PSIM simulation of voltage-fed series resonant inverter for induction heating systems

Muzaffer Çayır[1], Harun Özbay[2]

[1]Department of Electrical-Electronics Engineering Bandırma Onyedi Eylül University, Bandırma, Turkey, muzaffercayir99@gmail.com, ORCID: 0000-0002-1706-8576
[2]Department of Electrical Engineering, Bandırma Onyedi Eylül University, Bandırma, Turkey, hozbay@bandirma.edu.tr, ORCID: 0000-0003-1068-244X

In order to obtain alloys from metals or to weld in daily life, metals must be melted, rapidly heated and cooled, or partial heating must be performed. One of the effective methods used for such needs is the induction heating system. The hard-switching and soft-switching inverters are used in induction heating systems. In this study, the design and analysis of a voltage source series resonance inverter, one of the soft-switching inverters, for induction heating process has been carried out. Based on the information obtained as a result of the design, the necessary circuit elements for a series resonance inverter were determined and a simulation study was carried out with PSIM software. In the simulation study, the switching frequency is selected at different values and the response of the circuit according to the switching frequency is examined. Thus, the response of the designed series resonant inverter at the resonant frequency and outside the resonant frequency has been examined. Accordingly, the series resonance inverter designed for induction heating is capacitive when the switching frequency is below the resonance frequency, and it has been determined that switching losses occur at turn-on. In the case where the switching frequency is above the resonance frequency, it is inductive and it has been determined that the switching losses of the switches increase at turn-off. In the case where the switching frequency is equal to the resonance frequency, it is determined that soft switching occurs and maximum power transfer to the load is provided, and the simulation results obtained are presented.

***Keywords**: Induction Heating Systems, Series Resonance Inverters, PSIM*

1. Introduction

In daily life, metals must be partially heated in order to weld, or metals must be melted or rapidly heated and cooled to obtain alloys from metals. One of the effective methods used for such purposes is the induction heating system [1].

Induction heating is basically the process of converting electrical energy into heat energy. Unlike other heating methods, the heat is created by the induction method, not outside of the part to be heated. For this reason, only metal work-pieces can be heated. The work-piece and the coil are joined by the magnetic field. Thanks to the alternating current passing through the induction coil at a suitable frequency, a variable magnetic field is formed around the coil. A voltage is induced in the electrically conductive work-piece, which is in this magnetic field, and eddy currents pass from this part in the opposite direction to the coil current, and heat is released in the work-piece due to the resistance of the work-piece. Thus, the work-piece can be heated and melted without any physical contact between the work-piece and the induction coil. This process is called "Induction Heating" since the heat is generated due to the induction current [1].

The hard-switching and soft-switching inverters are used in the induction heating systems. In this study, the design and analysis of voltage source series resonance inverter, which is one of the soft-switching inverters, is investigated.

There are many studies conducted in the field of induction heating.

A. Dalcalı , H. Özbay , S. Öncü investigated the effect of operating frequency on the heating depth in the field of induction heating in a study they carried out. In the study, metal workpieces in the same dimensions and different material structures were analyzed by extracting a magnetic model for different operating frequencies with a 5-winding copper induction coil. Eddy losses were presented by examining the magnetic flux density (B) distributions and the skin effect on the workpieces with finite element analysis (SEA) [7].

A.Altintas, M.N. Yildiz, I. Kızılkaya designed and tested a micro-controlled liquid heater working with the principle of induction heating in a study they carried out. In the sample model in the study, 220 V AC voltage taken from the city electricity network was converted into DC voltage with the help of bridge type rectifier and filter. This obtained DC voltage was then applied to a 16.66 kHz parallel resonant circuit via a bridge type DC-AC converter. In the experimental studies, the city water network was used as a liquid. According to the results of the study, the temperature of the water with a flow rate of 1 lt/min in the developed sample model ranged from 30 °C to 64 °C, and the temperature of the water with a flow rate of 0.5 lt/min changed from 30 °C to 94 °C. has risen [8].

U. Unver, H.M. Unver carried out, aimed to analyze the efficiency change with experimental and numerical modeling depending on the heating of billet with diameters different from the coil design diameter in aluminum extrusion plants using induction heating system. As a result of the study, they presented that the material temperature and the absorbed power increased up to 5%, but the heating efficiency did not change, by placing the discs in the coil concentrically or eccentrically in the experimental setup manufactured as a tunnel type induction heating system. For this reason, they stated that some additional mechanisms are not needed to make the material concentric with the coil [9].

S. Cetin, B.S. Sazak presented a series resonance inverter application with three outputs for kitchen type induction heating devices on the subject they are working on. In this study, three heating coils that can give different output power at different frequencies can be controlled by the same inverter circuit. In this way, two semiconductor switches and control circuits are saved and the total system cost is reduced. A low-power prototype of the presented system is presented in the laboratory environment by simulating PSpice [10].

S. Öncü, B.S. Sazak implemented a kitchen type induction heating system with an E class inverter. In the study, a low cost and high efficiency single phase medium frequency domestic induction heating system was aimed without increasing the physical dimensions and weight. E class inverter is used as a DC/AC converter because it is economical and simple. PSpice simulation of the presented system has been made and a small powered working prototype of the circuit has been realized in the laboratory [11].

S. Koroglu, B.S. Sazak presented a half-bridge series resonance inverter induction heating system for kitchen applications in a study they carried out. In the study, a complete induction heating system including coil design was designed, a small powerful prototype was realized and tested. In the presented system, resonance switching technique is used and it is aimed to minimize the switching losses in this way. As a result of the calculations, it has been said that the presented system has a very high efficiency compared to the known kitchen heaters [12].

2. Class D Voltage Source Series Resonance Inverter

Class D DC-AC resonant inverters were developed by Baxandall in 1959 and are widely used in a variety of applications to convert DC energy to AC energy [2].

The use of resonant inverters, DC-DC resonant converters, radio transmitters, solid-state electronic ballasts for fluorescent lamps, high-frequency electrical process heating applied in induction welding, surface hardening, brazing and annealing, induction sealing for tamper-proof packaging, fiber optic manufacturing and plastics. applications such as dielectric heating for welding applications are frequently encountered [4].

Class D voltage switching inverters are powered by a DC voltage source. If the quality factor in the loaded condition is high enough, the current through the resonant circuit is sinusoidal and the currents through the switches are half-wave sinusoids. The voltages in the switches are in square wave form [4].

The class D series resonant inverter consists of two power switches, two diodes connected in reverse parallel to the switches, and RLC elements connected in series, as shown in Figure 1. DC input voltage is applied as power source. BJT, MOSFET, IGBT can be used as power switch. When the switches are conducting, current flows in the positive direction, and when the switches are insulated, current flows in the negative direction with the help of reverse parallel connected diodes.

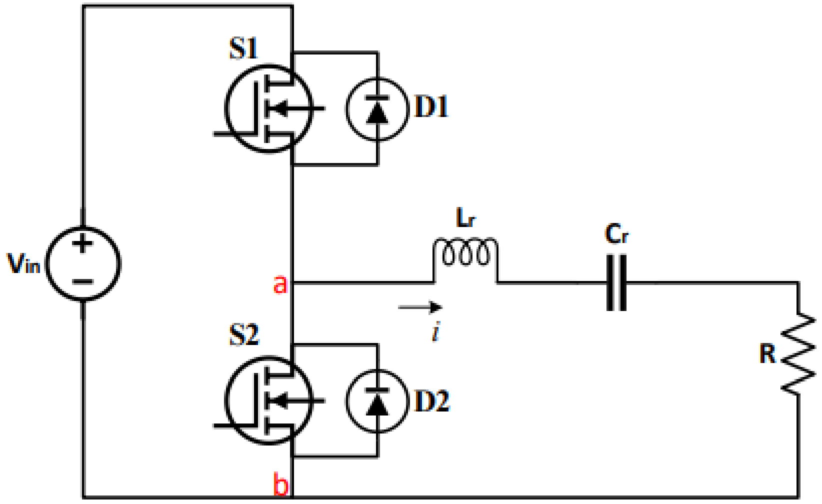

***Figure 1**. Class D voltage source series resonant inverter circuit*

One of the main advantages of Class D voltage switching inverters is that the voltage dropped on the transistors is low, equal to the supply voltage. This advantage makes it suitable to use class D voltage-switching inverters in high voltage applications where inverters are fed with grid voltage. Also, low voltage MOSFETs can be used. Such MOSFETs have low resistances, which reduces conduction losses and operating junction temperatures, and provides high efficiency.

The switching frequency of the voltage source series resonant inverter can be at the resonant frequency, below the resonant frequency or above the resonant frequency. The circuit is capacitive when the switching frequency is below the resonant frequency. In this case, there is no loss at the time of switching of the switches, but switching losses occur at the time of transmission. In addition, the switching of the switches is under high voltage and current, and very high currents can pass through the reverse parallel diodes.

The circuit is inductive when the switching frequency is above the resonant frequency. In this case, no loss occurs at the time of transmission of the switches, but switching losses occur at the time of cut-off.
If the switching frequency is at the resonant frequency, the circuit is pure ohmic and the impedance of the circuit is at its lowest. In this case, the switches turn on and turn off under soft switching conditions. Therefore, maximum power transfer to the load is ensured.

The angular resonance frequency and resonance frequency of the class D voltage source series resonant inverter are expressed by Equation 1.

$$\omega_r = 2.\pi.f_r = \frac{1}{\sqrt{L.C}} \qquad f_r = \frac{1}{2.\pi.\sqrt{L.C}} \tag{1}$$

The quality factor and power angle are shown by Equation 2. and Equation 3, respectively.

$$Q = \frac{\omega_r L}{R} \tag{2}$$

$$\theta = \arctan\left[Q\left(\frac{\omega_s}{\omega_r} - \frac{\omega_r}{\omega_s}\right)\right] \tag{3}$$

Coil reactance and capacitor reactance are calculated by Equation 4, and the total impedance of the circuit is calculated by Equation 5.

$$X_L = 2.\pi.f_s.L \quad , \qquad X_C = \frac{1}{2.\pi.f_s.C} \tag{4}$$

$$Z_{eq} = R + j(X_L - X_C) \tag{5}$$

The peak value and effective value of the coil current are expressed by equation 6.

$$\begin{gathered} V_{ab} = V_{max}\sin(\omega_s t) \quad , \quad V_{max} = \frac{2.V_{in}}{\pi} \cong 0{,}637.V_{in} \\ I_{L,max} = \frac{V_{max}}{Z_{eq}} \quad , \quad I_{rms} \cong 0{,}707.I_{L,max} \end{gathered} \tag{6}$$

The power dissipated on the resistor is calculated by Equation 7.

$$P_R = I_{rms}^2.R \tag{7}$$

$$P_R = \frac{2.V_{in}^2 cos^2\theta}{\pi^2.R}$$

3. PSIM Simulation for Different Switching Frequencies

Class-D voltage source series resonance inverter application, which circuit parameters are given in Table 1, has been implemented in PSIM software. The series resonance inverter shown in Figure 6 is analyzed for three different cases and the simulation results are shown. First, the case where the switching frequency is below the resonance frequency ($fs = 0.9fr$), then the case where it is equal to the resonance frequency ($fs = fr$) and finally the case where it is abow the resonance frequency (fs = 1.1fr) are examined.

***Table 1**. Circuit Parameters*

Source Voltage	V_S	60V
Resonant Coil	L_r	15µH
Resonant Capacitor	C_r	0.2µF
Series Resistor	R	2Ω
Resonant Frequency	f_r	91888.14924

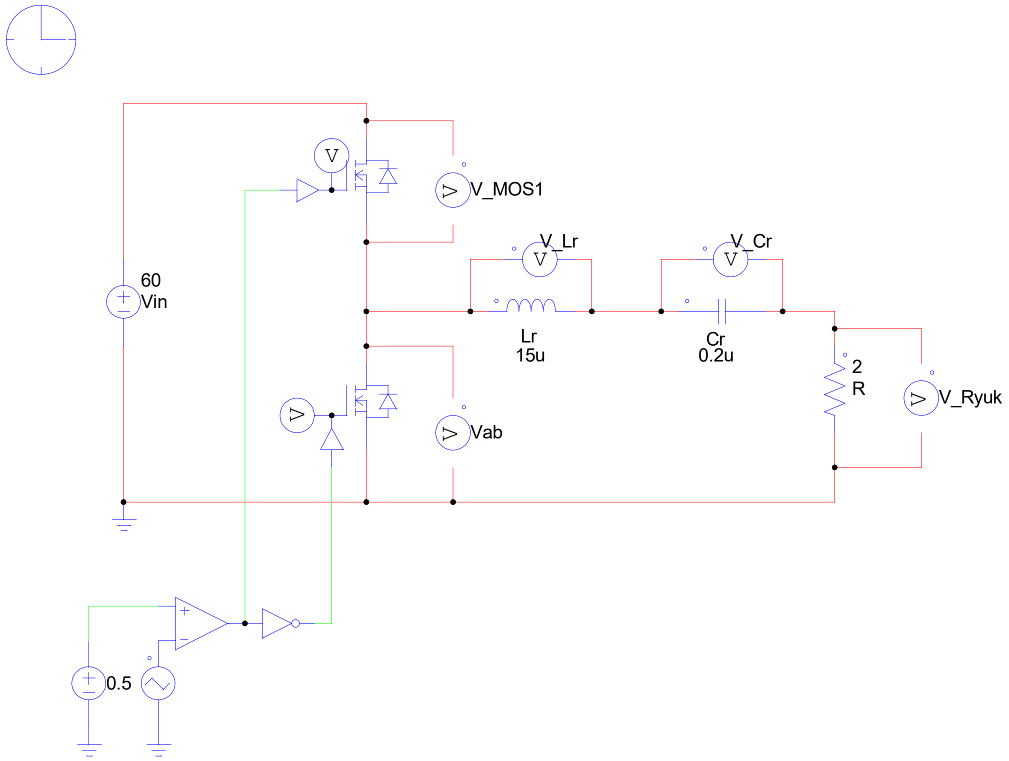

***Figure 2**. Voltage source series resonance inverter realized in PSIM*

The case where the switching frequency is below the resonant frequency ($f_s = 0.9f_r$)

$$f_r = \frac{1}{2.\pi\sqrt{L.C}} = \frac{1}{2.(3{,}14159).\sqrt{15.10^{-6}.0{,}2.10^{-6}}} = 91888{,}14924\ Hz$$

$$\omega_r = 2.\pi.f_r = 577350{,}2692\ rad/s$$

$$f_s = 0{,}9f_r = 82699{,}33432\ Hz \qquad \omega_s = 0{,}9\omega_r = 519615{,}2423\ rad/s$$

$$Q = \frac{\omega_r L}{R} = \frac{577350{,}2692.(15.10^{-6})}{2} = 4{,}33012$$

$$\theta = \arctan\left[Q\left(\frac{\omega_s}{\omega_r} - \frac{\omega_r}{\omega_s}\right)\right] = -42{,}42731° = -0{,}7404\ rad$$

$$X_L = 2.\pi.f_s.L = 7{,}79422\ \Omega$$

$$X_C = \frac{1}{2.\pi.f_s.C} = 9{,}62250\ \Omega$$

$$Z_{eq} = R + j(X_L - X_C) = 2 - j1{,}82828 \qquad Z_{eq} = 2{,}70972 \angle -42{,}42731°\ (Kap.)$$

$$V_{max} \cong 0{,}637.V_{in} = 38{,}22\ V$$

$$I_{L,max} = \frac{V_{max}}{Z_{eq}} = 14{,}10477 \angle -42{,}42731°\ A$$

$$I_{rms} \cong 0{,}707.I_{L,max} = 9{,}97207 \angle -42{,}42731°\ A$$

$$P_R = I_{rms}^2 R = 198{,}884\ VA$$

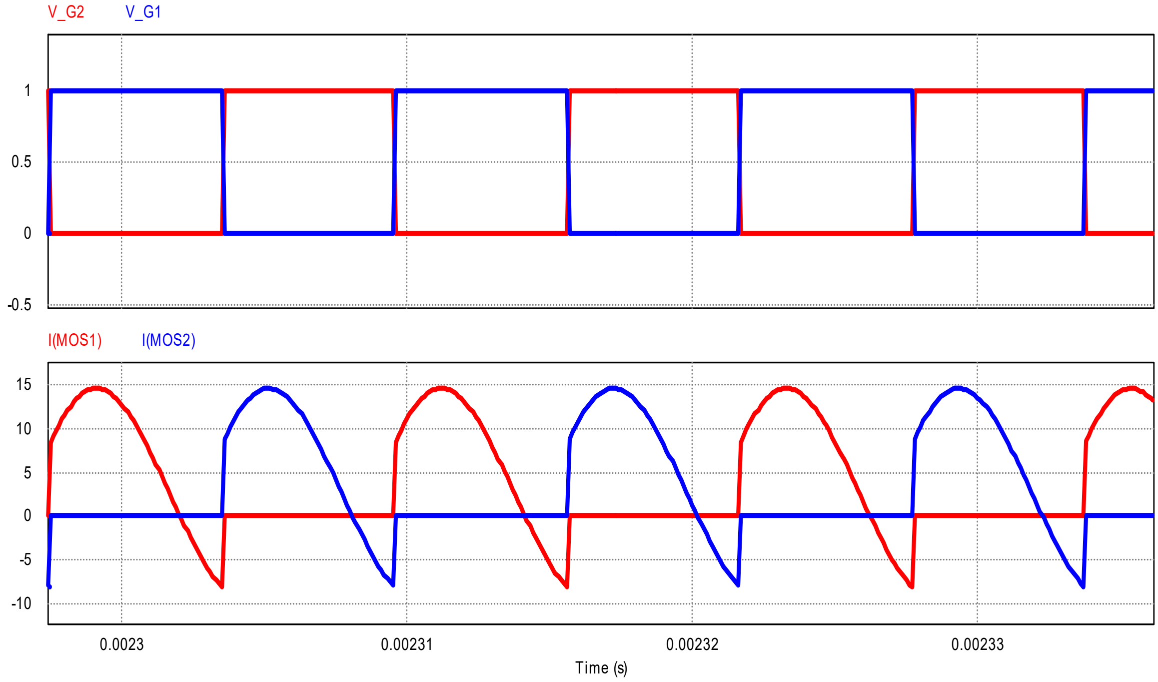

Figure 3. *Simulation results for fs = 0.9fr in a class D voltage source series resonant inverter*

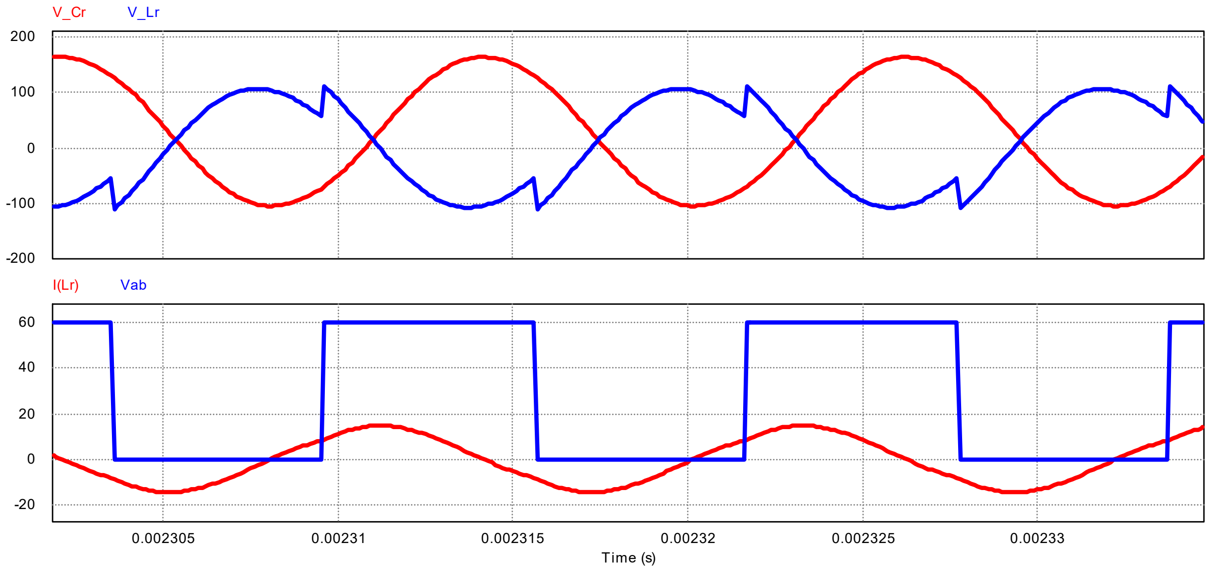

Figure 4. *Simulation results for fs = 0.9fr, voltage of the resonant coil & capacitor and Current of resonant coil & Vab.*

According the Figure 7 and Figure 8, it is seen that the voltage of the coil is at low levels. In addition, when the current passing through the MOSFETs is examined, it is seen that there are switching losses at the time of turn-on.

The case where the switching frequency is equal to the resonant frequency ($f_s = f_r$)

$$f_r = f_r = \frac{1}{2.\pi\sqrt{L.C}} = \frac{1}{2.(3{,}14159).\sqrt{15.10^{-6}.0{,}2.10^{-6}}} = 91888{,}14924\ Hz$$

$$\omega_s = \omega_r = 2.\pi.f_r = 577350{,}2692\ rad/s$$

$$X_L = 2.\pi.f_s.L = 8{,}66025\ \Omega$$

$$X_C = \frac{1}{2.\pi.f_s.C} = 8{,}66025\ \Omega$$

$$Z_{eq} = R + j(X_L - X_C) = 2\ \Omega\quad (Omik)$$

$$V_{max} \cong 0{,}637.V_{in} = 38{,}22\ V$$

$$I_{L,max} = \frac{V_{max}}{Z_{eq}} = 19.11\ A$$

$$I_{rms} \cong 0{,}707.I_{L,max} = 13{,}51077\ A$$

$$P_R = I_{rms}^2 R = 365{,}0818\ VA$$

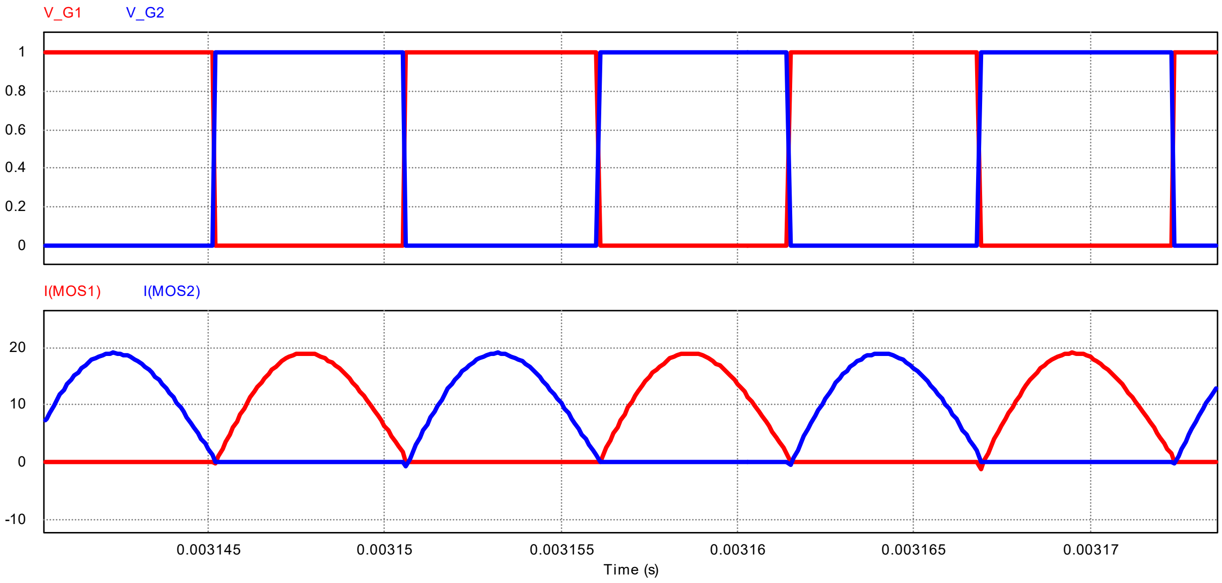

***Figure 5**. Simulation results for $fs = fr$ in a class D voltage source series resonant inverter*

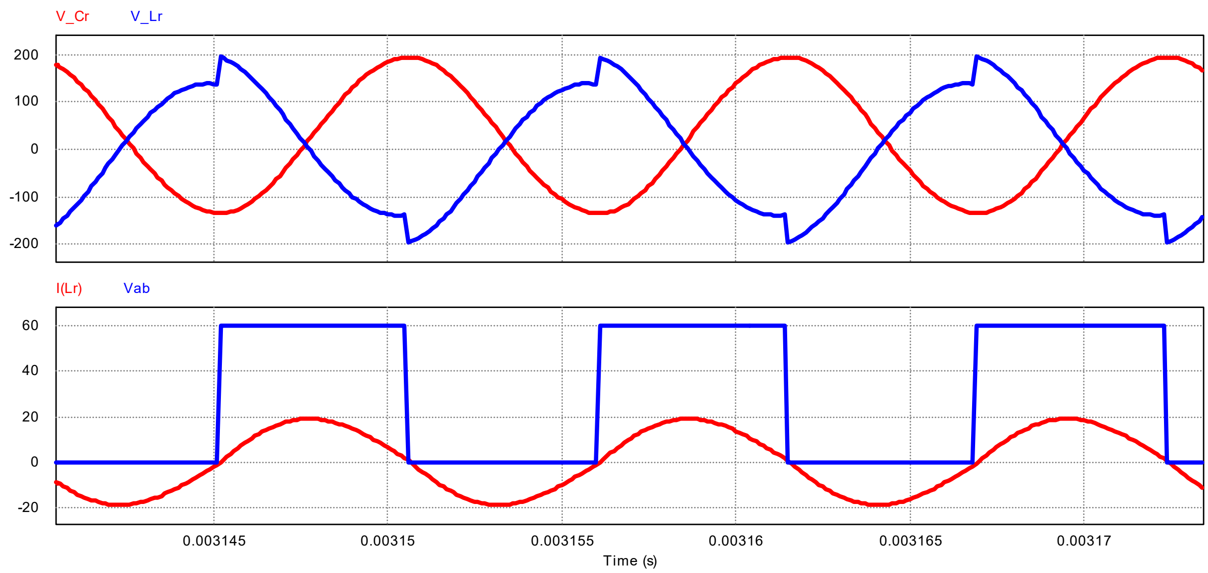

Figure 6. *Simulation results for fs = fr, voltage of the resonant coil & capacitor and Current of resonant coil & Vab.*

When looking at Figure 9 and Figure 10, it is seen that the voltage on the coil has increased. In addition, when the current passing through the coil is examined, it is observed that the switching are carried out sequentially and there is no loss.

The case where the switching frequency is abow the resonant frequency ($f_s = 1.1 f_r$)

$$f_r = \frac{1}{2.\pi\sqrt{L.C}} = \frac{1}{2.(3{,}14159).\sqrt{15.10^{-6}.0{,}2.10^{-6}}} = 91888{,}14924\ Hz$$

$$\omega_r = 2.\pi.f_r = 577350{,}2692\ rad/s$$

$$f_s = 1{,}1f_r = 101076{,}9642\ Hz \qquad \omega_s = 1{,}1\omega_r = 635085{,}2961\ rad/s$$

$$Q = \frac{\omega_r L}{R} = \frac{577350{,}2692.(15.10^{-6})}{2} = 4{,}33012$$

$$\theta = \arctan\left[Q\left(\frac{\omega_s}{\omega_r} - \frac{\omega_r}{\omega_s}\right)\right] = 41{,}0232° = 0{,}7159\ rad$$

$$X_L = 2.\pi.f_s.L = 9{,}52627\ \Omega$$

$$X_C = \frac{1}{2.\pi.f_s.C} = 7{,}87295\ \Omega$$

$$Z_{eq} = R + j(X_L - X_C) = 2 + j1{,}65332 \qquad Z_{eq} = 2{,}59489\ \angle 41{,}0232°\ (End.)$$

$$V_{max} \cong 0{,}637.V_{in} = 38{,}22\ V$$

$$I_{L,max} = \frac{V_{max}}{Z_{eq}} = 14{,}72894\ \angle 41{,}0232°\ A$$

$$I_{rms} \cong 0{,}707.I_{L,max} = 10{,}41336\ \angle 41{,}0232°\ A$$

$$P_R = I_{rms}^2 R = 216{,}876\ VA$$

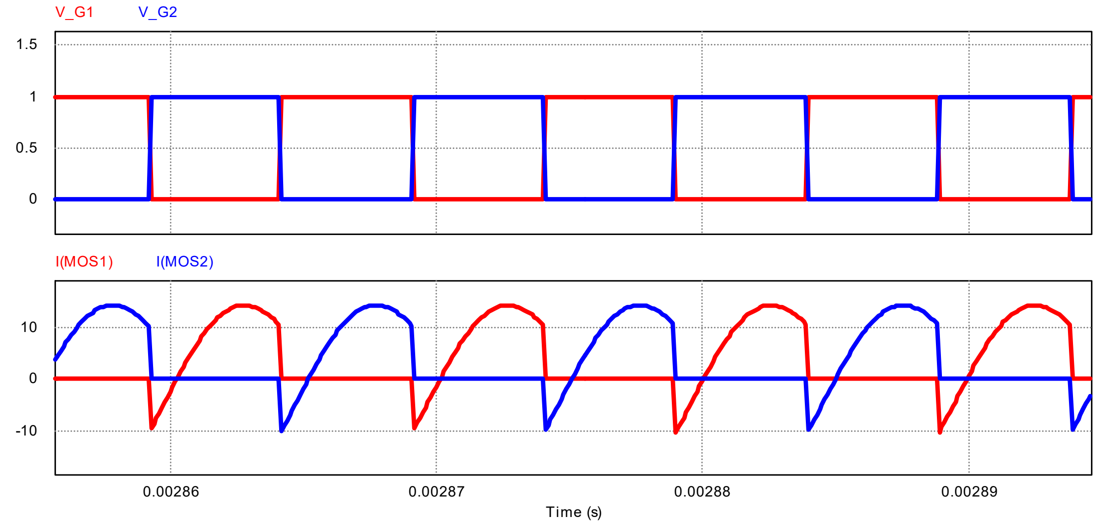

***Figure** 7. Simulation results for $fs = 1.1fr$ in a class D voltage source series resonant inverter*

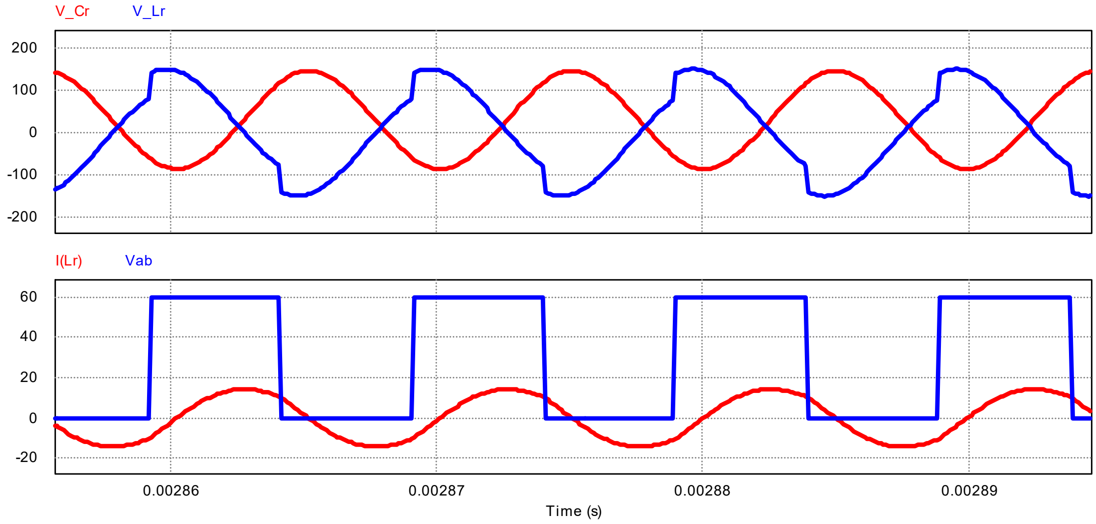

***Figure 8.** Simulation results for $fs = 1.1fr$, voltage of the resonant coil & capacitor and Current of resonant coil & Vab.*

Finally, when the Figure 11 and Figure 12 are examined, it is seen that switching losses occur at the moment when the switches are turn-off.

4. Conclusion

A voltage-fed series resonant inverters operate close to the resonant frequency to achieve maximum power transfer. In cases where the switching frequency is below the resonant frequency, since the inverter circuit will show capacitive properties, no loss occurred at the turn-off moment of the switches, but switching losses occurred at the time of turn-on. In addition, the switches are under high voltage and current, and very high currents can pass through the reverse parallel diodes. As a result, the switches may be damaged.

When the switching frequency is above the resonant frequency, since the inverter circuit will be inductive, no loss occurs at the time of turn-on, but switching losses occur at the time of turn-off. The inverter circuit is pure ohmic when the switching frequency is equal to the resonant frequency. In this case, the switches turn-on and turn-off under soft

switching conditions. Thus, no switching losses occur, only transmission losses. Therefore, maximum power transfer to the load is provided.
In this study, an inverter designed with a power of 360 VA and a resonance frequency of 91888,14924 has been analyzed for an induction system. According to the results obtained as a result of switching at the resonant frequency, it has been seen that the maximum coil current is 19 A.

As a result, the effects of switching frequency and resonance frequency on circuit operation in voltage fed series resonant inverter circuits were investigated. At the same time, it can be said that the switching frequency should be equal to the resonance frequency in order to get the best results.

REFERENCES

[1] I. Durukan, “Effects of induction heating parameters on forging billet temperature” M.S. thesis, The Grad. Sch. of Natural and Applied Sciences, Middle East Technical University, Ankara, 2007.
[2] M. K. Kazimierczuk and D. Czarkowski, “Resonant Power Converters” in Title of His Published Book, 2nd ed. New York, NY, USA: John Wiley & Sons, 2012.
[3] D. Czarkowski and M. K. Kazmierczuk, “ZVS class D series resonant inverter-discrete-time state-space simulation and experimental results” in IEEE Transactions on Circuits and Systems I: Fundamental Theory and Applications, vol. 45, no. 11, pp. 1141-1147, Nov. 1998.
[4] H. Özbay, “PDM-MPPT based solar powered induction heating system,” Eng. Sci. Technol. an Int. J., vol. 23, no. 6, pp. 1397–1414, 2020.
[5] A. Karafil, H. Ozbay, and S. Oncu, “Power control of resonant converter MPPT by pulse density modulation,” 2017 10th Int. Conf. Electr. Electron. Eng. ELECO 2017, vol. 2018-Janua, no. 1, pp. 360–364, 2018.
[6] H. E. Özden, “Yüksek Frekanslı İndüksiyon Isıtma Sistemi Tasarımı Ve Uygulaması” Yüksek Lisans Tezi, Karabük Üniversitesi Fen Bilimleri Enstitüsü, 2020.
[7] A. Dalcalı, H. Özbay, S. Öncü, “İndüksiyon Isıtmada Çalışma Frekansının Isıtma Derinliğine Etkisi” Journal of Engineering Sciences and Researches, vol. 2, no. 1, pp. 43-49, April, 2020.
[8] A. Altıntaş, M.N. Yıldız, İ. Kızılkaya, “İndüksiyon ısıtma prensibi ile çalışan mikrokontrol denetimli bir sıvı ısıtıcısı tasarımı,” Dumlupınar Üniversitesi Fen Bilimleri Enstitüsü Dergisi, vol. 29, pp. 45-52, Dec. 2012.
[9] Ü. Ünver, H.M. Ünver, “Tünel tipi indüksiyon fırını indüktörlerinde ısıtılacak parça çapının değişimine bağlı olarak sistem veriminin analizi” Journal of the Faculty of Engineering and Architecture of Gazi University, vol. 33, no. 1, pp. 155-165, Dec. 2016.
[10] S. Çetin, B.S. Sazak, “Mutfak tipi indüksiyon ısıtma cihazları için üç çıkışlı bir seri rezonans inverter uygulaması” Teknoloji, vol. 9, no. 1, pp. 7-16, 2006.
[11] S. Öncü, B.S. Sazak, “E sınıfı inverterli mutfak tipi bir indüksiyon ısıtma uygulaması” Journal of Engineering and Natural Sciences Sigma, vol. 2004, no. 2, pp. 68-73, April, 2004.
[12] S. Köroğlu, B.S. Sazak, “Mutfak uygulamaları için yarım köprü seri rezonans invertörlü indüksiyon ısıtma sistemi tasarımı” Journal of Engineering Sciences, vol. 8, no. 2, pp. 167-172, 2002.