Design of a Wireless Power Transfer System with Two Inputs with Large Voltage Differences for Missiles Mounted on Maritime Vessels

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ABSTRACT Missiles mounted on maritime vessels have two types of loads. One is the operating load consumed just before launch, and the other is the safety sensors load that must always be activated for safety. Because the operating load consumes a large power capacity, the power generated by the vessel's own power generators must be supplied. Meanwhile, the loads for safety sensors are supplied through an energy storage system (ESS) because the safety sensors must be supplied with power even when the generators stop. However, the voltage difference between the generated power and the ESS power reaches ten times or more. Therefore, there is a problem in that the input of the two power sources with a large input difference must be transferred to two loads through only a pair of coils. To solve this problem, a WPT system is proposed to overcome the voltage difference between the generated power and the ESS power. The design method of the proposed system is analyzed mathematically, and it is verified through simulations and experiments. The proposed system has a maximum dc to dc power transfer efficiency of 76.8% with a capacity of 550 W and has the advantage that power is continuously supplied to the sensor loads even if the input voltage source is changed. In addition, by operating the proposed WPT system under a wide load of 200 W to 1000 W, the effectiveness of the proposed WPT system is proved.

INDEX TERMS Wireless power transfer system, coils, missile, maritime vessel, power supply

I. INTRODUCTION

A wireless power transfer (WPT) system can transfer energy in the form of a magnetic field without connecting wires between the transmitter (TX) and receiver (RX) [1]-[3]. Therefore, many studies are being conducted to commercialize it in many fields where the connection of the conductor is cumbersome. Typical applications include electric railways, electric vehicles (EVs), drones, and automated guided vehicles (AGVs) [4]-[6]. In addition, in recent years, the WPT system has been widely applied to unmanned aerial vehicles (UAVs) and missiles that are often used in military activities [7].

Among them, research on WPT for missiles used in maritime vessels such as warships is active shown in Fig. 1. To apply the WPT system to missiles on maritime vessels, it is necessary to understand the power supply system of vessels [8]-[10]. In general, power sources used in maritime vessels include generated power and emergency power. The generated power is supplied to most loads on the maritime vessels; the voltage level of the generated power system usually supplied is several hundreds of volts. Because generated power is self-generated through generators within the marine vessel, the power capacity is large, but the reliability is relatively low. Therefore, the generated power cannot be used for the safety sensors of missiles that require a very high reliability. On the other hand, in the case of an emergency power supply, it uses a separate power system such as an energy storage system (ESS); their voltage level is several tens of volts. Thus, emergency power is referred to as ESS power. It is used for a small number of loads requiring very high reliability. Because ESS power can supply power even if the generators of the maritime vessel are temporarily stopped, the stability is very high, but it has
the operating load should be powered by the generated power, load must be supplied with high-reliability power. Therefore, supply must never be interrupted. That is, the safety sensor status of the missile (especially explosives), the power always work, so high reliability is not required. On the other ignition for powering the missile, etc. However, it does not communication between the launcher and the missile, missions just before the missile is launched, such as load requires a lot of power because it is used in many sensors and temperature sensors. Among them, the operating safety of the missiles containing explosives, such as oil leak the missile launch and the RX sensors load that diagnoses the into two categories: the operating load required just before the limitation of the storage capacity.

Meanwhile, the power supplied to the missiles must have a constant voltage level of several hundreds of volts, and the ESS power usually has a voltage level of several tens of volts. However, in the case of the WPT system with the LCC-S topology, because the RX rectifier (the input voltage of the dc to dc converter) needs a constant voltage characteristic as much as possible, an LCC-series (LCC-S) topology advantageous for the constant voltage characteristic must be applied [11]-[13]. In the LCC-S topology, the resonant network of the RX side is very simple. The weight can be light, and the volume also can be small, so it meets the requirements of the missiles.

However, to apply the WPT system to a missile system, two limitations need to be overcome. As shown in Fig. 2(b), two inputs have to transfer power to two outputs through only a pair of coils. It is best to have two TX systems, two coil pairs, and two RX systems. However, this is not realistic due to severe spatial restrictions in missiles. Specifically, because the RX sensors of missiles must never be disconnected from the power source, the ESS power shown in Fig. 2(a), and Fig. 2(b) must always be supplied even when the missile is not in operation. On the other hand, when the system is operating, generated power must be additionally supplied, and at this time, not only the operating load of the missile but also the RX sensor of the missile must be operated at the same time. That is, as shown in Fig. 2(b), the WPT system for missiles requires two inputs (generated and ESS power) to be transferred through only one pair of coils to two outputs (operating load and RX sensor network).

Another limitation is that the difference between the voltage level of the generated power and the ESS power is too large. The generated power usually has a voltage level of several hundreds of volts, and the ESS power usually has a voltage level of several tens of volts. However, in the case of the WPT system with the LCC-S topology, because the RX output voltage is proportional to the input voltage [11]-[13], the difference between the RX output voltage when the generated power is supplied and the ESS power when the ESS power is supplied inevitably reaches 10 times or more. In other words, when the operating power is added in a

### TABLE I

**THE REQUIREMENTS OF LOADS IN MISSILES AND THE POWER SUPPLY SYSTEM FOR MARITIME VESSELS THAT MEET THE REQUIREMENTS**

| Loads of missiles | Requirements of power source | Suitable power among the power supplied from maritime vessels |
|-------------------|------------------------------|-------------------------------------------------------------|
| Operating load    | - Instantaneous power        | Generated power                                             |
|                   | - High power capacity        |                                                             |
|                   | - Relatively low reliability |                                                             |
| Sensor load       | - Continuous power           | ESS power                                                   |
|                   | - Low power capacity         |                                                             |
|                   | - Very high reliability      |                                                             |

The disadvantage that the power capacity is not large due to the limitation of the storage capacity.

On the other hand, loads on the missile are also divided into two categories: the operating load required just before the missile launch and the RX sensors load that diagnoses the safety of the missiles containing explosives, such as oil leak sensors and temperature sensors. Among them, the operating load requires a lot of power because it is used in many missions just before the missile is launched, such as communication between the launcher and the missile, ignition for powering the missile, etc. However, it does not always work, so high reliability is not required. On the other hand, because the RX sensors load is used to check the safety status of the missile (especially explosives), the power supply must never be interrupted. That is, the safety sensor load must be supplied with high-reliability power. Therefore, the operating load should be powered by the generated power, and the RX sensors load should be powered by the ESS power with high reliability. The types of power sources on maritime vessels that meet each of the conditions required by the power sources required for missiles are summarized in TABLE I.

On the other hand, loads on the missile are also divided into two categories: the operating load required just before the missile launch and the RX sensors load that diagnoses the safety of the missiles containing explosives, such as oil leak sensors and temperature sensors. Among them, the operating load requires a lot of power because it is used in many missions just before the missile is launched, such as communication between the launcher and the missile, ignition for powering the missile, etc. However, it does not always work, so high reliability is not required. On the other hand, because the RX sensors load is used to check the safety status of the missile (especially explosives), the power supply must never be interrupted. That is, the safety sensor load must be supplied with high-reliability power. Therefore, the operating load should be powered by the generated power, and the RX sensors load should be powered by the ESS power with high reliability. The types of power sources on maritime vessels that meet each of the conditions required by the power sources required for missiles are summarized in TABLE I.

Meaning, the power supplied to the missiles must have a constant voltage characteristic for both the operating power and the sensor power. In particular, missiles must be light in weight and small in volume, and they do not include a battery shown in Fig. 2. Therefore, when a WPT system is applied to a missile, the output of the WPT system must be a constant voltage. Although, as shown in Fig. 2, for a complete constant voltage source, a dc to dc converter is required for the output of the RX (missile), but dc to dc converters have a limited input range of operable voltage. Because the output voltage of the RX (missile) is very simple. The weight can be light, and the volume also can be small, so it meets the requirements of the missiles.
situation where only the ESS power is supplied, it is impossible to supply a constant voltage to loads. Of course, dc to dc converters exist in front of the loads, but there is hardly any dc to dc converters capable of having a voltage range with a difference of up to 10 times or more as an input. Therefore, to apply the missile's WPT system, it is necessary to solve the load voltage regulation problem due to the voltage level difference between the generated power and the ESS power.

In previous studies, WPT systems for missiles or unmanned aerial vehicles have been proposed [7], [14]. However, these studies do not specifically differentiate between the operating load and the RX sensors load, so there is a limitation that these are difficult to apply to an actual missile system on the maritime vessels. In other words, previous studies on WPT systems for missiles are single-input and single-output systems. In addition, systems with two or more inputs and outputs were also studied [15]-[17], but in all these studies, only cases where the number of coils and inputs and outputs were the same were studied. Lastly, there have been studies to alleviate the change in the RX rectifier output voltage due to the wide input change on the TX side through a voltage doubler [18], but this study does not apply to the case where there are more than two inputs and outputs. Also, WPT systems having a dynamic input power range have been proposed in [19]-[20], but the situation where the input voltage difference reached 10 times or more was not considered and it is limited to a low-power system having a power range of less than several W.

In this paper, a WPT system for missiles mounted on a maritime vessel is proposed. The proposed WPT system can overcome the limitation due to the voltage difference between the two power sources (generated power and ESS power) supplied to the missiles by applying a quadratic boost converter [21]-[22] to the TX circuits. By using the characteristic of the large voltage conversion ratio of the quadratic boost converter [21]-[22], the effect of the large voltage difference between the ESS power and the generated power is overcome, thereby minimizing the change in the output voltage of the RX rectifier. In the proposed WPT system, the RX sensors of the missile operate only through ESS power for safety even when the missile is not operating.

Even if generated power is additionally supplied for the operation of the missile, power is delivered to the RX sensors and the operating load of the missile. In other words, power is continuously supplied to the RX sensors regardless of the type of input voltage.

This paper is arranged as follows. In Section II, the WPT system for missiles mounted on the proposed maritime vessel is introduced and analyzed through formulas. In Section III, the proposed system is demonstrated through simulation and experiments. In addition, after discussing some topics related to this study in Section IV, and finally, the conclusion is mentioned in Section V.

II. THE PROPOSED WPT SYSTEM FOR MISSILES MOUNTED ON MARITIME VESSELS

The requirements of the WPT system for missiles mounted on maritime vessels arranged in Section I are as follows.

1) When the missile is not operating, the RX sensors must always operate through the ESS power source.
2) When the missile is in the operating mode, generated power is additionally supplied to the system, so power must be supplied not only to the operating load but also to the RX sensors.
3) At the moment when only the ESS power is supplied and additional generated power is supplied, power must be continuously supplied to the RX sensors.
4) Despite the large voltage difference between the generated power and the ESS power, the input voltage of the RX sensors network must be constant.

A WPT system for missiles satisfying all four of the above requirements is proposed in this study.

Fig. 3 shows the WPT system proposed for missiles mounted on maritime vessels. The proposed WPT system has two types of input voltages (generated power and ESS power) as described in the introduction. The generated power is only supplied to perform the mission before the missile is launched, and the ESS power must always be supplied for the RX sensors. Similarly, there are two loads: an operating load and a load for the RX sensors. When only the ESS power is applied, the power supply is not required for the operating load, so a separate switch ($S_o$) is added for on/off.
An LCC-S topology with a constant voltage output is applied to supply a constant voltage to each load. A full-bridge inverter is present at the input, and a full-bridge rectifier is present at the output. On the other hand, to supply voltage to the power circuit IC of each side of the TX and RX, step-down converters (TX buck converter and RX flyback converter) exist on each side.

To analyze the characteristics of the basic WPT system, a first harmonic approximation (FHA) method was used [23]-[24]. The FHA has already been widely used in the analysis of WPT systems, and its utility has been proven. In the LCC topology on the TX side, the current $I_1$ in the TX coil is equal to (1).

$$I_1 = -j\omega_i C_p V_{inv} = -j\omega_i C_p \left(\frac{4}{\pi V_{in}}\right)$$

(1)

In (1), $\omega_i$ is the operating angular frequency of the inverter; $C_p$ is the parallel capacitor on TX side, and $V_{inv}$ and $V_i$ are the fundamental component of the output voltage and input voltage of the inverter, respectively. On the other hand, if the resonant frequency of the RX side ($\omega_{o_{RX}}$) is the same as the operating frequency, $V_{RX}$ is equal to the voltage induced in the RX coil by the TX current $I_1$ as shown in (2).

$$V_{RX} = j\omega_o M I_1 = \omega_o^2 M C_p \left(\frac{4}{\pi V_{in}}\right)$$

(2)

Additionally, because $V_{rect}$, which is the rectifier output voltage and the input voltage of the dc to dc converter of the RX, is the same as the magnitude of $V_{RX}$, it is same as (3).

$$V_{rect} = \omega_o^2 M C_p \left(\frac{4}{\pi V_{in}}\right)$$

(3)

As can be seen from (3), the RX rectifier output voltage $V_{rect}$ is proportional to the input voltage ($V_{in}$) of the TX inverter. If there is no additional power circuit on the input side of the TX inverter, the rectifier output voltage ($V_{rect}$) when the generated power is applied will be up to 10 times larger than that when the only ESS power is applied. In this study, it is assumed that the generated power is 400 V, and the ESS power is 30 V. In this case, the difference in the rectifier output voltage is more than 13 times; thus, the difference in the input voltage range of the dc to dc converter for the RX sensors on the RX side reaches 13 times. There are hardly any converters that can have this wide voltage range as an input. Moreover, in Fig. 3, there is a flyback converter for supplying power to the ICs of the power circuit on the RX side, which also has the RX rectifier output as an input. However, even the flyback converter cannot have an input range with a voltage difference of up to 13 times as the input due to the limit of the duty ratio of the switch. That is, if $V_{rect}$ when only ESS power is supplied is called $V_{rect-ESS}$ and when the generated power is supplied is called $V_{rect-GEN}$, as shown in Fig. 4, both voltages cannot be included in the input range of the RX dc to dc converter at the same time. For the RX sensors to operate seamlessly both when only the ESS power is supplied and when the generated power is additionally supplied, $V_{rect-ESS}$ and $V_{rect-GEN}$ must have ranges (4) and (5), respectively.

$$V_{min} < V_{rect-ESS} < V_{max}$$

(4)

$$V_{min} < V_{rect-GEN} < V_{max}$$

(5)

Here, $V_{min}$ and $V_{max}$ are the minimum and maximum voltages of the RX dc to dc converter input voltage range, respectively. Equations (4) and (5) are changed from Fig. 4(a) to Fig. 4(b) through the proposed method, allowing the RX converter to operate.

To solve the problem, a quadratic boost converter [21]-[22] is added to the rear end of the ESS power supply. To adjust the voltage difference of up to 13 times to a similar level, there is a limit to the voltage conversion range of general converters. Therefore, a quadratic converter that can convert the voltage at a large ratio is added. In addition, as shown in Fig. 5, a control circuit that detects whether the generated power is the input and disables the ESS power converter is also proposed. In the following sections B and C, cases when only the ESS power is applied and when both the ESS power and generated power are applied at the same time will be described in detail.

A. CASE 1: WHEN ONLY THE ESS POWER (30 V) IS SUPPLIED
The TX coil when the ESS power is applied is as shown in Fig. 6. The equivalent circuit when only the ESS power is the input.

Fig. 6 shows the equivalent circuit when only the ESS power is supplied to the proposed WPT system. Only the load for the RX sensors is supplied to the RX side, and the operating load is cut off through the switch ($S_e$). In addition, the flyback converter for the RX IC must also be operated, which also inputs the RX rectifier output voltage ($V_{\text{rect}}$).

The output voltage of the quadratic boost converter is equal to (6) [22].

$$V_{\text{in}} = \frac{1}{(1-D)^2} V_{\text{ESS}} \quad (6)$$

Here, $D$ is the duty ratio of the quadratic boost converter. Because the quadratic converter has a squared voltage conversion ratio, it is much larger than a typical boost converter.

The $V_{\text{rect-ESS}}$ obtained through (3) and (6) is the same as (7).

$$V_{\text{rect-ESS}} = \omega_0^2 M C_p \left( \frac{4}{\pi (1-D)^2} V_{\text{ESS}} \right) \quad (7)$$

As described above, (7) must satisfy the range of (4). On the other hand, the input voltage for the flyback converter for the RX IC is the same as $V_{\text{rect-ESS}}$. Similarly, $V_{\text{rect-ESS}}$ must be within the operating voltage range of the flyback converter. Because the missile is not equipped with a battery due to its weight and volume, all IC voltages must be supplied through a flyback converter.

Next, $V_{\text{rect-ESS}}$ within the range (4) should be selected. $V_{\text{rect-ESS}}$ is set equal to $V_{\text{min}}$. This is the same as (8).

$$\omega_0^2 M C_p \left( \frac{4}{\pi (1-D)^2} V_{\text{ESS}} \right) = V_{\text{min}} \quad (8)$$

The reason is that when $V_{\text{min}}$ is the minimum, the TX current $I_1$ becomes the minimum so that the power consumption in the TX coil also becomes the minimum. Through (1) of the current of the TX LCC topology, the power consumption of the TX coil when the ESS power is applied is as shown in (9).

$$P_{\text{TX-coil}} = \left( \omega_0 C_p \left( \frac{4}{\pi V_{\text{ess}}^2 (1-D)^2} \right) \right)^2 R_1 \quad (9)$$

That is, because the output voltage of the quadratic converter is lower, the power consumption in the TX coil is smaller. As shown in (8), the output voltage of the quadratic converter is set equal to $V_{\text{min}}$. Therefore, the duty ratio of the quadratic converter obtained from (8) is equal to (10).

$$D = 1 - \frac{4\omega_0^2 M C_p V_{\text{ESS}}}{\pi V_{\text{min}}} \quad (10)$$

On the other hand, it should be noted that the voltage for the ICs of the power electronic circuit on the TX side should always be operated by the ESS power. The reason is that the generated power is applied only right before the missile is launched, whereas the ESS power is always applied to the system. Therefore, the TX side buck converter for the TX ICs in Figs. 3 and 6 has the ESS power as an input. This is the same even when the missile is in operation mode.

### B. CASE 2: WHEN BOTH THE ESS POWER (30 V) AND THE GENERATED POWER (400 V) ARE SUPPLIED

When starting operation to perform various missions just before launching a missile, the WPT system must be additionally supplied with the generated power in addition to the ESS power shown in Fig. 3. Because the missile is in the operating mode, power must be supplied to the RX operating load in Fig. 3. Therefore, the operating switch ($S_e$) must be turned on.

In the operation mode, the inverter input voltage ($V_{\text{in}}$) must be equal to the generated power ($V_{\text{GEN}}$). This is because the ESS power ($V_{\text{ESS}}$) cannot be rated up to several hundreds of watts for the operating loads. If $V_{\text{in}}$ is supplied by $V_{\text{ESS}}$, the operating load is operated by the ESS power, and the missile system cannot operate due to an insufficient power supply. Because the ESS power is always supplied, a method to block the supply of the ESS power to the inverter is absolutely necessary in the operation mode. In this study, two methods are adopted. The first method is a method diode ($D_1$). When the generated power (400 V) higher than the output voltage of the quadratic boost converter is supplied, $D_1$ is automatically turned on. Accordingly, the input voltage $V_{\text{in}}$ of the inverter becomes 400 V ($V_{\text{GEN}}$).

Fig. 5 shows the second method using the proposed control system. Fig. 5 shows the proposed control loop of the quadratic boost converter for the TX side. In Fig. 5, a conventional control method for the converter output is included by sensing the output voltage ($V_{\text{in}}$) of the converter and comparing it with the reference value to perform PWM control. However, in this study, in addition to the conventional loop, a feedback loop is added that senses whether the generated power ($V_{\text{in-GEN}}$) is applied.
principle of this loop is to stop the PWM IC through a comparator when a certain voltage \( V_{\text{Vin-GEN}} \) is sensed. Therefore, because the operation of the quadratic boost converter is stopped, \( V_{\text{in}} \) is equal to the generated power \( V_{\text{GEN}} \).

Meanwhile, note that the TX buck converter for the IC power for the TX side is still operating by the ESS power as described above. The operation is only blocked by the quadratic converter, but the ESS power is still connected to the system shown in Fig. 3.

When the input of the TX inverter becomes \( V_{\text{GEN}} \), the RX rectifier voltage becomes equal to (5) by (11).

\[
V_{\text{rect-GEN}} = \alpha^2 M C_p \left( \frac{1}{n^2} V_{\text{GEN}} \right) \tag{11}
\]

Equation (11) must satisfy the input voltage range of the RX converters as in Figs. 4 and (5). When the missile system is not in operation, the RX load is all covered by the ESS power, whereas in the operation mode, all the RX loads are powered by the generated power. Table II summarizes the power supplied depending on whether the missile is operating and the source of power supply to the TX side and RX side accordingly.

### III. VERIFICATION

#### A. VERIFICATIONS THROUGH SIMULATIONS AND CALCULATIONS

The coil systems for the missile are designed through FEM-based magnetic field simulation and compare the output voltages of each RX rectifier with and without the proposed system through calculations.

1) Design WPT coils for missiles through finite element method (FEM)-based magnetic field simulation and compare the output voltages of each RX rectifier with and without the proposed system through calculations.

2) Verify the proposed system through experiments. In particular, look at the transient response at the moment when only the ESS power is supplied and then the generated power is supplied.

#### TABLE IV
SIMULATION RESULTS OF WPT COILS (AT 60 MM AIR GAP) AND PARAMETERS OF ELECTRICAL CIRCUITS

| Component                     | Value  |
|-------------------------------|--------|
| Resonant frequency of WPT system \( (f_r) \) | 105 kHz |
| Operating frequency of TX inverter \( (f_o) \) | 105 kHz |
| Inductance of Tx and Rx coils \( (L_1, L_2) \) | 37 \( \mu \)H |
| Resistance of Tx and Rx coils \( (R_1, R_2) \) | 80 m\( \Omega \) |
| Mutual inductance between Tx and Rx coils \( (M) \) | 7.01 \( \mu \)H |
| Coupling coefficient between coils | 0.189 |
| TX coil current \( (I_1) \) when generated power (400V) is supplied | 13 A |
| TX inductance \( (L_o) \) | 42 \( \mu \)H |
| TX parallel capacitance \( (C_p) \) | 54.7 nF |
| TX series capacitance \( (C_s) \) | 462 nF |
| RX series capacitance \( (C_2) \) | 62 nF |

#### TABLE V
COMMERCIAL CONVERTERS USED FOR RX SIDE IN THIS PAPER

| Component          | Model name          | Input range  | Output voltage |
|--------------------|---------------------|--------------|----------------|
| DC to DC converter for operating load | DCM3623TA 5N31B4T00 | 43 V ~ 154 V | 28 V           |
| DC to DC converter for RX sensors      | DCM3623TA 5N26B4T00 | 43 V ~ 154 V | 24 V           |

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the TX coil (inverter voltage through the proposed method.

(b) The rectifier output voltage difference when the input power sources are directly applied to the TX side.

FIGURE 8. The rectifier output voltage ($V_{\text{rect}}$) change according to the inverter of the conventional WPT system. (a) The rectifier output voltage difference when the voltage of ESS power is boosted and applied to the inverter voltage through the proposed method.

resonant equation of the series topology adopted on the RX side.

$$\frac{1}{2\pi \sqrt{L_1 C_1}} = \frac{1}{2\pi \sqrt{L_2 C_2}} = f_{n1} = f_o$$ (12)

$$\frac{1}{2\pi \sqrt{L_1 C_2}} = f_{n2} = f_o$$ (13)

In (12) and (13), $f_{n1}$ and $f_{n2}$ are the resonant frequencies of the TX side and the RX side, respectively, and $f_o$ is the operating frequency of the inverter. In this study, when the generated power ($V_{\text{GEN}}=400 \text{ V}$) is supplied, the current of the TX coil ($I_1$) is aimed to be 13 A SMS. Using the target TX coil current ($I_1$) and (1), a TX-sided parallel capacitor ($C_p$) can be obtained first. That is, when the target TX current is obtained, the circuits element values ($L_S$, $C_P$, $C_S$, and $C_2$) of all resonant systems are obtained by (1), (12), and (13), which are specified in Table IV.

Meanwhile, commercial dc to dc converters are used for the high reliability of the missiles. Each converter is shown in Table V. In Fig. 3 and Table V, the input voltage of the converters for the operating load and RX sensors is from 43 to 154 V. The minimum input voltage ($V_{\text{min}}$) of the RX dc to dc converter in Fig. 4 is 43 V, and the maximum input voltage ($V_{\text{max}}$) is 154 V. RX dc to dc converters operate only when the rectifier output voltage ($V_{\text{rect}}$) of the WPT system is included in a voltage range between 43 and 154 V. In other words, when both the ESS power and generated power are supplied, the rectifier output voltage ($V_{\text{rect}}$) must fall within the voltage range. To satisfy this, first, how much the ESS power voltage should be boosted through the quadratic boost converter is calculated, and the duty ratio ($D$) at this time is determined. And when the duty ratio ($D$) is the corresponding value, the rectifier output voltage ($V_{\text{rect}}$) is calculated.

First, $V_{\text{rect}-\text{GEN}}$ when generated power (400 V) is supplied to the input is equal to 65.1 V according to Table IV and (11). Additionally, if 30 V, which is the ESS power, is directly applied to the input of the WPT system, it is equal to 5.01 V according to Table IV and (3). That is, in the conventional WPT system, the rectifier output voltage by the input generated power (400 V) and the rectifier output voltage by the input ESS power (30 V) reach a difference of more than 13 times as much as the difference between the input voltages. These results are shown in Fig. 8(a). In this case, when the generated power is applied, the RX loads operate normally, but when only the ESS power is applied, the RX rectifier output voltage decreases below the minimum input voltage of the RX dc to dc converter. Accordingly, power is not delivered to the RX sensors.

For the output voltage of the rectifier to exceed the minimum input voltage ($V_{\text{min}}$) of the RX dc to dc converters even when ESS power is applied, the voltage of the ESS power is stepped up through the proposed system. The duty ratio ($D$) of the quadratic boost converter for the $V_{\text{rect-ESS}}$ of the proposed method to exceed $V_{\text{min}}$ is 0.676, calculated from (10) and Table IV. When the duty ratio $D$ is 0.676, the output of the quadratic boost converter is 286 V. In preparation for a stray voltage drop due to a line drop at the rear of the rectifier, if the output of the quadratic converter (input of the TX inverter) is adjusted to 300 V for the minimum margin ($D=0.683$), the output voltage of the rectifier at this time is 48.8 V. These results are summarized in Fig. 8(b). When the ESS power is boosted and applied to the WPT system through the proposed method, the RX converter can operate normally because the rectifier output voltage ($V_{\text{rect}}$) exceeds the minimum input voltage ($V_{\text{min}}$) of the RX dc to dc converter. Thus, power is normally delivered to the RX sensors.

B. VERIFICATIONS THROUGH EXPERIMENTS

FIGURE 9. Actual fabricated WPT coils for missiles mounted on maritime vessels. (a) The actual coils system. (b) The coils system that is mounted in the housing that simulates actual missiles.

TABLE VI

| Component                | Value   |
|--------------------------|---------|
| Inductance of Tx and Rx coils ($L_1$, $L_2$) | 37.8 μH |
| Resistance of Tx and Rx coils ($R_1$, $R_2$) | 78 mΩ   |
| Mutual inductance between Tx and Rx coils ($M$) | 7.88 μH |
| Coupling coefficient between coils | 0.208   |

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Table VI shows the measured electrical parameters of the manufactured coils. As in the simulation, the target value of the TX coil current is 13 A_{RMS}, so the values of the resonant network of the WPT system for the actual experiment according to (1), (12), and (13) are shown in Table VII.

Fig. 10(a) shows an input PCB board for processing the two inputs (the ESS power and generated power) which are proposed in this paper. The generated power ($V_{GEN}$) is directly connected to the TX inverter, and the ESS power ($V_{ESS}$) passes through the quadratic boost converter and is connected to the TX inverter. Meanwhile, Table VIII shows the circuit element values of the quadratic boost converter. The symbols of all the circuit elements can be seen from Fig. 3. As in Fig. 3, the converter for the TX IC is also configured. Additionally, Fig. 10(b) shows all the TX circuits including the TX inverter and the resonant system. The full bridge inverter is connected to the TX coil through the LCC topology. All the circuits are mounted on an aluminum housing system for the missile.

Table VI shows the measured electrical parameters of the manufactured coils.

**TABLE VII**

| Component                                      | Value               |
|------------------------------------------------|---------------------|
| TX coil current ($I_1$) when generated power (400V) is supplied | 13 A_{RMS}          |
| Resonant frequency of WPT system ($f_r$)        | 105 kHz             |
| Operating frequency of TX inverter ($f_o$)      | 105 kHz             |
| TX inductance ($L_1$)                           | 42 μH               |
| TX parallel capacitance ($C_p$)                 | 56 nF               |
| TX series capacitance ($C_s$)                   | 470 nF              |
| RX series capacitance ($C_r$)                   | 68 nF               |

Fig. 11 shows the PCB board of the RX circuits. The AC power from the RX coil goes through a resonant network (series topology) and then is rectified through a full-bridge rectifier. The rectifier output is directly connected to the RX dc to dc converter shown in Fig. 3. For sufficient dc to dc converter capacity, the RX dc to dc converters are grouped, and 5 converters are responsible for the operating load, and 3 converters are responsible for the RX sensors load. As previously explained in Fig. 3, a flyback converter for the RX IC power is also configured. Additionally, Fig. 12 shows the overall experimental configuration of the WPT system. As explained in the overall circuit diagram of Fig. 3, two power supplies are prepared for the two inputs (the ESS power and generated power), and two electronic loads are configured for the two outputs (the operating load and RX sensors load). Because there are dc to dc converters for the voltage regulation on the RX side, the electronic loads operate in the constant current (CC) mode. In addition, all...
power analysis is performed through a power analyzer, and all waveforms are extracted through an oscilloscope.

Fig. 13 shows the output waveform of the quadratic boost converter (inverter input waveform $V_{in}$), the gate-source ($V_{GS}$) waveform, and the drain-source ($V_{DS}$) waveform of the switch ($S_a$) when only the ESS power is applied to the WPT system. The corresponding voltage symbols are detailed in Fig. 5. From the $V_{GS}$ waveform in the Fig. 13, it can be seen that the duty ratio ($D$) of the quadratic converter switch $S_a$ is 0.693. In the simulations and calculations, it was calculated that the duty ratio ($D$) should be 0.683 to step up the ESS power (30 V) to 300 V, and the calculated and actual measured values are similar. Therefore, the output of the quadratic boost converter ($V_{in}$) can be seen, and the voltage input ($V_{ESS}$) of 30 V is stepped up to 300 V. On the other hand, because $V_{in}$, which is the output of the quadratic boost converter and the input of the inverter at the same time, is 300 V, the output of the inverter is a square wave with an amplitude of 300 V seen in Fig. 14(a). Meanwhile, Figs. 14(b) and 14(c) show the voltage and current of the TX and RX coils, respectively.

Finally, Table IX shows the measured voltage, current, and real power of each part when the input to the WPT system is only the ESS power (30 V). The symbols of each element of Table IX are all shown in Fig. 3. In order to increase the reliability of all power measurements, input and output power were measured twice with an oscilloscope (KEYSIGHT - MXR series) and a power analyzer (YOKOGAWA - WT1800E) as shown in Fig. 12. In particular, in the case of a WPT coil with a high quality factor (Q), an error in power measurement may be occur. Therefore, the reliability of the data is secured by confirming that the power values measured through the oscilloscope and the power analyzer match. Therefore, since all values in Table IX were measured twice through an oscilloscope and a power analyzer, the data can be said to be reliable. Meanwhile, as described above, when only the ESS power is supplied, power is not supplied to the operating power, but power is delivered only to the RX sensors load. In this study, it is assumed that the rated power of the RX sensors load is 100 W, and as shown in Table IX, 100 W is actually delivered to the load. Because the voltage input to the WPT system is only the ESS power which is 30 V, the ESS power is stepped up to 300 V through the quadratic boost converter. In addition, the RX rectifier output voltage is 46.1 V, which exceeded $V_{min}$ (43 V), the minimum voltage range for the RX converters to operate. Therefore, with a voltage regulation of 24 V, 100 W of power is supplied to the RX sensors load. On the other hand, note that the power for the ICs supplied to the TX and RX is several watts or less, so it is excluded from the measurement.

Fig. 15 shows the transient responses when only the ESS power ($V_{ESS}$) is supplied and when additionally the generated power ($V_{GEN}$) is supplied to the WPT system. Fig. 15(a) shows the input voltage ($V_{in}$) of the inverter and the current of the TX coil ($I_1$). The input of the TX inverter $V_{in}$ is...
changed to 400 V as the generated power (400 V) is additionally supplied. Moreover, as can be seen from (1), when the TX inverter input voltage increases, the current in the TX ($I_1$) coil also increases. In fact, the current in the TX coil ($I_1$) increases from 9.6 to 12.9 A RMS. The ratio of the current change is actually exactly the same as the ratio of 300 and 400 V, which is the change in the TX inverter input voltage ($V_{in}$). Because the TX coil current ($I_1$) is changed, the rectifier output voltage ($V_{rect}$) also changes according to (2) and (3), which is shown in Fig. 15(b). The rectifier voltage also increased from 46.2 V when only the ESS power is supplied to 63.4 V when the generated power is additionally supplied. The rectifier voltage ($V_{rect}$) is the input voltage of the RX dc to dc converter. Because both 46.2 and 63.4 V are the operating ranges ($V_{min}$ ~ $V_{max}$) of the RX dc to dc converter, the voltage for the RX sensors ($V_{sens}$) is regulated.
input voltage \( V_{\text{in}} \) is delivered to each electronic load in Fig. 12. Because the operating load and RX sensors load, and power of the WPT system proposed in this paper is 450 W for the generated power is applied, and power is supplied to each electronic load, respectively, when the generated power (400 V) is applied. As can be seen in Fig. 16(b), the current of the TX coil \( (I_1) \) is 12.9 A\text{RMS}. This is very similar to the 13 A\text{RMS} that is targeted in the simulations and calculations.

Table X shows the measured voltage, current, and real power of each part when the generated power is supplied. As in Table IX, the measurement power values of Table X were measured twice through the oscilloscope and power analyzer as shown in Fig. 12, and it was confirmed that each measurement value was consistent. In particular, it was confirmed that the measured power values of the oscilloscope and the power analyzer match each other in the power measurement of coils. Meanwhile, 450 W is supplied to the operating load, and 100 W is supplied to the RX sensors load. Unlike the case where only the ESS power is supplied previously, the DC input of the generated power is the input of the TX inverter. The overall power transfer efficiency (dc to dc) of the system is defined as the sum of the dc output power \( (P_{\text{oper}} + P_{\text{sens}}) \) divided by the dc input power \( (P_{\text{in-DC}}) \). When generated power is supplied, the dc to dc efficiency is 76.8%.

The proposed WPT system is also verified under various loads. Table XI shows voltages, currents and power of input and output when the proposed system is operated under various loads from 200 W to 1000 W. In various loads, the load for the RX sensors is fixed at 100 W, and only the operating load is increased. As shown in Table XI, it can be seen that the proposed WPT system works well under various load conditions. Also, Fig. 17 shows the power transfer efficiency when the proposed WPT system is operated from 200 W to 1000 W. Since the power transfer efficiency of the proposed WPT system is maintained even under various load conditions, the effectiveness of the proposed system is sufficient.

### IV. DISCUSSION

#### A. OPERATING FREQUENCY SELECTION CRITERIA IN THIS STUDY

In the WPT system of this study, 105 kHz is used as the operating frequency. There are two main reasons for
choosing the frequency as 105 kHz. First, for the higher RX rectifier output voltage. In general, 85 kHz is mainly used in a high-power WPT system for an electric vehicle wireless charging system [25]. However, in this study, as in (7), even when a relatively low voltage \(V_{\text{ESS}}\) is applied to the input, the output voltage of the rectifier must be within the range of the input voltage of the dc to dc converter in Table V. Since the input voltage range of the dc to dc converter is proportional to the operating frequency of the WPT system as in (7), a higher frequency of 105 kHz is selected.

Second, since the application of this study is for missiles, it must follow military standards. The military specification for electromagnetic interference (EMI) adopted in this study is MIL-STD-461G [26]. We aimed to use a frequency band corresponding to RE 102 (radiated emission 102) (10 kHz – 18 GHz) as a frequency for radiation of the WPT system for missiles. At the same time, the RE 101 frequency band (30 Hz – 100 kHz) is excluded from the operating frequency of the WPT system. Although it is difficult to list in detail due to military security reasons, the RE 101 (30 Hz – 100 kHz) frequency band is a band widely used in maritime vessels. Therefore, the reason for selecting the operating frequency as 105 kHz is not only to satisfy the voltage range of the dc to dc converter described above, but also to avoid the frequency range widely used in the military applications. Meanwhile, Fig. 18 shows the results for some frequency bands (100 kHz to 30 MHz) among the values measured by the RE 102 standard of the WPT system of this paper.

**B. MAXIMUM VOLTAGE DIFFERENCE BETWEEN ESS POWER AND GENERATED POWER IN WHICH THE PROPOSED SYSTEM CAN OPERATE**

In this study, the voltage difference between ESS power \(V_{\text{ESS}}\) and generated power \(V_{\text{GEN}}\) is about 13 times. Despite the voltage difference between the two power supplies, the proposed system allows the RX-side rectifier output voltage \(V_{\text{rect}}\) to fall within the input voltage range of the dc to dc converter ((4), and (5)). However, a voltage difference of 13 times is only a requirement of this study. Therefore, even if the difference between \(V_{\text{ESS}}\) and \(V_{\text{GEN}}\) is wider, the proposed WPT system can still work. In this discussion, the maximum input voltage difference that the proposed system can handle is investigated.

| Studies | Application | Power capacity | Operates two loads with two input power |
|---------|-------------|----------------|---------------------------------------|
| Proposed WPT system | Missiles | Up to 1 kW | O |
| [7] | Missiles | 300 W | X |
| [5], [27] | Drones | 150 W | X |
| [28] | UAVs | 325 W | X |

In order to calculate the maximum voltage difference that the proposed system can handle, let the RX rectifier output voltage by the ESS power supply in (4) \(V_{\text{rect-ESS}}\) be equal to \(V_{\text{min}}\), and \(V_{\text{rect GEN}}\) in (5) equal to \(V_{\text{max}}\). The \(V_{\text{rect-ESS}}\) is equivalent to (7), and \(V_{\text{rect GEN}}\) is equivalent to (11). Then, the ratio of \(V_{\text{ESS}}\) and \(V_{\text{GEN}}\) is as follows (14).

\[
\frac{V_{\text{GEN}}}{V_{\text{ESS}}} = \frac{1}{(1-D)^2} \frac{V_{\text{rect-GEN}}}{V_{\text{rect-ESS}}} = \frac{1}{(1-D)^2} \frac{V_{\text{max}}}{V_{\text{min}}} \tag{14}
\]

Equation (14) shows the ratio of the maximum voltage difference applicable to the proposed system. If the maximum duty ratio \(D_{\text{max}}\) of the quadratic boost converter is 0.9, and the maximum and minimum ratio of the input voltage range \(V_{\text{max}}/V_{\text{min}}\) of the dc to dc converter is about 3.5 times as shown in Table V, the maximum voltage difference applicable by (14) is about 350. Ideally, the proposed system operates normally even if the voltage difference between the two power sources is up to 350 times. However, as the duty ratio \(D\) increases, the loss of the quadratic boost converter increases, and the rectifier output voltage \(V_{\text{rect}}\) should be designed with a margin from the operable voltage range \((V_{\text{min}} - V_{\text{max}})\) of the dc to dc converter. Therefore, in an actual system, it is inevitable to have a ratio of a voltage difference smaller than 350 times. However, obviously, the proposed WPT system can operate sufficiently even with an input voltage difference of more than 13 times, so the effectiveness of the system is sufficient.

**C. COMPARISON WITH OTHER HIGH-POWER WPT SYSTEMS OF SEVERAL HUNDRED W OR MORE**

As can be seen from the experiments in Section IV, it has been demonstrated that the proposed system can transfer power up to 1000 W. It is necessary to compare the performance of the proposed system with other conventional WPT systems that transfer the power of several hundred. Table XII shows the comparison between the system proposed in this paper and previous studies. The main comparison targets are missiles, which are the applications covered in this paper, and drones and UAVs similar to missiles.

Although the WPT system for missiles has been studied up to 300 W through the conventional study [7], it has a limitation in that it is a WPT system that transfers power to a single load through a single power source. Likewise, studies for drones and UAVs all deliver up to 325 W of power [5], [27]-[28], but these studies have nothing to do with transferring power to two loads through two input...
power sources. That is, this study is a very practical study designed in consideration of the actual missile operation environment, and has the advantage of being able to transfer power to two loads with two input power sources with a voltage difference of 13 times.

V. CONCLUSION

The missiles mounted on maritime vessels have two main power consuming load: one is the operating load, and the other is the safety sensors load. The operating load is consumed just before the missile is launched, and the consumption capacity is large and only needs to be temporarily supplied. On the other hand, safety sensors exist to measure the temperature, humidity, etc. for the safety of the explosives included for the propulsion of the missiles, and although the power consumption is small, power must be supplied at all times. On the other hand, there are two types of power sources that are supplied from the power system of maritime vessels: generated power and emergency power through an ESS. The self-generated power may be temporarily cut off if there is a problem with the generator. Therefore, the ESS power should be used as a power source for the safety sensors of the missile, and generated power should be used as a power source for mission performance just before the missile is launched. However, if the WPT system is applied to the missile, the voltage difference between the ESS power and the generated power is 10 times or more, so there is a problem in the voltage regulation of various loads on the RX side.

In this paper, we proposed a WPT system that can overcome the voltage difference between the ESS power and the generated power by stepping up the ESS power by about 10 times using a quadratic boost converter and its control method. In addition, the proposed system can continuously supply the power to the sensors of the missile even when the generated power is additionally supplied. The proposed system was analyzed through calculations and verified through simulations and experiments. In the experiment, the effectiveness of the proposed system was demonstrated through the operation of a 550 W class WPT system. In the actual experiment, when only 30 V of ESS power was supplied, the 30 V was stepped up to 300 V, and then, it was supplied to the TX inverter. Thus, the power was delivered to the sensor power. In addition, power was continuously supplied to the RX sensor in the transient response to which an additional 400 V of generated power was supplied. Power was supplied to the operating load and the RX sensors load with a dc to dc efficiency of 76.8% even in the operation mode. In addition, the proposed system maintained the power transfer efficiency under various load conditions (200 W ~ 1000 W).

As for further research related to this study, it should be applied to the various loads consumed by the actual missile rather than the electronic loads by applying it to the actual missile system. In addition, the interaction between the various surrounding environments between the actual missile launcher and the missile and the WPT system in this paper should be checked. In particular, safety issues such as magnetic induction to the missile’s metal housing must be confirmed before being applied to an actual missile system.

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