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A High-Voltage DC-DC LLC Resonant Converter by Using a Symmetrical Voltage Multiplier Circuit

Reza Takarli[1], Mohammadreza Adib[1], Abolfazl Vahedi[1], Reza Beiranvand[2]

[1]Iran University of Science and Technology; Reza_Takarli@elec.iust.ac.ir; Mohammadreza_Adib@elec.iust.ac.ir; aVahedi@iust.ac.ir
[2] Tarbiat Modares University, Tehran, Iran; Beiranvand@modares.ac.ir

Abstract
High voltage converters are commonly used in various applications, namely, PFC, HVDC, water treatment, and high-voltage dc power supplies. This paper proposes a high-voltage output DC-DC LLC resonant converter, which provides some good features such as soft switching leading to low electromagnetic interference, that can enable the opportunity to achieve higher efficiency and high-frequency operation to increase the converter power density. The resonant converters are characterized by the ability to control the output voltage through switching frequency modulation within a wide range of load changes and input voltage fluctuations while maintaining soft switching. The proposed LLC is fed by the input inverter with six switches, which halves the voltage stresses on the switches. Meanwhile, on the output rectifying stage, a symmetrical multiplier boosts the resonant tank voltage by four, which significantly improves the power density, as compared to the conventional Cockcroft-Walton and full bridge diode rectifiers. It also reduces the transformer turns ratio while the output impedance remains relatively unchanged. The given converter operational principles are discussed and mathematically analyzed in detail. To validate the proposed structure, it has been simulated using OrCAD/Capture under different conditions.

Keywords: DC-DC power conversion, high voltage converter, LLC resonant converter, voltage multiplier, water treatment.

Introduction

Resonant converters are capable of soft switching in a broad range of load changes, which makes them a suitable candidate in many applications like high-voltage output, battery chargers, and other applications where high power density and efficiency are needed [1]–[5]. High-voltage DC-DC converters have various applications, such as PFC, HVDC, high-voltage DC supplies, high-voltage insulation resistance tests, etc [6]–[10]. Meanwhile, excessive fossil fuel utilization, the population's rapid growth, and fertilizer usage threaten human and animal lives by contaminating the water. Hence, the urgent need for water treatment has become more critical in recent years. One of the most viable approaches for water treatment is using power electronics pulses that cause no consequences and contamination [11]. The megger test is used to determine the strength of the motor winding insulation. Temperature, humidity, moisture, and dust particles are all factors that influence the insulation resistance quality of an electrical system. Electrical and mechanical stress negatively affect it as well, so it has become imperative to monitor the insulation resistance (IR) of equipment on a regular basis to prevent any fatalities or electric shocks [9], [10].

Conventional switching power supplies which mostly use hard switching like pulse width modulation (PWM) have limitations such as producing high electromagnetic radiation and often do not reach high efficiency and high power density; Thus, soft switching converters have been developed to overcome these limitations [1], [12]–[14].

Regarding the type of tank, many resonant tanks can be used as they offer soft switching in a wide range of load changes. However, because of high order or insufficient gain-frequency curve, the control of some tanks is too complex. Resonant tanks like CLLC or LCLC are used in bi-directional applications due to their relatively symmetrical characteristic [15]–[17]. It is not necessary to have a symmetrical characteristic in unidirectional applications. 3rd-order tanks are more utilized for easier controllability and design in unidirectional applications. LLC and LCC types are two of the most conventional 3th-order widely used and are suitable in high-voltage converters [12], [18]–[20].

Also, it is popular to use conventional rectifier structures for rectification. Voltage multipliers are considered better candidates for multiplying the voltage because of their simplicity, low cost, and high efficiency. Moreover, transformers with high turns ratio are utilized in high-voltage converters to reach higher gains. A high turns ratio, increases inductance leakage and parasitic capacitance, which can cause voltage spikes and higher switching losses on power switching devices. To mitigate these issues, a voltage multiplier can be used to lower turns ratio, which results in higher power density due to the minimization of the transformer size[21]–[24]. They are mainly two types of voltage multipliers based on their place in the circuit. The first one is placed in a circuit as a middle stage to improve the stress of switches. The second one is simply put on the output stage to boost the voltage level and rectification [25]–[27].

Proposed High-voltage LLC Resonant converter

A resonant converter based on an LLC tank is proposed to provide high voltage on the output. As shown in Figure 1, a multiplier is placed on the rectification side, and a new arrangement is utilized to reduce the blocking voltage that is needed on the inverter side. The proposed converter is suitable for applications with high input and output voltage. Figure 1 shows the proposed six-switch arrangement (S_1 – S_6) for the inverter. Unlike the full-bridge inverter, this arrangement allows the inverter to have the MOSFETs' halve blocking voltage which makes them suitable for high-voltage input applications. Moreover, it can enable the opportunity to utilize low-voltage MOSFETs.

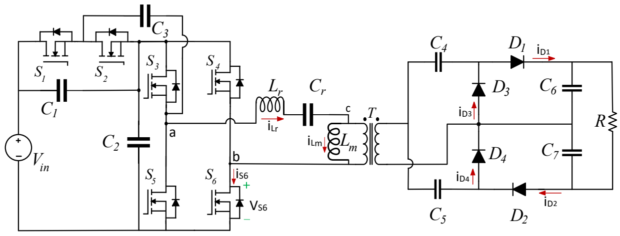

Figure 1. The proposed configuration of the high voltage input/output converter

The inverter is fed by an 800 V DC link and provides a square wave between ±400 V for the LLC resonant tank. A transformer provides galvanic isolation and utilizes the turns ratio to boost the voltage. In the output stage, four diodes are placed as a rectifier to multiply the voltage of the secondary side of the transformer by a factor of four. The rectifier consists of four diodes, D_1 – D_4, and four capacitors, C_4 – C_7.

The switching frequency determines the input/output gain in a resonant tank when the LLC tank is fed by the inverter. In the next stage, the produced voltage is multiplied by the turns ratio. Then, the voltage is quadrupled by the rectifier.

Operation Mode

Two half cycles with the same sequence of switching are defined due to the symmetric operation of the rectifier. In the first half cycle, S_1, S_3 and S_6 are on and conducting. V_{ab} and V_{cb} are positive, output voltage is larger than V_{c2}, $I_{Lm} < 0$ and $I_{Lr} < 0$. Due to the constant voltage of L_m, the current of L_m increases linearly, and the resonant's current increases sinusoidally until it reaches zero. In the next interval, the current of L_m will increase linearly until it becomes zero. The output diode D_1, conducts, and its current rise linearly during these two intervals. When the voltage of the transformer on the secondary side becomes larger than the voltage of C_5, the D_4 diode will turn on (D_1 and D_4 are on). In the half of the cycle, the current of the resonant tank, I_{Lr}, reaches its peak in a sinusoidal form. Then, the current of L_m increases, and its value becomes equal to the decreasing I_{Lr}. At this moment, the current of D_1 and D_4 reaches zero and turns off. At the end of this interval, no energy will be transferred to the secondary side, and the secondary current of the transformer will stay zero too. Since the circuit has a symmetrical structure, in the second half cycle, the counterpart switches are responsible for transferring energy.

In the second half cycle, S_2, S_4, and S_5 are conducting while S_1, S_2 and S_6 are off. Similar to the previous half cycle, Firstly, the current of L_m and L_r are positive. I_{Lm} is decreasing linearly and I_{Lr} is decreasing in a sinusoidal form. The end of this interval is when I_{Lr} reaches zero. During these two intervals, the output diode D_2 conducts and its current rise linearly. When the voltage of the secondary side of the transformer becomes larger than the voltage of C_4, the diode D_3 turns on (D_2 and D_3 are on). The next interval ends when I_{Lm} reaches zero. At this moment, I_{Lr} reaches its negative peak and starts increasing. Decreasing I_{Lm} and increasing I_{Lr} continue until I_{Lm} becomes equal to I_{Lr}. This point is the endpoint of the interval and no energy will be transferred to the secondary as the current of the transformer becomes zero, and all diodes stay in an off state until the next cycle.

Figure 2 shows the diodes' current, the secondary side of the transformer, magnetizing and leakage current, and the input voltage of the resonant tank.

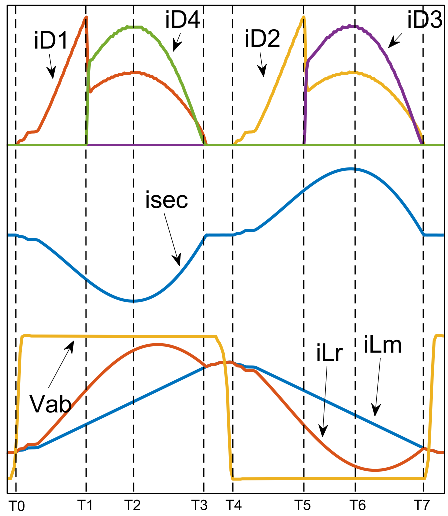

Figure 2. Waveform of the different parts of converter in one cycle

Steady-State Analysis of the Resonant Tank and the Rectifier

In previous sections, the operation mode of the input inverter has been explained, and in this section, a further explanation regarding the LLC types resonant converter and its gain-frequency characteristic are provided, which are needed in the design stage. Additionally, the multiplier rectifier part, which is based on diodes and capacitors, is also discussed.

A. LLC Resonant converter

In this research, a resonant converter with an LLC tank is used. Various types of the resonant tank can contribute to producing output voltage; LLC is generally considered paramount among others since it owns a plethora of desirable characteristics, namely, easy to design and control, simple structure, integration in magnetic parts, high efficiency in a wide range of loads, narrow change in frequency, short circuit protection [1], [3], [12], [28], [29].

In conventional PWM converters, in order to control the output voltage, the pulse width will vary. In a resonant converter, the witching frequency adjusts the output. Besides, other factors, such as load and designed parameters, affect the output voltage. The duty cycle is usually kept at 50%. In fact, a resonant tank acts like a variable gain controlled by frequency. In this paper, an LLC-type resonant converter is chosen because of the aforementioned reasons. For a simple analysis of the resonant tank, fundamental harmonic approximation (FHA) is generally used [1], [3], [28]–[30]. This section provides the gain-frequency equation based on FHA for an LLC converter. The equivalent circuit based on FHA for an LLC resonant tank is shown in Figure 3.

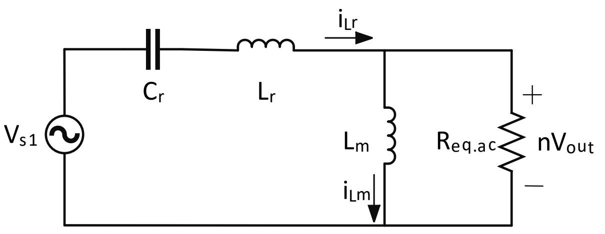

Figure 3. FHA equivalent circuit for the LLC tank

In equation (1), turns ratio of the transformer is defined as n, and $R_{eq.ac}$ in a conventional rectifier is the equivalent resistor as follows:

$$R_{eq.ac} = n^2 \frac{8}{\pi^2}\frac{V_{out}}{I_{out}} = n^2 \frac{8}{\pi^2}\frac{V_{out}^2}{P_{out}} \quad (1)$$

Full FHA analysis is provided in [30] accordingly, the gain-frequency equation can be expressed as below:

$$Gain(f_n, L, Q) = \frac{nv_{out}}{v_{in}} = \frac{1}{\sqrt{\left(1+L-\frac{l}{f_n^2}\right)^2+Q^2\cdot\left(f_n-\frac{1}{f_n}\right)^2}} \quad (2)$$

The quality factor is denoted as Q and is expressed as follows:

$$Q = \frac{Z_0}{R_{eq,ac}} = \frac{\pi^2}{8}\frac{I_{out}}{V_{out}}\frac{1}{n^2}Z_0 = \frac{\pi^2}{8}\frac{P_{out}}{(nV_{out})^2}Z_0 \quad (3)$$

Z_0 is defined as below:

$$Z_0 = \sqrt{\frac{L_r}{C_r}} = 2\pi f_{r1} L_r = \frac{1}{2\pi f_{r1} C_r} \quad (4)$$

The normalized inductance and frequency are defined as:

$$\mathrm{L} = \frac{L_r}{L_m} \quad (5)$$

$$\mathrm{F} = \frac{f_s}{f_{r1}} \quad (6)$$

L and F are the inductance ratio and frequency ratio, respectively. To maintain soft switching, it is necessary to operate within the inductive region. The gain-frequency curve in this region has a negative slope. The gain equation depends on frequency, load, and inductance ratio. as the value of L is constant after implementation, a 3-D representation of the formula is provided to illustrate both factors in Figure 4.

B. *Symmetrical Voltage Quadruple*

This section presents the principle of the utilized rectifier in the output stage to multiply the provided voltage by the resonant tank by a factor of four. To show the viability of the proposed differential equation method versus FHA method, equations based on the FHA method need to be developed. Using FHA, the equation for the output voltage is obtained. A series of equations are then derived for the ripple voltage and the equivalent reflected resistance. As a result of the combination of multiplying voltage capacitors (C_4-C_7), the symmetrical rectifier is the same as a conventional rectifier.

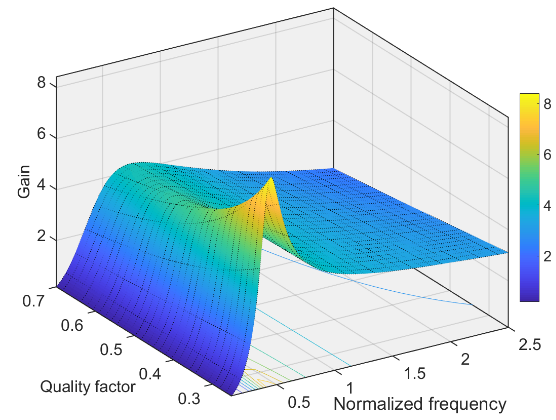

Figure 4. 3D representation of LLC resonant tank characteristic

Based on FHA, it is assumed that the fundamental component is kept; hence, the parameter would be in a sinusoidal form. According to Figure 2, which represent the whole circuit, the output voltage can be defined as the sum of capacitor C_6 and C_7. The derivative of it can be written as:

$$\frac{dv_{out}(t)}{dt} = \frac{dv_{C6}(t)}{dt} + \frac{dv_{C7}(t)}{dt} \quad (7)$$

By assuming the symmetrically of the arrangement, $C_6 = C_7 = C_{out}$, the following equation can be expressed:

$$\frac{dv_{out}(t)}{dt} = \frac{(i_{C4}(t)-i_{RL}(t))}{C_{out}} - \frac{i_{RL}(t)}{C_{out}} \quad (8)$$

i_{c4} and i_{RL} are the capacitor C4 and load current, respectively. It can easily be shown that the below equation is attainable by defining A and B coefficients such as:

$$\frac{dv_{out}(t)}{dt} + A\, v_{out}(t) - B\sin(\omega_s t) = 0 \quad (9)$$

$$A = \frac{4k+1}{R_L C_{out}(2k+1)} \quad (10)$$

$$B = \frac{kI_{ps}}{C_{out}(2k+1)} \quad (11)$$

In the above equation, I_{ps} is the peak of the secondary side current of the transformer. Also, k is defined as:

$$k = \frac{c_6}{c_4} = \frac{c_7}{c_5} \quad (12)$$

By solving the differential equation, the average value of the output voltage and the ripple according to FHA analysis will be:

$$< v_{out}(t) >= \frac{2I_{ps}R_L k}{\pi(4k+1)} \quad (13)$$

$$V_{ripple} = v_{out}\left(\frac{3\pi}{4\omega_s}\right) - v_{out}\left(\frac{\pi}{4\omega_s}\right) \quad (14)$$

The equivalent resistor, which is reflected on the primary side, can be driven as:

$$R_e = \frac{R_L/n^2}{2\pi^2\left(\frac{1}{4k}+1\right)^2} \quad (15)$$

From the equation, R_e is clearly dependent on the ratio of the output capacitor and the turns ratio. The worth noticing point is the k factor that defines the ratio of the output capacitor. In high-voltage converters, the current of output is small, so the ripple should be kept low. As a large value for 'k' leads to a smaller capacitor which consequently aggravates the ripple, it should be set at a modest value.

Simulation Results

To validate the functionality of the high-voltage DC/DC LLC resonant converter that is proposed, a detailed simulation using PSpice/OrCAD has been done. The specifications are provided in Table 1. The voltage of the inverter is assumed to be 800 V, and the desired high-voltage output is considered to be 6.5 kV. The switching frequency associated with it is roughly 250 kHz. The converter's output power is considered 1000 watts on average, and for convenience, a resistor is placed as a load in the simulation.

Table 1. Specifications of the Proposed Converter

parameters	value	Unit
Input Voltage	800	V
Output Voltage	6500	V
Magnetizing inductance L_m	100	uH
Series inductance L_r	7	uH
Primary capacitor C_r	48	nF
Rectifier capacitors $C_5= C_6= C_7= C_8$	76	nF
Turns ratio (N_p/N_s)	0.25	-

The output-to-input gain will be 8.125 if the switching frequency is set to 250 kHz; thus, 6500 V output voltage can be attained from 800 V input voltage as shown in Figure 5. Noticing the magnified region, the output ripple is clearly under one percent of output voltage. The voltage multiplier in the output stage quadruples the resonant tank voltage. To reach 6500 V, the resonant tank and transformer gain should be set to two; thus, the voltage of the secondary side of the transformer which is provided by the resonant should be roughly 1625 V which can be attained by setting the frequency to 250 kHz.

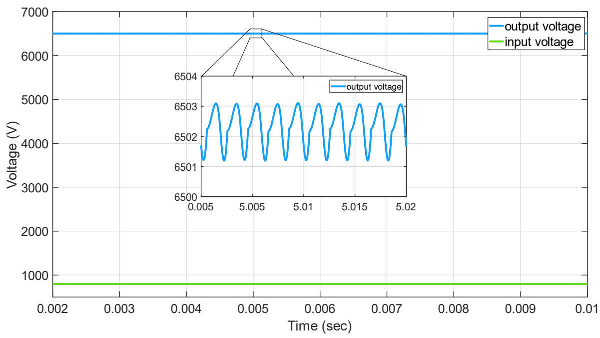

Figure 5. Input voltage and output voltage waveforms of the converter

It is important to choose certain parameters during the design stage, such as L, which represents the ratio between leakage and magnetizing inductance. However, some considerations should be noted to balance efficiency and the range of frequency changes to adjust the output voltage.

In order to show the superb capability of the input inverter, Figure 6 clearly illustrates that the voltage of input switches is limited to 50% of the feeding voltage, which is 800V. Halving the switches' voltage stress provides the opportunity to use conventional low-voltage switches and higher switching frequency due to the faster discharging of switches' capacitors. While the switch's blocking voltage is confined to 400 V, the voltage of the resonant tank is 800 V peak to peak and this provides the gain of unity for the inverter stage. In the half-bridge inverters, the gain is 0.5. So, the gain of the resonant tank stage should be doubled to provide the total gain. Since the higher gain in the resonant tank is where the gain-frequency curve experiences a lower slope and is close to the capacitive region, the probability of losing soft switching will be increased. In the capacitive region, the current leads the voltage the body diode of switches will not conduct, resulting in losing soft switching.

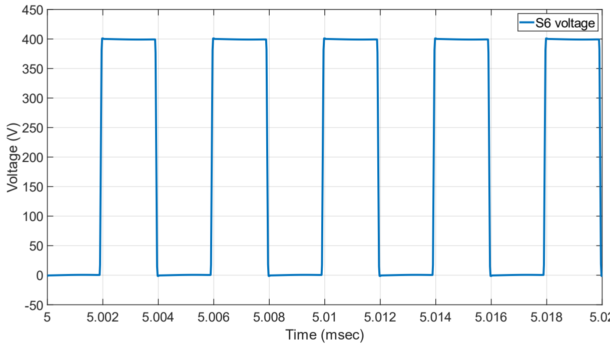

Figure 6. Voltage waveform of the input inverter switch (S6)

Resonant converters offer a number of advantages, including zero-voltage switching, which leads to higher efficiency and reduced EMI. In Figure 7, the soft switching operation is attained. During the transition from off-state to on-state, the current passes through the body diode of MOSFETs. Therefore, the charge of the output capacitor becomes roughly zero. Consequently, when MOSFETs are turned on, their voltage is limited by the voltage drop over their body diode. This can be seen by comparing Figure 6 and Figure 7, which represent the current and voltage of one switch.

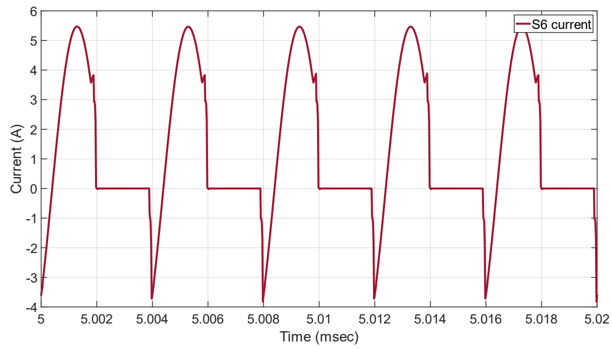

Figure 7. Current waveform of the input inverter switch (S6)

The current of output diodes is shown in Figure 8. As soon as D_1 conducts, a charge is applied to the series capacitor, followed by D_3 turning on. In the next cycle, the counterpart diodes will conduct. Because there is a dead time between each half cycle, the output diodes' current reach zero before the next interval and experience zero-current switching. In these applications, output voltages are high, and currents are relatively low, so conduction losses in diodes can be neglected. Furthermore, output diodes should be chosen from high voltage types due to the blocking voltage that is needed in high voltage applications, in this configuration, the blocking voltage that is needed is around 3.3 kV.

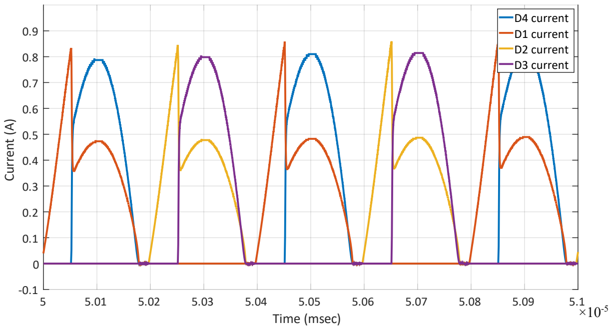

Figure 8. Waveform of the output diodes current of the output diodes

A number of important waveforms of the converter can be seen in Figure 9, which were explained theoretically in the previous section. The waveform of the resonant tank, which is equal to the leakage inductance's current (I_{Lr}), displays a relatively sinusoidal shape as expected. Simultaneously, the current of magnetizing inductance (I_{Lm}) experiences linear changes as the voltage across it is constant, so according to $I_L = L\times dv/dt$, the current's steep is constant. In Figure 9(a), these two currents are presented, and when currents reach together, transferring energy to the secondary will be finished, and circulating energy will remain in the resonant tank. In the absence of energy being transferred to the secondary side of the transformer, the current on the secondary side will remain zero, as shown in Figure 9(b), this current then will be rectified by the multiplier stage and feeds the output. Moreover, the resonant tank is fed by the new input structure that has been explained previously. As it can be seen in Figure 9(c), while the input voltage was assumed to be 800 V. The upper band of the resonant tank voltage is 400 V, and the lower band is -400 V, which is a manifestation of reducing voltage stress of input switches.

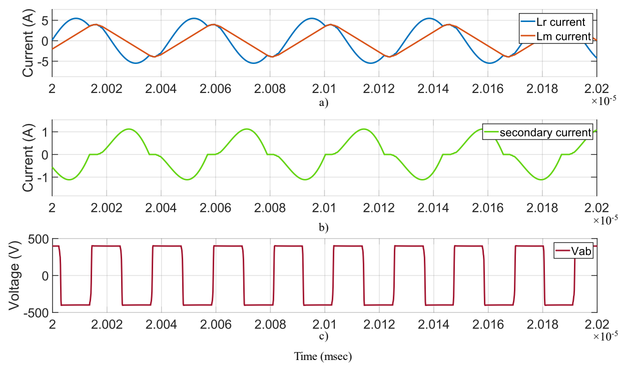

Figure 9. Different simulated waveforms of the proposed resonant converter. a) current of resonant tank and magnetizing inductance; b) current of secondary side of the transformer; c) input voltage of the resonant tank (Vab).

Conclusions

In this paper, a high-voltage converter based on an LLC resonant tank is presented. The input voltage is considered to be 800 V, and 6500 V for output voltage. in order to provide the proper gain, a voltage quadrupler is utilized as a rectifier stage, utilizing a voltage multiplier in such applications can decrease the additional gain burden on the resonant tank and turns ratio; as a result of the simple and inexpensive design, it is justified to utilize four diodes and capacitors. Moreover, it can contribute to a better resonant tank operation in the vicinity of the resonance frequency since the gain required is approximately equal to unity, since the model and operation of a resonant tank are more suitable in that region. Meanwhile, a novel arrangement with six switches has been used to halve the voltage stress on the input switches. With regard to the resonant tank, analysis based on FHA has been investigated, and mathematical equations have been derived in order to design and determine the switching frequency range and gain. The given results illustrate the zero-voltage switching on the inverter side and zero-current switching on the voltage multiplier side, leading to higher efficiency and lower EMI in practice.

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