International Journal of Control and Automation
Vol.7, No.7 (2014), pp. 145-156
http://dx.doi.org/10.14257/ijca.2014.7.7.12

Electrical Parameters and Conducted Noise on Subsea Environments

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Abstract

This study examines conductive noise in long distance cables in a subsea environment. The inverters currently used in subsea plants generate conducted noise, which is the cause of damage and insulation failure of electric motor bearings. In particular, it is important to analyze the characteristics of transient voltages for different subsea temperature and pressure changes. To analyze the transient voltages, the effects of L, R, and C for different temperature and pressure changes were investigated. Among the analysis factors of L, R, and C, the capacitance C was identified as the factor that influences conductive noise the most. As a result, we analyzed the impact of the electrical components (L, R, and C) on the noise in the design stage of a long-distance cable, focusing on the variables of pressure, and presented the guidelines for designing a subsea plant model.

Keywords: *Subsea, Long cable, Inverter, Conductive noise, FEM (Finite Element Model)*

1. Introduction

In recent years, with shallow-water oil resources gradually depleting, subsea technologies have been attracting attention for the exploitation of the deep-water offshore oil resources. Accordingly, research on designing a cable that reduces electrical power loss at offshore plants for obtaining ocean resources is being actively conducted. However, the electric-motor drive inverters currently used in subsea plants generate conducted noise as a result of an abrupt voltage change. This conducted noise can cause electromagnetic interference (EMI), damage to motor bearings, and insulation failure. Further, increase in the length of the cable connecting inverter and motor is directly associated with the increase in the conducted noise. Therefore, an accurate noise analysis should be performed by taking into account the variables of length and pressure [1, 2].

Offshore plant systems for operating induction motors consist of a three-phase power source, inverter, and long distance umbilical cables [3]. Furthermore, to smoothly control the speed of the induction motors, the PWM (pulse-width modulation) method is applied using IGBTs (insulated gate bipolar transistors), which facilitates high-speed switching [4]. However, the transient voltages generated by high-speed switching greatly affect the dielectric strength, life, and reliability of induction motors [5]. The majority of the studies on subsea environments have investigated pressure-dependent changes in the cable's L, R, and C, thereby numerically extracting them; however, the change in the entire system has not been taken into consideration [6, 7]. Second, cable-related studies have presented various design methods such as mathematical modeling of a long-distance cable based on the L, R, and C (electrical components) values [2, 8], mathematical cable modeling by taking into account transient distortion frequency [9], and cable model design method using the finite element analysis (FEA) [10]; however, most of

ISSN: 2005-4297 IJCA

these studies have focused on cables with limited lengths of several hundred meters, rendering them inapplicable to subsea plants. Thus, research should be carried out to model a long-distance cable ($\geq$ 2 km) suitable for subsea plants.

With this background, we performed a mathematical modeling of a 2-km power transmission cable tailored to the electrical architecture of subsea plants. We also analyzed the effects of the electrical characteristics and the output filter on the cable, depending on the changes in the subsea environment. Thus, we attempted to provide subsea plant designing guidelines.

2. Power Transmission Cable Modeling

2.1. Electrical-motor Drive system Configuration

The subsea power system model investigated in this study consists of a three-phase input terminal, a converter, a DC link, a pulse width modulation (PWM) inverter, a cable, and an electric motor. A variable speed drive (VSD) and an electric motor model optimized for subsea application were modeled using Powersim (PSIM).

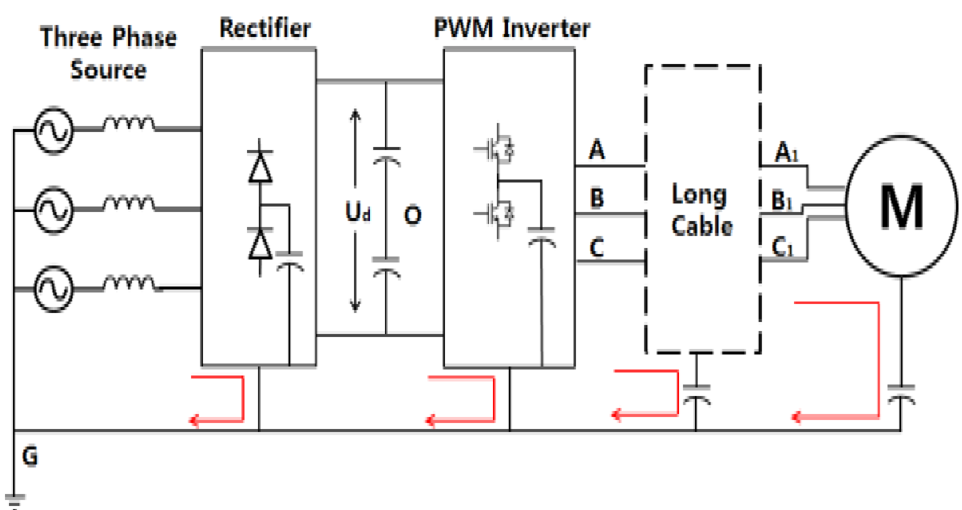


Figure 1. AC Motor Drive System

2.2. Effects of Temperature on Capacitance

As shown by Eq. (1), the electrical characteristics of cables are expressed by the impedance (Z), and, as the cable length increases, the resistance (R) increases. However, the inductance (X_L) can be ignored because it shows smaller changes than the resistance. Furthermore, in the case of capacitance (X_C), as cable length increases, the mutual capacitance (C_m) between the three-phase cables has a greater influence on the overall impedance (Z). Moreover, as the temperature increases, the distance between the conductors (and, therefore, the mutual capacitance (C_m)) decreases. Consequently, the cable's capacitance (X_c) has a large influence on the occurrence of conductive noise. The relationship between the capacitance and temperature is shown in Eq. (4) [6].

$$Z = R + j(X_L + X_C)\ . \qquad (1)$$

$$X_C = \frac{1}{2\pi f C}. \quad (2)$$

$$C = C_m + C_i + C_g. \quad (3)$$

$$C = \frac{1}{63 \times (2.79 + 0.0158T) \times 10^{-5}}. \quad (4)$$

Here, T is the temperature (°C) and C is the capacitance (pF). Given that the capacitance for different temperature changes in a vacuum is considered in this study, the capacitance value is the same when the pressure is 0. When the capacitance increases owing to significant changes in the cable, the reactance and conductive noise will decrease.

2.3. Power Transmission Cable Model and Capacitance Pressure Coefficient

The four-wire cable model was configured as schematized in Figure 2. Z_a, Z_b, and Z_c can be obtained as per the formulas outlined in Table 1. The model parameter values are expressed as a value per unit meter and R, L, C_b, and C_i values were obtained using their respective formulas [8].

Table 1. Cable Parameter Formulas

Cable parameter	Conductor resistance	Capacity C_b (line-to-gnd)	Capacity C_i (line-to-line)	Inductor L
Formulas	$R = 4R_{CM}$	$C_b = \frac{C_{CM}}{4}$	$C_i = \frac{C_{DM} - C_b}{4}$	$L = L_{CM} + \frac{3}{4}L_{DM}$

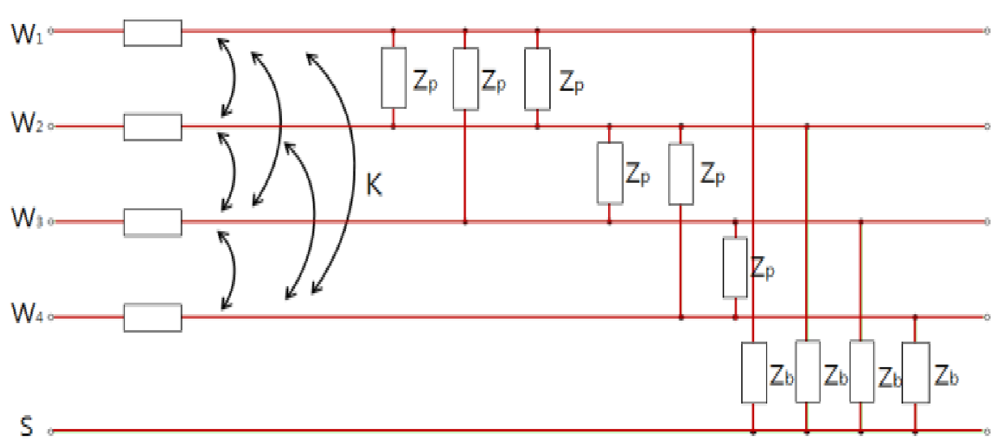


Figure 2. Four-wire Cable Model

Given the fact that the pressure exerted on the cable has the greatest effect on the capacitance, only the capacitance is considered in the modeling. The value of the capacitance under the application of pressure can be obtained using the pressure coefficient as Eq. (5) [6], [7].

$$C(P) \cong C(0)\left\{1+\frac{2}{3}\left[\frac{(1+\sigma)\frac{b^2}{a^2}}{\frac{b^2}{a^2}+(1-2\sigma)}\right]\left[\frac{(\varepsilon-1)(\varepsilon+2)}{3\varepsilon}+\frac{1-\frac{a^2}{b^2}}{2\ln\frac{b}{a}}\right]kP\right\}. \tag{5}$$

3. Simulation and Results

3.1. Configuration

Figure 3 illustrates the finite element method (FEM) analysis process on the three-phase four-wire cable, and the resulting data. In this study, the simulation focused on the derivation of the R and C parameters as a function of temperature. Results showed that the structure of the three-phase cable significantly influences the reactance.

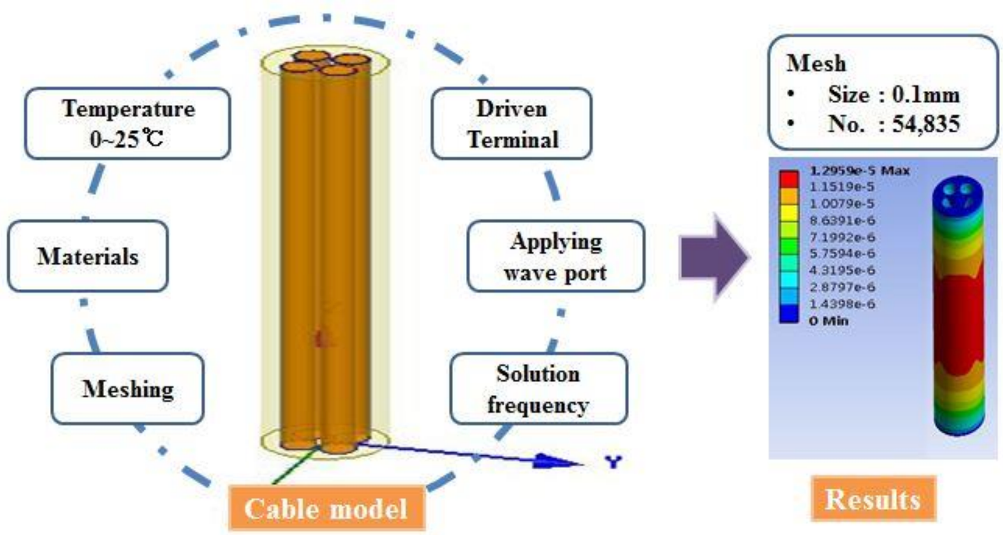


Figure 3. Process of FEM Analysis

Simulation of a 100-m cable and PWM inverter system was performed using PSIM, power electronic simulation software. The entire system consists of a VSD model, a rectifier, a DC link, and including an inverter comprising gate bipolar transistor (IGBT) modules, as well as three-phase input terminal, output filter, and electric motor with a timescale of 250 μs/div. A voltage of 300 V was applied, and a PWM signal generated in the inverter output terminal was configured to be inputted into the motor via the cable. Figure 4 shows the model configuration for upscaling from 100 m to 2km. The parameter values were obtained using the formulas outlined in Table 1. Additionally, validity test of the analyses was performed by comparing the simulation and experimental outputs implemented on the 100-m cable model.

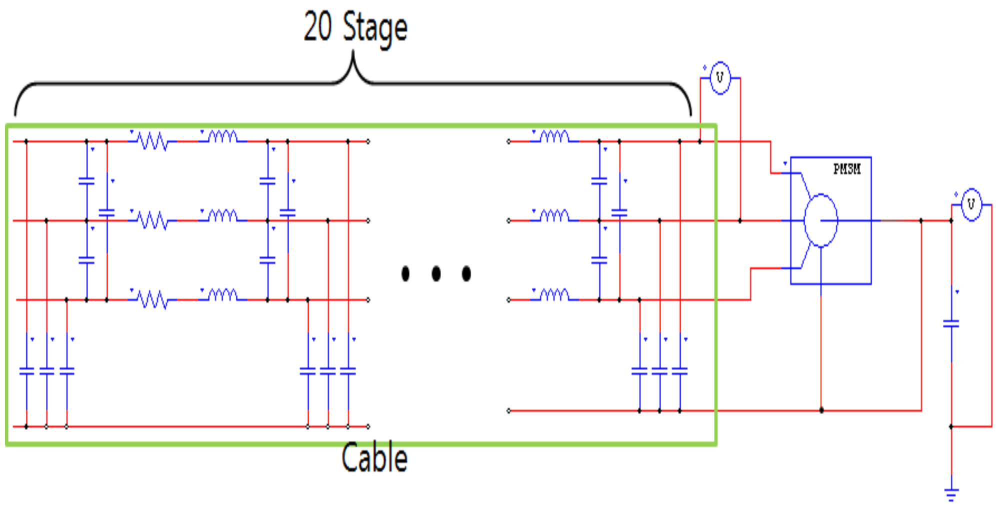


Figure 4. Cable and PWM Inverter System Simulation Circuit

3.2. Electrical Parameters in Temperature Changes

Figure 5 shows the changes in impedance versus temperature. As shown in Figure 2, the impedance does not change with temperature. This is because the changes in resistance and reactance are inversely proportional to each other. In other words, if the resistance increases, the reactance decreases, and vice versa. Figure 6 shows the reactance versus temperature. The reactance is the sum of the inductance (L) and capacitance (C). If the reactance is negative, it indicates that the reactance is capacitive. This means that as the absolute value of the capacitive reactance increases, the value of capacitance also increases.

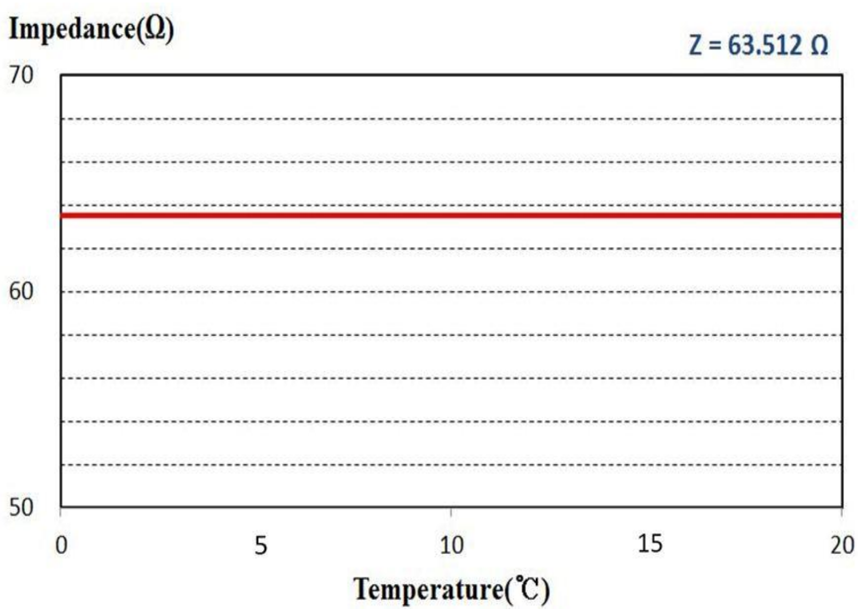


Figure 5. Impedance Variation in Cable

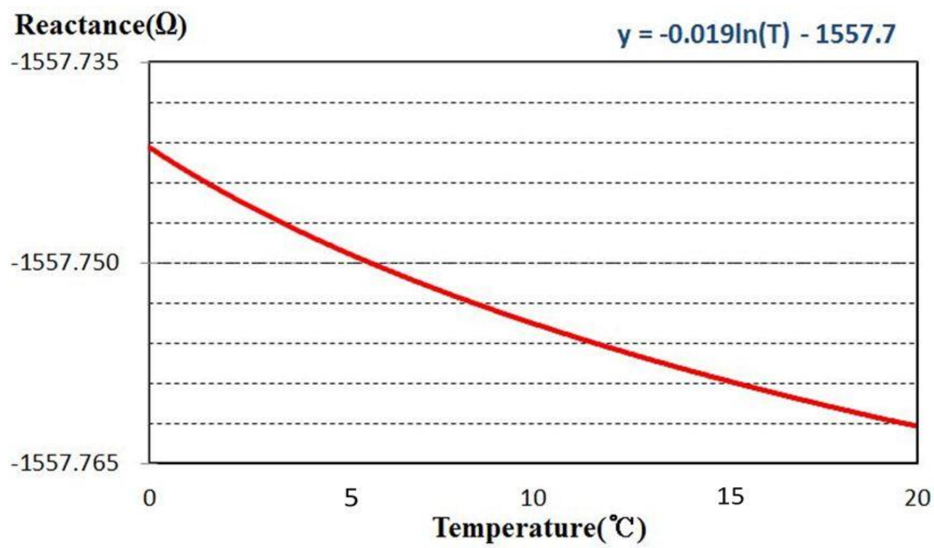


Figure 6. Reactance Variation in Cable

Figures 7 and 8 show the resistance and the capacitance of the cable versus temperature, respectively. As shown in Figures 7 and 8, as the temperature increases, the capacitance decreases. Therefore, it can be inferred that the cable shape changes as the volume expands because of increased temperatures. Therefore, it was confirmed that reactance part plays a major role in the capacitance increase or decrease.

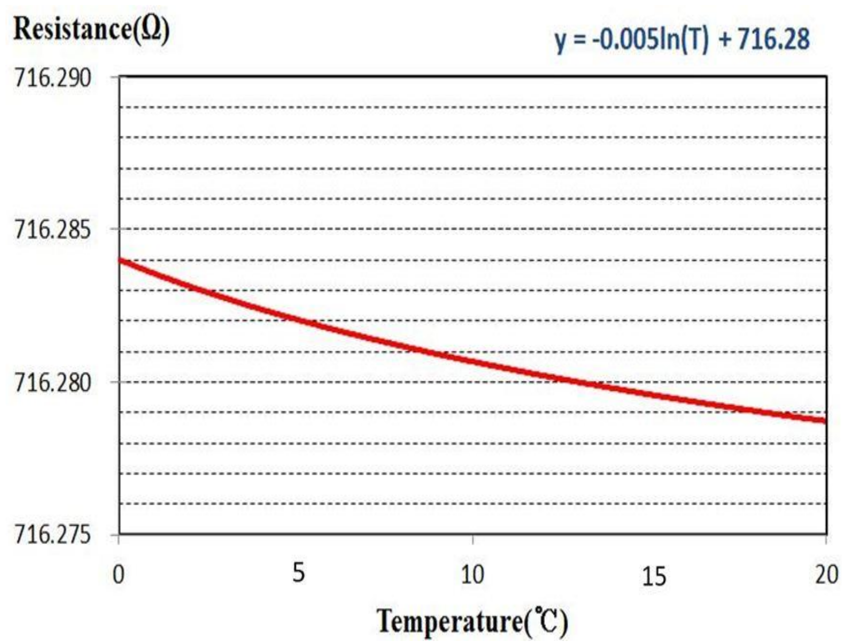


Figure 7. Resistance Variation in Cable

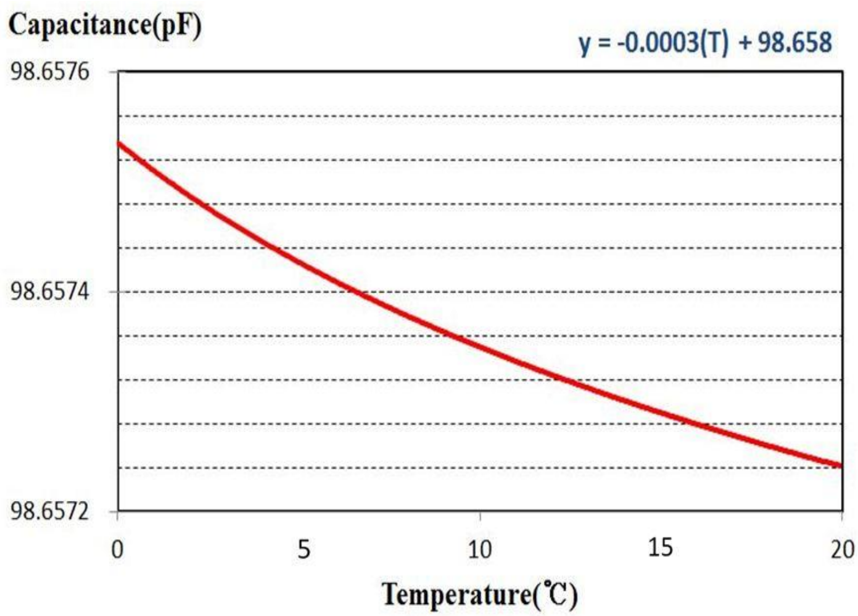
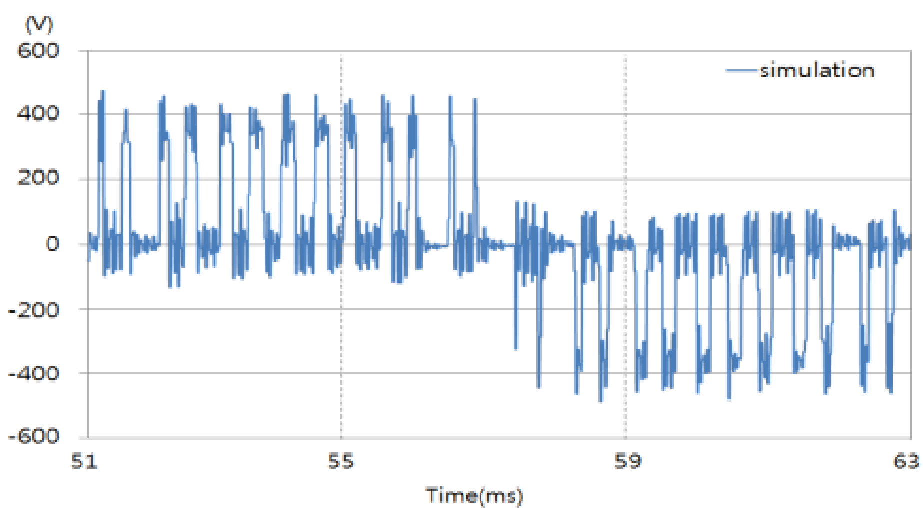


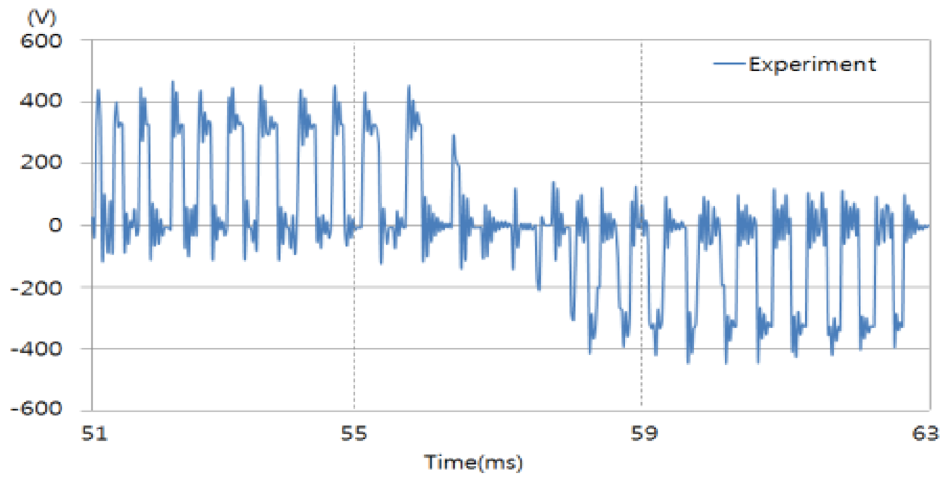
Figure 8. Capacitance Variation in Cable

3.3. Results

Fig. 4 represents the output values of the comparison between the simulation and the experiment conducted on a 100-m cable. The setting values for the experiment are identical to those in the simulation, and the inter-wire voltages were measured on cables a and b. As shown in Fig. 4, there is no significant difference between the measured values and the simulation outputs. The reliability of the simulation was thus established, which verified the reliability of the basic method we used for modeling a 2-km cable.



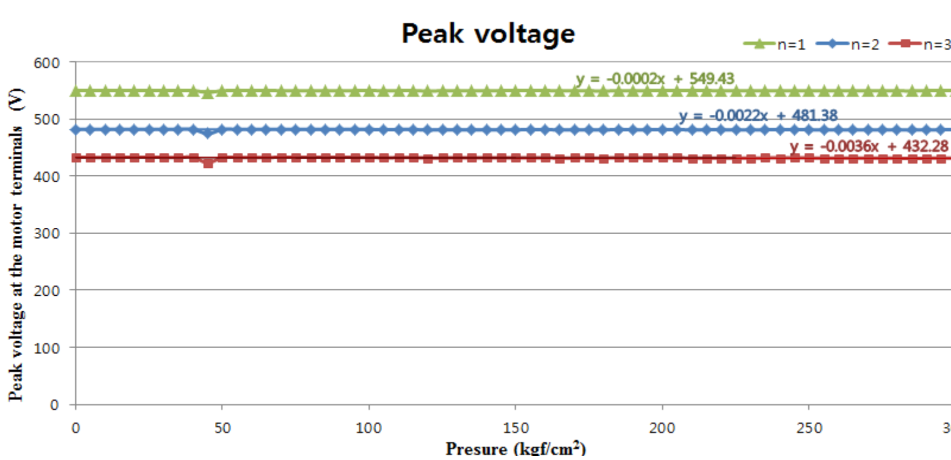
(a) Simulation Graph



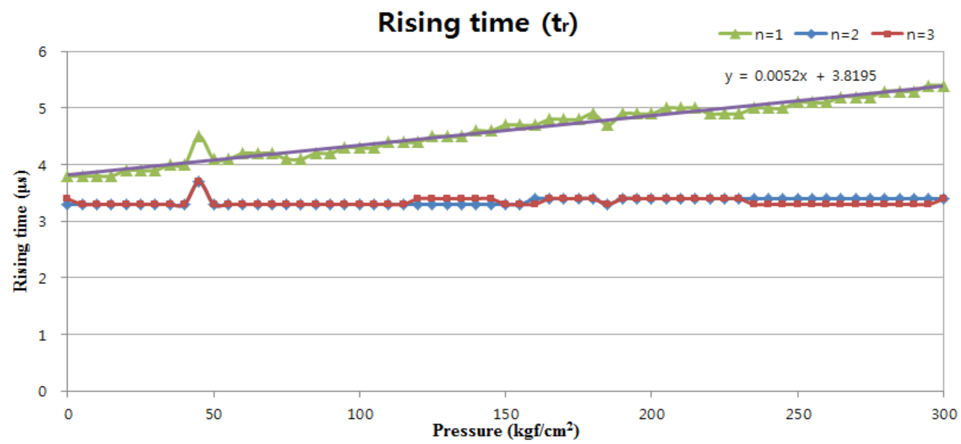
(b) Experimental graph

Figure 9. Comparison between the 100-m Cable and the Simulation Model

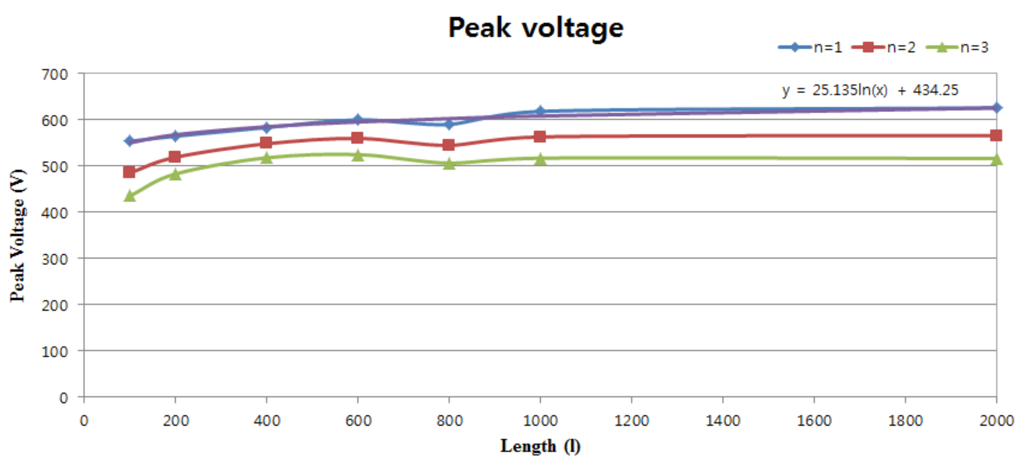
Figure 10 shows the graphs representing the change in the peak voltage of the motor terminal and the rise time depending on the changes in the applied pressure and cable length. The analysis of graphs (a) and (b) representing the pressure-dependent characteristics yielded the finding that the capacitance increases proportional to the pressure increase, and the rise time was subsequently increased because of the charge-and-discharge effect. It was also found that decreased peak voltage led to a voltage dip. The analysis of graphs (c) and (d) representing the cable length-dependent characteristics yielded the finding that the increase in length led to the increase in capacitance and decrease in resistance and inductance, resulting in the increase in rise time and peak voltage. It was thus verified by the analysis of the pressure-dependent voltage characteristics that the increase in capacitance induces a decrease in rise time and peak voltage. In contrast, the increase in peak voltage proportional to the increase in length was considered attributable to the increase in current induced by the decrease in inductance and resistance, which in turn leads to an increase in voltage.



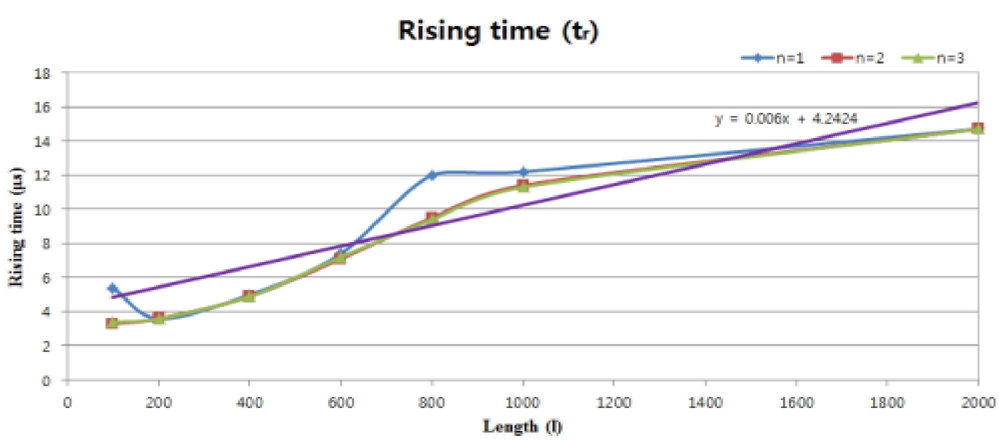
(a) Change in peak voltage



(b) Change in rise time



(c) Change in peak voltage



(d) Change in rise time

Figure 10. Peak Voltage Characteristics Depending on Pressure and Length

4. Conclusion

In this study, the electrical parameters of long distance cables as a function of temperature were analyzed. The results of deriving the parameters verified that both resistance and capacitance decreased as the temperature increased. The resistance and the capacitance appeared to be affected by the change in the distance between conductors that occur at increased temperatures. The results of the analyses of the motor terminal voltage characteristics depending on the changes in the applied pressure and cable length yielded the findings that in terms of the pressure-dependent voltage characteristics, an increase in capacitance induces a proportional decrease in rise time and peak voltage and that peak voltage increased in direct proportion to the cable length.

This study is significant in that it presented a methodology for reducing the conducted noise occurring in subsea plants by performing analyses of the electrical characteristics depending of the subsea cable length as well as the voltage characteristic depending on the changes in the subsea environment.

Acknowledgement

This work was supported by the 2014 year Research Fund of University of Ulsan.

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