Method of noise reduction for high-voltage systems applied in subsea plants

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Abstract—This paper is conducted a research of the cable and filter design considering the deep sea floor environment. The electric architecture which is being used in the subsea plant is comprised of the power supply unit of the high voltage, high-capacity drive system, long cable, and electric motor in the sea area. Conducted emission is occurred by the rapid voltage change at the moment of switching at high speed of inverter for driving motors. The more the length of the cable is lengthened, the worse the motor is influenced by transient voltage. Thus, the over voltage occurred in the drive motor was confirmed by designed wire which is considered R, L, line-to-line C, line-to-gnd C of long cable used in the subsea plant. A guide line of the subsea plant model is also suggested by using a filter to reduce conducted noise of PWM inverter drive system.

Keywords—subsea; long cable; output filter; transient voltage; EMI

I. INTRODUCTION

Recently, as oil resources have become scarce, oil is being produced not only from the continental shelf but also the subsea. As oil is produced from the subsea, subsea production technology is gaining more attention. The electrical architecture for producing oil from the subsea consists of input power supplied from the sea, a variable speed drive (VSD), a step-up transformer, an umbilical cable, a step-down transformer, and an electric motor [1].

Currently, inverters for driving electric motors used in the subsea generate electrical noise due to rapid voltage changes in high-speed switching elements. This conducted noise component generates leakage current through parasitic capacitors in the winding and enclosure. Additionally, it causes electro-magnetic interference (EMI), damage to motor bearings, motor breakdown, and induced lesions in nearby communication lines. In particular, common mode noise in the conducted noise components greatly affects the input/output of high-voltage systems as well as the high-capacity drive system. Furthermore, when the cable length between an inverter and a motor becomes extensive, it requires a filter design that considers the common node noise [2, 9].

Studies on long-distance cable design for motor systems used in general industries and filter design to suppress the conducted noise have been conducted continuously. Based on the electrical properties of resistance, inductance, and capacitance (R, L, and C), a long-distance cable of several hundred meters was modeled while mathematical modeling was performed for a 5-m power cable, which considered R, L, C, and the dielectric conductance per unit length G [2, 3]. In addition, the cable’s mathematical modeling considered the ringing frequency generated in the power cable, while the cable model design method used finite element analysis (FEA) [4, 5]. However, no study on the mathematical modeling of 2-km cables that considers line-to-line capacitance and line-to-earth capacitance has been conducted. In the previous studies, noise suppression by common and differential-mode filters in cable less than 300 m long [7], inverter output filter design [8], and motor terminal filter design [6] have been proposed. Nonetheless, no study on noise removal methods for long-distance cables of more than 2-km as used in the subsea plants has been performed, raising demand for such a study.

Therefore, the present study modeled a VDS, an electric motor, and a 2-km power cable mathematically based on the electrical architecture of the subsea plant and proposed a filtering method that can significantly reduce electrical noise.

II. SUBSEA POWER SYSTEM MODELING

A. VSD and electric motor model

The VSD and electric motor model applied to the subsea was modeled using Powersim(PSIM). The subsea power system model in this study consisted of a three-phase input terminal, a line impedance stabilization network (LISN), a converter, a pulse width modulation (PWM) inverter, a cable, and an electric motor. The PWM inverter consisted of six insulated gate bipolar transistor (IGBT) modules, while the electric motor was a permanent magnet synchronous motor (PMSM) model that is widely used for subsea operations.
B. Power cable model

Once the long-distance cable for the subsea connects the voltage to the source PWM inverter and electric motor, the cable operates as a distributed-parameter circuit. The long-distance cable has an impedance of $30$–$70 \Omega$, whereas the inverter has a relatively smaller internal impedance that limits it as a voltage source. Therefore, an impedance mismatch between the long-distance cable and the inverters can be generated at the inverter terminals. Furthermore, an inverter output filter can be generated in motor terminals that have high impedance values. The electrical reflections due to such an inverter output filter causes an overvoltage in the motor terminal. In addition, because this overvoltage can induce a resonant frequency in the cables, an oscillating or ringing voltage can occur at specific frequencies. This ringing frequency is determined by the cable length and the velocity of the incident and reflected waves inside the cable. The ringing frequency is known to be inversely proportional to the cable length. A relationship between ringing frequency $f_{\text{ring}}$ and cable length $l$ can be defined by (1) [4].

\begin{equation}
    f_{\text{ring}} = \frac{3 \times 10^7}{l}
\end{equation}

The present study aimed to analyze a 2-km cable, but it is difficult to validate this realistically due to space constraints. Thus, in order to validate the theoretical analysis of the present study, the cable was divided into 20 stages [2]. An experiment was conducted with 1/20 of the cable length of 2 km, which was 100 m. The theoretical analysis could be validated through this scaled-down cable.

C. Design of the output filter parameter

Switching rise time $t_r$ was obtained with overvoltage below 20% of the modeled 10-m electrical motor cable. Here, the cut-off frequency $f_c$ was calculated with a 3-dB damping ratio.

\begin{equation}
    R_1 \geq \frac{4L_f}{C_f} (R_1 \equiv 2L_f C_f \equiv \frac{4L_f}{C_f})
\end{equation}

\begin{equation}
    \frac{1 + \omega RC}{1 - \omega^2 LC + \omega RC} = \frac{1}{\sqrt{2}} (\equiv 0.707)
\end{equation}

Using (2) and (3), the output filter parameter values can be obtained [6].

### III. Simulation and FFT Analysis

#### A. Simulation

Figures 3 and 4 show the simulation circuit diagram of the PWM inverter system including modeling of the output filter and the 100-m and 2-km cables using the PSIM program.

The 4-line cable model was configured as shown in Fig. 2. The series impedance $Z_s$ consists of $R$ and $L$ for each line, while parallel impedance $Z_p$ consists of $C$ and $G$ between the lines. The parallel impedance $Z_p$ consists of $C$ and $G$ between the lines and external housing. The power lines in the equivalent models shown in Fig. 2 are configured with the common and differential modes. $R_{CM}$, $L_{CM}$, $C_{CM}$, and $G_{CM}$ values of the common mode parameters can be obtained by measuring between all the lines and the shield with an LCR meter, while $R_{DM}$, $L_{DM}$, $C_{DM}$, and $G_{DM}$ values of the differential mode parameters can be obtained by measuring between two connected lines with an LCR meter. Such correlations are summarized in Table 1. The model parameter values are represented by unit value per meter, and $R$, $L$, $C_b$, and $C_i$ values of the 100-m and 2-km cables were obtained by dividing them into 20 stages [3].

#### TABLE I. CABLE PARAMETER FORMULAS

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

The 100-m cable model was configured without applying a noise reduction filter as shown in Fig. 3 to validate the analysis of the 100-m cable model. Using the equation in Table 1, parameter values were inputted. A voltage of 300 V was
applied, and a PWM signal generated in the inverter output terminal was applied to the motor via the cable.

The characteristic analysis of the 2-km cable was performed without a noise reduction filter as shown in Fig. 3 while Fig. 4 shows the characteristic analysis with the filter for comparing the two characteristic values. Using the equation in Table 1, parameter values were inputted. A voltage of 6.6 kV was applied, which is the same as that used in a subsea motor. The PWM signal generated in the output terminal of the electric motor inverter was inputted into the motor via the cable.

The entire system consisted of an inverter using an IGBT module, a DC link, a three-phase input terminal, and a VSD model including a rectifier, an output filter, and an electric motor.

B. Simulation Results

Figure 6 shows a comparison of the experimental and theoretical analysis results for a 100-m cable. The three-phase PWM inverter applied to the 100-m cable used the IGBT, and the timescale was 250 μs/div. In addition, the result for the line-to-line voltage from the theoretical analysis also formed a three-phase PWM signal using the IGBT applied in the experiment. As shown in Fig. 6, the experimental and simulation values were close to each other.

Accordingly, the simulation’s reliability and base method for modeling the 2-km cable was confirmed.

Fig. 5. The block diagram of experiments.

Fig. 6. Compare of a real 100-m cable model and simulation model

Fig. 7. Simulation results of 2-km cable model system.

Figure 7 shows the analysis result for the 2-km cable. The line-to-line voltage of the inverter output terminal in (a) without a filter was −6.6 to 6.6 kV, while the line-to-line voltage of the motor input terminal was −11.025 to 11.077 kV. Furthermore, the transient voltage that was generated by the inverter output filter acting on the inverter increased by about 67.8% compared to the reference value. In (c) where the output filter was applied, the line-to-line voltage of the inverter output terminal was −6.6 to 6.6 kV while the line-to-line voltage of the motor input terminal was −9.164 to 9.283 kV. The conductor noise of the inverter increased due to the cable so that an overvoltage of about 40.7% was generated, which was validated by the simulation. In the 2-km cable model, the voltage in the model with a filter decreased by 1.794 kV more than the model without a filter, while the voltage decreased by 649 V more than the model with the RC filter (c). This was because the filter increased the rise time of the inverter voltage, thereby limiting unexpected input voltage acting on the motor. Accordingly, it was validated that the output filter could limit the transient voltage increase effectively in a 2-km cable as well.
C. FFT analysis

Figure 8 shows the result of a fast Fourier transform (FFT) in a 2-km cable system. In (a) where no filter was applied, the FFT had about 91 dBμV at 2 Hz while having about 20 dBμV at 50 kHz. Above 13 kHz, about 90 dBμV was recorded. In (b) where an RC filter was applied, the FFT result showed that the conducted noise was suppressed to less than 85 dBμV from 2 Hz to 50 kHz while suppressing the noise to less than approximately 37 dBμV above 40 kHz. In (c) where an output filter was applied, the FFT result showed that conducted noise was suppressed to less than 85 dBμV from 2 Hz to 50 kHz. The noise was suppressed to less than approximately 30 dBμV above 40 kHz.

The overall noise was reduced because the filter protected the motor terminal against voltage increase due to travelling waves, which validated the compliance to military standard, MIL-STD-461F specified by the United States Department of Defense. Moreover, based on this result, it was validated that the output filter reduced the conducted noise in the 2-km cable system as well.

The noise was suppressed to less than approximately 30 dBμV above 40 kHz. In (c) where an output filter was applied, the FFT result showed that the conducted noise was suppressed to less than 85 dBμV at 2 Hz while having about 20 dBμV at 50 kHz. Above 13 kHz, about 90 dBμV was recorded. In (b) where an RC filter was applied, the FFT result showed that the conducted noise was suppressed to less than 37 dBμV above 40 kHz. In (a) where no filter was applied, the FFT result showed that the conducted noise was suppressed to less than 85 dBμV from 2 Hz to 50 kHz while suppressing the noise to less than approximately 37 dBμV above 40 kHz.

IV. Conclusion

The present study proposed a novel analysis model for an output filter for reducing conducted noise generated when electric motors are driven by a PWM inverter and a 2-km cable, assuming the pump motor is the one widely used in subsea plants. Experiments and theoretical analysis of models for 100-m cables used in a subsea plant were conducted. Based on the validated theoretical analysis model, a theoretical analysis of a 2-km subsea cable was conducted.

The analysis result for the 2-km cable system showed that without a filter, the overvoltage of the line-to-line voltage waveform was 67.8%, which was considerably high, while the conducted noise was significantly large, recording below 91 dBμV. With RC and output filters, the overvoltage of the motor terminal was decreased to 40.7%, while conducted noise was reduced below 85 dBμV, which satisfies MIL-STD-461F. In addition, the conducted noise of the output filter was suppressed above 40 kHz, which was more effective than the RC filter. Through the filter design method proposed in this study, the ringing voltage of the line-to-line voltage waveform due to high-speed switching of the inverter was validly reduced by 27%. Furthermore, it was found that an output filter consisting of R, L, and C was more efficient than an output filter consisting of only R and C in an electric motor for long-distance subsea cables. The present study proposed a quantitative design method and a guideline for filters appropriate for conducted noise reduction and a long-distance cable model applicable to a subsea plant environment.

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