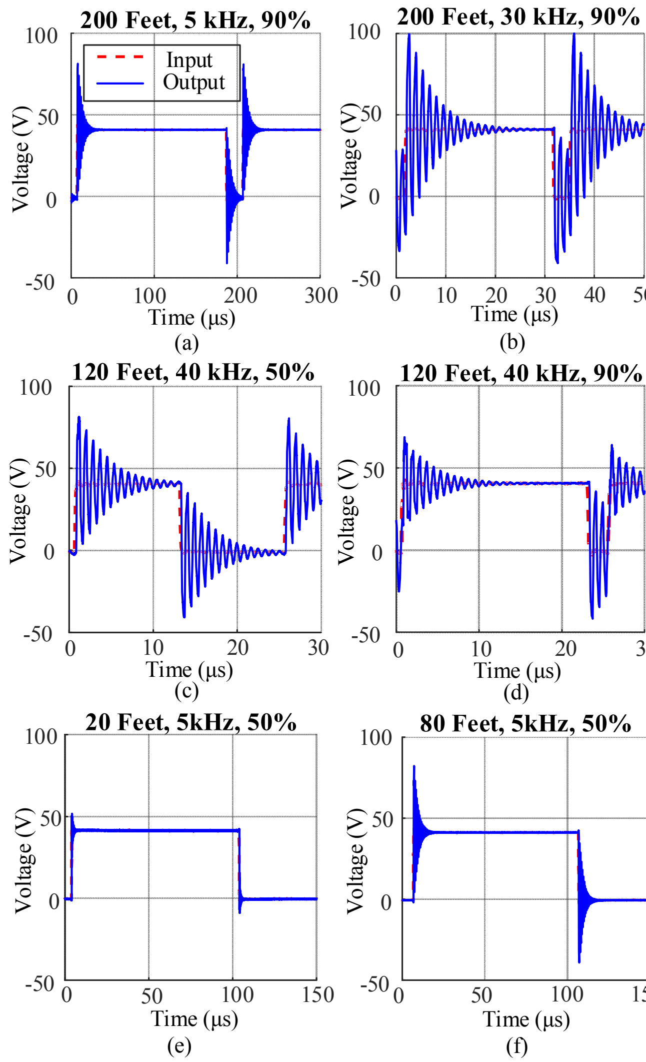


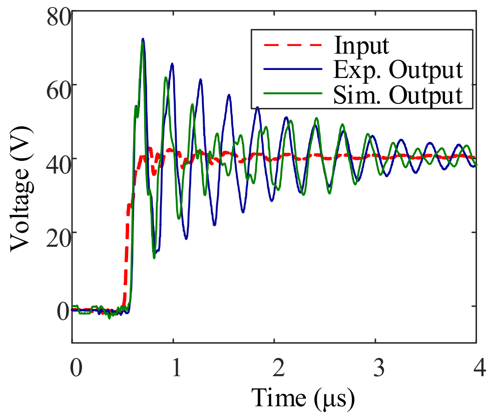

Fig. 8. Selective experimental test results for RWP.

RWP simulation, therefore, is proved to show the correct trend when considering the effects of system parameters on the overvoltage at the output of the power cable.

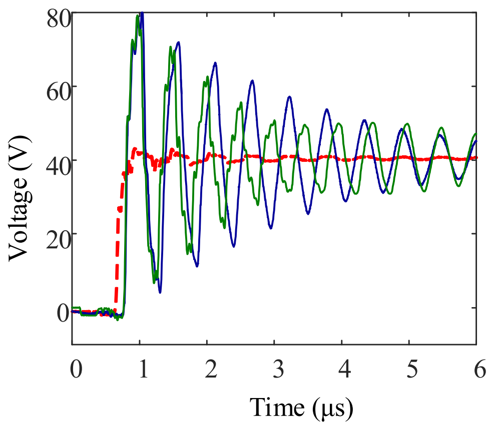
## *C. Simulation and Experimental Results Comparison*

To perform a direct comparison of the overvoltage in the RWP simulation and the experimental test, the ideal trapezoidal voltage source used in the simulation circuit, as shown in Fig. 5, was replaced by the actual voltage measured at the input of the Belden power cable in the tests. RWP simulations with parameters listed in Table III were run, and the results were compared with the experiment test results.

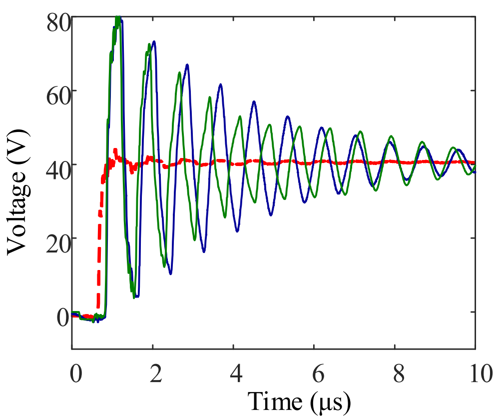
The simulated RWP overvoltage exhibited a discrepancy with the experimental test results regardless of the test parameters. To demonstrate such discrepancy, selected simulation and experimental test results are compared in Fig. 9. The input voltage switching frequency is selected to be 40 kHz and the duty cycle 50%. Results for three different power cable lengths (40 ft, 80 ft, and 120 ft) are presented and analyzed. In Fig. 9 the red dashed line is the measured input voltage, the solid dark blue line is the measured output voltage




(a) 40-ft cable




(b) 80-ft cable




(c) 120-ft cable

Fig. 9. RWP overvoltage comparison between the simulation and the experimental test results.

for a given length of the power cable, and the solid dark green line is the output from the simulation. For all three lengths presented in Fig. 9, a clear discrepancy between the simulation and the experimental test results can be observed.

The discrepancy, to be more specific, occurs for both the general shape and the oscillation frequency of the overvoltage waveform. While the difference in the shapes of waveform is hard to quantify, the difference in the oscillation frequencies is calculated and summarized in Table IV for all cable lengths

Table IV. Error in oscillation frequency for comparisons between simulation and experimental test results of all cable lengths under a switching frequency of 5 kHz and a duty cycle of 50%

| **Length (ft)** | **Exp. $f_o$ (MHz)** | **Sim $f_o$ (MHz)** | **Error** |
|---|---|---|---|
| 10 | 11.25 | 14.29 | 27.2% |
| 20 | 6.8 | 7.69 | 13.1% |
| 40 | 3.46 | 3.85 | 11.27% |
| 80 | 1.78 | 2.0 | 12.3% |
| 120 | 1.17 | 1.31 | 11.9% |
| 200 | 0.703 | 0.781 | 11% |

under 5 kHz switching frequency and 50% duty cycle. The overvoltage oscillation always is faster than the experimental test results. The error, based on Table IV, decreases with the increasing power cable length

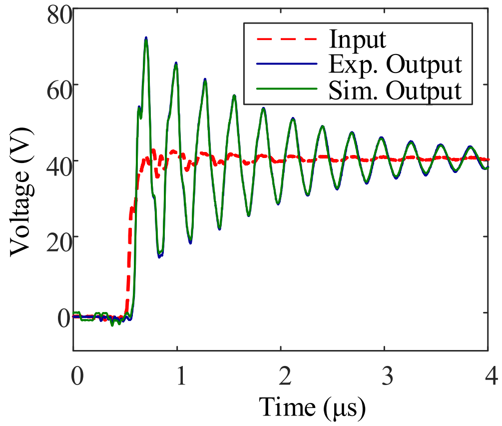
### *D. Cable Elongation Compensation in Simulations*

In order to mitigate this error introduced in the simulation, a cable elongation compensation method was used.

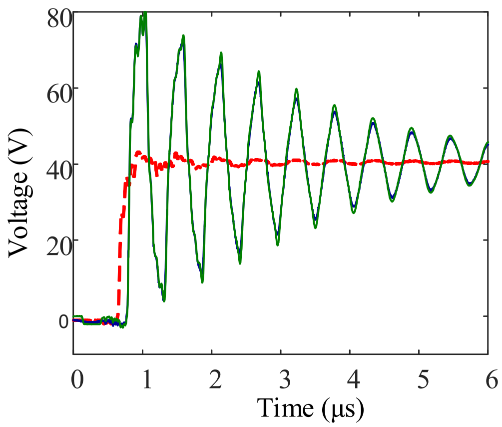
By increasing the length of the cable in the simulation, the oscillation frequency of the reflected voltage decreases. It was found that when increasing the length of the cable in the simulation to match the oscillation frequency of the simulation to the experimental test results, the general shape of the overvoltage in the simulation also became consistent with that in the experimental tests. Fig. 10 gives the comparison for the same three cable lengths presented in Fig. 9. With modified cable length in the simulation, not only the oscillation frequency but also the general shape of the waveform match well with the experimental test results. The discrepancy in the general shape and the oscillation frequency between the simulation and the experimental test results therefore is successfully compensated by increasing the length of the power cable in the simulation.

The modified lengths in the simulation are summarized in Table V, and the elongation percentage is calculated. The elongation percentage is higher for shorter cables under test, and this is consistent with the oscillation errors presented in Table IV. The oscillation errors for shorter cables are higher, and therefore the elongation percentage needs to be higher to compensate the error.

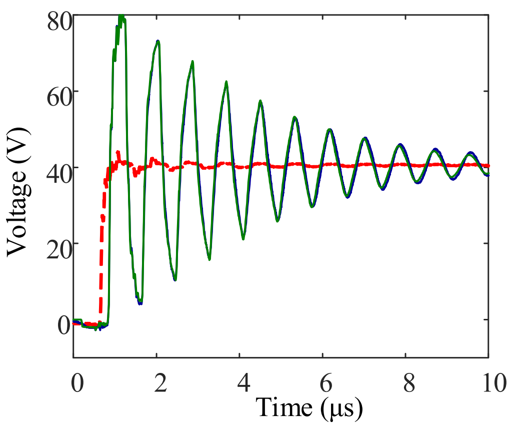
From the test results shown in Figs. 8-9, it is observed that the FEA simulation of the power cable lacks accuracy. The causes for this error are not yet well understood. From the discrepancy in the oscillation frequency, however, it could be inferred that the capacitance effect in the simulation may be the cause of error, which explains the effectiveness of the elongation compensation method. The error in the capacitance in the simulation could be the result of an idealized cable construction shown in Fig. 4 and the error in the electrical properties of the material used in the cable. To continue this work, 1) an even longer cable will be used for the comparison of the simulation and experimental test results since the discrepancy goes down with the longer cable under test; and 2) an impedance analyzer will be used to measure the *RLGC*




(a) 40-ft cable, 43.25-ft in simulation




(b) 80-ft cable, 86.56-ft in simulation




(c) 120-ft cable, 129.84-ft in simulation

Fig. 10. RWP overvoltage comparison between the simulation with modified cable length and the experimental test results.

parameters of the Belden cable to compare with the FEA simulation results.

## V. Conclusions

To construct a model for the reflected wave phenomenon (RWP), this work proposed to use finite element analysis (FEA) to simulate the electrical characteristics of the power cable. By creating a two-port network based on the electrical characteristics, a circuit could be established to model the

Table V. Modified length in the simulation based on the elongation compensation method.

| **Length (ft)** | **Modified Length (ft)** | **Elongation Percentage** |
|---|---|---|
| 10 | 11.75 | 17.5% |
| 20 | 22.75 | 13.75% |
| 40 | 43.25 | 8.2% |
| 80 | 86.56 | 8.2% |
| 120 | 129.84 | 8.2% |
| 200 | 216.4 | 8.2% |

overvoltage at the output of the power cable due to RWP. In the simulation the switching frequency, the voltage rise time, the duty ratio, and the cable length were all proved to heavily impact the RWP overvoltage. To verify the accuracy of the constructed model, experimental tests were conducted. A 42-V variable frequency drive (VFD) system was implemented, and the generated PWM voltage was fed to the Belden power cable. The overvoltage waveforms from the experimental tests and the simulation results were compared, and constant errors in both the general shape of the overvoltage and the oscillation frequency were observed. To compensate for such errors, a method of cable elongation in the simulation was adopted. By increasing the length of the cable model in the simulation, the overvoltage waveform generated in the simulation reached good agreement with the ones from the experimental tests. The source of the discrepancy is not yet well understood. From the fact that longer cable under test shows lower error in the oscillation frequency when comparing simulation and experimental test results, it could be inferred that the capacitance effect may be the cause. The error in the simulated capacitance may come from an idealized construction of the cable or inaccurate electrical properties of the materials used, or both. Further investigations will be conducted to identify the cause of this discrepancy.

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