Full-Range Regulation Method for Half-Bridge Series Resonant Converter

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ABSTRACT

The half-bridge series resonant converters (SRCs) are concerned about stepping down the output voltage to achieve a full-range regulation method. One of the best methods used to achieve a full-range regulation is a fixed on-time modulation method (FTM). The FTM's method main characteristics or features are low current stress and high efficiency. Additionally, zero voltage switching (ZVS) is used to turn-on the transistors and zero current switching (ZCS) is applied to turn-off diodes. Performance analysis is applied by using a MATLAB simulation and theoretical study to get the voltage gain curves, current stresses, and efficiency. Other alternative methods have been implemented, like frequency modulation (FM) and the asymmetrical pulse modulation method (APWM), to compared with our study the FTM method and decide which method can be the best one used in the half-bridge SRC to achieve a full-range regulation.

Keywords: Full-range Regulation, Zero Current Switching (ZCS), Zero Voltage Switching (ZVS), Half-Bridge Series Resonant Converter, Voltage Gain, Current Stress, Efficiency.

ÖZ

Yarım köprü seri rezonans dönüştürücüler (SRC's), tam aralıklı bir düzenleme yöntemi elde etmek için çıkış voltajının düşürülmesiyle ilgilenir. Tam aralıklı bir düzenleme elde etmek için kullanılan en iyi yöntemlerden biri, sabit zamanlı modülasyon yöntemidir (FTM). FTM yönteminin ana özellikleri düşük akım baskısı ve yüksek verimliliktir. Ek olarak, transistörleri açmak için sıfır voltaj anahtarlaması (ZVS) kullanılır ve diyotları kapatmak için sıfır akım anahtarlaması (ZCS) uygulanır. Performans analizi, gerilim kazanç eğrilerini, anahtar akımlarını ve verimliliği elde etmek için MATLAB simülasyonu ve teorik çalışma kullanılarak yapılmıştır. Frekans modülasyonu (FM) ve asimetrik darbe modülasyonu yöntemi (APWM) gibi diğer alternatif yöntemler, FTM yöntemi ile karşılaştırıldı ve yarım köprü SRC'de hangi yöntemin en iyi şekilde kullanılabileceğine karar vermek için çalışma yapıldı.

Anahtar Kelimeler: Tam Aralıklı Düzenleme, Sıfır Akım Anahtarlama (ZCS), Sıfır Gerilim Anahtarlama (ZVS), Yarım Köprü Serisi Rezonans Dönüştürücü, Gerilim Kazanımı, Akım Stresi, Verimlilik.

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Chapter 1

INTRODUCTION

1.1 Brief Information

In the past few years, resonant converters have gained increased popularity and are extensively utilized across diverse sectors such as servers, telecommunications, and consumer electronics. An appealing feature of these converters is their capability to easily attain high efficiency and support high-frequency operation, thanks to their inherent wide soft-switching ranges [1].

Series resonant converter is a type of converter that uses a series resonant circuit to control the input voltage and current of a power supply. It typically consists of a switching circuit, a resonant tank, a transformer, and a rectifier circuit. The resonant tank includes a resonant inductor, a resonant capacitor, and a magnetizing inductor connected in series. The transformer has a core, a primary winding, and multiple secondary windings. The converter can also include a parallel resonant circuit with a lower resonant frequency than the series resonant circuit. This parallel resonant circuit helps to obtain a DC voltage from the rectifier. The series resonant converter is designed to reduce power loss and limit the operating frequency for light loads [2], [3].

When series resonant converters run above the resonant frequency, they exhibit a number of benefits. Inherent short-circuit protection, zero-voltage commutations, restricted harmonics in the resonant current, maximum power transfer at a low

switching frequency, and the presence of transformer leakage inductance in the resonant link are all examples. However, a significant constraint develops under low-load current levels. They forfeit the soft commutation advantage in such cases, resulting in a loss of control over the output voltage [4].

A resonant converter usually comprises three major components: a switch network, a resonant tank, and a rectifier network as shown in Fig.1. The switch network creates a pulsing voltage or current from a direct current or voltage source and sends it to the next step, the resonant tank. The rectifier network, on the contrary, takes the pulsing voltage or current from the resonant tank and transforms it to a steady DC voltage or current.

The amplitude gain of the resonant tank, a two-port network comprised of capacitors and inductors, is adjusted by adjusting the frequency of the pulsing signal. In some switch and rectifier network designs, a DC blocking capacitor is required to maintain the inductor volt-second balance. This delicate balancing process is critical for avoiding transformer saturation [1].

When the converter operates at its resonant frequency, the voltage across the resonant capacitor is maximized, resulting in efficient power transfer to the load. The resonant frequency of the circuit is determined by the values of the inductor and capacitor, and can be adjusted to match the desired operating frequency of the converter. Series resonant converters are often used in applications such as high-frequency power supplies and induction heating systems [5].

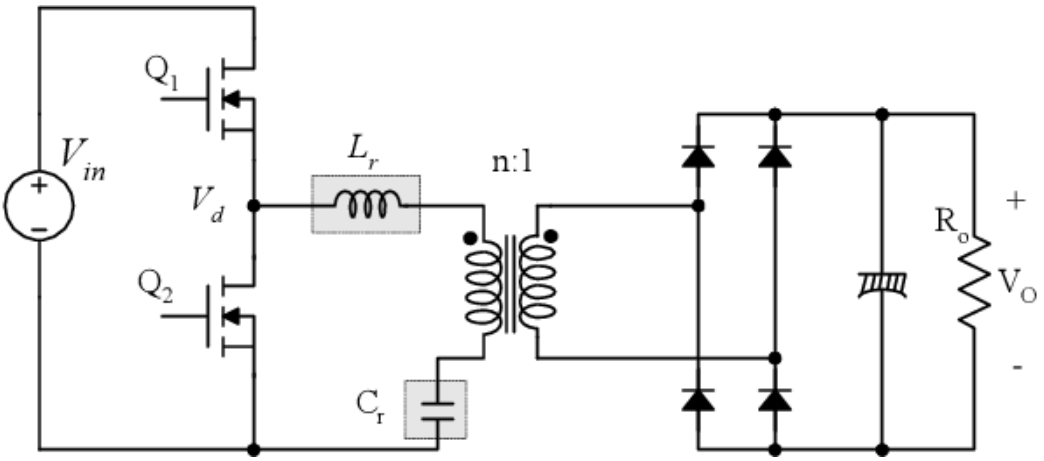


Figure 1:Half-Bridge Series Resonance Circuit

A half-bridge converter is a kind of DC-DC converter that uses a transformer to create electrical isolation and can generate an output voltage that is either greater or lower than the input voltage. Among the variety of resonant converters, the LC series resonant converter is the most popular and easiest to use. This setup places the rectifier-load network in series with the LC resonant network. Together, the load and the resonant network act as a voltage divider. The resonant network's impedance varies as the driving voltage, Vd, is changed in frequency. As a result, the reflected load and this impedance share the input voltage. Because it is a voltage divider, an LC series resonant converter's DC gain is always smaller than 1. All of the input voltage is supplied to the load in light-load situations, which occur when the load impedance is significantly higher than the resonant network's impedance. Controlling the output under little load becomes difficult as a result. In theory, an infinite frequency would be required to provide output control with no load [6].

A half-bridge series resonant converter (SRC) is a power converter topology that allows for full range regulation for all loads. It features low current stresses, zero voltage switching (ZVS) turn-on for transistors, and zero current switching (ZCS) turn-

off for diodes. The converter is designed to transfer the maximum amount of energy from the input voltage to the battery, making it suitable for applications involving battery charging in UPS [7].

The converter can operate in both full-bridge and half-bridge states, with maximized ZVS operation and minimized circulating current [8].

It achieves automatic current sharing characteristics and ZVS through the use of a magnetizing inductance of the transformer. The converter has a reduced number of switches and a small resonant capacitance, improving power density and overall efficiency. The control strategy of the converter is consistent, making it easier to regulate power flow [8].

Where ZVS is a technique used in DC/DC converters and switch power supply circuits to reduce power consumption and improve efficiency. It involves switching the power supply alternately and periodically between two primary windings or current branches, while ensuring that the voltage across the switches or power tubes is reduced to zero during the switching process [9].

ZVS circuits typically include control devices, such as detectors and logic units, to adjust the switching time and generate control pulses based on the AC voltage input. The use of resonant loads, transformers, and various types of inverters further enhances the performance of ZVS circuits. ZVS circuits are known for their simple structure, low energy consumption, and reliable function, making them suitable for a wide range of applications in integrated circuits and power supply systems.

The factors that affect the efficiency of a half bridge resonant converter include the switching frequency range, circuit design, component volumes, and the control strategy used [10].

The number of switches and the resonant capacitance also play a role in improving power density and overall efficiency [11].

Additionally, the elimination of electrolytic filter capacitors and the use of film capacitors can reduce complexity, cost, and improve efficiency.

The addition of a bidirectional switch and a fixed primary-side duty cycle can further enhance efficiency and limit voltage stress on active power components [12].

A number of factors affect resonant converter efficiency, and an important one is the control strategy used. Using frequency modulation (FM) for output power control is one such method. This method involves adjusting the switching frequency (f_s) to produce the required variations in output power. It becomes necessary to increase the switching frequency in order to reduce output power while operating above the resonance frequency (f_r) [13].

FM method has a significant impact on the performance of a series resonant converter. In the context of dual-active-bridge (DAB) converters, FM schemes are used to achieve ZVS and zero ZCS over a wide operating range, resulting in reduced conduction and switching losses [14].

Additionally, FM techniques can minimize circulating current and eliminate switching losses, leading to improved efficiency and performance [15].

Furthermore, FM methods such as generalized trajectory-switching modulation (GTSM) can enhance the transient performance of multi-phase-shift modulated DABSRC, mitigating transient oscillations and dc offsets [16].

Moreover, hybrid fixed-frequency modulation strategies have been proposed to address issues such as high switch loss, noise, and electromagnetic interference (EMI) in resonant converters, achieving lower switching loss, higher efficiency, and better ZVS characteristics [17].

Still, there are problems with this approach. EMI and switching losses both rise with the switching frequency. FM thus suffers from changing the switching frequency for output power control. Furthermore, because of the fluctuating switching frequency, the filter's design becomes more difficult to operate below the resonance frequency. Despite these shortcomings, FM has benefits like an easy-to-apply and simple structure [18].

There is the pulse-width modulation (PWM) control technique with a consistent frequency. This method controls the voltage by adjusting the dead time of the transistors. Consequently, the converters are unable to function under ZVS operation, leading to increased switching losses [19]. The PWM method affects series resonant converters by enabling them to maintain high efficiency over a wide output voltage range. PWM controlled resonant converters have the capability to boost the output voltage independently of the resonant tank components. However, they may

experience efficiency drop between two resonant points. To address this limitation, a proposed resonant converter with "sequential PWM" achieves multiple resonant points while doubling the output voltage. This converter significantly reduces turnoff loss and maximum resonant current, resulting in competitive high efficiency over a wide output voltage range [20].

The averaging method used to derive small signal models of PWM converters fails for resonant converters due to the absence of a DC component in tank currents and voltages. To overcome this, a simple and straightforward modeling technique is proposed for series resonant converters, which captures the large signal behavior and "beat frequency dynamics" of the converter [21].

This thesis will mainly focus on the fixed on-time regulation series resonance converter half- bridge. Utilizing the Frequency Regulation (FR) control approach, the converters achieve ZVS for transistor turn-on and ZCS for diode turn-off. Effective regulation across the full range is attainable through meticulous control of frequency and duty ratio. These attributes empower the converters to operate at significantly higher frequencies, facilitating their integration into microchips [19].

Fixed on-time modulation method has been proposed to improve the performance of series resonant converters (SRCs) in terms of switching loss, efficiency, and ZVS characteristics. This method is applied to a wide range of outputs based on the SRC, where asymmetrical voltage-cancellation control (AVC control) and its improved strategy (IAVC control) are used in different gain ranges. The hybrid modulation strategy achieves lower switching loss, higher efficiency, and better ZVS characteristics in wide voltage output and load ranges [22].

Additionally, fixed-frequency SRCs with phase-shift modulation have been analyzed, and three operation modes have been identified. A passive robust auxiliary circuit has been proposed to ensure ZVS in all three modes, and experimental results confirm the achievement of ZVS [23].

Therefore, the fixed on-time modulation method improves the performance of SRCs by reducing switching loss, improving efficiency, and maintaining ZVS at light load conditions.

1.2 Thesis Contribution

The main goal of this work is to thoroughly analyze the regulation mechanisms of a Half Bridge Series Resonant Converter (HB-SRC), with an emphasis on improving and expanding on the research published in the reference paper" Full-Range Regulation Method for Half-Bridge Series Resonant Converter" by Jiayi Kong, Keyue Ma Smedle, and Hong Cheng. The mathematical formulations used in the paper are carefully derived and proposed in this pursuit, providing a strong basis for the analyses that follow.

MATLAB simulations are used to reproduce the experimental findings reported in the reference paper " Full-Range Regulation Method for Half-Bridge Series Resonant Converter" by Jiayi Kong, Keyue Ma Smedle, and Hong Cheng, investigating the relationships between voltage gain, currents, and normalized frequency and duty ratio. Three different modulation techniques were examined in the investigation: FM, PWM, and FTM. By conducting a thorough analysis, the accuracy of the findings presented in the reference paper " Full-Range Regulation Method for Half-Bridge Series

Resonant Converter" by Jiayi Kong, Keyue Ma Smedle, and Hong Cheng was confirmed and also additional insights into the behavior of the system are provided.

Efficiency evaluations were a noteworthy addition to the existing results. The HB-SRC's effectiveness was thoroughly assessed under the three modulation techniques, providing insight into the general effectiveness and real-world applicability of each strategy. This extension makes the research more applicable and provides insightful information about the benefits and drawbacks of various modulation strategies.

By integrating theoretical calculations, simulation verifications, and efficiency evaluations, this thesis adds to the corpus of information already available on HB-SRCs. The results not only corroborate the conclusions of the reference paper but also expand our knowledge of the regulatory mechanisms and efficiency factors in HB-SRCs under various modulation schemes. These contributions open the door to well-informed choices when designing and implementing HB-SRCs for a range of applications.

1.3 Thesis Organization

This thesis delves deeply into the topic of Half Bridge Series Resonant Converters (HB-SRCs), an essential element in the field of power electronics. Extending and improving the theoretical framework is the main goal of the research, with a special emphasis on the mathematical formulas that serve as the foundation of the reference paper. The basis for our ensuing research and simulations is laid by this fundamental work.

In Chapter 2, the core of the theory is explored along with the complexities of HB-SRCs, and for the key mathematical formulations that are necessary to comprehend

their behavior all the formulations emphasized were on the FTM regulation method. In order to prepare the ground for the ensuing empirical analysis, this chapter attempts to establish a solid theoretical framework.

In Chapter 3, the outcomes of the MATLAB simulations are presented. It describes the simulation setup in great detail and shows and analyzes the results for voltage gain, currents, and how these depend on duty ratio and normalized frequency for every modulation technique.

The chapter also presents an efficiency analysis that clarifies the general performance of HB-SRCs under various modulation schemes. This chapter's results and discussions seek to establish links between theoretical ideas and real-world applications.

In Chapter 4, we finally present our findings and provide an explanation of the contributions of this thesis by summarizing the most important lessons learned from the simulations. We discuss the study's limitations and suggest directions for further investigation. Through reading these chapters, readers will obtain a thorough grasp of our work's theoretical foundations, empirical analyses, and wider implications in expanding the field's understanding of HB-SRCs in power electronics.

Chapter 2

THEORETICAL ANALYSIS

2.1 Full-Range Regulation Method for Series Resonant Converter

A fixed on-time modulation strategy for the half bridge SRC is presented in Article [6]. The aim is to provide a full-range regulation method in a limited switching frequency range. This FTM technique allows for using ZVS to turn-on transistors and ZCS to turn-off diodes. The control scheme, operation principle, and voltage regulation are discussed in the following sections. Furthermore, the circuit is analyzed to deduce the output voltage.

Fig. 2. shows the structure of the half-bridge SRC, which mainly consists of three different parts. Power switching, wherein S_1 and S_2 are the MOSFETs that are connected with interior antiparallel diodes. Compared to other converter designs, the SRC can operate more efficiently due the complementary actions of MOSFETs. Also, the switching performance in the practical use of MOSFETs is affected by parasitic capacitances. The resonant tank is composed of an inductor Lr and a capacitor Cr. When S_2 is turned on, the resonant tank stores energy, then stored energy is released to the output capacitor and the load when S_2 is switched off and S_1 is switched on. During SRC operation the MOSFETs switch on and off at a specific frequency, which tend to push the resonant tank to release and store energy in a resonant manner. One important characteristic of the resonant tank in the Series Resonant Converter (SRC) is resonant frequency fr, which is

$$f_r = \frac{1}{2\pi\sqrt{L_r C_r}} \tag{1}$$

Moreover, the SRC also comprises power diodes $D_{1\text{-}4}$. Switching off or on of the MOSFETs allows these diodes to provide the path for flowing of energy. The output capacitor C_0 is expected to be sufficiently large to keep the output voltage stable with minimal fluctuation.

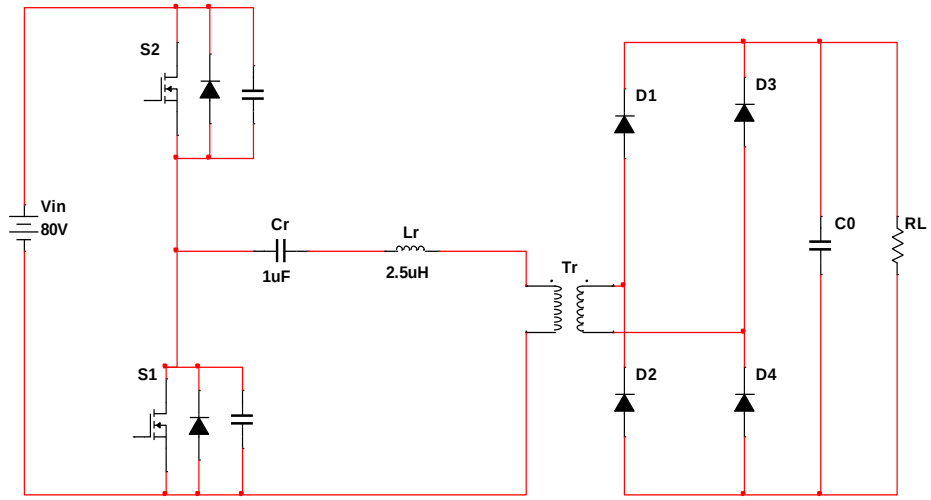


Figure 2: Schematic Diagram of the Half Bridge SRC

.

The FTM method involves a constant turn-on time for the transistor S_1, defined as

$$t_{on} = \frac{1}{2f_r} \tag{2}$$

Fig. 3 shows the control scheme employed by the FTM method. By using equation (2), d_1 that refers to the duty cycle of transistor S_1 can be calculated as

$$d_1 = \frac{F}{2} \tag{3}$$

where the normalized frequency (F) given by

$$F = \frac{f_s}{f_r} \tag{4}$$

In (4), f_s represents the switching frequency of the SRC.

The duty cycle of transistor S_2 is defined as

$$d_2 = 1 - d_1 \tag{5}$$

$$d_2 = 1 - \frac{F}{2} \tag{6}$$

Which varies from 0.5 to 0 as the F increases from 1 to 2.

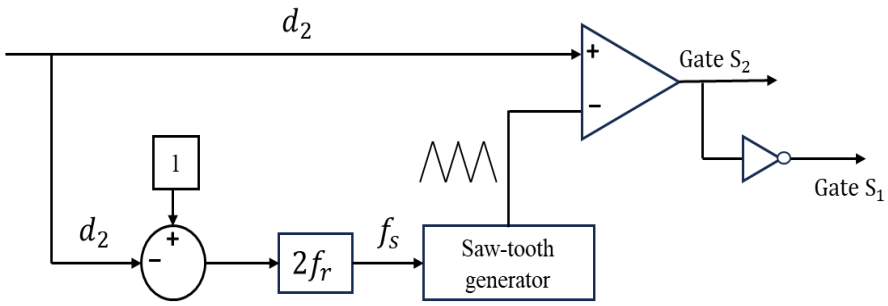


Figure 3: FTM Control Scheme

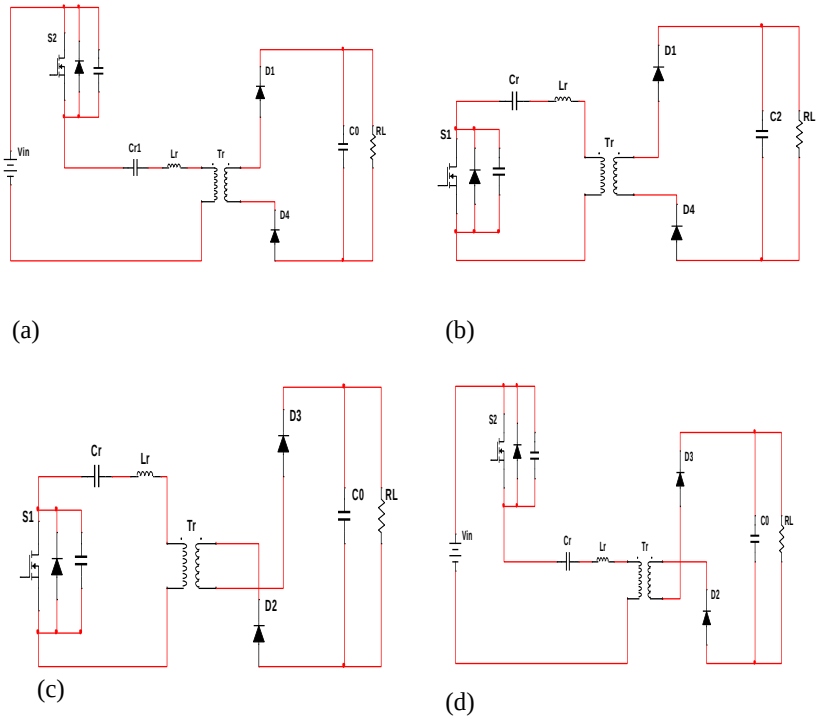


Figure 4: Half Bridge SRC Switching States. (a) State 1 [t0-t1]. (b) State 2 [t1-t3]. (c) State 3 [t3-t4]. (d) State 4 [t4-t6].

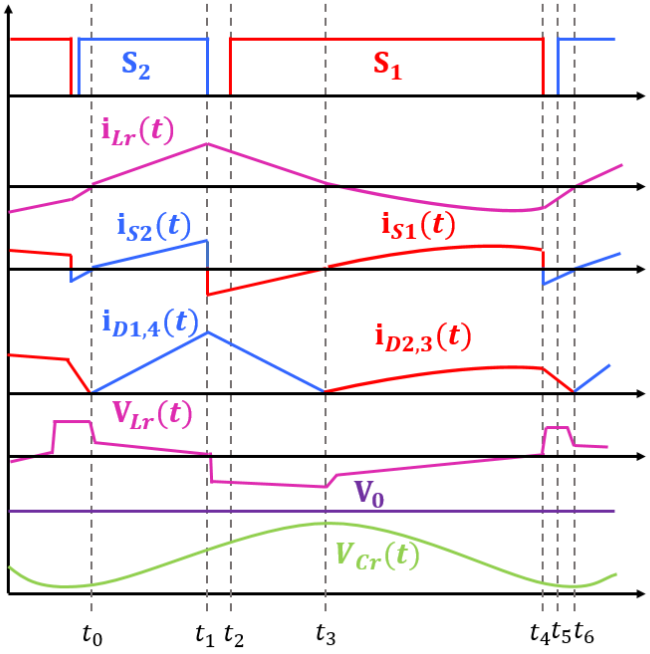


Figure 5: Waveforms of Operation of the Half-Bridge SRC [13].

Fig. 4. shows the four switching states of the half-bridge series resonant circuit, and their waveforms of operation can be seen in Fig. 5.

2.1.1 State 1[t_0-t_1]

In state 1 [t_0-t_1], as shown in Fig. 4(a), transistor S_2 is turned on. The resonant current of the inductor $i_{Lr}(t)$ starts to increase at t_0 and gradually increases until t_1, whereas, the resonant capacitor voltage $V_{Cr}(t)$ gradually decreases to reach its minimum value, V_{Crmin}. In the rectifier, the power diodes D_2 and D_3 turn off under ZCS, and the power diodes D_1 and D_4 start conducting, as shown in Fig. 4(a). According to Fig. 5, transistor S_2 turns off at t_1, where there is a small-time interval between t_1 and t_2 called the deadtime to prevent the danger of having the two transistor switches (S_1, S_2) turn on at the same time. At t_0, there are initial conditions that can be used to find the resonant inductor current equation and the resonant capacitor equation. They are $i_{Lr}(t_0) = 0$ and $V_{Cr}(t_0) = V_{Crmin}$. The equations can be derived as follows.

In the range between [t_0, t_1]:

The switch is closed at $t < t_0$

Starting with the balance of voltages in the resonant circuit.

$$V_{Lr} + V_{Cr} = 0$$

$$L_r \frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt = 0$$

Taking the derivative of this equation gives

$$\frac{d}{dt}\left(L_r \frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt\right) = 0$$

$$L_r \frac{di_{lr}^2(t)}{d^2t} + \frac{1}{C_r} i_{lr}(t) = \quad (7)$$

Substitute $\mathbf{i_{lr}(t)} = Ke^{st}$ in equation (7)

$$L_r \frac{d^2}{dt^2}(Ke^{st}) + \frac{1}{C_r}(Ke^{st}) = 0$$

$$s^2 Ke^{st} + \frac{1}{L_r C_r}(Ke^{st}) = 0$$

$$Ke^{st}\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$s^2 = -\frac{1}{L_r C_r}$$

$$s = \pm j\sqrt{\frac{1}{L_r C_r}}$$

$$\text{Let } w_r = \sqrt{\frac{1}{L_r C_r}}$$

$$s = \pm jw_r$$

$$i_{lr}(t) = K_1 e^{jw_r t} + K_2 e^{-jw_r t}$$

Then write the exponential form in a trigonometric form

$$i_{lr}(t) = K_1(\cos(w_r t) + j\sin(w_r t)) + K_2(\cos(w_r t) - j\sin(w_r t))$$

$$i_{lr}(t) = (K_1 + K_2)\cos(w_r t) + j(K_1 - K_2)\sin(w_r t)$$

$$\text{Let } A_1 = K_1 + K_2 \text{ and } A_2 = j(K_1 - K_2)$$

$$i_{lr}(t) = A_1\cos(w_r t) + A_2\sin(w_r t)$$

Now we need to find A_1 and A_2 at initial condition at t_0.

$$V_{cr}(t_0) = V_{cr_{min}}$$

$$i_{lr}(t_0) = A_1\cos(w_r t_0) + A_2\sin(w_r t_0)$$

$$0 = A_1\cos(w_r t_0) + A_2\sin(w_r t_0)$$

$$V_{lr}(t_0) = L_r\frac{di_{lr}(t_0)}{dt}$$

$$A_1 = -\frac{A_2\sin(w_r t_0)}{\cos(w_r t_0)} \quad (8)$$

$$\frac{di_{lr}(t_0)}{dt} = \frac{V_{lr}(t_0)}{L_r}$$

Where $V_{lr}(t_0) = V_{in} - V_{cr_{min}} - nV_0$

$$\text{But } \frac{di_{lr}(t_0)}{dt} = -A_1 w_r\sin(w_r t_0) + A_2 w_r\cos(w_r t_0)$$

$$\frac{1}{L_r}V_{lr}(t_0) = -A_1 w_r\sin(w_r t_0) + A_2 w_r\cos(w_r t_0)$$

$$A_1 = \frac{-\frac{1}{L_r}V_{lr}(t_0) + A_2 w_r\cos(w_r t_0)}{w_r\sin(w_r t_0)} \quad (9)$$

Take equation (8) equal to equation (9), then we can find A_2

$$-\frac{A_2\sin(w_r t_0)}{\cos(w_r t_0)} = \frac{-\frac{1}{L_r}V_{lr}(t_0) + A_2 w_r\cos(w_r t_0)}{w_r\sin(w_r t_0)}$$

$$-A_2 w_r\ \sin^2(w_r t_0) = -\frac{1}{L_r}V_{lr}(t_0)\cos(w_r t_0) + A_2 w_r\cos^2(w_r t_0)$$

$$A_2 w_r\cos^2(w_r t_0) + A_2 w_r\ \sin^2(w_r t_0) = \frac{1}{L_r}V_{lr}(t_0)\cos(w_r t_0)$$

$$A_2 w_r[\cos^2(w_r t_0) + \sin^2(w_r t_0)] = \frac{1}{L_r} V_{lr}(t_0)\cos(w_r t_0)$$

$$A_2 w_r[1] = \frac{1}{L_r} V_{lr}(t_0)\cos(w_r t_0)$$

$$A_2 = \frac{\frac{1}{L_r} V_{Lr}(t_0)\cos(w_r t_0)}{w_r}$$

Substitute A_2 in equation (8) to find A_1

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_0)\cos(w_r t_0)}{w_r} \times \frac{\sin(w_r t_0)}{\cos(w_r t_0)}$$

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_0)\sin(w_r t_0)}{w_r}$$

$$i_{lr}(t) = -\frac{\frac{1}{L_r} V_{lr}(t_0)\sin(w_r t_0)}{w_r}\cos(w_r t) + \frac{\frac{1}{L_r} V_{lr}(t_0)\cos(w_r t_0)}{w_r}\sin(w_r t)$$

$$i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_0)}{w_r}[-\cos(w_r t)\sin(w_r t_0) + \cos(w_r t_0)\sin(w_r t)]$$

Using the following trigonometric identity

$$\sin A\cos B - \cos A\sin B = \sin(A - B)$$

Then the resonant inductor current equation become

$$i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_0)}{w_r}[\sin(w_r t - w_r t_0)]$$

Kirchhoff's Voltage Law (KVL) must be applied the primary side of the transformer to find $V_{Lr}(t_0)$, which mean the algebraic sum of the voltage drops and rises in a closed loop is zero.

$$w_r = \sqrt{\frac{1}{L_r C_r}} \qquad \text{and} \quad V_{lr}(t_0) = V_{in} - V_{cr_{min}} - nV_0$$

We get

$$i_{lr}(t) = \frac{1}{L_r} \times \frac{V_{in} - V_{cr_{min}} - nV_0}{\sqrt{\frac{1}{L_r C_r}}} \sin(w_r(t - t_0))$$

$$i_{lr}(t) = \frac{V_{in} - V_{cr_{min}} - nV_0}{\sqrt{\frac{L_r^2}{L_r C_r}}} \sin(w_r(t - t_0) \qquad \text{but} \quad w_r = 2\pi f_r$$

Then the resonant inductor current equation is:

$$i_{lr}(t) = (V_{in} - V_{cr_{min}} - nV_0)\sqrt{\frac{C_r}{L_r}} \sin 2\pi f_r(t - t_0) \tag{10}$$

KVL around the inverter-side loop

$$V_{cr} + V_{lr} + nV_0 - V_{in} = 0$$

$$V_{cr} = V_{in} - V_{lr} - nV_0$$

$$\text{but } V_{lr} = L_r \frac{di_{lr}(t)}{dt}$$

Derivative of resonant current equation at t in the first state

$$\frac{di_{lr}(t)}{dt} = (V_{in} - V_{cr_{min}} - nV_0)\sqrt{\frac{C_r}{L_r}} 2\pi f_r \cos 2\pi f_r\,(t - t_0)$$

$$\text{but } w_r = 2\pi f_r = \sqrt{\frac{1}{L_r C_r}}$$

$$V_{cr}(t) = V_{in} - nV_0 - L_r[(V_{in} - V_{cr_{min}} - nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{1}{L_r C_r}} \cos 2\pi f_r\,(t - t_0)$$

$$V_{cr}(t) = V_{in} - nV_0 - (V_{in} - V_{cr_{min}} - nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{L_r^2}{L_r C_r}} \cos 2\pi f_r\,(t - t_0)$$

Then the resonant capacitor voltage of the first state is:

$$V_{cr}(t) = V_{in} - nV_0 - (V_{in} - V_{cr_{min}} - nV_0) \cos 2\pi f_r\,(t - t_0) \tag{11}$$

Where n is the turn ratio of transformer and its *1:2.1*.

2.1.2 State 2 [t_1-t_3]

In Fig.5 the second switching state occurs between t_1 and t_3. The resonant inductor current i_{Lr} (*t*) gradually decreases starting at t_1, and it becomes zero at t_3. Also, according to Fig. 4(b), transistor S_2 is switched off, which lets the internal antiparallel diode of S_1 start conducting current. After a very short time at t_2, transistor S_1 turns on under ZVS. Furthermore, the voltage of the resonant capacitor reaches its maximum value V_{Crmax}. The boundary conditions can be considered at t_3 from Fig. 5, which help to derive the equations of the resonant current and voltage: $i_{Lr}(t_3) = 0$, $V_{Cr\,(t3)} = V_{Crmax}$. The equations are derived as follows.

In the range between [t_1, t_3]:

$$V_{Lr} + V_{Cr} = 0$$

$$L_r \frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt = 0$$

Taking the derivative of this equation gives

$$\frac{d}{dt}\left(L_r \frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt\right) = 0$$

$$L_r \frac{di_{lr}^2(t)}{dt^2} + \frac{1}{C_r} i_{lr}(t) = 0 \qquad (12)$$

Substitute $\mathbf{i_{lr}(t)} = Ke^{st}$ in equation (12)

$$L_r \frac{d^2}{dt^2}(Ke^{st}) + \frac{1}{C_r}(Ke^{st}) = 0$$

$$s^2 Ke^{st} + \frac{1}{L_r C_r}(Ke^{st}) = 0$$

$$Ke^{st}\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$s^2 = -\frac{1}{L_r C_r}$$

$$s = \pm j\sqrt{\frac{1}{L_r C_r}}$$

$$\text{Let } w_r = \sqrt{\frac{1}{L_r C_r}}$$

$$s = \pm jw_r$$

$$i_{lr}(t) = K_1 e^{jw_r t} + K_2 e^{-jw_r t}$$

Then write the exponential form in a trigonometric form

$$i_{lr}(t) = K_1(\cos(w_r t) + j\sin(w_r t)) + K_2(\cos(w_r t) - j\sin(w_r t))$$

$$i_{lr}(t) = (K_1 + K_2)\cos(w_r t) + j(K_1 - K_2)\sin(w_r t)$$

$$\text{Let } A_1 = K_1 + K_2 \text{ and } A_2 = j(K_1 - K_2)$$

$$i_{lr}(t) = A_1\cos(w_r t) + A_2\sin(w_r t)$$

Now we need to find A_1 and A_2 at initial condition at t_3.

$$i_{lr}(t_3) = 0$$

$$V_{cr}(t_3) = V_{cr_{max}}$$

$$i_{lr}(t_3) = A_1\cos(w_r t_3) + A_2\sin(w_r t_3)$$

$$0 = A_1\cos(w_r t_3) + A_2\sin(w_r t_3)$$

$$A_1 = -\frac{A_2\sin(w_r t_3)}{\cos(w_r t_3)} \qquad (13)$$

$$\text{Now } V_{lr}(t_3) = L_r\frac{di_{lr}(t_3)}{d_t}$$

$$\frac{di_{lr}(t_3)}{dt} = \frac{V_{lr}(t_3)}{L_r}$$

$$\text{Where } V_{lr}(t_3) = -V_{cr_{max}} - nV_0$$

$$\text{But } \frac{di_{lr}(t_3)}{dt} = -A_1 w_r\sin(w_r t_3) + A_2 w_r\cos(w_r t_3)$$

$$\frac{1}{L_r}V_{lr}(t_3) = -A_1 w_r \sin(w_r t_3) + A_2 w_r \cos(w_r t_3)$$

$$A_1 = \frac{-\frac{1}{L_r}V_{lr}(t_3) + A_2 w_r \cos(w_r t_3)}{w_r \sin(w_r t_3)} \tag{14}$$

Take equation (13) equal to equation to equation (14), then we can find A_2

$$-\frac{A_2 \sin(w_r t_3)}{\cos(w_r t_3)} = \frac{-\frac{1}{L_r}V_{lr}(t_3) + A_2 w_r \cos(w_r t_3)}{w_r \sin(w_r t_3)}$$

$$-A_2 w_r \ \sin^2(w_r t_3) = -\frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3) + A_2 w_r \cos^2(w_r t_3)$$

$$A_2 w_r \cos^2(w_r t_3) + A_2 w_r \ \sin^2(w_r t_3) = \frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3)$$

$$A_2 w_r[\cos^2(w_r t_3) + \ \sin^2(w_r t_3)] = \frac{1}{L_r}V_{lr(t_3)}\cos(w_r t_3)$$

$$A_2 w_r[1] = \frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3)$$

$$A_2 = \frac{\frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3)}{w_r}$$

Substitute A_2 in equation (13) to find A_1

$$A_1 = -\frac{\frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3)}{w_r} \times \frac{\sin(w_r t_3)}{\cos(w_r t_3)}$$

$$A_1 = -\frac{\frac{1}{L_r}V_{lr}(t_3)\sin(w_r t_3)}{w_r}$$

$$i_{lr}(t) = -\frac{\frac{1}{L_r}V_{lr}(t_3)\sin(w_r t_3)}{w_r}\cos(w_r t) + \frac{\frac{1}{L_r}V_{lr}(t_3)\cos(w_r t_3)}{w_r}\sin(w_r t)$$

$$i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_3)}{w_r}[-\cos(w_r t)\sin(w_r t_3) + \cos(w_r t_3)\sin(w_r t)]$$

$$\sin A \cos B - \cos A \sin B = \sin(A - B)$$

By using the following trigonometric identity, we can find that

$$i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_3)}{w_r}[\sin(w_r t - w_r t_3)]$$

$$\text{Using } w_r = \sqrt{\frac{1}{L_r C_r}} \qquad \text{and} \qquad V_{lr}(t_3) = -(V_{cr_{max}} + nV_0)$$

$$i_{lr}(t) = \frac{1}{L_r} \times \frac{-(V_{cr_{max}} + nV_0)}{\sqrt{\frac{1}{L_r C_r}}} \sin(w_r(t - t_3)$$

$$i_{lr(t)=} \frac{-(V_{cr_{max}} + nV_0)}{\sqrt{\frac{L_r^2}{L_r C_r}}} \sin(w_r(t - t_3)$$

$$\text{but } w_r = 2\pi f_r$$

Then the resonant inductor current of state 2 is

$$i_{lr}(t) = -\left(V_{cr_{max}} + nV_0\right)\sqrt{\frac{C_r}{L_r}} \sin 2\pi f_r(t - t_3) \tag{15}$$

To find the voltage of resonant capacitor, KVL around the in the interval side must be applied then

$$V_{cr} + V_{lr} + nV_0 = 0$$

$$V_{cr} = -(V_{lr} + nV_0)$$

$$\text{but } V_{lr} = L_r \frac{di_{lr}(t)}{dt}$$

$$\frac{di_{lr}(t)}{dt} = -(V_{cr_{max}} + nV_0)\sqrt{\frac{C_r}{L_r}} 2\pi f_r \cos 2\pi f_r\,(t - t_3)$$

$$\text{but } w_r = 2\pi f_r = \sqrt{\frac{1}{L_r C_r}}$$

$$V_{cr}(t) = -nV_0 + L_r[(V_{cr_{max}} + nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{1}{L_r C_r}} \cos 2\pi f_r\,(t - t_3)]$$

$$V_{cr}(t) = -nV_0 + (V_{cr_{max}} + nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{L_r^2}{L_r C_r}} \cos 2\pi f_r\,(t - t_3)$$

The resonant capacitor voltage equation of state 2 is:

$$V_{cr}(t) = -nV_0 + \left(V_{cr_{max}} + nV_0\right)\cos 2\pi f_r\,(t - t_3) \tag{16}$$

2.1.3 State 3 [t_3-t_4]

From t_3 to t_4, depicted in Fig. 5. during this period, the resonant current reverses and swings until S_1 turns off. where both i_{Lr} (t) and V_{Cr} (t) are decreasing. Related to Fig.4(c), power diodes D_1 and D_4 turn off under ZCS operation, whereas power diodes D_2 and D_3 turn on at t_3. Based on Fig. 5, at this period the boundary condition can be used to get the resonant voltage and current are i_{Lr} (t_3) = 0 and V_{Cr} (t_3) = V_{Crmax}. Derivations of equations for resonant inductor current and capacitor voltage are as follows.

In the range between [t_3, t_4]

$$V_{Lr} + V_{Cr} = 0$$

$$L_r\frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt = 0$$

Taking the derivative of this equation gives

$$\frac{d}{dt}\left(L_r\frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt\right) = 0$$

$$L_r\frac{di_{i_{lr}}^2(t)}{dt^2} + \frac{1}{C_r}i_{lr}(t) = 0 \tag{17}$$

Let $i_{lr}(t) = Ke^{st}$ and substitute it in equation (17)

$$L_r\frac{d^2}{dt^2}(Ke^{st}) + \frac{1}{C_r}(Ke^{st}) = 0$$

$$s^2Ke^{st} + \frac{1}{L_rC_r}(Ke^{st}) = 0$$

$$Ke^{st}\left(s^2 + \frac{1}{L_rC_r}\right) = 0$$

$$\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$s^2 = -\frac{1}{L_r C_r}$$

$$s = \pm j\sqrt{\frac{1}{L_r C_r}}$$

$$\text{Let } w_r = \sqrt{\frac{1}{L_r C_r}}$$

$$s = \pm j w_r$$

$$i_{lr}(t) = K_1 e^{j w_r t} + K_2 e^{-j w_r t}$$

Then write the exponential form in a trigonometric form

$$i_{lr}(t) = K_1(\cos(w_r t) + j\sin(w_r t)) + K_2(\cos(w_r t) - j\sin(w_r t))$$

$$i_{lr}(t) = (K_1 + K_2)\cos(w_r t) + j(K_1 - K_2)\sin(w_r t)$$

$$\text{Let } A_1 = K_1 + K_2 \text{ and } A_2 = j(K_1 - K_2)$$

$$i_{lr}(t) = A_1 \cos(w_r t) + A_2 \sin(w_r t)$$

Now we need to find to find A_1 and A_2, using initial condition at t_3:

$$i_{lr}(t_3) = 0$$

$$V_{cr}(t_3) = V_{cr_{max}}$$

$$i_{lr}(t_3) = A_1 \cos(w_r t_3) + A_2 \sin(w_r t_3)$$

$$0 = A_1 \cos(w_r t_3) + A_2 \sin(w_r t_3)$$

$$A_1 = -\frac{A_2 \sin(w_r t_3)}{\cos(w_r t_3)} \tag{18}$$

$$\text{Now } V_{lr}(t_3) = L_r \frac{di_{lr}(t_3)}{dt}$$

$$\frac{di_{lr}(t_3)}{dt} = \frac{V_{lr}(t_3)}{L_r}$$

$$\text{Where } V_{lr(t_3)} = -V_{cr_{max}} + nV_0$$

$$\text{but } \frac{di_{lr}(t_3)}{dt} = -A_1 w_r \sin(w_r t_3) + A_2 w_r \cos(w_r t_3)$$

$$\frac{1}{L_r} V_{lr}(t_3) = -A_1 w_r \sin(w_r t_3) + A_2 w_r \cos(w_r t_3)$$

$$A_1 = \frac{-\frac{1}{L_r} V_{lr}(t_3) + A_2 w_r \cos(w_r t_3)}{w_r \sin(w_r t_3)} \tag{19}$$

Take equation (18) equal to equation (19), to find the value of A_2

$$-\frac{A_2 \sin(w_r t_3)}{\cos(w_r t_3)} = \frac{-\frac{1}{L_r} V_{lr}(t_3) + A_2 w_r \cos(w_r t_3)}{w_r \sin(w_r t_3)}$$

$$-A_2 w_r \sin^2(w_r t_3) = -\frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3) + A_2 w_r \cos^2(w_r t_3)$$

$$A_2 w_r \cos^2(w_r t_3) + A_2 w_r \sin^2(w_r t_3) = \frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)$$

$$A_2 w_r [\cos^2(w_r t_3) + \sin^2(w_r t_3)] = \frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)$$

$$A_2 w_r [1] = \frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)$$

$$A_2 = \frac{\frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)}{w_r}$$

$$\text{where } A_1 = -\frac{A_2 \sin(w_r t_3)}{\cos(w_r t_3)} \text{ from equation(18)}$$

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)}{w_r} \times \frac{A_2 \sin(w_r t_3)}{\cos(w_r t_3)}$$

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_3) \sin(w_r t_3)}{w_r}$$

Then substitute the value of A_1 and A_2 in the resonant inductor current equation

$$i_{lr}(t) = -\frac{\frac{1}{L_r} V_{lr}(t_3) \sin(w_r t_3)}{w_r} \cos(w_r t) + \frac{\frac{1}{L_r} V_{lr}(t_3) \cos(w_r t_3)}{w_r} \sin(w_r t)$$

$$i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_3)}{w_r}[-\cos(w_r t)\sin(w_r t_3) + \cos(w_r t_3)\sin(w_r t)]$$

Using the trigonometric form equation that mentioned below to simplify the resonant inductor current equation

$$\sin A\cos B - \cos A\sin B = \sin(A - B)$$

$$\text{then } i_{lr}(t) = \frac{1}{L_r}\frac{V_{lr}(t_3)}{w_r}[\sin(w_r t - w_r t_3)]$$

$$but\ w_r = \sqrt{\frac{1}{L_r C_r}}\ and\ V_{lr(t_3)} = -V_{cr_{max}} + nV_0$$

$$i_{lr}(t) = \frac{1}{L_r} \times \frac{-(V_{cr_{max}} - nV_0)}{\sqrt{\frac{1}{L_r C_r}}}\sin(w_r(t - t_3)$$

$$i_{lr}(t) = \frac{-(V_{cr_{max}} - nV_0)}{\sqrt{\frac{L_r^2}{L_r C_r}}}\sin(w_r(t - t_3) \quad \text{but } w_r = 2\pi f_r$$

Then the resonant inductor current of state 3 is:

$$\Rightarrow \quad i_{lr}(t) = -(V_{cr_{max}} - nV_0)\sqrt{\frac{C_r}{L_r}}\sin 2\pi f_r(t - t_3) \tag{20}$$

Apply a KVL in the primary side of the transformer to find the resonant capacitor voltage at t

$$V_{cr} + V_{lr} - nV_0 = 0$$

$$V_{cr} = -V_{lr} + nV_0$$

$$\text{but } V_{lr} = L_r\frac{di_{lr}(t)}{dt}$$

Derivative of the resonant inductor current at state 3 is

$$\frac{di_{lr}(t)}{dt} = -(V_{cr_{max}} - nV_0)\sqrt{\frac{C_r}{L_r}}2\pi f_r\cos 2\pi f_r\,(t - t_3)$$

$$\text{but } w_r = 2\pi f_r = \sqrt{\frac{1}{L_r C_r}}$$

$$V_{cr}(t) = nV_0 - L_r[-(V_{cr_{max}} - nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{1}{L_r C_r}}\cos 2\pi f_r\,(t - t_3)]$$

$$V_{cr}(t) = nV_0 + (V_{cr_{max}} - nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{L_r^2}{L_r C_r}}\cos 2\pi f_r\,(t - t_3)$$

Then the resonant capacitor voltage equation at state 3 is:

$$\Rightarrow V_{cr}(t) = nV_0 + \left(V_{cr_{max}} - nV_0\right)\cos 2\pi f_r\,(t - t_3) \quad (21)$$

2.1.4 State 4 [t_4-t_6]

Finally, the last switching state, shown in Fig. 4(d), occurs in the intervals of t_4 and t_6. Transistor S_1 turns off, and the $i_{Lr}(t)$ starts gradually increasing since the internal antiparallel diode of S_2 starts conducting. After a few times at t5, the S_2 transistor switches on with ZVS operation, while the voltage of the resonant capacitor $V_{Cr}(t)$ still decreases and reaches zero at t_6. After that, the period will finish, and another period will begin in the same process. The boundary condition that will be considered will be taken at t_6. Where $i_{Lr}(t_6) = 0$ and $V_{Cr}(t_6) = V_{Crmin}$, it will be helpful to obtain the equations of resonant current and voltage as

In the range between [t_4, t_6]

$$V_{Lr} + V_{Cr} = 0$$

$$L_r\frac{di_{lr}(t)}{dt} + \frac{1}{C_r}\int i_{lr}(t)dt = 0$$

Taking the derivative of this equation gives

$$\frac{d}{dt}\left(L_r\frac{di_{lr}(t)}{d_t} + \frac{1}{C_r}\int i_{lr}(t)dt\right) = 0$$

$$L_r \frac{di_{i_{Lr}}^2(t)}{dt^2} + \frac{1}{C_r} i_{lr}(t) = 0 \quad (22)$$

Let $i_{lr}(t) = Ke^{st}$ and substitute it in equation (22)

$$L_r \frac{d^2}{dt^2}(Ke^{st}) + \frac{1}{C_r}(Ke^{st}) = 0$$

$$s^2 Ke^{st} + \frac{1}{L_r C_r}(Ke^{st}) = 0$$

$$Ke^{st}\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$\left(s^2 + \frac{1}{L_r C_r}\right) = 0$$

$$s^2 = -\frac{1}{L_r C_r}$$

$$s = \pm j\sqrt{\frac{1}{L_r C_r}}$$

$$\text{Let } w_r = \sqrt{\frac{1}{L_r C_r}}$$

$$s = \pm j w_r$$

According to differential equation, it can be written in an exponential form, then

$$i_{lr}(t) = K_1 e^{j w_r t} + K_2 e^{-j w_r t}$$

Then write the exponential form in a trigonometric form

$$i_{lr}(t) = K_1(\cos(w_r t) + j\sin(w_r t)) + K_2(\cos(w_r t) - j\sin(w_r t))$$

$$i_{lr}(t) = (K_1 + K_2)\cos(w_r t) + j(K_1 - K_2)\sin(w_r t)$$

$$\text{Let } A_1 = K_1 + K_2 \text{ and } A_2 = j(K_1 - K_2)$$

$$i_{lr}(t) = A_1 \cos(w_r t) + A_2 \sin(w_r t)$$

We need to find A_1 and A_2, initial condition at t_6 is:

$$i_{lr}(t_6) = 0$$

$$V_{cr}(t_6) = V_{cr_{min}}$$

$$i_{lr}(t_6) = A_1 \cos(w_r t_6) + A_2 \sin(w_r t_6)$$

$$0 = A_1 \cos(w_r t_6) + A_2 \sin(w_r t_6)$$

$$A_1 = -\frac{A_2 \sin(w_r t_6)}{\cos(w_r t_6)} \tag{23}$$

$$\text{Now } V_{lr}(t_6) = L_r \frac{di_{lr}(t_6)}{dt}$$

$$\frac{di_{lr}(t_6)}{dt} = \frac{V_{lr}(t_6)}{L_r}$$

$$\text{Where } V_{lr}(t_6) = V_{in} - V_{cr_{min}} + nV_0$$

$$\text{but } \frac{di_{lr}(t_6)}{dt} = -A_1 w_r \sin(w_r t_6) + A_2 w_r \cos(w_r t_6)$$

$$\frac{1}{L_r} V_{lr}(t_6) = -A_1 w_r \sin(w_r t_6) + A_2 w_r \cos(w_r t_6)$$

$$A_1 = \frac{-\frac{1}{L_r} V_{lr}(t_6) + A_2 w_r \cos(w_r t_6)}{w_r \sin(w_r t_6)} \tag{24}$$

Take equation (23) equal to equation (24) to find A_2

$$-\frac{A_2 \sin(w_r t_6)}{\cos(w_r t_6)} = \frac{-\frac{1}{L_r} V_{lr}(t_6) + A_2 w_r \cos(w_r t_6)}{w_r \sin(w_r t_6)}$$

$$-A_2 w_r \sin^2(w_r t_6) = -\frac{1}{L_r} V_{lr(t_6)} \cos(w_r t_6) + A_2 w_r \cos^2(w_r t_6)$$

$$A_2 w_r \cos^2(w_r t_6) + A_2 w_r \sin^2(w_r t_6) = \frac{1}{L_r} V_{lr}(t_6) \cos(w_r t_6)$$

$$A_2 w_r [\cos^2(w_r t_6) + \sin^2(w_r t_6)] = \frac{1}{L_r} V_{lr}(t_6) \cos(w_r t_6)$$

$$A_2 w_r [1] = \frac{1}{L_r} V_{lr}(t_6) \cos(w_r t_6)$$

$$A_2 = \frac{\frac{1}{L_r} V_{lr}(t_6) \cos(w_r t_6)}{w_r} \tag{25}$$

$$\text{where } A_1 = -\frac{A_2 \sin(w_r t_6)}{\cos(w_r t_6)} \text{ from equation(23)}$$

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_6) \cos(w_r t_6)}{w_r} \times \frac{A_2 \sin(w_r t_6)}{\cos(w_r t_6)}$$

$$A_1 = -\frac{\frac{1}{L_r} V_{lr}(t_6) \sin(w_r t_6)}{w_r}$$

$$i_{lr}(t) = -\frac{\frac{1}{L_r} V_{lr}(t_6) \sin(w_r t_6)}{w_r} \cos(w_r t) + \frac{\frac{1}{L_r} V_{lr}(t) \cos(w_r t_6)}{w_r} \sin(w_r t)$$

$$i_{lr}(t) = \frac{1}{L_r} \frac{V_{lr}(t)}{w_r} [-\cos(w_r t) \sin(w_r t_6) + \cos(w_r t_6) \sin(w_r t)]$$

$$\sin A \cos B - \cos A \sin B = \sin(A - B)$$

According to this trigonometric equation the resonant inductor current can be written as:

$$i_{lr}(t) = \frac{1}{L_r} \frac{V_{lr}(t_6)}{w_r} [\sin(w_r t - w_r t_6)]$$

$$\text{but } w_r = \sqrt{\frac{1}{L_r C_r}} \qquad \text{and} \quad V_{lr}(t_6) = V_{in} - V_{cr_{min}} + nV_0$$

$$i_{lr}(t) = \frac{1}{L_r} \times \frac{V_{in} - V_{cr_{min}} + nV_0}{\sqrt{\frac{1}{L_r C_r}}} \sin(w_r(t - t_6))$$

$$i_{lr}(t) = \frac{V_{in} - V_{cr_{min}} + nV_0}{\sqrt{\frac{\mathbf{L_r^2}}{\mathbf{L_r C_r}}}} \sin(w_r(t - t_6))$$

$$\text{but } w_r = 2\pi f_r$$

Then the resonant inductor current equation at sate 4 is:

$$\Rightarrow \quad i_{lr}(t) = (V_{in} - V_{cr_{min}} + nV_0) \sqrt{\frac{C_r}{L_r}} \sin 2\pi f_r (t - t_6) \qquad (26)$$

Applying KVL around the inverting side to find the resonant capacitor voltage at state 4.

$$V_{cr} + V_{lr} - nV_0 - V_{in} = 0$$

$$V_{cr} = V_{in} - V_{lr} + nV_0$$

$$\text{but } V_{lr} = L_r \frac{di_{lr}(t)}{dt}$$

Derivative of resonant inductor current at state 4 is:

$$\frac{di_{lr}(t)}{dt} = (V_{in} - V_{cr_{min}} + nV_0)\sqrt{\frac{C_r}{L_r}}\, 2\pi f_r \cos 2\pi f_r\,(t - t_6)$$

$$\text{but } w_r = 2\pi f_r = \sqrt{\frac{1}{L_r C_r}}$$

$$V_{cr}(t) = V_{in} + nV_0 - L_r[(V_{in} - V_{cr_{min}} + nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{1}{L_r C_r}}\cos 2\pi f_r\,(t - t_6)]$$

$$V_{cr}(t) = V_{in} + nV_0 - (V_{in} - V_{cr_{min}} + nV_0)\sqrt{\frac{C_r}{L_r}}\sqrt{\frac{L_r^2}{L_r C_r}}\cos 2\pi f_r\,(t - t_6)$$

Then the resonant capacitor voltage equation at state 4 is:

$$\Rightarrow V_{cr}(t) = V_{in} + nV_0 - (V_{in} - V_{cr_{min}} + nV_0)\cos 2\pi f_r\,(t - t_6) \quad (27)$$

2.2 Voltage Gain

Voltage gain can be calculated by dividing the output voltage over the input voltage, where the output voltage is related to the voltage of load R_L and the input voltage is given as V_{in}=80V.

The half-bridge SRC static voltage gain using FTM technique can be obtained according to the volt-seconds principle of L_r, and the charge balance principle of C_r and C_0. Derivation of the static voltage gain equation is as follows.

$$\text{Unknown: } V_0, V_{cr\,min}, V_{cr\,max}, t_3, t_4$$

$$\text{at } t_0 < t < t_1 \rightarrow S_2 \text{ is ON}$$

$$[w_s(t_1 - t_0) = 2\pi d_2] \times \frac{w_r}{w_s}$$

$$w_r(t_1 - t_0) = \frac{2\pi d_2 w_r}{w_s} = \frac{2\pi d_2}{F}$$

Take the resonant inductor equation at state 1 equal to resonant inductor equation at state 2. Also, the same for resonant capacitor voltage

$$\underline{at\ t = t_1:}$$

$$i_{lr}(t_1): (V_{in} - V_{cr\,min} - nV_0)\frac{1}{Z_r}\sin[w_r(t_1 - t_0)]$$

$$= (V_{cr\,max} + nV_0)\frac{1}{Z_r}\sin[w_r(t_3 - t_1)]$$

$$V_{cr}(t_1): V_{in} - nV_0 - (V_{in} - V_{cr\,min} - nV_0)\cos[w_r(t_1 - t_0)]$$

$$= -nV_0 + (V_{cr\,max} + nV_0)\cos[w_r(t_3 - t_1)]$$

$$\text{Let } \theta_{13} = w_r(t_3 - t_1) \text{ and } h = \cos\left(\frac{2\pi d_2}{F}\right)$$

$$i_{lr}(t_1): (V_{in} - V_{cr\,min} - nV_0)\sin\left(\frac{2\pi d_2}{F}\right) = (V_{cr\,max}\, nV_0)\sin\theta_{13} \quad (27)$$

$$V_{cr}(t_1): V_{in} - (V_{in} - V_{cr\,min} - nV_0)h = (V_{cr\,max} + nV_0)\cos\theta_{13} \quad (28)$$

Take the resonant inductor equation at state 3 equal to resonant inductor equation at state 4. Also, the same for resonant capacitor voltage

$$\underline{\text{at } t = t_4:}$$

$$\text{Let } \theta_{34} = w_r(t_4 - t_3) \text{ and } \theta_{46} = w_r(t_6 - t_4)$$

$$i_{lr}(t_4): -(V_{cr\,max}$$

$$- nV_0)\frac{1}{Z_r}\sin[w_r(t_4 - t_3)]$$

$$= (V_{in} - V_{cr\,min} + nV_0)\frac{1}{Z_r}\sin[w_r(t_4 - t_6)]$$

$$-(V_{cr\,max} - nV_0)\sin\theta_{34} = -(V_{in} - V_{cr\,min} + nV_0)\sin\theta_{46}$$

$$(V_{cr\,max} - nV_0)\sin\theta_{34} = (V_{in} - V_{cr\,min} + nV_0)\sin\theta_{46} \quad (29)$$

$$V_{cr}(t_4): nV_0 + (V_{cr\,max} - nV_0)\cos[w_r(t_4 - t_3)]$$

$$= V_{in} + nV_0 - (V_{in} - V_{cr\,min} + nV_0)\cos[w_r(t_4 - t_6)]$$

$$: (V_{cr\,max} - nV_0)\cos[w_r(t_4 - t_3)] = V_{in} - (V_{in} - V_{cr\,min} + nV_0)\cos[w_r(t_4 - t_6)]$$

$$(V_{cr\,max} - nV_0)\cos\theta_{34} = V_{in} - (V_{in} - V_{cr\,min} + nV_0)\cos\theta_{46} \quad (30)$$

Now add the square of equation (27) and (28)

$$(V_{cr\,max} + nV_0)^2\sin^2\theta_{13} = (V_{in} - V_{cr\,min} - nV_0)^2\sin^2\left(\frac{2\pi d_2}{F}\right)$$

$$(V_{cr\,max} + nV_0)^2\cos^2\theta_{13} = [V_{in} - (V_{in} - V_{cr\,min} - nV_0)h]^2$$

$$(V_{cr\,max} + nV_0)^2[\sin^2\theta_{13} + \cos^2\theta_{13}]$$

$$= \left[(V_{in} - V_{cr\,min} - nV_0)^2\sin^2\left(\frac{2\pi d_2}{F}\right) + {V_{in}}^2\right.$$

$$\left. - 2hV_{in}(V_{in} - V_{cr\,min} - nV_0) + (V_{in} - V_{cr\,min} - nV_0)^2h^2\right]$$

$$(V_{cr\,max} + nV_0)^2$$

$$= \left[(V_{in} - V_{cr\,min} - nV_0)^2\left[\sin^2\left(\frac{2\pi d_2}{F}\right) + h^2\right] + {V_{in}}^2\right.$$

$$\left. - 2hV_{in}(V_{in} - V_{cr\,min} - nV_0)\right]$$

$$(V_{cr\,max} + nV_0)^2 = (V_{in} - V_{cr\,min} - nV_0)^2 + {V_{in}}^2 - 2hV_{in}(V_{in} - V_{cr\,min} - nV_0)$$

Multiply by $\frac{1}{{V_{in}}^2}$

$$\left(\frac{V_{cr\,max} + nV_0}{V_{in}}\right)^2 = \left(\frac{V_{in} - V_{cr\,min} - nV_0}{V_{in}}\right)^2 + \left(\frac{V_{in}}{V_{in}}\right)^2 - \frac{2hV_{in}(V_{in} - V_{cr\,min} - nV_0)}{V_{in}}$$

$$\text{Let } \alpha = \frac{V_{cr\,max}}{V_{in}}, \qquad \beta = \frac{V_{cr\,min}}{V_{in}}, \qquad M = \frac{V_0}{V_{in}}$$

Where is α is the voltage gain of maximum voltage of resonant capacitor, β is the voltage gain of minimum voltage of resonant capacitor

$$(\alpha + nM)^2 = (1 - \beta - nM)^2 + 1 - 2h(1 - \beta - nM) \tag{31}$$

Now add the square of equation (29) and (30)

$$(V_{cr\,max} - nV_0)^2 \sin^2\theta_{34} = (V_{in} - V_{cr\,min} + nV_0)^2 \sin^2\theta_{46}$$

$$(V_{cr\,max} - nV_0)^2 \cos^2\theta_{34} = [V_{in} - (V_{in} - V_{cr\,min} + nV_0)\cos\theta_{46}]^2$$

$$(V_{cr\,max} - nV_0)^2[\sin^2\theta_{34} + \cos^2\theta_{34}]$$

$$= \big[(V_{in} - V_{cr\,min} + nV_0)^2 \sin^2\theta_{46} + {V_{in}}^2$$

$$- 2\cos\theta_{46} V_{in}(V_{in} - V_{cr\,min} + nV_0)$$

$$+ (V_{in} - V_{cr\,min} + nV_0)^2 \cos^2\theta_{46}\big]$$

$$(V_{cr\,max} - nV_0)^2[\sin^2\theta_{34} + \cos^2\theta_{34}]$$

$$= (V_{in} - V_{cr\,min} + nV_0)^2[\sin^2\theta_{46} + \cos^2\theta_{46}] + {V_{in}}^2$$

$$- 2\cos\theta_{46} V_{in}(V_{in} - V_{cr\,min} + nV_0)$$

$$but\ \theta_{46} = 0 \ \rightarrow cos\theta_{46} = 1$$

$$(V_{cr\,max} - nV_0)^2 = (V_{in} - V_{cr\,min} + nV_0)^2 + {V_{in}}^2 - 2V_{in}(V_{in} - V_{cr\,min} + nV_0)$$

Multiply by $\frac{1}{{V_{in}}^2}$

$$\left(\frac{V_{cr\,max} - nV_0}{V_{in}}\right)^2 = \left(\frac{V_{in} - V_{cr\,min} + nV_0}{V_{in}}\right)^2 + \left(\frac{V_{in}}{V_{in}}\right)^2 - \frac{2V_{in}(V_{in} - V_{cr\,min} + nV_0)}{V_{in}}$$

$$(\alpha - nM)^2 = (1 - \beta + nM)^2 + 1 - 2(1 - \beta + nM) \tag{32}$$

- $(\alpha - nM)^2 = (1 - (1 - \beta + nM))^2$
- $(\alpha - nM)^2 = (\beta - nM)^2$
- $(\alpha - nM) = \pm(\beta - nM)$
- $\alpha - nM = \beta - nM$ is rejected

- $\alpha - nM = -(\beta - nM)$ is accepted

Based on volt-second principle of L_r, the integral of resonant inductor current for one complete period must be equal to zero

$$\int_{t_0}^{t_6} i_{Lr} dt = 0$$

The integration of resonant inductor for each state are:

$$\int_{t_0}^{t_1} i_{Lr} dt = \frac{V_{in} - V_{cr\,min} - nV_0}{Z_r} \int_{t_0}^{t_1} \sin[w_r(t - t_0)] dt$$

- $\int_{t_0}^{t_1} i_{Lr} dt = \frac{V_{in} - V_{cr\,min} - nV_0}{w_r Z_r} \left[1 - \cos\left(\frac{2\pi d_2}{F}\right)\right]$

$$\int_{t_1}^{t_3} i_{Lr} dt = \frac{-(V_{cr\,max} + nV_0)}{Z_r} \int_{t_1}^{t_3} \sin[w_r(t - t_3)] dt$$

$$\int_{t_1}^{t_3} i_{Lr} dt = \frac{(V_{cr\,max} + nV_0)}{w_r Z_r} \left[1 - \cos[w_r(t_1 - t_3)]\right]$$

- $\int_{t_1}^{t_3} i_{Lr} dt = \frac{(V_{cr\,max} + nV_0)}{w_r Z_r} [1 - \cos\theta_{13}]$

$$\int_{t_3}^{t_4} i_{Lr} dt = \frac{-(V_{cr\,max} - nV_0)}{Z_r} \int_{t_3}^{t_4} \sin[w_r(t - t_3)]\, dt$$

$$\int_{t_3}^{t_4} i_{Lr} dt = \frac{(V_{cr\,max} - nV_0)}{w_r Z_r} [\cos[w_r(t_4 - t_3)] - 1]$$

- $\int_{t_3}^{t_4} i_{Lr} dt = \frac{(V_{cr\,max} - nV_0)}{w_r Z_r} (\cos\theta_{34} - 1)$

$$\int_{t_4}^{t_6} i_{Lr} dt = \frac{V_{in} - V_{cr\,min} + nV_0}{Z_r} \int_{t_4}^{t_6} \sin[w_r(t - t_6)] dt$$

$$\int_{t_4}^{t_6} i_{Lr} dt = \frac{V_{in} - V_{cr\,min} + nV_0}{Z_r} [\cos[w_r(t_4 - t_6)] - 1]$$

$$\int_{t_4}^{t_6} i_{Lr}dt = \frac{V_{in} - V_{cr\,min} + nV_0}{w_r Z_r}[\cos\theta_{46} - 1]$$

Now according to volt-second principle of L_r:

$$\int_{t_0}^{t_6} i_{Lr}dt = 0$$

$$(V_{in} - V_{cr\,min} - nV_0)(1 - h) + (V_{cr\,max} + nV_0)(1 - \cos\theta_{13}) + (V_{cr\,max} - nV_0)(\cos\theta_{34} - 1) + (V_{in} - V_{cr\,min} + nV_0)(\cos\theta_{46} - 1) = 0$$

Multiply by $\frac{1}{V_{in}}$ $\quad\quad$ $\theta_{46} = 0 \rightarrow \cos\theta_{46} = 1$

$$(1 - \beta - nM)(1 - h) + (\alpha + nM)(1 - \cos\theta_{13}) + (\alpha - nM)(\cos\theta_{34} - 1) = 0 \quad (33)$$

Now from equation (28):

Multiply by $\frac{1}{V_{in}}$

$$\frac{V_{in}}{V_{in}} - \frac{(V_{in} - V_{cr\,min} - nV_0)h}{V_{in}} = \frac{(V_{cr\,max} + nV_0)}{V_{in}}\cos\theta_{13}$$

$$1 - (1 - \beta - nM)h = (\alpha + nM)\cos\theta_{13}$$

- $\cos\theta_{13} = \frac{1-(1-\beta-nM)h}{(\alpha+nM)}$

Now from equation (30):

Multiply by $\frac{1}{V_{in}}$

$$\frac{V_{in}}{V_{in}} - \frac{(V_{in} - V_{cr\,min} + nV_0)}{V_{in}}\cos\theta_{46} = \frac{(V_{cr\,max} - nV_0)}{V_{in}}\cos\theta_{34}$$

$$1 - (1 - \beta + nM) = (\alpha - nM)\cos\theta_{34}$$

- $\cos\theta_{34} = \frac{\beta-nM}{\alpha-nM}$

Substitute in equation (33)

$$(1-\beta-nM)(1-h)+(\alpha+nM)\left(1-\frac{1-(1-\beta-nM)h}{(\alpha+nM)}\right)$$

$$+(\alpha-nM)\left(\frac{\beta-nM}{\alpha-nM}-1\right)=0$$

$$(1-\beta-nM)(1-h)+(\alpha+nM-1+(1-\beta-nM)h)+(\beta-nM-\alpha+nM)$$

$$=0$$

$$(1-\beta-nM)-h(1-\beta-nM)+\alpha+nM-1+(1-\beta-nM)h+\beta-\alpha=0$$

$$\triangleright \quad 0=0$$

Then we can say volt-second inductor is verified

Based on charge balance principle of C_r and C_0

$$n\int_{t_0}^{t_3} i_{Lr}dt+n\int_{t_3}^{t_6}(-i_{Lr}dt)=\frac{V_0}{R_L}.T$$

$$w_sT=2\pi \qquad T=\frac{2\pi}{w_s}=\frac{2\pi}{2\pi f_s}=\frac{1}{f_s}=\frac{1}{Ff_r} \qquad w_rT=2\pi f_rT=\frac{2\pi}{F}$$

$$\int_{t_0}^{t_3} i_{Lr}dt=\frac{(V_{in}-V_{cr\,min}-nV_0)}{w_rZ_r}(1-h)+\frac{(V_{cr\,max}+nV_0)}{w_rZ_r}(1-\cos\theta_{13})$$

$$\int_{t_3}^{t_6}(-i_{Lr}dt)=\frac{(V_{cr\,max}-nV_0)}{w_rZ_r}(1-\cos\theta_{34})+\frac{V_{in}-V_{cr\,min}+nV_0}{w_rZ_r}(1-\cos\theta_{46})$$

$$(1-\beta-nM)(1-h)+(\alpha+nM)(1-\cos\theta_{13})+(\alpha-nM)(1-\cos\theta_{34})+$$

$$(1-\beta+nM)(1-\cos\theta_{46})=\frac{w_rZ_r}{nR_L}.T=\frac{M}{nC_rR_Lf_s}=\frac{M}{nw} \qquad (34)$$

$$\text{where } w=C_rR_Lf_s$$

substitute the value of $\cos\theta_{13}$, $\cos\theta_{46}$, $\cos\theta_{46}$ in equation (34):

$$(1-\beta-nM)(1-h)+(\alpha+nM-1+(1-\beta-nM)h)+(\alpha-\beta)=\frac{M}{nw}$$

$$1-\beta-nM-h(1-\beta-nM)+\alpha+nM-1+h(1-\beta-nM)+(\alpha-\beta)=\frac{M}{nw}$$

$$2\alpha - 2\beta = \frac{M}{nw}$$

$$\alpha - \beta = \frac{M}{2nw} \tag{35}$$

Then subtract equation (31) and (32) we can find that

$$(\alpha + nM)^2 = (1 - \beta - nM)^2 + 1 - 2h(1 - \beta - nM) \tag{31}$$

$$(\alpha - nM)^2 = (1 - \beta + nM)^2 + 1 - 2(1 - \beta + nM) \tag{32}$$

$$(\alpha + nM)^2 - (\alpha - nM)^2$$

$$= \left[(1 - \beta - nM)^2 + 1 - 2h(1 - \beta - nM)\right.$$

$$\left. - [(1 - \beta + nM)^2 + 1 - 2(1 - \beta + nM)]\right]$$

$$4\alpha nM = [\beta^2 - 2\beta - 2nM + n^2M^2 + 2n\beta M + 1 - 2h(1 - \beta - nM) - \beta^2 + 2\beta$$

$$- 2nM - n^2M^2 + 2n\beta M - 1 + 2(1 - \beta + nM)]$$

$$4\alpha nM = -4nM + 4n\beta M - 2h(1 - \beta - nM) + 2(1 - \beta + nM)$$

$$4nM(\alpha - \beta) = 2(1 - h)(1 - \beta) - 2h(-nM) + 2nM - 4nM$$

$$4nM(\alpha - \beta) = 2(1 - h)(1 - \beta) - 2h(-nM) - 2nM$$

$$2nM(\alpha - \beta) = (1 - h)(1 - \beta) - (1 - h)nM$$

From equation (35) we can find that

$$\alpha - \beta = \frac{M}{2nw}$$

$$2\left(\frac{M}{2nw}\right)nM = (1 - h)(1 - \beta) - (1 - h)nM$$

$$\frac{M^2}{w} = (1 - h)(1 - \beta - nM) \tag{36}$$

Now from equation also we can find that

$$\alpha - nM = -(\beta - nM)$$

$$\alpha + \beta = 2nM \tag{37}$$

Add equation (35) and equation (37) to find α and β

$$2\alpha = 2nM + \frac{M}{2nw}$$

$$\alpha = \left(n + \frac{1}{4nw}\right) M$$

$$\beta = 2nM - \alpha$$

$$\beta = 2nM - \left(n + \frac{1}{4nw}\right) M$$

$$\beta = \left(n - \frac{1}{4nw}\right) M$$

Go back to equation (36) to find the static voltage gain

$$M^2 = w(1-h)(1-\beta-nM) = w(1-h)(1-\beta) - nw(1-h)M$$

$$M^2 = w(1-h)(1-\beta) - nw(1-h)M$$

$$M^2 = w(1-h)\left[1 - \left(n - \frac{1}{4nw}\right) M\right] - nw(1-h)M$$

$$M^2 = w(1-h) - w(1-h)\left(n - \frac{1}{4nw}\right) M - nw(1-h)M$$

$$M^2 = w(1-h) - \left(n - \frac{1}{4nw} + n\right) w(1-h)M$$

$$M^2 = w(1-h) - \left(2n - \frac{1}{4nw}\right) w(1-h)M$$

$$M^2 + \left(2n - \frac{1}{4nw}\right) w(1-h)M - w(1-h) = 0$$

The determinant of the quadratic equation is:

$$\delta = \left(2n - \frac{1}{4nw}\right)^2 w^2(1-h)^2 + 4w(1-h)$$

$$\delta = \left(\frac{8wn^2 - 1}{4nw}\right)^2 w^2(1-h)^2 + 4w(1-h)$$

$$\delta = \frac{(8wn^2 - 1)^2 w^2(1-h)^2}{16n^2w^2} + 4w(1-h)$$

$$\delta = \frac{(8wn^2-1)^2(1-h)^2 + 64wn^2(1-h)}{16n^2}$$

$$M = \frac{-\left(2n - \frac{1}{4nw}\right)w(1-h) + \frac{1}{4n}\left[[(8wn^2-1)^2(1-h)^2 + 64wn^2(1-h)\right]^{\frac{1}{2}}}{2}$$

$$M = -\left(\frac{8wn^2-1}{8nw}\right)w(1-h) + \frac{1}{8n}[(8wn^2-1)^2(1-h)^2 + 64wn^2(1-h)]^{\frac{1}{2}}$$

Then the static voltage gain is:

$$\Rightarrow \quad M = \frac{(8wn^2-1)(h-1) + [(8wn^2-1)^2(1-h)^2 + 64wn^2(1-h)]^{\frac{1}{2}}}{8n}$$

$$(8wn^2-1)^2(1-2h+h^2) + 64wn^2(1-h)$$

$$(8wn^2-1)^2h^2 + (1-2h)(8wn^2-1)^2 + 64wn^2(1-h)$$

$$(1-2h)(64w^2n^4 - 16wn^2 + 1) + 64wn^2(1-h)$$

$$(1-2h)64w^2n^4 - (1-2h)16wn^2 + (1-2h) + 64wn^2(1-h)$$

$$(1-2h)64w^2n^4 + (1-2h) + 16wn^2[4(1-h) - (1-2h)]$$

$$(1-2h)(64w^2n^4 + 1) + 16wn^2(3-2h)$$

$$(1-2h)(64w^2n^4 + 1) + 16wn^2(1-2h+2)$$

$$(1-2h)(64w^2n^4 + 1 + 16wn^2) + 32wn^2$$

$$(8wn^2-1)^2(1-2h) + 32wn^2$$

Then, the maximum and minimum voltage gain of resonant capacitor are:

- $M = \frac{(8wn^2-1)(h-1)+\sqrt{(8wn^2-1)^2h^2+(8wn^2-1)^2(1-2h)+32wn^2}}{8n}$ (38)

- $M_{cr\,max} = \alpha = \left(n + \frac{1}{4nw}\right)M$

- $M_{cr\,max} = \alpha = \left(n + \frac{1}{4nw}\right)\left(\frac{(8wn^2-1)(h-1)+\sqrt{(8wn^2-1)^2h^2+(8wn^2-1)^2(1-2h)+32wn^2}}{8n}\right)$ (39)

- $M_{cr\,min} = \beta = \left(n + \frac{1}{4nw}\right)M$

$$\text{➢} \quad M_{cr\,min} = \beta = \left(n - \frac{1}{4nw}\right)\left(\frac{(8wn^2-1)(h-1)+\sqrt{(8wn^2-1)^2h^2+(8wn^2-1)^2(1-2h)+32wn^2}}{8n}\right) \tag{40}$$

The theoretical result of the minimum and maximum ratios of the voltage that flow over the capacitor over the input voltage at load resistance equal to 32 ohms, versus normalized frequency are shown in Fig. 6.

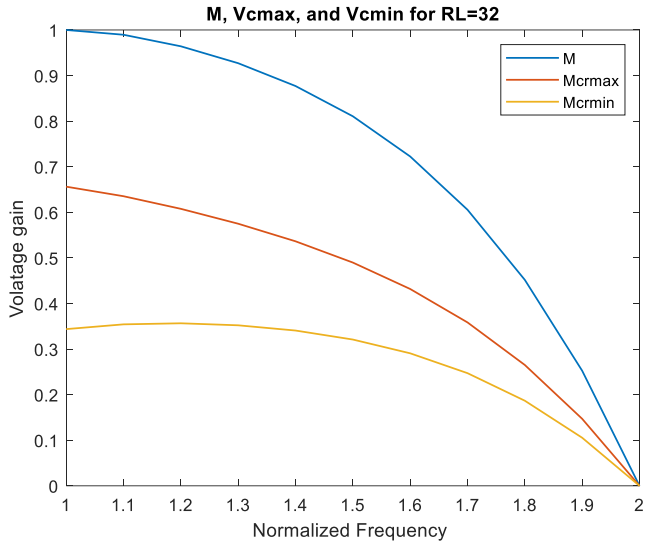


Figure 6: Theoretical Result of Static Voltage Gain (M),M_(cr max), and M_(cr min)

2.3 Current Stress

This task will introduce the derivation equations of current stresses in S_1, S_2 and $D_{1\text{-}4}$. Current stress is the current with RMS value; it can be computed by using this formula $I_{rms} = \frac{1}{T}\int I^2\,dt$, for one complete period. Where T is the time needed to complete one period.

2.3.1 Current Stresses of S_1

Since the current of S_1, when it was on in state 2 and 3 is opposite to the resonant inductor current so the S_1 current it will be:

$$i_{S1} = -i_{Lr} \quad t_1 \le t \le t_4$$

$$i_{S1} = (V_{crmax} + nV_0)\frac{1}{Z_r}\sin\left(w_r(t-t_3)\right) \quad t_1 \le t \le t_3$$

$$i_{S1} = (V_{crmax} - nV_0)\frac{1}{Z_r}\sin\big(w_r(t-t_3)\big) \quad t_3 \le t \le t_4$$

$$\int_{t_0}^{t_6} i_{S1}^2 dt = \int_{t_1}^{t_3} (V_{crmax} + nV_0)^2 \frac{1}{Z_r^2}\sin\big(w_r(t-t_3)\big)^2 dt$$

$$+ \int_{t_3}^{t_4} (V_{crmax} - nV_0)^2 \frac{1}{Z_r^2}\sin\big(w_r(t-t_3)\big)^2 dt$$

$$\theta_{34} = \pi \rightarrow \sin\theta_{34} = 0$$

Take the integral of the switch one current in state 2 and 3

$$\int_{t_1}^{t_3} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2}\int_{t_1}^{t_3} \big[1 - \cos\big(2w_r(t-t_3)\big)\big] dt$$

$$\int_{t_1}^{t_3} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2}\Big[(t_3 - t_1) + \frac{1}{2w_r}\big(\sin\big(2w_r(t_1 - t_3)\big)\big)\Big]$$

$$\int_{t_1}^{t_3} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2}\Big[(t_3 - t_1) - \frac{1}{2w_r}\big(\sin\big(2w_r(t_3 - t_1)\big)\big)\Big]$$

$$w_r(t_3 - t_1) = \theta_{13}$$

$$\int_{t_1}^{t_3} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2w_r}\theta_{13} - \frac{1}{4w_r}\sin(2\theta_{13})$$

$$\int_{t_3}^{t_4} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2}\int_{t_1}^{t_3} \big[1 - \cos\big(2w_r(t-t_3)\big)\big] dt$$

$$\int_{t_3}^{t_4} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2}\Big[(t_4 - t_3) - \frac{1}{2w_r}\big(\sin\big(2w_r(t_4 - t_3)\big)\big)\Big]$$

$$\int_{t_3}^{t_4} \sin\big(w_r(t-t_3)\big)^2 dt = \frac{1}{2w_r}\theta_{34} - \frac{1}{4w_r}\sin(2\theta_{34})$$

$$\int_{t_0}^{t_6} i_{S1}^2 dt = \frac{(V_{crmax} + nV_0)^2}{Z_r^2}\Big[\frac{1}{2w_r}\theta_{13} - \frac{1}{4w_r}\sin(2\theta_{13})\Big]$$

$$+ \frac{(V_{crmax} - nV_0)^2}{Z_r^2}\Big[\frac{1}{2w_r}\theta_{34} - \frac{1}{4w_r}\sin(2\theta_{34})\Big]$$

$$\int_{t_0}^{t_6} i_{S1}^2 dt = \frac{1}{4w_r Z_r^2}[(V_{crmax} + nV_0)^2(2\theta_{13} - \sin(2\theta_{13}))$$

$$+ (V_{crmax} - nV_0)^2(2\theta_{34} - \sin(2\theta_{34}))]$$

$$\text{Multply by } \frac{V_{in}^2}{V_{in}^2}$$

$$\int_{t_0}^{t_6} i_{S1}^2 dt = \frac{V_{in}^2}{4w_r Z_r^2}[(\alpha + nM)^2(2\theta_{13} - \sin(2\theta_{13}))$$

$$+ (\alpha - nM)^2(2\theta_{34} - \sin(2\theta_{34}))]$$

$$\text{where } \sin(2\theta_{13}) = 2\sin\theta_{13}\cos\theta_{13}$$

$$\sin(2\theta_{34}) = 2\sin\theta_{34}\cos\theta_{34}$$

$$\int_{t_0}^{t_6} i_{S1}^2 dt = \frac{V_{in}^2}{4w_r Z_r^2}[(\alpha + nM)^2(2\theta_{13} - 2\sin\theta_{13}\cos\theta_{13})$$

$$+ (\alpha - nM)^2(2\theta_{34} - 2\sin\theta_{34}\cos\theta_{34})]$$

Then multiply by $\frac{1}{T}$ and take a square root of it to find the rms current of the switching

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S1}^2 dt = \frac{w_s}{2\pi}.\frac{V_{in}^2}{4w_r Z_r^2}[2(\alpha + nM)^2(\theta_{13} - \sin\theta_{13}\cos\theta_{13})$$

$$+ 2(\alpha - nM)^2(\theta_{34} - \sin\theta_{34}\cos\theta_{34})]$$

$$F = \frac{w_s}{w_r}$$

$$I_{S1rms} = \sqrt{\frac{1}{T}\int_{t_0}^{t_6} i_{S1}^2 dt}$$

$$I_{S1rms} = \frac{V_{in}}{2Z_r}\left[\frac{F}{\pi}(\alpha + nM)^2(\theta_{13} - \sin\theta_{13}\cos\theta_{13})\right.$$

$$\left. + \frac{F}{\pi}(\alpha - nM)^2(\theta_{34} - \sin\theta_{34}\cos\theta_{34})\right]^{\frac{1}{2}}$$

$$\alpha = \frac{V_{crmax}}{V_{in}} \text{ and } M = \frac{V_0}{V_{in}}$$

$$I_{S1rms} = \frac{V_{in}}{2Z_r}\left[\frac{F}{\pi}\left(\frac{V_{crmax} + nV_0}{V_{in}^2}\right)^2 (\theta_{13} - \sin\theta_{13}\cos\theta_{13}) + \frac{F}{\pi}\left(\frac{V_{crmax} - nV_0}{V_{in}^2}\right)^2 (\theta_{34} - \sin\theta_{34}\cos\theta_{34})\right]^{\frac{1}{2}}$$

$$I_{S1rms} = \frac{1}{2Z_r}\left[F\frac{(V_{crmax} + nV_0)^2(\theta_{13} - \sin\theta_{13}\cos\theta_{13})}{\pi} + F\frac{(V_{crmax} - nV_0)^2(\theta_{34} - \sin\theta_{34}\cos\theta_{34})}{\pi}\right]^{\frac{1}{2}}$$

We need to write the equation in this form $I_{S1rms} = \frac{1}{2Z_r}\sqrt{F(Z_1 + Z_2)}$,so we need to find the value $\cos\theta_{13}$and$\cos\theta_{34}$, then

$$\sin\left(\frac{2\pi d_2}{F}\right)^2 = 1 - \cos\left(\frac{2\pi d_2}{F}\right)^2 = 1 - h^2$$

$$\sin\left(\frac{2\pi d_2}{F}\right) = \sqrt{1 - h^2}$$

From equation (1)

$$\sin\left(\frac{2\pi d_2}{F}\right) = \frac{V_{crmax} + nV_0}{V_{in} - V_{crmin} - nV_0}\sin\theta_{13} = \sqrt{1 - h^2}$$

$$\left(\frac{V_{crmax} + nV_0}{V_{in} - V_{crmin} - nV_0}\right)^2 \sin{\theta_{13}}^2 = 1 - h^2$$

$$h^2 = 1 - \left(\frac{V_{crmax} + nV_0}{V_{in} - V_{crmin} - nV_0}\right)^2 \sin{\theta_{13}}^2$$

$$\text{where } \sin{\theta_{13}}^2 = 1 - \cos{\theta_{13}}^2$$

$$h^2 = 1 - \left(\frac{V_{crmax} + nV_0}{V_{in} - V_{crmin} - nV_0}\right)^2 \left(1 - \cos{\theta_{13}}^2\right)$$

from equation 2

$$h = \frac{V_{in} - (V_{crmax} + nV_0)\cos\theta_{13}}{V_{in} - V_{crmin} - nV_0}$$

Take the value of h are equal to find $\cos\theta_{13}$

$$\left(\frac{V_{in}-(V_{crmax}+nV_0)\cos\theta_{13}}{V_{in}-V_{crmin}-nV_0}\right)^2$$

$$=1-\left(\frac{V_{crmax}+nV_0}{V_{in}-V_{crmin}-nV_0}\right)^2+\left(\frac{V_{crmax}+nV_0}{V_{in}-V_{crmin}-nV_0}\right)^2\cos{\theta_{13}}^2$$

$$\frac{(V_{in}-(V_{crmax}+nV_0)\cos\theta_{13})^2}{(V_{in}-V_{crmin}-nV_0)^2}$$

$$=1-\left(\frac{V_{crmax}+nV_0}{V_{in}-V_{crmin}-nV_0}\right)^2+\left(\frac{V_{crmax}+nV_0}{V_{in}-V_{crmin}-nV_0}\right)^2\cos{\theta_{13}}^2$$

$$(V_{in}-(V_{crmax}+nV_0)\cos\theta_{13})^2$$

$$=(V_{in}-V_{crmin}-nV_0)^2-(V_{crmax}+nV_0)^2$$

$$+(V_{crmax}+nV_0)^2\cos{\theta_{13}}^2$$

$$V_{in}^2-2V_{in}(V_{crmax}+nV_0)\cos\theta_{13}+(V_{crmax}+nV_0)^2\cos{\theta_{13}}^2$$

$$=(V_{in}-V_{crmin}-nV_0)^2-(V_{crmax}+nV_0)^2$$

$$+(V_{crmax}+nV_0)^2\cos{\theta_{13}}^2$$

Then K_1 is:

$$\cos\theta_{13}=\frac{V_{in}^2-(V_{in}-V_{crmin}-nV_0)^2+(V_{crmax}+nV_0)^2}{2V_{in}(V_{crmax}+nV_0)}=K_1$$

$$\text{where } \cos\theta_{13}\sin\theta_{13}=\cos\theta_{13}\sqrt{1-\cos{\theta_{13}}^2}=K_1\sqrt{1-{K_1}^2}$$

$$Z_1=\frac{(V_{crmax}+nV_0)^2\left(a\cos K_1-K_1\sqrt{1-{K_1}^2}\right)}{\pi}$$

$$\text{then } \theta_{34}=\pi$$

$$Z_2=\frac{(V_{crmax}-nV_0)^2(\pi-\sin\pi\cos\pi)}{\pi}$$

$$Z_2=\frac{(V_{crmax}+nV_0)^2\pi}{\pi}=(V_{crmax}-nV_0)^2$$

Then the rms current of S_1 is:

$$I_{S1rms} = \frac{1}{2Z_r}\sqrt{F(Z_1 + Z_2)} \tag{41}$$

2.3.2 Current Stresses of S_2

Since the current of S_2, when it was in state 1 is same to the resonant inductor current so the S_2 current it will be:

$$i_{S2} = i_{Lr} \qquad t_0 \le t \le t_1$$

$$i_{S2} = \frac{V_{in} - V_{crmin} - nV_0}{Z_r}\sin\left(w_r(t - t_0)\right)$$

$$\int_{t_0}^{t_6} i_{S2}^2\, dt = \int_{t_0}^{t_1} i_{S2}^2\, dt + \int_{t_4}^{t_6} i_{S2}^2\, dt$$

$$\theta_{46} = 0 \rightarrow \sin\theta_{46} = 0 \rightarrow \int_{t_4}^{t_6} i_{S2}^2\, dt = 0$$

$$\int_{t_0}^{t_6} i_{S2}^2\, dt = \int_{t_0}^{t_1} \left(\frac{V_{in} - V_{crmin} - nV_0}{Z_r}\right)^2 \sin\left(w_r(t - t_0)\right)^2 dt$$

$$\int_{t_0}^{t_1} \sin\left(w_r(t - t_0)\right)^2 dt = \frac{1}{2}\int_{t_0}^{t_1} \left[1 - \cos\left(2w_r(t - t_0)\right)\right] dt$$

$$\int_{t_0}^{t_1} \sin\left(w_r(t - t_0)\right)^2 dt = \frac{1}{2}\,(t_1 - t_0) - \frac{1}{4w_r}\left(\sin\left(2w_r(t_1 - t_0)\right)\right)$$

$$\int_{t_0}^{t_1} \sin\left(w_r(t - t_0)\right)^2 dt = \frac{1}{2}\,(t_1 - t_0) - \frac{1}{4w_r}\sin\left(2\left(\frac{2\pi d_2}{F}\right)\right)$$

$$\int_{t_0}^{t_1} \sin\left(w_r(t - t_0)\right)^2 dt = \frac{1}{2}\,(t_1 - t_0) - \frac{1}{4w_r}\left[2\sin\left(\frac{2\pi d_2}{F}\right)\cos\left(\frac{2\pi d_2}{F}\right)\right]$$

$$\text{where } \cos\left(\frac{2\pi d_2}{F}\right) = h$$

$$w_r\,(t_1 - t_0) = \frac{2\pi d_2}{F}$$

$$\int_{t_0}^{t_1} \sin\left(w_r(t - t_0)\right)^2 dt = \frac{1}{2w_r}\left(\frac{2\pi d_2}{F}\right) - \frac{1}{4w_r}\left[2h\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

$$\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{(V_{in} - V_{crmin} - nV_0)^2}{{Z_r}^2}\left[\frac{1}{2w_r}\left(\frac{2\pi d_2}{F}\right) - \frac{1}{4w_r}\left[2h\sin\left(\frac{2\pi d_2}{F}\right)\right]\right]$$

$$\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{(V_{in} - V_{crmin} - nV_0)^2}{2w_r{Z_r}^2}\left[\frac{2\pi d_2}{F} - h\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

Multiply by $\frac{V_{in}^2}{V_{in}^2}$

$$\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{V_{in}^2}{2w_r{Z_r}^2}(1 - \beta - nM)^2\left[\frac{2\pi d_2}{F} - h\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{w_s}{2\pi}.\frac{V_{in}^2}{2w_r{Z_r}^2}(1 - \beta - nM)^2\left[\frac{2\pi d_2}{F} - h\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

where $\frac{w_s}{w_r} = F$

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{V_{in}^2}{4{Z_r}^2}(1 - \beta - nM)^2\left[2d_2 - \frac{Fh}{\pi}\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

$$d_2 = 1 - \frac{F}{2}$$

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{V_{in}^2}{4{Z_r}^2}(1 - \beta - nM)^2\left[2\left(1 - \frac{F}{2}\right) - \frac{Fh}{\pi}\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{V_{in}^2}{4{Z_r}^2}(1 - \beta - nM)^2\left[2 - F - \frac{Fh}{\pi}\sin\left(\frac{2\pi d_2}{F}\right)\right]$$

But $\sin\left(\frac{2\pi d_2}{F}\right) = \sqrt{1 - \cos\left(\frac{2\pi d_2}{F}\right)^2} = \sqrt{1 - h^2}$

$$\frac{1}{T}\int_{t_0}^{t_6} i_{S2}^2\,dt = \frac{V_{in}^2}{4{Z_r}^2}(1 - \beta - nM)^2\left[2 - F - \frac{Fh}{\pi}\sqrt{1 - h^2}\right]$$

$$I_{S2rms} = \frac{V_{in}}{2Z_r}(1 - \beta - nM)\sqrt{2 - F - \frac{Fh}{\pi}\sqrt{1 - h^2}}$$

$$I_{S2rms} = \frac{V_{in}}{2Z_r}\left(\frac{V_{in} - V_{crmin} - nV_0}{V_{in}}\right)\sqrt{2 - F - \frac{Fh}{\pi}\sqrt{1 - h^2}}$$

$$I_{S2rms} = \frac{V_{in} - V_{crmin} - nV_0}{Z_r}\sqrt{2 - F - \frac{Fh}{\pi}\sqrt{1-h^2}} \quad (42)$$

2.3.3 Current Stress of $D_{1\text{-}4}$

To find the current stress of $D_{1\text{-}4}$, this formula must be applied, so the current stress of $D_{1\text{-}4}$ is on state 1 and 2.

$$I_{D_{1-4}avg} = \frac{1}{T}\int_{t_0}^{t_6} I_{D_{1-4}}\,dt$$

$$I_{D_{1-4}} = ni_{Lr} \qquad t_0 \le t \le t_1$$

$$I_{D_{1-4}} = -ni_{Lr} \qquad t_1 \le t \le t_3$$

$$I_{D_{1-4}avg} = \frac{n}{T}\left[\int_{t_0}^{t_1} i_{Lr}\,dt + \int_{t_1}^{t_3}(-i_{Lr})\,dt\right]$$

$$\int_{t_0}^{t_1} i_{Lr}\,dt = \frac{V_{in} - V_{crmin} - nV_0}{Z_r}\int_{t_0}^{t_1}\sin\big(w_r(t-t_0)\big)\,dt$$

$$\int_{t_0}^{t_1} i_{Lr}\,dt = \frac{nV_0 + V_{crmin} - V_{in}}{w_r Z_r}\big[\cos\big(w_r(t_1-t_0)\big) - 1\big]$$

$$\int_{t_0}^{t_1} i_{Lr}\,dt = \frac{nV_0 + V_{crmin} - V_{in}}{w_r Z_r}\left[\cos\left(\frac{2\pi d_2}{F}\right) - 1\right]$$

$$\int_{t_0}^{t_1} i_{Lr}\,dt = \frac{nV_0 + V_{crmin} - V_{in}}{w_r Z_r}[h-1]$$

$$\int_{t_1}^{t_3}(i_{Lr})\,dt = \int_{t_1}^{t_3}\frac{-(V_{crmax} + nV_0)}{Z_r}\sin\big(w_r(t-t_3)\big)\,dt$$

$$\int_{t_1}^{t_3}\sin\big(w_r(t-t_3)\big)\,dt = -\frac{1}{w_r}\big[1 - \cos\big(w_r(t_3-t_1)\big)\big]$$

$$\int_{t_1}^{t_3}\sin\big(w_r(t-t_3)\big)\,dt = -\frac{1}{w_r}[1 - \cos(\theta_{13})]$$

$$\int_{t_1}^{t_3}\sin\big(w_r(t-t_3)\big)dt = \frac{1}{w_r}[K_1 - 1]$$

$$\int_{t_1}^{t_3}(i_{Lr})\,dt = \frac{-(V_{crmax}+nV_0)}{w_r Z_r}(K_1-1)$$

$$I_{D_{1-4}avg} = \frac{n}{T}\left[\int_{t_0}^{t_1} i_{Lr}\,dt + \int_{t_1}^{t_3}(i_{Lr})\,dt\right]$$

$$I_{D_{1-4}avg} = \frac{nw_s}{2\pi w_r Z_r}[(nV_0+V_{crmin}-V_{in})(h-1)-(V_{crmax}+nV_0)(K_1-1)]$$

$$ButF = \frac{w_s}{w_r}$$

Then the current stress of $D_{1\text{-}4}$ is:

$$\Rightarrow\ I_{D_{1-4}avg} = \frac{nF[(nV_0+V_{crmin}-V_{in})(h-1)-(V_{crmax}+nV_0)(K_1-1)]}{2\pi Z_r} \qquad (43)$$

Chapter 3

SIMULATION RESULTS

3.1 Methodology

In this research, half-bridge SRC will be simulated in Matlab using fixed on-time modulation method (FTM) as a step-down converter used in a limited range of switching frequencies in order to achieve full-range voltage regulation. Fig. 7 shows the Simulink model of our study, which consists of a half-bridge SRC circuit diagram, scheme control diagram, and scope to display the outputs.

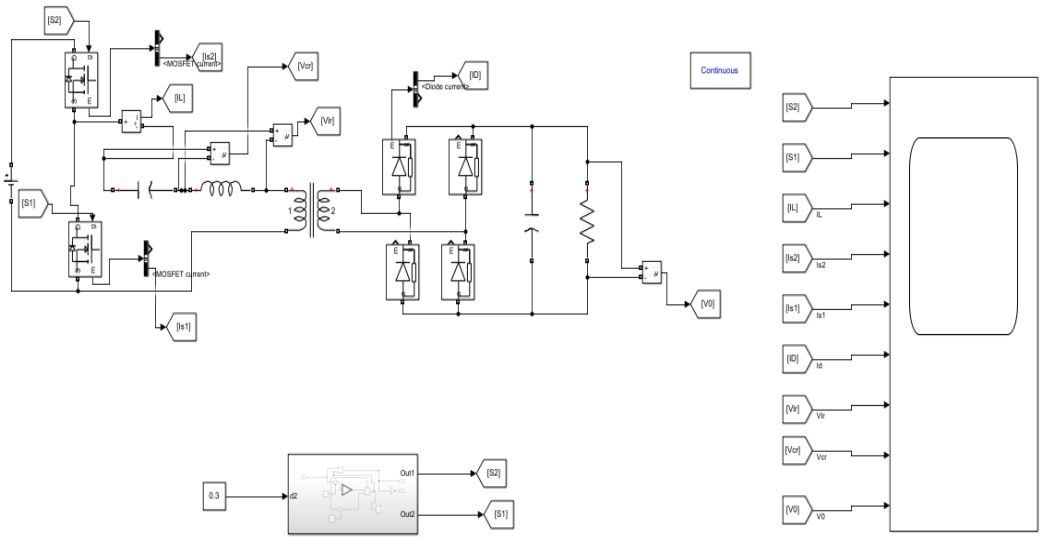


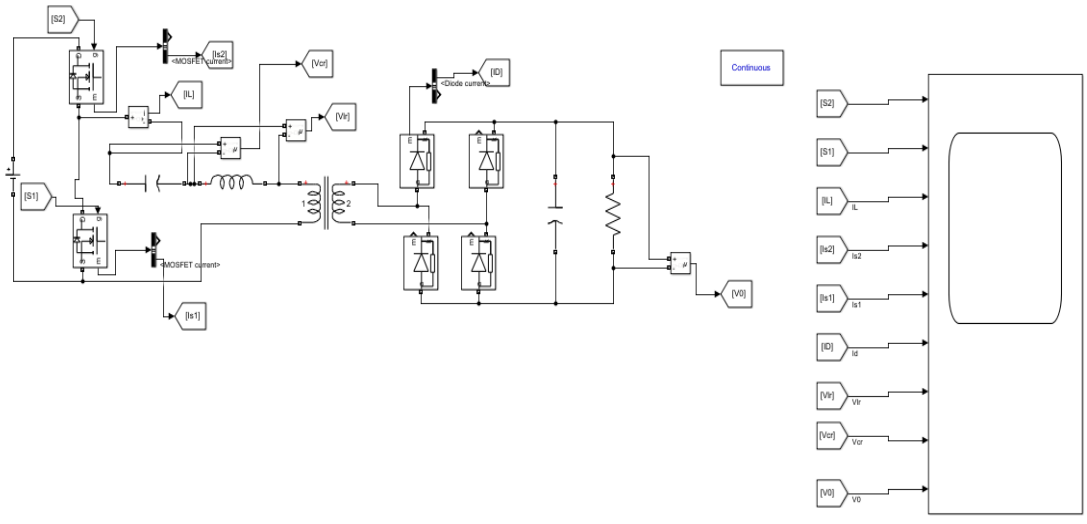
Figure 7: Simulink Model of General Process

Table 1: Half-Bridge Series Resonant Converter Parameters

P_0	<200W	fr	100 KH_Z
V_{in}	80V	L_r	2.5µH
n	0.476	C_r	1µF
V_0	29-80V	C_0	80µF
Maximum output current I_{0max}/A	2.5A	D_{1-4}	RURP1510
f_s	100-200 KH_Z	S_{1-2}	IRFB4137PbF

3.2 Half-Bridge SRC Simulink Model

Fig. 8 shows the simulation model of the half-bridge SRC, where S_1 and S_2 are the power switching MOSFETs connected with the control system by two different "goto"s (S_1, S_2). A resonant tank that consists of two main components, a resonant inductor and a resonant capacitor, is also connected by the scope using i_{Lr} "goto" to get the result of the inductor resonant current and V_{cr} "goto" to be able to have the voltage of the resonant capacitor. These two results have a critical role in studying the four different states for one period as mentioned in Chapter 2. "Goto" I_D is used for measuring the current passing through the power diodes.



. Figure 8: Half-bridge SRC Simulink Model

3.3 Control Diagram of FTM method

Fig. 9 illustrates how the FTM method works by switching on or off the MOSFETs. Duty ratio d_2 is the input of our control system, and it varies from 0 to 0.5. In our study, we used $d_2 = 0.3$. Then d_2 is subtracted from a constant value (1); the result of this subtraction must be multiplied by $2f_r$ in order to find the switching frequency f_s, and it is actually mentioned in the figure 9 as 200e3, which means the switching frequency equal to 200 Khz ,where the resonant frequency is equal to 100 Khz,. After that, switching frequencies will be integrated using an integrator. This integrator will start increasing until it reaches 1. The reset will occur as shown in Fig. 10. The reset will be done when a constant value (1) is subtracted from each value of the integral and given a value nearest to zero. At the end, the result of the integral will be compared with d_2. If d_2 is greater than the output of the integrator, S_2 turns on and S_1 turns off; otherwise, S_2 turns off and S_1 turns on.

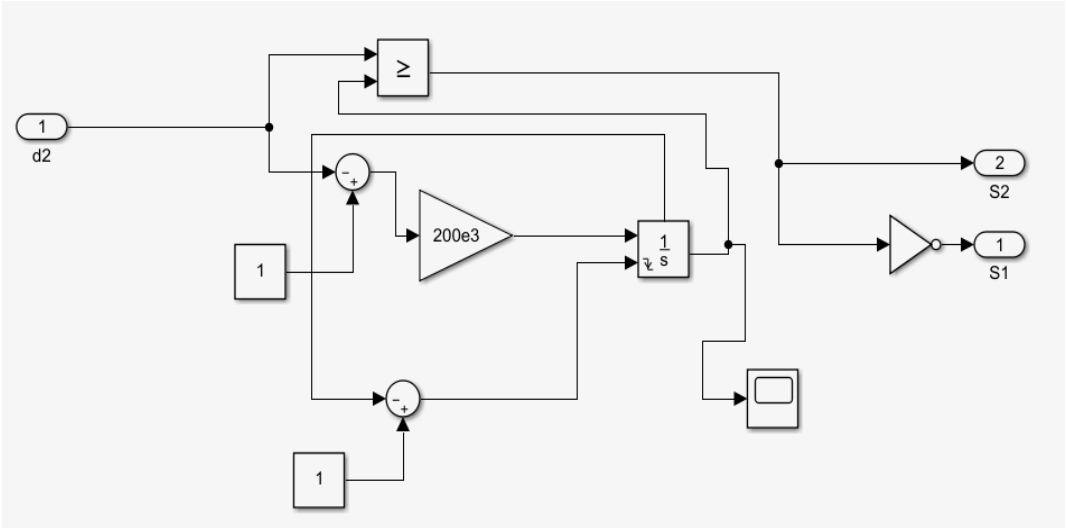


Figure 9: FTM Method Control Diagram.

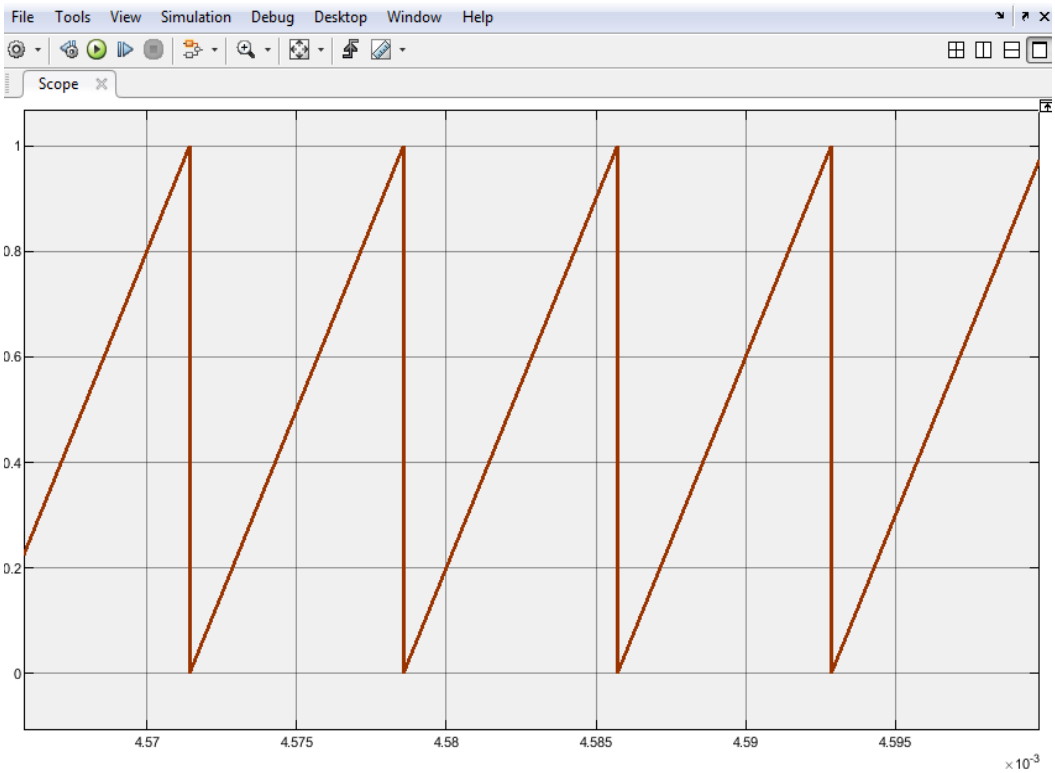


Figure 10: Integrator Output in Control System of FTM Method.

3.4 Waveforms of Operation of the Half-bridge SRC

Fig. 11. displays the simulation waveforms of operation of the half-bridge SRC using FTM method for one period. Four different states occur during this period, the process of which is explained in Chapter 2.

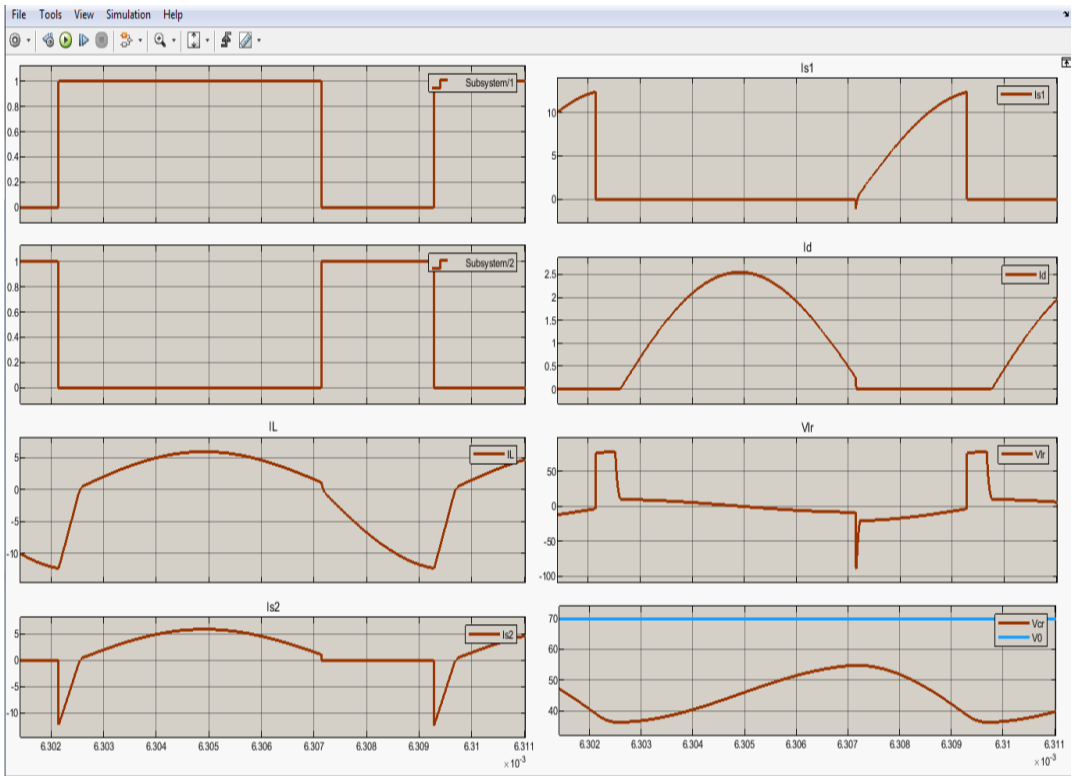


Figure 11: Simulation of Half-Bridge SRC For One Period.

3.5 Voltage Gain

3.5.1 Static Voltage Gain (M)

Voltage gain can be expressed as the output voltage over the input voltage. Output voltage is the voltage of the load at different values of duty ratio (d_2) in a range between 0 and 0.5, and input voltage is given as 80 volts. Fig. 12(a) displays the simulation results of static voltage gain as a function of d_2, and Fig. 12(b) represents the simulated results of static voltage gain as a function of F. Output voltage will be calculated by collecting the value of load voltage (V_{RL}) in the simulation under a varying value of d_2, while the normalized frequency axis must be computed by using a specific formula that has a relationship with d_2, which is $F = 1 - \frac{d_2}{2}$.

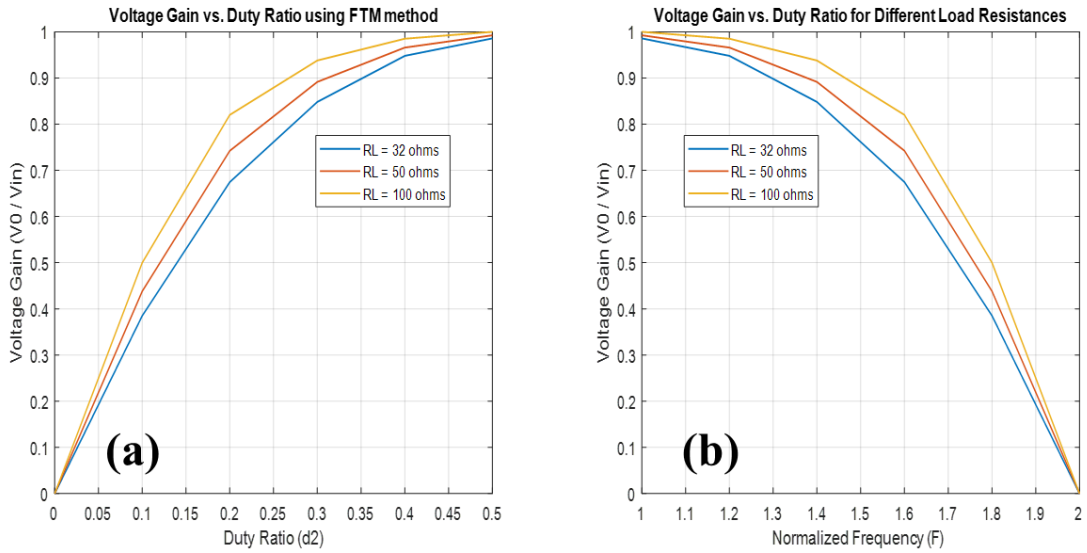


Figure 12: Half-Bridge SRC Voltage Gain Curves. (a)Voltage Gain as a Function of d2. (b)Voltage Gain as Versus Normalized Frequency (F).

The line graphs presented in both Figures 12(a) and 12(b) show three different values of load resistance (R_L= 32, 50, and 100 ohms). According to Fig. 12 (a), overall, we can see that, there is a noticeable increase in static voltage gain for all values of load resistance. Whereas, at load resistance equal to 100 ohms, it always has the higher static voltage gain for different values of d_2, except at d_2 equal to 0.5, all of them will have the same static voltage gain, which is approximately about 1.

For Fig. 12 (b), in general, there is a gradual decrease of the static voltage gain graph versus the normalized frequency for different values of F that vary between 1 and 2. While, voltage gain at R_L= 100 ohms is still the highest and at R_L= 32 ohms the lowest for all values of the normalized frequency, at F=2, the voltage gain at all the three resistance values will reach zero.

3.5.2 Voltage Gain of Maximum Capacitor Voltage (M_{Crmax})

The voltage gain of the maximum capacitor voltage can be represented as the maximum voltage of the capacitor in one complete period at different values of d_2 in

the range between 0 and 0.5 for different load resistances (R_L =32, 50, and 100 ohms) over the input voltage (V_{in}=80 volt). The maximum capacitor voltage for the three different loads can be collected from the Simulink model by taking a "goto" of V_{Cr} and connecting it to the workspace, as well as using a clock that is connected to another workspace to specify the time during the cycle. Then, one complete period is chosen at each value of d_2 and maximum value of the capacitor voltage is taken. Fig. 13(a) represents the MATLAB simulation results for the maximum ratio of the voltage across the capacitor versus duty ratio (d_2), while Fig. 13(b) illustrates the MATLAB simulation results for the maximum ratio of the capacitor voltage as a function of F.

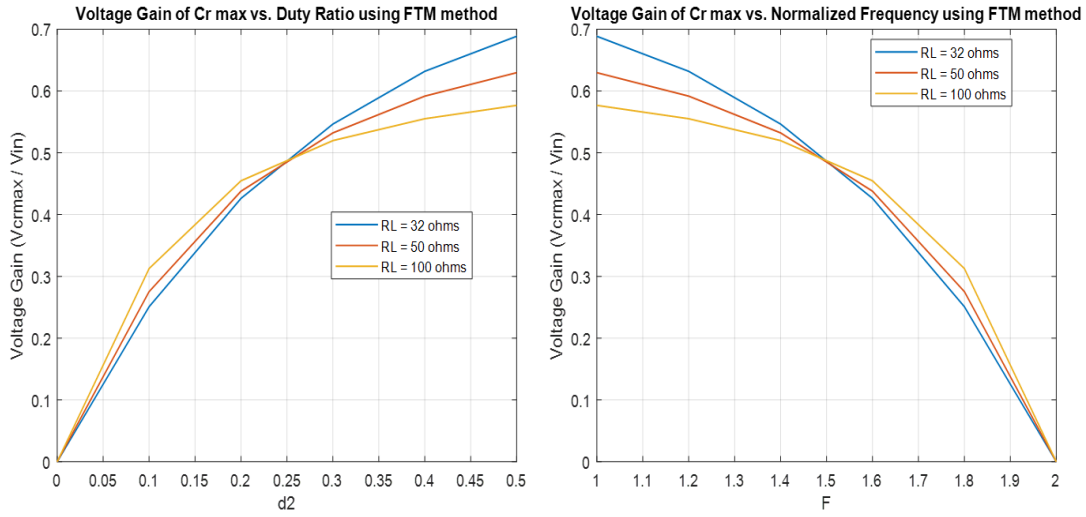


Figure 13: Maximum Ratio of Voltage Capacitor. (a) Maximum Ratio Versus d2. (b) Maximum Ratio Versus F.

The line graphs in Figs. 13(a) and 13(b) indicate the ratio of maximum voltage across capacitors for three different values of load resistance. Regarding to Fig. 13(a), the maximum ratio of voltage capacitor is increasing over the different value of d_2 in a range between 0 and 0.5 for the different values of load resistance R_L. Moreover, the voltage gain of Cr maximum was the highest at R_L= 100 ohms and lowest at R_L = 32 ohms for a duty ratio that varies between 0 and 0.2. while, after d_2 starts increasing

from 0.25 till 0.5, then R_L= 100 ohms become the lowest and R_L= 32 ohms is the highest.

After studying the result of Fig. 13(b), we conclude that the ratio of maximum voltage capacitor is gradually decreasing for the three different loads over the normalized frequency range between 1 and 2. When F changes from 1 to 1.5, R_L= 32 ohms has the highest voltage gain of maximum capacitor voltage and R_L= 100 ohms has the lowest. On the other hand, R_L= 100 ohms has the highest curve of maximum ratio of capacitor voltage and R_L= 32 is the lowest. Finally, the voltage gains of maximum capacitor voltage for the three loads become zero at F=2.

3.5.3 Voltage Gain of Minimum Capacitor Voltage (M_{Crmin})

The voltage gain of the minimum capacitor voltage can be defined as the minimum voltage of the capacitor in one complete period at different value of d_2 in the range between 0 and 0.5 for different load resistances (R_L =32, 50, and 100 ohms) divided by the input voltage (V_{in}=80 volt). The minimum capacitor voltage for the three different loads can be collected from the Simulink by taking a "goto" of V_{Cr} and connecting it to the workspace, as well as using a clock that is connected to another workspace to specify the time in the cycle. Then, one complete period is chosen at each value of d_2 and minimum value of the capacitor voltage is taken. Fig. 15(a) represents the MATLAB simulation results for the minimum ratio of the voltage across the capacitor versus d_2, while Fig. 15(b) illustrates the MATLAB simulation results for the minimum ratio of the capacitor voltage as a function of F.

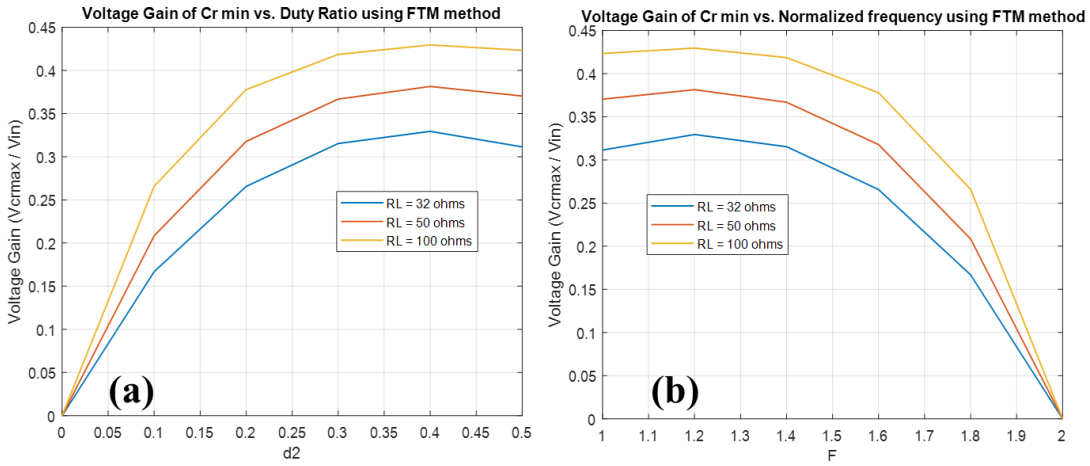


Figure 14: Minimum Ratio of Voltage Capacitor. (a) Minimum Ratio Versus d2. (b) Minimum Ratio Versus F.

The line graphs in both Fig. 14(a) and Fig. 14(b) display the ratio of minimum voltage across capacitors for three different values of load resistance. Regarding Fig. 14(a), the minimum ratio of capacitor voltage is gradually increasing over the different values of d_2 in the range between 0 and 0.5 for the different values of load resistance R_L. Furthermore, the voltage gain of Cr maximum was the greatest at R_L= 100 ohms and smallest at R_L = 32 ohms for d_2 that varies between 0 and 0.5.

After studying the result of Fig. 14(b), we find that the ratio of minimum voltage capacitor is gradually decreasing for the three different loads over F ranges between 1 and 2. Then R_L= 100 ohms has the highest curve of voltage gain of the minimum resonant capacitor voltage in that range, whereas R_L= 32 is the lowest.

3.5.4 M, M_{Crmax} and M_{Crmin} for Each Load

Fig. 15(a), Fig. 15(b), and Fig. 15(c) provide the voltage gain, the voltage gain of the maximum capacitor voltage, and the voltage gain of the minimum capacitor voltage for each load resistance (R_L= 32 ohms, R_L= 50 ohms, and R_L= 100 ohms. respectively). The MATLAB code is provided in the Appendix.

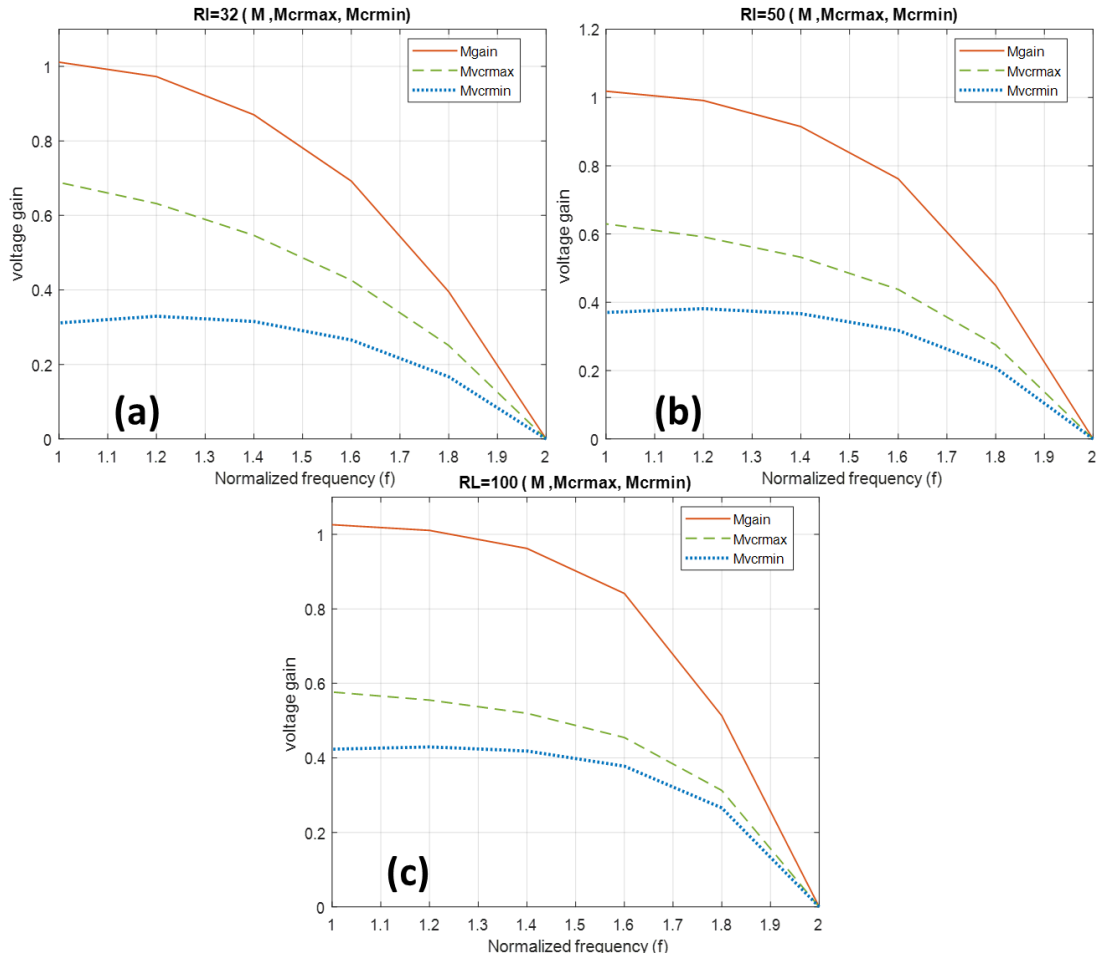


Figure 15: Voltage Gain (M, M Crmax, MCrmin) Curves for Half_Bridge SRC. (a) V-Gain (M, M Crmax, MCrmin) at RL=30 Ohms. (b) V-Gain (M, M Crmax, MCrmin) RL=50 Ohms. (c) V-Gain (M, M Crmax, MCrmin) at RL=100 Ohms

3.6 Current Stress

3.6.1 Switching Current Stress

In this section, current stress for the power switches will be studied. Since the time intervals used by the simulation solver are not equal, the following formula will be used to find the current stress in MATLAB simulation:

$$I_{s,rms} = \left(\frac{1}{T} \sum_{k=1}^{N} i_s^2(t_k).\Delta t_k \right)^{\frac{1}{2}}$$

where, $\Delta t_k = t_k - t_{k-1}$, is the time between two consecutive samplings in one complete period. T is the time needed for one period to start and finish. $i_s^2(t_k)$ will be

computed by collecting data from the Simulink model by connecting a “goto” of the current to the workspace. One complete period of the current as observed on the scope is selected. A clock is connected to another workspace in order to specify the time required for one period (T), and to calculate the time intervals between two consecutive samplings (Δt_k).

Fig 16(a) and Fig. 16(b) display the half_bridge SRC current stress curves at three different loads for switches S_1, S_2 versus the normalized frequency.

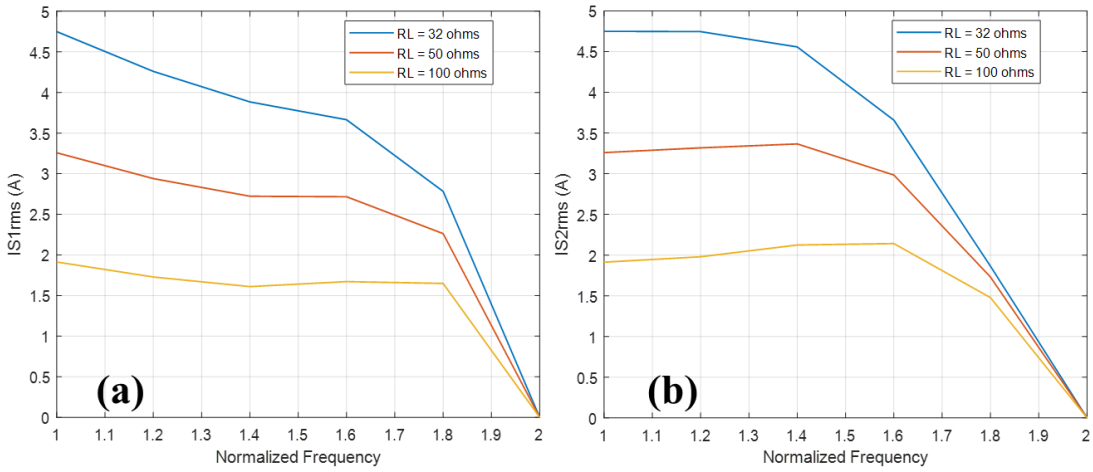


Figure 16: Switching Current Stress Curves for the Half-Bridge SRC. (a) Current Stress of S1. (b) Current Stress of S2.

Fig. 16(a) confirms that when normalized frequency is equal to 1 (F=1), the current stress of transistor S_1 will be maximum. Also, according to relation formula between normalized, resonant and switching frequency which is$F = \frac{f_s}{f_r}$, and what is observed in Fig. 16(a), the maximum current stress will occur when the resonant frequency is equal to the switching frequency. The maximum current stress of S_2 completely depends on the load resistance as mentioned in Fig. 16(b).

3.6.2 Diode Current Stress

The current stress simulation results of the four diodes used in our study can be expressed by finding the diode average current for one complete period. Diode current values are obtained for one complete cycle from the Simulink and mean values are found at each value of normalized frequency. Fig. 18 shows the diode current stress ($I_{D1\text{-}4}$), versus normalized frequency.

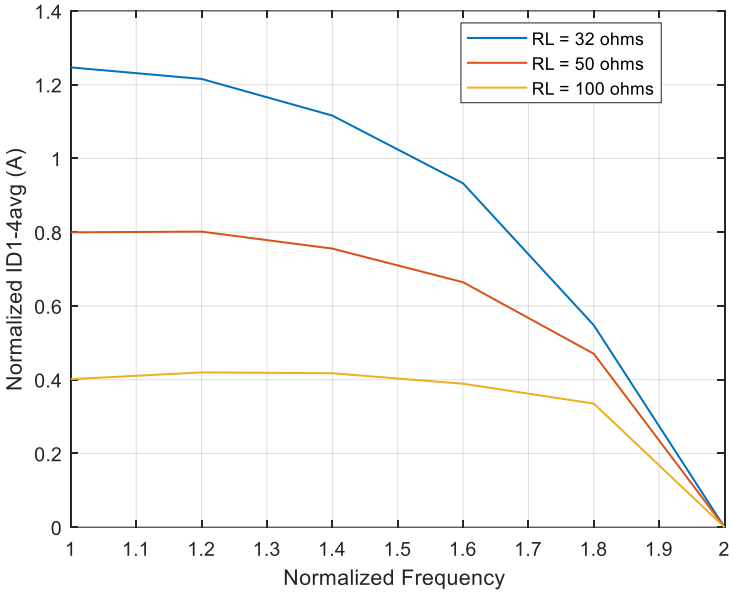


Figure 17: Current Stress of Diodes (D1-4).

The line graphs in Fig. 17 show the diodes have the highest current stress at R_L= 32 ohms, while they have the lowest stress at load resistance equal to 100 ohms as the normalized frequency varies between 1 to 2. Furthermore, the maximum current stress for the four diodes $D_{1\text{-}4}$ happen when the resonant frequency is exactly equal to the switching frequency, where the normalized frequency is equal to 1.

3.6.3 Current Stress

In this task Fig. 18(a), Fig. 18(b), and Fig. 18(c) represent the simulation results for current stresses of S_1, S_2 and $ID_{1\text{-}4}$ as a function of the output voltage, respectively.

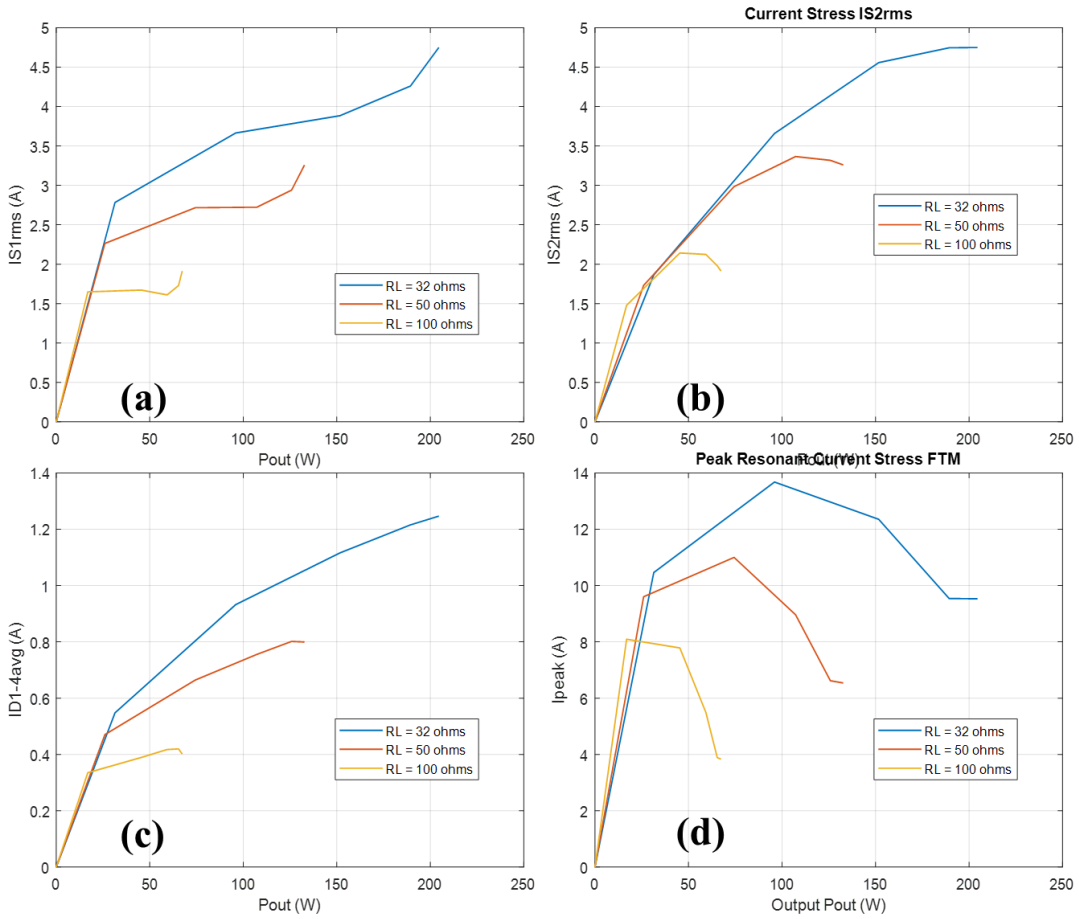


Figure 18: Current Stress Versus Output Power for Half-Bridge SRC. (a) Current Stress Versus Output Power of S1. (b) Current Stress Versus Output Power of S2, (c) Current Stress Versus Output Power of D1-4. (d) Peak Resonant Current Stress.

3.7 Normalized Current Stress

The normalized current stress for the power switches (S_1 and S_2), and the diodes (D_{1-4}) can be derived by dividing the simulation results of the current stress over the normalized current (I_{0max}) which is equal to 2.5A. Fig. 19(a), Fig. 19(b), and Fig. 19(c) represent the normalized current stresses of S_1, S_2 and ID_{1-4} versus the normalized frequency, respectively.

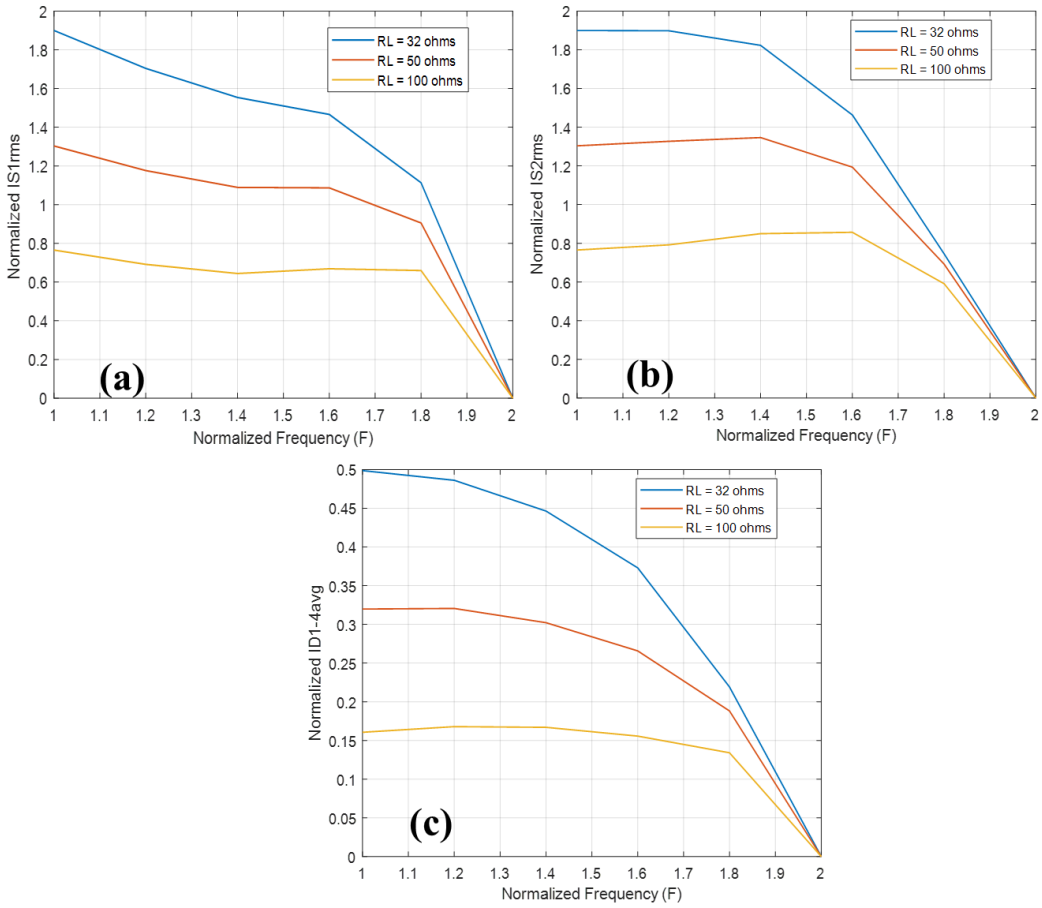


Figure 19: Normalized Current Stress Curves for Half-Bridge SRC. (a) Normalized Current Stress of S1. (b) Normalized Current Stress of S2. (c) Normalized Current Stress of D1-4.

3.8 Efficiency

The efficiency of the half_bridge SRC using the FTM technique must be calculated as output power over input power, as mentioned in chapter 2. The input power is defined as input voltage (V_{in}= 80 Volts) multiplied by the average input current. By using MATLAB simulation, the average input current can be expressed by the specific formula $I_{in} = \frac{1}{T}\sum_{k=0}^{N} i_{S_2}(t_k).\Delta t_k$. where i_{S2} is the current passing through power switch S_2 in one complete period. Output power is calculated by using this formula $P_0 = \frac{V_0^2}{R_L}$, where V_0 will be found from the Simulink at each normalized frequency for

different load resistances. Fig. 20 displays the efficiency for three different load resistances as a function of normalized frequency.

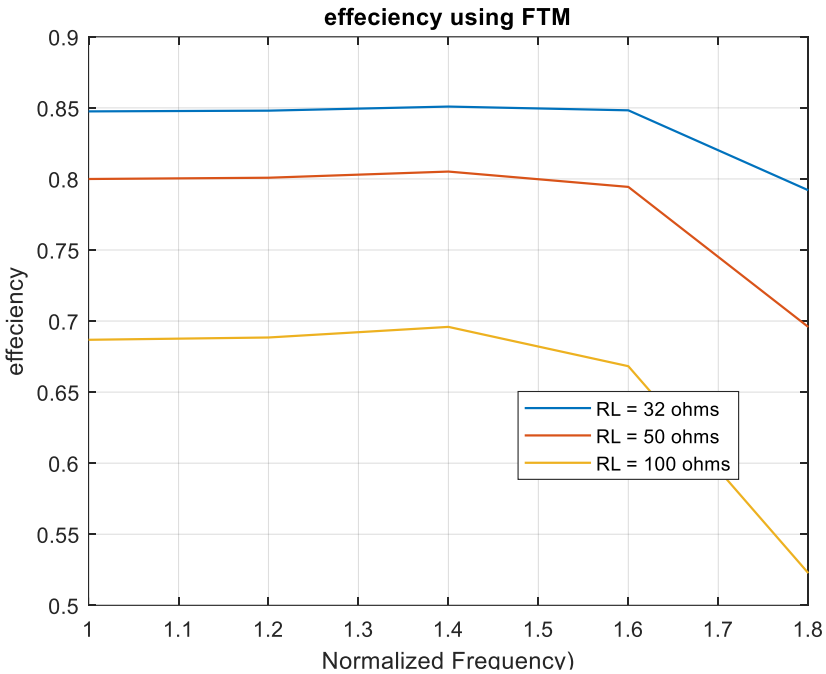


Figure 20: Efficiency of Half-Bridge SRC.

At a load resistance equal to 32 ohms, the efficiency will be highest. However, it will be lowest when the resonant load is equal to 100 ohms, as the normalized frequency varies between 1 and 1.8. When F = 2, half-bridge SRC efficiency will be undefined, as mentioned in Fig. 20.

3.9 Frequency Modulation Method (FM)

The control system of the frequency modulation technique is displayed in Fig. 21. In this method, the duty ratio ($d_1 = d_2 = 0.5$) is fixed, but the switching frequency (f_s) is variable and ranges between 100 KHz to 400 KHz, while the resonant frequency (f_r) is fixed at 100KHz, so the normalized frequency will vary from 1 to 4.

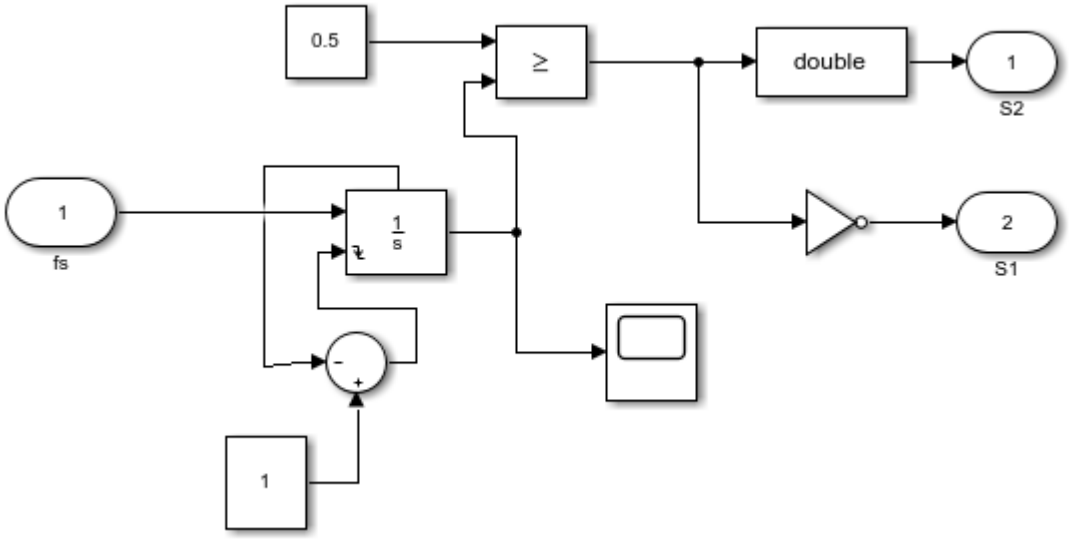


Figure 21: Control Scheme of FM Method.

Related to Fig. 21, the switching frequency will enter the integrator, the output of which will be subtracted from the constant value of 1. If the result of the subtraction reaches nearest to zero the integrator will do a reset. Then the integrator output will be compared by the relational operator with the fixed d_2= 0.5 at each different value of f_s. If d_2 is greater than or equal to the integrator output, switch 2 (S_2) will be on and S_1 will be off; if not, S_1 will be on and S_2 must be off. Fig. 22 shows the integrator output signal and how it resets. Also Fig.23 displays the waveform of the half-bridge series resonant converter using FM method for one complete period.

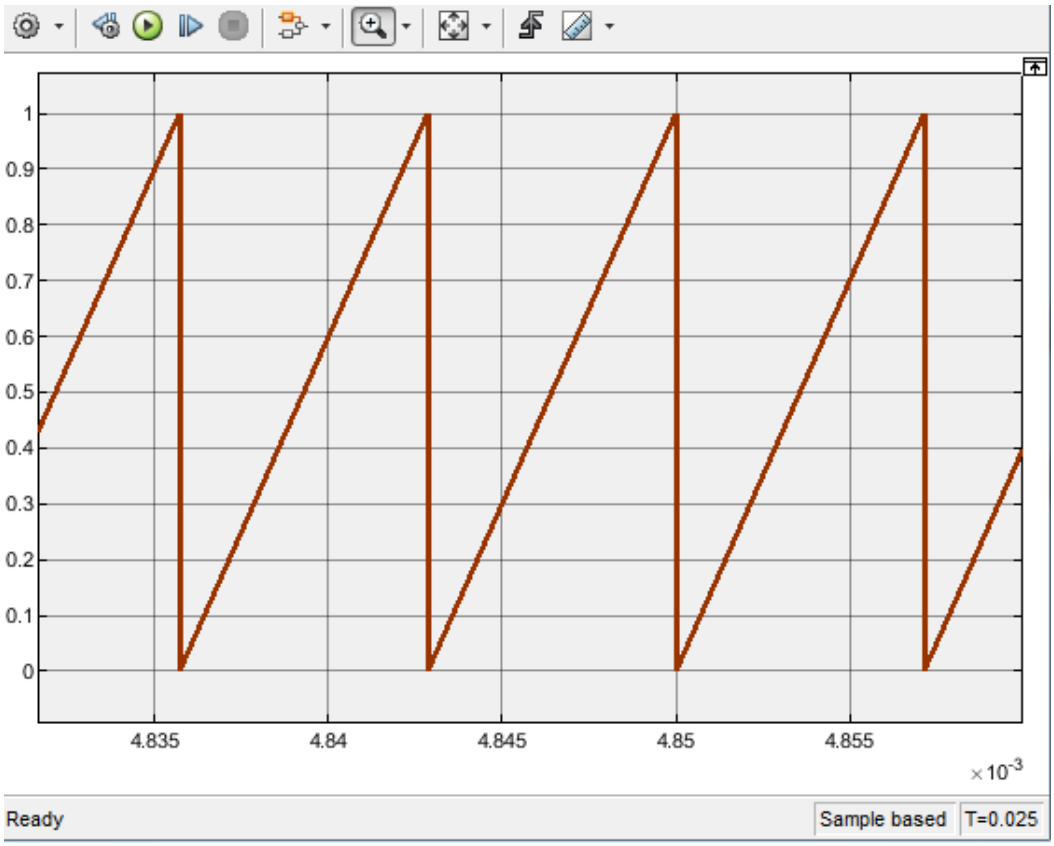


Figure 22: Integrator Results in Control System of FM method.

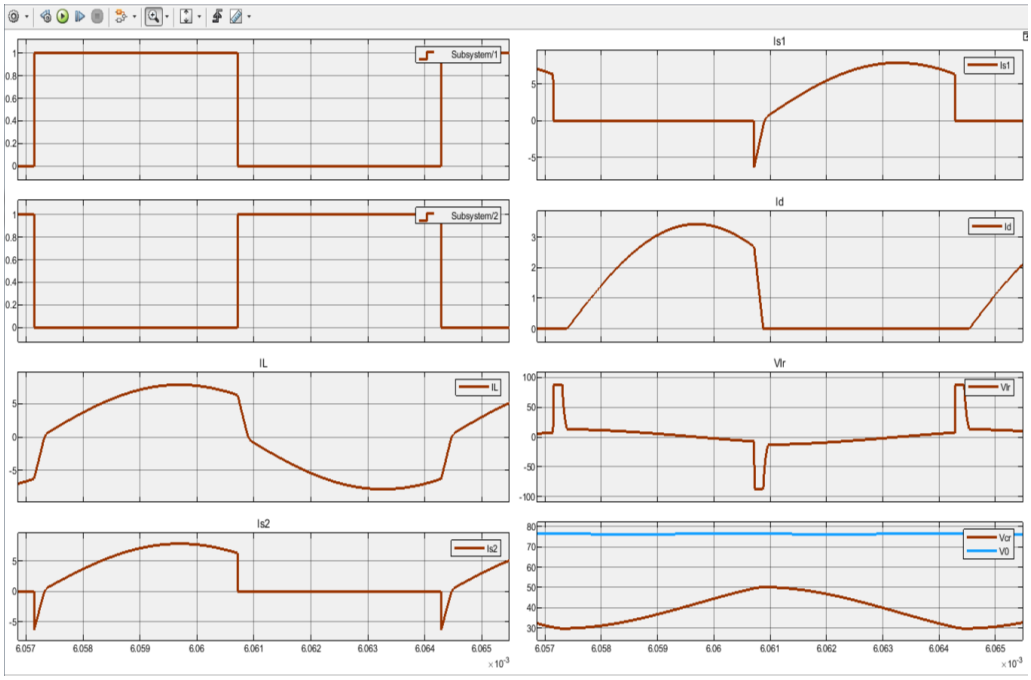


Figure 23: FM Method Waveform for One Complete Period.

3.10 Asymmetrical Pulse Width Modulation Method (APWM)

In asymmetrical pulse modulation method, the control system can be implemented as shown in Fig. 24. where the duty ratio (d_2) varies between 0 and 0.5, the same as in the FTM method, but the switching frequency and the resonant frequency are equal and have a constant value of 100 KHz ($f_r = f_s = 100$ KHz).

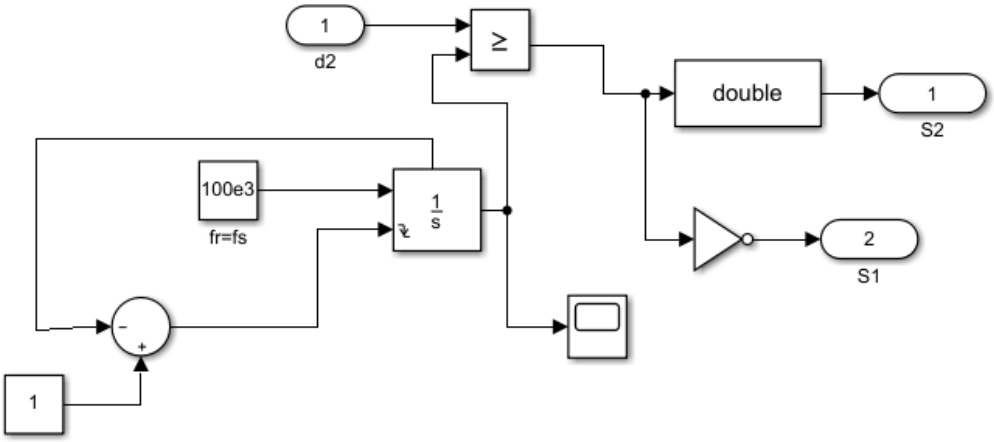


Figure 24: Control Scheme of APWM Method.

Regarding what is shown in Fig. 24 the control system will operate in the same way as the other two methods (FTM, FM) for the integrator part, where the input of the integrator, which is the switching frequency, has the same value as the resonant frequency. However, the output of the integrator will be compared with the input duty ratio (d_2), that varies between 0 and 0.5. Then, if d_2 is greater than or equal to the integrator output, S_2 will turn on; if not, S_1 will switch on. Fig. 25 corresponds to the integrator signal of APWM, similar to those of FTM and FM methods. Also Fig. 26 represents the waveform of half-bridge series resonant converter using APWM method.

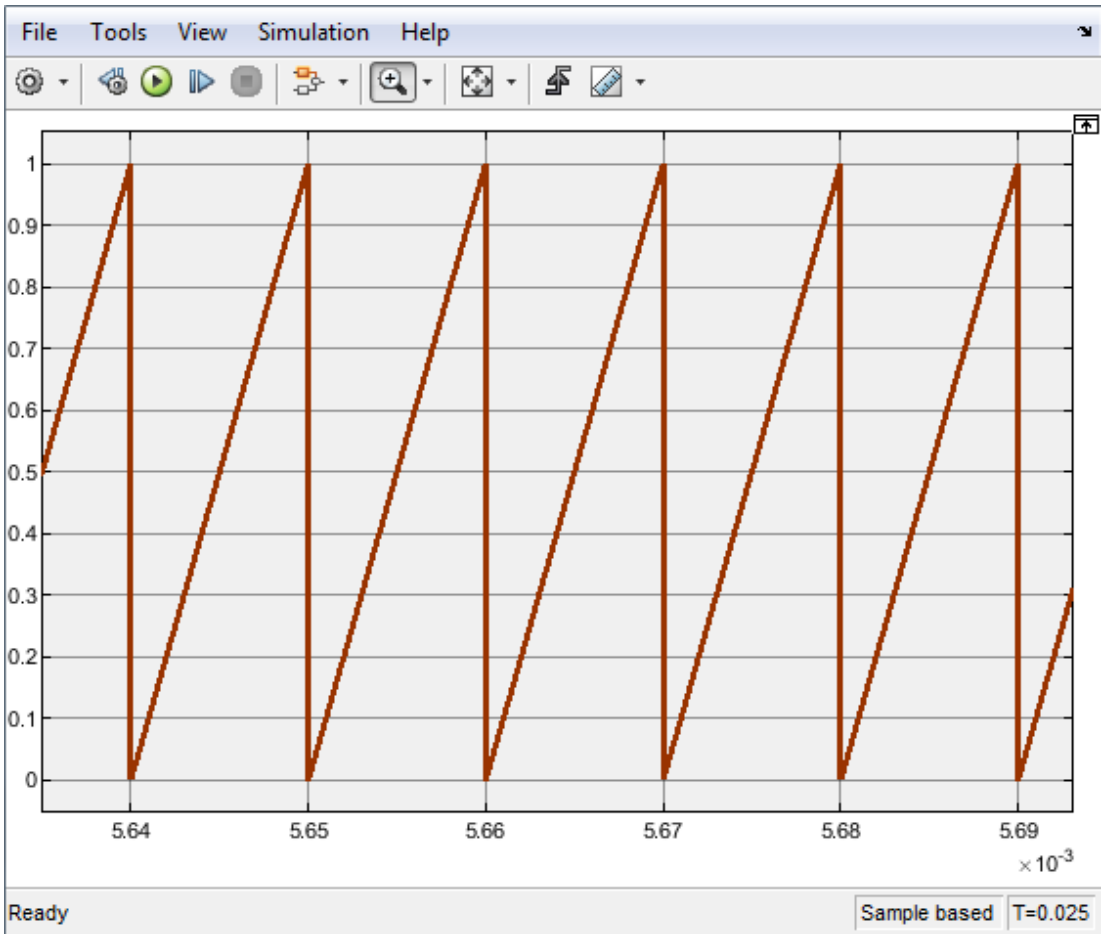


Figure 25: Integrator Output in Control System of APWM Method.

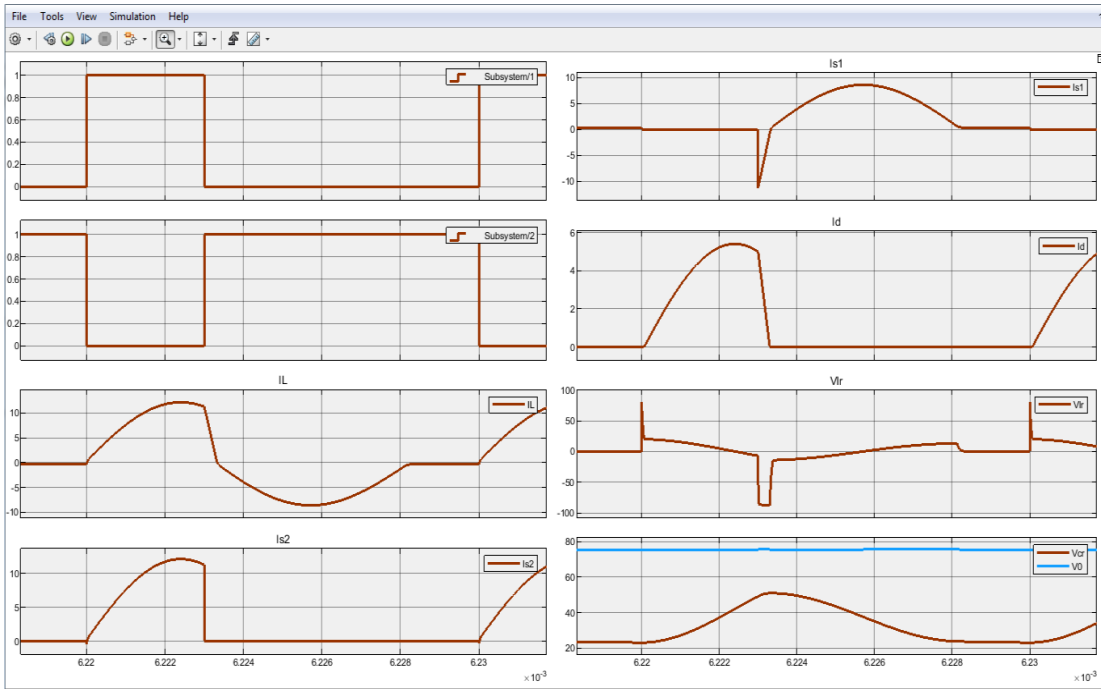


Figure 26: APWM Method Waveform for One Complete Period.

3.11 Comparison Part

In this part, some simulation results will be compared between the three different methods used in our study. These comparisons will be mainly about voltage gain, current stresses, and efficiency.

3.11.1 Voltage Gain

Fig. 27. displays that the Matlab simulation and the theoretical results of the voltage gain (M, M_{Crmax}, M_{Crmin}) for RL=32 ohms are approximately same; there is a little difference due to an experimental error.

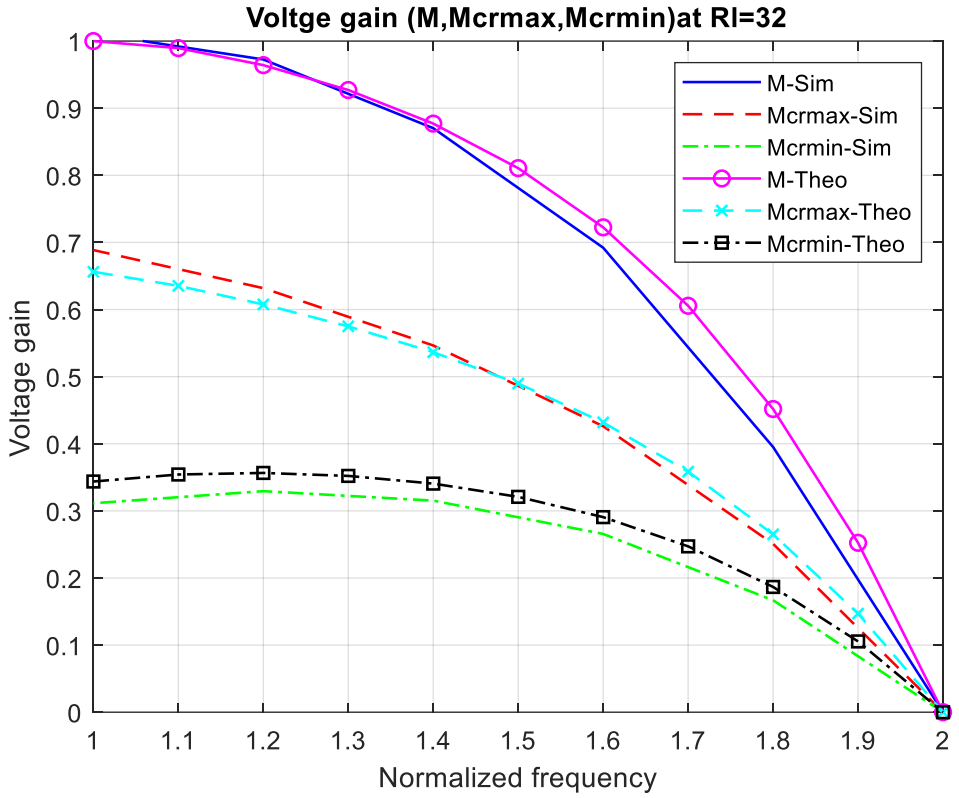


Figure 27: Half-Bridge SRC Voltage Gain Curves. Comparison Between Simulation Result and Theoretical Result of Voltage Gain at RL=32 Ohms.

Fig. 28(a) displays the voltage gain comparison between FTM and FM methods as a function of normalized frequency. While, Fig. 28(b) provides the voltage gain comparison between FTM and APWM methods as a function of duty ratio.

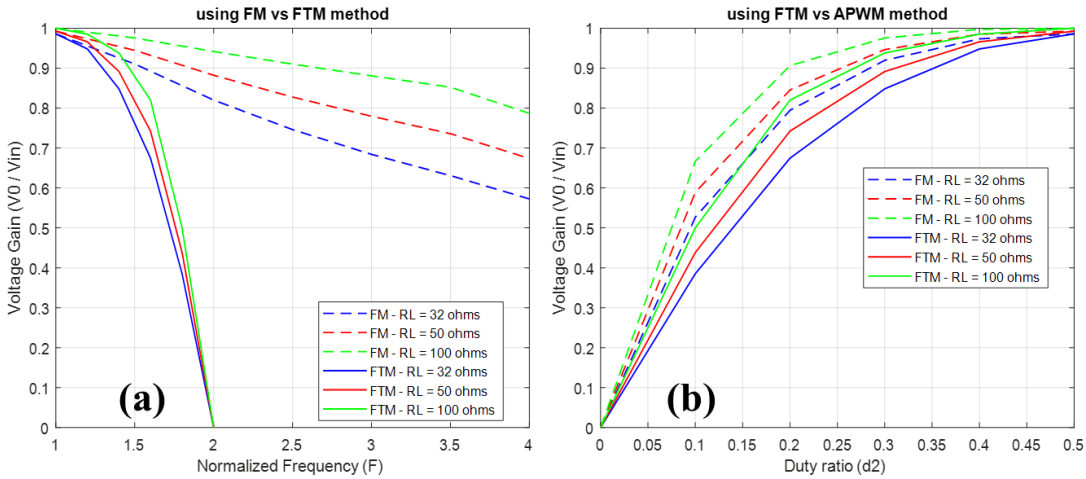


Figure 28: Half-Bridge SRC Voltage Gain Comparison. (a) Comparison Between FTM Method and FM Method. (b) Comparison Between FTM Method and APWM Method.

Starting with Fig. 28(a), when the load resistance equals 50 ohms, the half bridge SRC voltage gain with FTM technique becomes 0 at normalized frequency equals 2. However, when normalized frequency is equal to 4, the half bridge SRC voltage gain remains equal 0.69. Then, as shown in Fig. 28(b). when F=1, full range regulate could be accomplished through the APWMN and FTM algorithms. Nevertheless, APWM method obtains higher and less voltage gain than the FTM method over the same duty ratio.

3.11.2 Current Stress

Fig. 29(a), Fig. 29(b), Fig. 29(c), and Fig. 29(d) depict the current stress curves of S_1, S_2, $D_{1\text{-}4}$ and I_{peak} with FTM, FM, and APWM methods, respectively, as a function of output power.

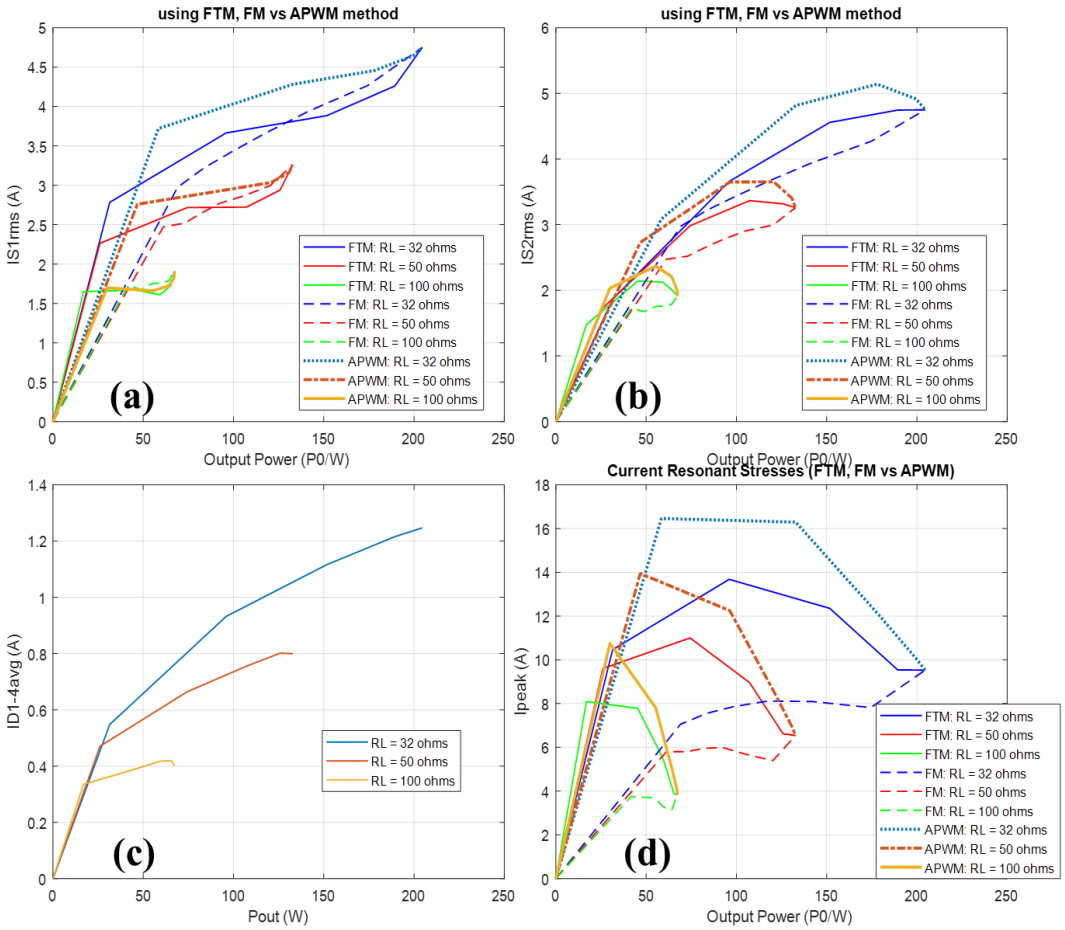


Figure 29: FTM, FM, and APWM Method Current Stress Curves. (a) S1 Current Stresses. (b) S2 Current Stress. (c) D1-4 Current Stress. (d) Peak Resonant Current Stresses

In Fig. 29(a), Regardless of the load resistance, the APWM technique has the greatest current stress compared to the three. Also, the FTM method has a higher current stress of S_1 than FM method when there is low output power, but when the output power increases to reach a particular value, S_1 current stress using FM technique will be higher than using FTM technique. As shown in Fig. 29(b), when the output power is low, the current stress of S_2 with the FM method is higher than that of the FTM method, while when the output power increases, the current stress of S_2 with the FM method is lower than that of the FTM method. Whereas, S_2 current stress with the FTM technique is usually lower than that of the APWM method. Moreover, when the output power is low, S_2 current stress with the APWM technique is smaller than that of the FM

technique, however, when the output power increases, S_2 current stress in FM method is lower than that of the APWM method. According to Fig. 29(c), the average diode current for the three methods is exactly the same. Fig. 29(d) shows the peak resonant current stresses for the three methods, which are the same as the S_2 current peak values. It can be seen that the peak current with the FM method is the lowest. On the other hand, the peak current with the APWM method has the highest values. In the end, full-range regulate is not reached with FM technique, but it is with the APWM and FTM techniques. Moreover, FTM algorithm has smaller current stresses than the APWM algorithm. So, to attain full-range regulation, FTM method is the best one.

3.11.3 Efficiency

Fig. 30(a), Fig. 30(b), and Fig. 30(c) depict the efficiency of the two methods (FTM and APWM) for the load resistances R_L= 32 ohms, R_L= 50 ohms, and R_L= 100 ohms respectively, versus of duty ratio d_2.

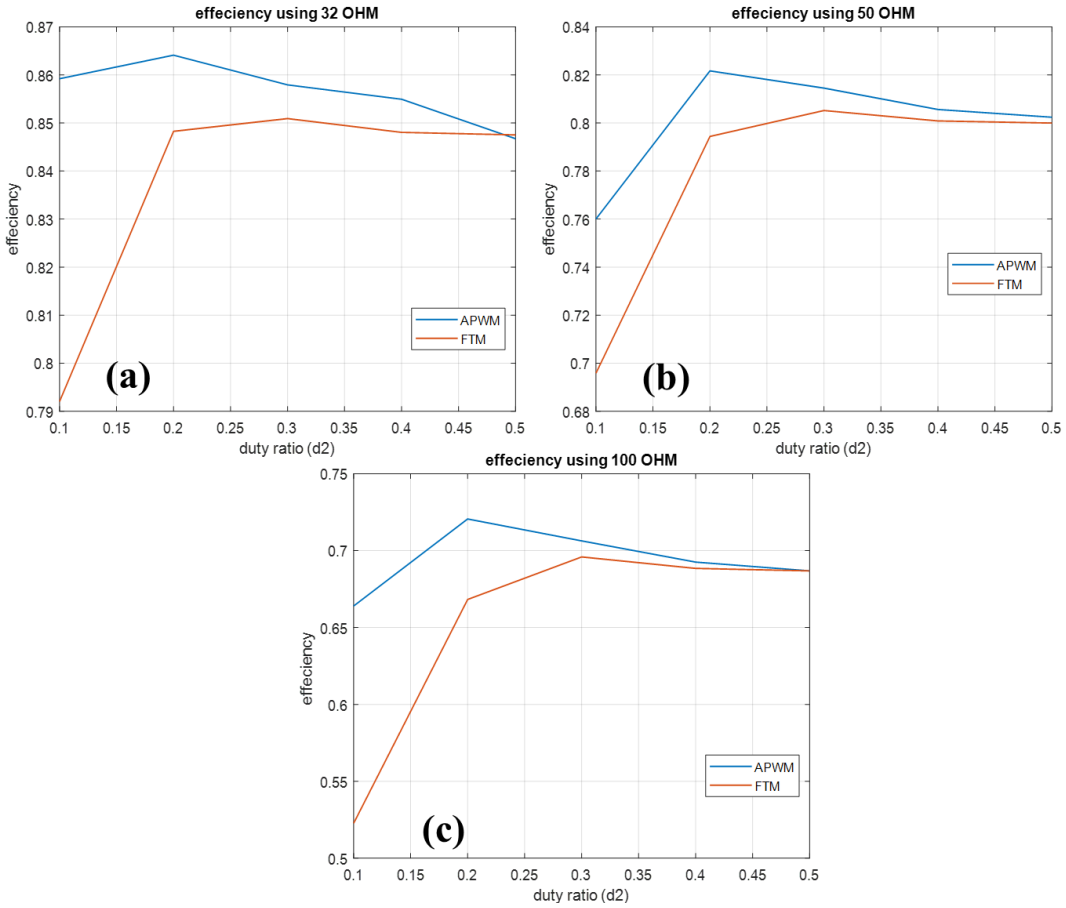


Figure 30: FTM and APWM Method Efficiency Curves. (a) Efficiency of RL = 32 Ohms. (b) Efficiency of RL = 50 Ohms. (c) Efficiency of RL = 100 Ohms.

As shown in Fig. 30(a), Fig. 30(b), and Fig. 30(c), whatever the load resistances, the APWM approach has the best efficiency of the two.

As shown in Fig. 31(a), Fig. 31(b), and Fig. 31(c). When the normalized frequency between is 1 and 1.5, the efficiency with the FM technique is smaller than that with the FTM technique, but when the normalized frequency rise from 1.5 to 2, the efficiency with the FM method is larger than that with FTM method. Where FM method cannot attain a full-range regulation.

Both APWM and FTM techniques efficiency will stop at F = 1.8 since the output power and the input power at F = 2 are equal to zero. While the FM method can give an efficiency value at F=2.

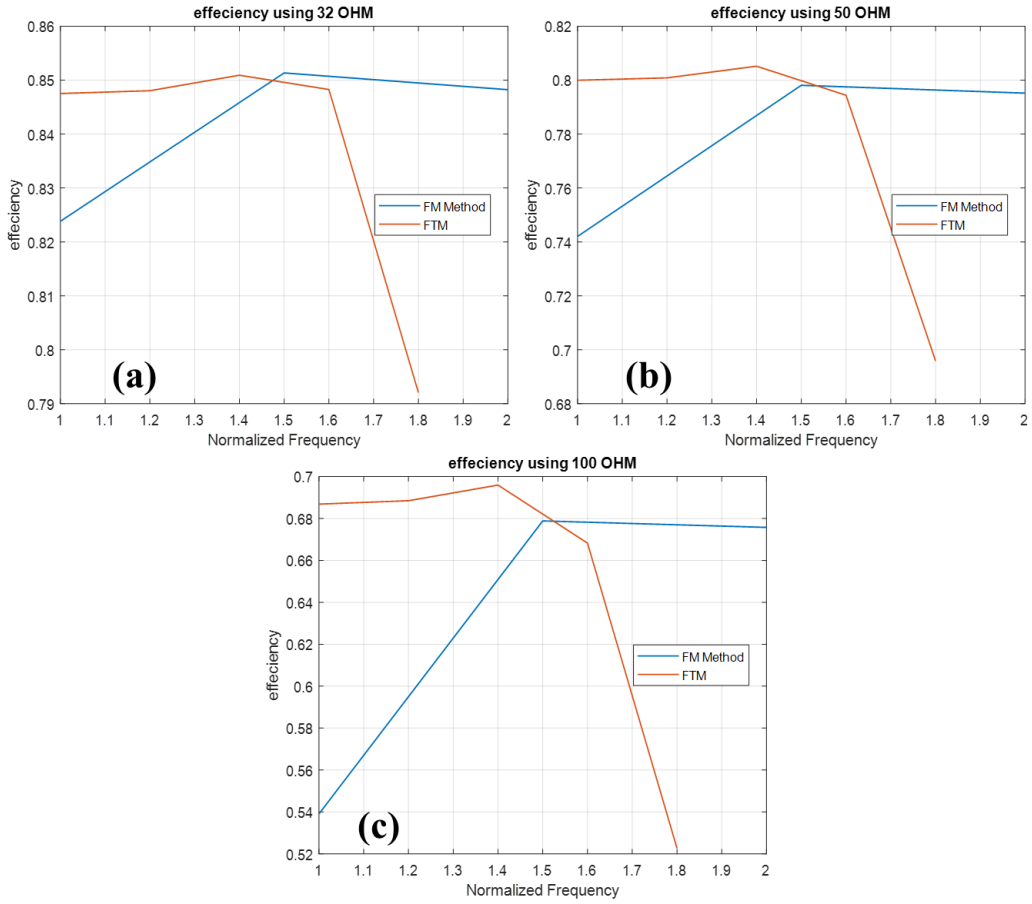


Figure 31: FTM and FM Method Efficiency Curves. (a) Efficiency of RL = 32 Ohms. (b) Efficiency of RL = 50 Ohms. (c) Efficiency of RL = 100 Ohms.

Chapter 4

CONCLUSION AND FUTURE STUDY

Our study focused on the half-bridge series resonant converter to achieve full-range regulation for three different load resistances. The FM method cannot attain a full-range regulation. The APWM method achieves full-range regulation with high current stress and high efficiency. Furthermore, the FTM method also has high efficiency and low current stress. Therefore, FTM is the best option used in the half-bridge SRC to attain a full-range regulation. The MATLAB simulation results validated the theoretical analysis in our study. The performance of the half-bridge SRC with the FTM method for different configurations that can be tested under different setup or parameter values and it used to facilitate engineering design, reduce losses, and increase efficiency.

Some of the possible future work in the context of this thesis are listed below:

- Using advanced materials for resonant components (inductors and capacitors) to minimize losses.
- Develop control strategies for the FTM method that are mainly used to maximize the efficiency; this includes an artificial-intelligence-based control method.
- Improve the efficiency of the Half Bridge SRC by optimizing the transformer's design. This entails investigating cutting-edge core materials, reducing leakage inductance, and turn-ratio optimization.

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APPENDIX

Static voltage gain using FTM algorithm (M) as a function of d_2
MATLAB code:

```
% Define the input parameters
Vin = 80; % Input voltage (V)
Lr = 2.5e-6 % Resonant inductor value (H)
Cr = 1e-6; % Resonant capacitor value (F)
f = 100e3; % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)

% Initialize arrays to store the output voltages for each RL value
%V0 =
[out32.V32(1,1),out32.V32(2,1),out32.V32(3,1),out32.V32(4,1),out32.V
32(5,1),out32.V32(6,1);out50.V50(1,1),out50.V50(2,1),out50.V50(3,1),
out50.V50(4,1),out50.V50(5,1),out50.V50(6,1);out100.V100(1,1),out100
.V100(2,1),out100.V100(3,1),out100.V100(4,1),out100.V100(5,1),out100
.V100(6,1)];

V0 =
[V32(1,1),V32(2,1),V32(3,1),V32(4,1),V32(5,1),V32(6,1);V50(1,1),V50(
2,1),V50(3,1),V50(4,1),V50(5,1),V50(6,1);V100(1,1),V100(2,1),V100(3,
1),V100(4,1),V100(5,1),V100(6,1)];


%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
Vin=80;
Vgain = zeros(length(RL_values), length(d2_range));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        Vgain(j, i)=V0(j, i)/ Vin;
    end
end
figure;
%Vgain=Vgain(:,:)./max(max(Vgain));
Vgain=Vgain(:,:)./max(max(Vgain));

for j = 1:length(RL_values)
    plot(d2_range, Vgain(j, :), 'DisplayName', sprintf('RL = %d
ohms', RL_values(j)));
    hold on;
end
xlabel('Duty Ratio (d2)');
ylabel('Voltage Gain (V0 / Vin)');
title('Voltage Gain vs. Duty Ratio using FTM method');
legend('Location', 'Best');
grid on;
```

The minimum and maximum ratios of the voltage that flow the capacitor over the input voltage and the static gain with the FTM method as a function of F theoretical result MATLAB code:

```
n=0.5;
Cr=1.e-06;
RL=32;
fr=100.e+03;
% F=1:0.1:2;
for k = 1:11
    F = 1 + (k-1)/10;
    d2=1-(F/2);
    fs=F*fr;
    w = Cr*RL*fs;
    h = cos(2*pi*d2/F);
    D = (8*w*n^2-1)^2*h^2+(8*w*n^2+1)^2*(1-2*h)+32*w*n^2;
    M(k)= ((8*w*n^2-1)*(h-1)+sqrt(D))/(8*n);

    a=(8*M(k)*w^2*n^3)*(1-h);
    b=M(k)^2*(-1+(4*w*n^2));
    c=(8*w^2*n^2)*(h-1);
    d=(4*M(k)*w*n)*(h-1);
    e=(4*n*w)*((2*h*w*n)-(2*w*n)-M(k));
    m=M(k)^2*(1+(4*w*n^2));

    Vcmax(k)=(a+b+c+d)/e;
    Vcmin(k)=(a+m+c)/e;
end
k=1:11;
```

The maximum ratio of the voltage that flow the capacitor divided by the input voltage with the FTM method as a function of F MATLAB code:

```
% Define the input parameters
Vin = 80;       % Input voltage (V)
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;% Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F_range= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
%%
%RL=32 ohms
% d2=0
V10FTM=0;

% d2=0.1
N1=1511209;  N2=1511771;
v11=Vcr32FTM1(N1:N2-1);
V11FTM=max(v11);

% d2=0.2
N1=1253361;  N2=1253997;
v12=Vcr32FTM2(N1:N2-1);
V12FTM=max(v12);
```

```
% d2=0.3
N1=1205555;  N2=1206282;
v13=Vcr32FTM3(N1:N2-1);
V13FTM=max(v13);

% d2=0.4
N1=1151150;  N2=1152009;
v14=Vcr32FTM4(N1:N2-1);
V14FTM=max(v14);

% d2=0.5
N1=1119408;  N2=1120418;
v15=Vcr32FTM5(N1:N2-1);
V15FTM=max(v15);

Vcrmax32FTM=[V10FTM, V11FTM, V12FTM, V13FTM, V14FTM, V15FTM];
%%
%RL=50ohm
% d2=0
V20FTM=0;

% d2=0.1
N1=1242253;  N2=1242921;
v21=Vcr50FTM1(N1:N2-1);
V21FTM=max(v21);

% d2=0.2
N1=1227982;  N2=1228727;
v22=Vcr50FTM2(N1:N2-1);
V22FTM=max(v22);

% d2=0.3
N1=1119813;  N2=1120542;
v23=Vcr50FTM3(N1:N2-1);
V23FTM=max(v23);

% d2=0.4
N1=1128103;  N2=1128953;
v24=Vcr50FTM4(N1:N2-1);
V24FTM=max(v24);

% d2=0.5
N1=1125107;  N2=1126123;
v25=Vcr50FTM5(N1:N2-1);
V25FTM=max(v25);

Vcrmax50FTM=[V20FTM, V21FTM, V22FTM, V23FTM, V24FTM, V25FTM];
%%
%RL=100ohm
% d2=0
V30FTM=0;

% d2=0.1
N1=1262777;  N2=1263404;
v31=Vcr100FTM1(N1:N2-1);
V31FTM=max(v31);

% d2=0.2
N1=1088462;  N2=1089101;
```

```
v32=Vcr100FTM2(N1:N2-1);
V32FTM=max(v32);

% d2=0.3
N1=1167318;  N2=1168050;
v33=Vcr100FTM3(N1:N2-1);
V33FTM=max(v33);

% d2=0.4
N1=1074238;  N2=1075085;
v34=Vcr100FTM4(N1:N2-1);
V34FTM=max(v34);

% d2=0.5
N1=1166089;  N2=1167115;
v35=Vcr100FTM5(N1:N2-1);
V35FTM=max(v35);

Vcrmax100FTM=[V30FTM, V31FTM, V32FTM, V33FTM, V34FTM, V35FTM];

Vcrmax=[Vcrmax32FTM;Vcrmax50FTM;Vcrmax100FTM];
%%
F_range= (1-d2_range)*2; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
Vin=80;
Vgaincrmax = zeros(length(RL_values), length(F_range));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range)
         F = F_range(i);
        Vgaincrmax(j, i)=Vcrmax(j, i)/ Vin;
    end
end
figure;
%Vgain=Vgain(:,:)./max(max(Vgain));
%Vgaincrmax=Vgaincrmax(:,:)./max(max(Vgaincrmax));

for j = 1:length(RL_values)
    plot(F_range, Vgaincrmax(j, :), 'DisplayName', sprintf('RL = %d
ohms', RL_values(j)));
    hold on;
end
xlabel('F');
ylabel('Voltage Gain (Vcrmax / Vin)');
title('Voltage Gain of Cr max vs. Normalized Frequency using FTM
method');
legend('Location', 'Best');
grid on;


V22FTM=max(v22);
```

The minimum ratio of the voltage that flow the capacitor divided by the input voltage with the FTM method as a function of F MATLAB code:

```
% Define the input parameters
Vin = 80;       % Input voltage (V)
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;    % Resonant capacitor value (F)
```

```
f = 100e3;      % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
%%
%RL=32 ohms
% d2=0
V10FTM=0;

% d2=0.1
N1=1511209;  N2=1511771;
v11=Vcr32FTM1(N1:N2-1);
V11FTM=min(v11);

% d2=0.2
N1=1253361;  N2=1253997;
v12=Vcr32FTM2(N1:N2-1);
V12FTM=min(v12);

% d2=0.3
N1=1205555;  N2=1206282;
v13=Vcr32FTM3(N1:N2-1);
V13FTM=min(v13);

% d2=0.4
N1=1151150;  N2=1152009;
v14=Vcr32FTM4(N1:N2-1);
V14FTM=min(v14);

% d2=0.5
N1=1119408;  N2=1120418;
v15=Vcr32FTM5(N1:N2-1);
V15FTM=min(v15);

Vcrmin32FTM=[V10FTM, V11FTM, V12FTM, V13FTM, V14FTM, V15FTM];
%%
%RL=50ohm
% d2=0
V20FTM=0;

% d2=0.1
N1=1242253;  N2=1242921;
v21=Vcr50FTM1(N1:N2-1);
V21FTM=min(v21);

% d2=0.2
N1=1227982;  N2=1228727;
v22=Vcr50FTM2(N1:N2-1);
V22FTM=min(v22);

% d2=0.3
N1=1119813;  N2=1120542;
v23=Vcr50FTM3(N1:N2-1);
V23FTM=min(v23);

% d2=0.4
N1=1128103;  N2=1128953;
v24=Vcr50FTM4(N1:N2-1);
V24FTM=min(v24);
```

```
% d2=0.5
N1=1125107;  N2=1126123;
v25=Vcr50FTM5(N1:N2-1);
V25FTM=min(v25);

Vcrmin50FTM=[V20FTM, V21FTM, V22FTM, V23FTM, V24FTM, V25FTM];
%%
%RL=100ohm
% d2=0
V30FTM=0;

% d2=0.1
N1=1262777;  N2=1263404;
v31=Vcr100FTM1(N1:N2-1);
V31FTM=min(v31);

% d2=0.2
N1=1088462;  N2=1089101;
v32=Vcr100FTM2(N1:N2-1);
V32FTM=min(v32);

% d2=0.3
N1=1167318;  N2=1168050;
v33=Vcr100FTM3(N1:N2-1);
V33FTM=min(v33);

% d2=0.4
N1=1074238;  N2=1075085;
v34=Vcr100FTM4(N1:N2-1);
V34FTM=min(v34);

% d2=0.5
N1=1166089;  N2=1167115;
v35=Vcr100FTM5(N1:N2-1);
V35FTM=min(v35);

Vcrmin100FTM=[V30FTM, V31FTM, V32FTM, V33FTM, V34FTM, V35FTM];

Vcrmin=[Vcrmin32FTM;Vcrmin50FTM;Vcrmin100FTM];
%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F_range= (1-d2_range)*2;
RL_values = [32, 50, 100]; % Load resistance values (ohms)
Vin=80;
Vgaincrmin = zeros(length(RL_values), length(F_range));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range)
         F = F_range(i);
        Vgaincrmin(j, i)=Vcrmin(j, i)/ Vin;
    end
end
figure;
%Vgain=Vgain(:,:)./max(max(Vgain));
%Vgaincrmin=Vgaincrmin(:,:)./max(max(Vgaincrmin));

for j = 1:length(RL_values)
```

```
    plot(F_range, Vgaincrmin(j, :), 'DisplayName', sprintf('RL = %d
ohms', RL_values(j)));
    hold on;
end
xlabel('F');
ylabel('Voltage Gain (Vcrmax / Vin)');
title('Voltage Gain of Cr min vs. Normalized frequency using FTM
method');
legend('Location', 'Best');
grid on;
```

Normalized current stress of S_1 versus the normalized frequency using FTM technique MATLAB code:

```
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
I0=2.5;
%%
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 401988 ; N2 = 403002;
T11=t32F1(N2)-t32F1(N1);
tss=t32F1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=IS132F1(N1:N2-1);
I11sqr= i11.*i11;
A11= I11sqr.*deltat11;
I11=sqrt((1/T11)*sum(A11))/I0;

%F2=1.2 (d2=0.4)
N1 = 466765;  N2 = 467636;
T12=t32F2(N2)-t32F2(N1);
tss=t32F2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS132F2(N1:N2-1);
I12sqr= i12.*i12;
A12= I12sqr.*deltat12;
I12=sqrt((1/T12)*sum(A12))/I0;  % normalized rms

%F3=1.4 (d2=0.3)
N1 = 440111;  N2 = 440838;
T13=t32F3(N2)-t32F3(N1);
tss=t32F3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
i13=IS132F3(N1:N2-1);
I13sqr= i13.*i13;
A13= I13sqr.*deltat13;
I13=sqrt((1/T13)*sum(A13))/I0;  % normalized rms

%F4=1.6 (d2=0.2)
N1 = 375208;  N2 = 375848;
T14=t32F4(N2)-t32F4(N1);
```

```
tss=t32F4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS132F4(N1:N2-1);
I14sqr= i14.*i14;
A14= I14sqr.*deltat14;
I14=sqrt((1/T14)*sum(A14))/I0;  % normalized rms

%F5=1.8 (d2=0.1)
N1 = 437631;  N2 = 438201;
T15=t32F5(N2)-t32F5(N1);
tss=t32F5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS132F5(N1:N2-1);
I15sqr= i15.*i15;
A15= I15sqr.*deltat15;
I15=sqrt((1/T15)*sum(A15))/I0;  % normalized rms

%F6=2 (d2=0)
I16=0;

% define the rms values of IS1 in matrix (RL=32ohm)
IS132rms= [I16, I15, I14, I13, I12, I11];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 261716 ; N2 = 262737;
T21=t50F1(N2)-t50F1(N1);
tss=t50F1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS150F1(N1:N2-1);
I21sqr= i21.*i21;
A21= I21sqr.*deltat21;
I21=sqrt((1/T21)*sum(A21))/I0;

%F2=1.2 (d2=0.4)
N1 = 288205 ; N2 = 289050;
T22=t50F2(N2)-t50F2(N1);
tss=t50F2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS150F2(N1:N2-1);
I22sqr= i22.*i22;
A22= I22sqr.*deltat22;
I22=sqrt((1/T22)*sum(A22))/I0;

%F3=1.4 (d2=0.3)
N1 = 326180 ; N2 = 326913;
T23=t50F3(N2)-t50F3(N1);
tss=t50F3(N1:N2);
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS150F3(N1:N2-1);
I23sqr= i23.*i23;
A23= I23sqr.*deltat23;
I23=sqrt((1/T23)*sum(A23))/I0;

%F4=1.6 (d2=0.2)
```

```
N1 = 385980 ; N2 = 386627;
T24=t50F4(N2)-t50F4(N1);
tss=t50F4(N1:N2);
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS150F4(N1:N2-1);
I24sqr= i24.*i24;
A24= I24sqr.*deltat24;
I24=sqrt((1/T24)*sum(A24))/I0;

%F5=1.8 (d2=0.1)
N1 = 502360 ; N2 = 502931;
T25=t50F5(N2)-t50F5(N1);
tss=t50F5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS150F5(N1:N2-1);
I25sqr= i25.*i25;
A25= I25sqr.*deltat25;
I25=sqrt((1/T25)*sum(A25))/I0;

%F6=2 (d2=0)
I26=0;

IS150rms= [I26, I25, I24, I23, I22, I21];

%RL=100ohm
%F1=1 (d2=0.5)
N1 = 391567 ; N2 = 392584;
T31=t100F1(N2)-t100F1(N1);
tss=t100F1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS1100F1(N1:N2-1);
I31sqr= i31.*i31;
A31= I31sqr.*deltat31;
I31=sqrt((1/T31)*sum(A31))/I0;

%F2=1.2 (d2=0.4)
N1 = 309364 ; N2 = 310211;
T32=t100F2(N2)-t100F2(N1);
tss=t100F2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS1100F2(N1:N2-1);
I32sqr= i32.*i32;
A32= I32sqr.*deltat32;
I32=sqrt((1/T32)*sum(A32))/I0;

%F3=1.4 (d2=0.3)
N1 = 359742 ; N2 = 360474;
T33=t100F3(N2)-t100F3(N1);
tss=t100F3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS1100F3(N1:N2-1);
I33sqr= i33.*i33;
A33= I33sqr.*deltat33;
I33=sqrt((1/T33)*sum(A33))/I0;
```

```
%F4=1.6 (d2=0.2)
N1 = 467379 ; N2 = 468019;
T34=t100F4(N2)-t100F4(N1);
tss=t100F4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS1100F4(N1:N2-1);
I34sqr= i34.*i34;
A34= I34sqr.*deltat34;
I34=sqrt((1/T34)*sum(A34))/I0;

%F5=1.8 (d2=0.1)
N1 = 634241 ; N2 = 634904;
T35=t100F5(N2)-t100F5(N1);
tss=t100F5(N1:N2);
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS1100F5(N1:N2-1);
I35sqr= i35.*i35;
A35= I35sqr.*deltat35;
I35=sqrt((1/T35)*sum(A35))/I0;
%F6=2 (d2=0)
I36=0;

IS1100rms= [I36, I35, I34, I33, I32, I31];

IS1rms=[IS132rms;IS150rms;IS1100rms];
%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
NormIS1rms = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        NormIS1rms(j, i)=IS1rms(j, i);
    end
end

figure;
%NormIS1rms=NormIS1rms(:,:)./max(max(NormIS1rms));

for j = 1:length(RL_values)
    plot(F, NormIS1rms(j, :), 'DisplayName', sprintf('RL = %d ohms',
RL_values(j)));
    hold on;
end
xlabel('Normalized Frequency (F)');
ylabel('Normalized IS1rms');
legend('Location', 'Best');
grid on;
```

Normalized current stress versus the normalized frequency using FTM method MATLAB code:

```
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;    % Resonant capacitor value (F)
```

```
f = 100e3;     % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
I0=2.5;
%%
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 504380 ; N2 = 505394;
T11=t32F1(N2)-t32F1(N1);
tss=t32F1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=IS232F1(N1:N2-1);
I11sqr= i11.*i11;
A11= I11sqr.*deltat11;
I11=sqrt((1/T11)*sum(A11))/I0;

%F2=1.2 (d2=0.4)
N1 = 596395;  N2 = 597266;
T12=t32F2(N2)-t32F2(N1);
tss=t32F2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS232F2(N1:N2-1);
I12sqr= i12.*i12;
A12= I12sqr.*deltat12;
I12=sqrt((1/T12)*sum(A12))/I0;  % normalized rms

%F3=1.4 (d2=0.3)
N1 = 544085;  N2 = 544812;
T13=t32F3(N2)-t32F3(N1);
tss=t32F3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
i13=IS232F3(N1:N2-1);
I13sqr= i13.*i13;
A13= I13sqr.*deltat13;
I13=sqrt((1/T13)*sum(A13))/I0;  % normalized rms

%F4=1.6 (d2=0.2)
N1 = 581943;  N2 = 582583;
T14=t32F4(N2)-t32F4(N1);
tss=t32F4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS232F4(N1:N2-1);
I14sqr= i14.*i14;
A14= I14sqr.*deltat14;
I14=sqrt((1/T14)*sum(A14))/I0;  % normalized rms

%F5=1.8 (d2=0.1)
N1 = 570706;  N2 = 571274;
T15=t32F5(N2)-t32F5(N1);
tss=t32F5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS232F5(N1:N2-1);
I15sqr= i15.*i15;
A15= I15sqr.*deltat15;
I15=sqrt((1/T15)*sum(A15))/I0;  % normalized rms
```

```
%F6=2 (d2=0)
I16=0;

% define the rms values of IS1 in matrix (RL=32ohm)
IS232rms= [I16, I15, I14, I13, I12, I11];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 618849 ; N2 = 619863;
T21=t50F1(N2)-t50F1(N1);
tss=t50F1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS250F1(N1:N2-1);
I21sqr= i21.*i21;
A21= I21sqr.*deltat21;
I21=sqrt((1/T21)*sum(A21))/I0;

%F2=1.2 (d2=0.4)
N1 = 421208 ; N2 = 422054;
T22=t50F2(N2)-t50F2(N1);
tss=t50F2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS250F2(N1:N2-1);
I22sqr= i22.*i22;
A22= I22sqr.*deltat22;
I22=sqrt((1/T22)*sum(A22))/I0;

%F3=1.4 (d2=0.3)
N1 = 476376 ; N2 = 477104;
T23=t50F3(N2)-t50F3(N1);
tss=t50F3(N1:N2);
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS250F3(N1:N2-1);
I23sqr= i23.*i23;
A23= I23sqr.*deltat23;
I23=sqrt((1/T23)*sum(A23))/I0;

%F4=1.6 (d2=0.2)
N1 = 516597 ; N2 = 517238;
T24=t50F4(N2)-t50F4(N1);
tss=t50F4(N1:N2);
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS250F4(N1:N2-1);
I24sqr= i24.*i24;
A24= I24sqr.*deltat24;
I24=sqrt((1/T24)*sum(A24))/I0;

%F5=1.8 (d2=0.1)
N1 = 534324 ; N2 = 534898;
T25=t50F5(N2)-t50F5(N1);
tss=t50F5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS250F5(N1:N2-1);
I25sqr= i25.*i25;
```

```
A25= I25sqr.*deltat25;
I25=sqrt((1/T25)*sum(A25))/I0;

%F6=2 (d2=0)
I26=0;

IS250rms= [I26, I25, I24, I23, I22, I21];

%RL=100ohm
%F1=1 (d2=0.5)
N1 = 463066 ; N2 = 464080;
T31=t100F1(N2)-t100F1(N1);
tss=t100F1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS2100F1(N1:N2-1);
I31sqr= i31.*i31;
A31= I31sqr.*deltat31;
I31=sqrt((1/T31)*sum(A31))/I0;

%F2=1.2 (d2=0.4)
N1 = 449620 ; N2 = 450467;
T32=t100F2(N2)-t100F2(N1);
tss=t100F2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS2100F2(N1:N2-1);
I32sqr= i32.*i32;
A32= I32sqr.*deltat32;
I32=sqrt((1/T32)*sum(A32))/I0;

%F3=1.4 (d2=0.3)
N1 = 448717 ; N2 = 449445;
T33=t100F3(N2)-t100F3(N1);
tss=t100F3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS2100F3(N1:N2-1);
I33sqr= i33.*i33;
A33= I33sqr.*deltat33;
I33=sqrt((1/T33)*sum(A33))/I0;

%F4=1.6 (d2=0.2)
N1 = 525557 ; N2 = 526196;
T34=t100F4(N2)-t100F4(N1);
tss=t100F4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS2100F4(N1:N2-1);
I34sqr= i34.*i34;
A34= I34sqr.*deltat34;
I34=sqrt((1/T34)*sum(A34))/I0;

%F5=1.8 (d2=0.1)
N1 = 708045 ; N2 = 708699;
T35=t100F5(N2)-t100F5(N1);
tss=t100F5(N1:N2);
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS2100F5(N1:N2-1);
```

```
I35sqr= i35.*i35;
A35= I35sqr.*deltat35;
I35=sqrt((1/T35)*sum(A35))/I0;
%F6=2 (d2=0)
I36=0;

IS2100rms= [I36, I35, I34, I33, I32, I31];

IS2rms=[IS232rms;IS250rms;IS2100rms];
%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
NormIS2rms = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        NormIS2rms(j, i)=IS2rms(j, i);
    end
end

figure;
%NormIS1rms=NormIS1rms(:,:)./max(max(NormIS1rms));

for j = 1:length(RL_values)
    plot(F, NormIS2rms(j, :), 'DisplayName', sprintf('RL = %d ohms',
RL_values(j)));
    hold on;
end
xlabel('Normalized Frequency (F)');
ylabel('Normalized IS2rms');
legend('Location', 'Best');
grid on;
```

Normalized current stress of $D_{1\text{-}4avg}$ versus the normalized frequency using FTM technique MATLAB code:

```
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
I0=2.5;
%%
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 666573 ; N2 = 667587;
%T11=t32F1(N2)-t32F1(N1);
%tss=t32F1(N1:N2);
%Nss=length(tss);
%deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=ID132F1(N1:N2-1);
%I11sqr= i11.*i11;
%A11= I11sqr.*deltat11;
%I11=sqrt((1/T11)*sum(A11))/I0;
I11=mean(i11)/I0;
```

```
%F2=1.2 (d2=0.4)
N1 = 623266;  N2 = 624137;
i12=ID132F2(N1:N2-1);
I12=mean(i12)/I0;  % normalized rms

%F3=1.4 (d2=0.3)
N1 = 655475;  N2 = 656204;
i13=ID132F3(N1:N2-1);
I13=mean(i13)/I0;  % normalized rms

%F4=1.6 (d2=0.2)
N1 = 690298;  N2 = 690941;
i14=ID132F4(N1:N2-1);
I14=mean(i14)/I0;  % normalized rms

%F5=1.8 (d2=0.1)
N1 = 710236;  N2 = 710804;
i15=ID132F5(N1:N2-1);
I15=mean(i15)/I0;  % normalized rms

%F6=2 (d2=0)
I16=0;

% define the rms values of IS1 in matrix (RL=32ohm)
ID132avg= [I16, I15, I14, I13, I12, I11];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 588128 ; N2 = 589140;
i21=ID150F1(N1:N2-1);
I21=mean(i21)/I0;

%F2=1.2 (d2=0.4)
N1 = 586970 ; N2 = 587816;
i22=ID150F2(N1:N2-1);
I22=mean(i22)/I0;

%F3=1.4 (d2=0.3)
N1 = 561565 ; N2 = 562297;
i23=ID150F3(N1:N2-1);
I23=mean(i23)/I0;

%F4=1.6 (d2=0.2)
N1 = 747336 ; N2 = 748053;
i24=ID150F4(N1:N2-1);
I24=mean(i24)/I0;

%F5=1.8 (d2=0.1)
N1 = 703814 ; N2 = 704395;
i25=ID150F5(N1:N2-1);
I25=mean(i25)/I0;

%F6=2 (d2=0)
I26=0;

ID150avg= [I26, I25, I24, I23, I22, I21];

%RL=100ohm
```

```
%F1=1 (d2=0.5)
N1 = 636251 ; N2 = 637266;
i31=ID1100F1(N1:N2-1);
I31=mean(i31)/I0;

%F2=1.2 (d2=0.4)
N1 = 663918 ; N2 = 664767;
i32=ID1100F2(N1:N2-1);
I32=mean(i32)/I0;

%F3=1.4 (d2=0.3)
N1 = 748441 ; N2 = 749169;
i33=ID1100F3(N1:N2-1);
I33=mean(i33)/I0;

%F4=1.6 (d2=0.2)
N1 = 742558 ; N2 = 743197;
i34=ID1100F4(N1:N2-1);
I34=mean(i34)/I0;

%F5=1.8 (d2=0.1)
N1 = 825619 ; N2 = 826200;
i35=ID1100F5(N1:N2-1);
I35=mean(i35)/I0;
%F6=2 (d2=0)
I36=0;

ID1100avg= [I36, I35, I34, I33, I32, I31];

ID1avg=[ID132avg;ID150avg;ID1100avg];
%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
NormID1avg = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        NormID1avg(j, i)=ID1avg(j, i);
    end
end

figure;
%NormIS1rms=NormIS1rms(:,:)./max(max(NormIS1rms));

for j = 1:length(RL_values)
    plot(F, NormID1avg(j, :), 'DisplayName', sprintf('RL = %d ohms',
RL_values(j)));
    hold on;
end
xlabel('Normalized Frequency (F)');
ylabel('Normalized ID1-4avg');
legend('Location', 'Best');
grid on;
```

Efficiency with the FTM method MATLAB code:

```
Lr = 2.5e-6;    % Resonant inductor value (H)
Cr = 1e-6;    % Resonant capacitor value (F)
f = 100e3;     % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F= (1-d2_range)*2;
RL_values = [32, 50, 100];% Load resistance values (ohms)
Vin=80;
%%
V0_32=[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1)];
V0_50=[V050(1,1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1)];
V0_100=[V0100(1,1),V0100(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100
(6,1)];
V0 =
[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1);V050(1,
1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1);V0100(1,1),V010
0(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100(6,1)];
pout32= (V0_32.*V0_32)/32;
pout50= (V0_50.*V0_50)/50;
pout100= (V0_100.*V0_100)/100;
P0out=[pout32; pout50; pout100];
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 504380 ; N2 = 505394;
T11=t32F1(N2)-t32F1(N1);
tss=t32F1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=IS232F1(N1:N2-1);
A11= i11.*deltat11;
I11FTM=(1/T11)*sum(A11);

%F2=1.2 (d2=0.4)
N1 = 596395;  N2 = 597266;
T12=t32F2(N2)-t32F2(N1);
tss=t32F2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS232F2(N1:N2-1);
A12= i12.*deltat12;
I12FTM=(1/T12)*sum(A12);  % normalized rms

%F3=1.4 (d2=0.3)
N1 = 544085;  N2 = 544812;
T13=t32F3(N2)-t32F3(N1);
tss=t32F3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
i13=IS232F3(N1:N2-1);
A13= i13.*deltat13;
I13FTM=(1/T13)*sum(A13);  % normalized rms

%F4=1.6 (d2=0.2)
N1 = 581943;  N2 = 582583;
T14=t32F4(N2)-t32F4(N1);
tss=t32F4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS232F4(N1:N2-1);
```

```
A14= i14.*deltat14;
I14FTM=(1/T14)*sum(A14);  % normalized rms

%F5=1.8 (d2=0.1)
N1 = 570706;  N2 = 571274;
T15=t32F5(N2)-t32F5(N1);
tss=t32F5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS232F5(N1:N2-1);
A15= i15.*deltat15;
I15FTM=(1/T15)*sum(A15);  % normalized rms

%F6=2 (d2=0)
I16FTM=0;

% define the rms values of IS1 in matrix (RL=32ohm)
P1FTM= [I16FTM, I15FTM, I14FTM, I13FTM, I12FTM, I11FTM];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 618849 ; N2 = 619863;
T21=t50F1(N2)-t50F1(N1);
tss=t50F1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS250F1(N1:N2-1);
A21= i21.*deltat21;
I21FTM=(1/T21)*sum(A21);

%F2=1.2 (d2=0.4)
N1 = 421208 ; N2 = 422054;
T22=t50F2(N2)-t50F2(N1);
tss=t50F2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS250F2(N1:N2-1);
A22= i22.*deltat22;
I22FTM=(1/T22)*sum(A22);

%F3=1.4 (d2=0.3)
N1 = 476376 ; N2 = 477104;
T23=t50F3(N2)-t50F3(N1);
tss=t50F3(N1:N2);
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS250F3(N1:N2-1);
A23= i23.*deltat23;
I23FTM=(1/T23)*sum(A23);

%F4=1.6 (d2=0.2)
N1 = 516597 ; N2 = 517238;
T24=t50F4(N2)-t50F4(N1);
tss=t50F4(N1:N2);
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS250F4(N1:N2-1);
A24= i24.*deltat24;
I24FTM=(1/T24)*sum(A24);
```

```
%F5=1.8 (d2=0.1)
N1 = 534324 ; N2 = 534898;
T25=t50F5(N2)-t50F5(N1);
tss=t50F5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS250F5(N1:N2-1);
A25= i25.*deltat25;
I25FTM=(1/T25)*sum(A25);

%F6=2 (d2=0)
I26FTM=0;

P2FTM= [I26FTM, I25FTM, I24FTM, I23FTM, I22FTM, I21FTM];

%RL=100ohm
%F1=1 (d2=0.5)
N1 = 463066 ; N2 = 464080;
T31=t100F1(N2)-t100F1(N1);
tss=t100F1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS2100F1(N1:N2-1);
A31= i31.*deltat31;
I31FTM=(1/T31)*sum(A31);

%F2=1.2 (d2=0.4)
N1 = 449620 ; N2 = 450467;
T32=t100F2(N2)-t100F2(N1);
tss=t100F2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS2100F2(N1:N2-1);
A32= i32.*deltat32;
I32FTM=(1/T32)*sum(A32);

%F3=1.4 (d2=0.3)
N1 = 448717 ; N2 = 449445;
T33=t100F3(N2)-t100F3(N1);
tss=t100F3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS2100F3(N1:N2-1);
A33= i33.*deltat33;
I33FTM=(1/T33)*sum(A33);

%F4=1.6 (d2=0.2)
N1 = 525557 ; N2 = 526196;
T34=t100F4(N2)-t100F4(N1);
tss=t100F4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS2100F4(N1:N2-1);
A34= i34.*deltat34;
I34FTM=(1/T34)*sum(A34);

%F5=1.8 (d2=0.1)
N1 = 708045 ; N2 = 708699;
T35=t100F5(N2)-t100F5(N1);
tss=t100F5(N1:N2);
```

```
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS2100F5(N1:N2-1);
A35= i35.*deltat35;
I35FTM=(1/T35)*sum(A35);
%F6=2 (d2=0)
I36FTM=0;

P3FTM= [I36FTM, I35FTM, I34FTM, I33FTM, I32FTM, I31FTM];

PinFTM=[P1FTM;P2FTM;P3FTM].*Vin;
%%
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
RL_values = [32, 50, 100]; % Load resistance values (ohms)
effeciency = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        effeciency(j, i)=P0out(j, i)/ PinFTM(j, i);
    end
end

figure;
%NormIS1rms=NormIS1rms(:,:)./max(max(NormIS1rms));

for j = 1:length(RL_values)
    plot(F, effeciency(j, :), 'DisplayName', sprintf('RL = %d ohms',
RL_values(j)));
    hold on;
end
xlabel('Normalized Frequency (F)');
ylabel('effeciency');
title('effeciency using FTM');
legend('Location', 'Best');
grid on;
```

Voltage gain comparison between the FM technique and FTM technique versus the normalized frequency MATLAB code:

```
Vin = 80;       % Input voltage (V)
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
F_range1=[2,1.8,1.6,1.4,1.2,1];
F_range2=1:0.5:4;
RL_values = [32, 50, 100];% Load resistance values (ohms)

%Rl=32ohm
V32FMM=[V32FM(8,1),V32FM(7,1),V32FM(6,1),V32FM(5,1),V32FM(4,1),V32FM
(3,1),V32FM(2,1)];

%RL=50ohm
V50FMM=[V50FM(8,1),V50FM(7,1),V50FM(6,1),V50FM(5,1),V50FM(4,1),V50FM
(3,1),V50FM(2,1)];
```

```
%RL=100ohm
V100FMM=[V100FM(8,1),V100FM(7,1),V100FM(6,1),V100FM(5,1),V100FM(4,1)
,V100FM(3,1),V100FM(2,1)];

% Initialize arrays to store the output voltages for each RL value
V0FM=[V32FMM;V50FMM;V100FMM];
V0FTM =
[0,V32(2,1),V32(3,1),V32(4,1),V32(5,1),V32(6,1);V50(1,1),V50(2,1),V5
0(3,1),V50(4,1),V50(5,1),V50(6,1);V100(1,1),V100(2,1),V100(3,1),V100
(4,1),V100(5,1),V100(6,1)];


Vin=80;
Vgain1 = zeros(length(RL_values), length(F_range1));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range1)
         F = F_range1(i);
        Vgain1(j, i)=V0FTM(j, i)/ Vin;
    end
end
Vgain2 = zeros(length(RL_values), length(F_range2));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range2)
         F = F_range2(i);
        Vgain2(j, i)=V0FM(j, i)/ Vin;
    end
end
figure;


Vgain1=Vgain1(:,:)./max(max(Vgain1));
Vgain2=Vgain2(:,:)./max(max(Vgain2));
line_styles1={'b-', 'r-', 'g-'};

line_styles2 = {'b--', 'r--', 'g--'};

for j = 1:length(RL_values)
    plot(F_range2, Vgain2(j, :),line_styles2{j}, 'DisplayName',
sprintf('FM - RL = %d ohms', RL_values(j)));
    hold on;
end
hold on;
for j = 1:length(RL_values)
    plot(F_range1, Vgain1(j, :), line_styles1{j},'DisplayName',
sprintf('FTM - RL = %d ohms', RL_values(j)));
    hold on;
end
xlabel('Normalized Frequency (F) ');
ylabel('Voltage Gain (V0 / Vin)');
title('using FM vs FTM method');
legend('Location', 'Best');
grid on;
```

Voltage gain comparison between the APWM technique and FTM technique versus duty ratio d_2, MATLAB code:

```
Vin = 80;       % Input voltage (V)
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
d2_range = 0:0.1:0.5;
RL_values = [32, 50, 100];% Load resistance values (ohms)

% Initialize arrays to store the output voltages for each RL value
V0APWM=
[V32APWM(1,1),V32APWM(2,1),V32APWM(3,1),V32APWM(4,1),V32APWM(5,1),V3
2APWM(6,1);V50APWM(1,1),V50APWM(2,1),V50APWM(3,1),V50APWM(4,1),V50AP
WM(5,1),V50APWM(6,1);V100APWM(1,1),V100APWM(2,1),V100APWM(3,1),V100A
PWM(4,1),V100APWM(5,1),V100APWM(6,1)];
V0FTM=
[V32(1,1),V32(2,1),V32(3,1),V32(4,1),V32(5,1),V32(6,1);V50(1,1),V50(
2,1),V50(3,1),V50(4,1),V50(5,1),V50(6,1);V100(1,1),V100(2,1),V100(3,
1),V100(4,1),V100(5,1),V100(6,1)];


Vin=80;
Vgain1 = zeros(length(RL_values), length(d2_range));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        Vgain1(j, i)=V0FTM(j, i)/ Vin;
    end
end
Vgain2 = zeros(length(RL_values), length(d2_range));
for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        Vgain2(j, i)=V0APWM(j, i)/ Vin;
    end
end
figure;


Vgain1=Vgain1(:,:)./max(max(Vgain1));
Vgain2=Vgain2(:,:)./max(max(Vgain2));
line_styles1={'b-', 'r-', 'g-'};

line_styles2 = {'b--', 'r--', 'g--'};

for j = 1:length(RL_values)
    plot(d2_range, Vgain2(j, :),line_styles2{j}, 'DisplayName',
sprintf('FM - RL = %d ohms', RL_values(j)));
    hold on;
end
hold on;
for j = 1:length(RL_values)
    plot(d2_range, Vgain1(j, :), line_styles1{j},'DisplayName',
sprintf('FTM - RL = %d ohms', RL_values(j)));
    hold on;
end
xlabel('Duty ratio (d2) ');
ylabel('Voltage Gain (V0 / Vin)');
title('using FTM vs APWM method');
```

```
legend('Location', 'Best');
grid on;
```

Current stress of S_2 comparison between the FM, FTM, and APWM algorithms versus the output power, MATLAB code:

```
Vin = 80;       % Input voltage (V)
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
F_range1=[2,1.8,1.6,1.4,1.2,1];
F_range2=1:0.5:4;
RL_values = [32, 50, 100];% Load resistance values (ohms)
d2_range = 0:0.1:0.5;
%%
% Current Stress S using FTM
V0_32=[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1)];
V0_50=[V050(1,1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1)];
V0_100=[V0100(1,1),V0100(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100
(6,1)];
V0 =
[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1);V050(1,
1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1);V0100(1,1),V010
0(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100(6,1)];
pout32= (V0_32.*V0_32)/32;
pout50= (V0_50.*V0_50)/50;
pout100= (V0_100.*V0_100)/100;
pout=[pout32; pout50; pout100];
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 504380 ; N2 = 505394;
T11=t32F1(N2)-t32F1(N1);
tss=t32F1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=IS232F1(N1:N2-1);
I11sqr= i11.*i11;
A11= I11sqr.*deltat11;
I11FTM=sqrt((1/T11)*sum(A11));

%F2=1.2 (d2=0.4)
N1 = 596395;  N2 = 597266;
T12=t32F2(N2)-t32F2(N1);
tss=t32F2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS232F2(N1:N2-1);
I12sqr= i12.*i12;
A12= I12sqr.*deltat12;
I12FTM=sqrt((1/T12)*sum(A12));  % normalized rms

%F3=1.4 (d2=0.3)
N1 = 544085;  N2 = 544812;
T13=t32F3(N2)-t32F3(N1);
tss=t32F3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
```

```
i13=IS232F3(N1:N2-1);
I13sqr= i13.*i13;
A13= I13sqr.*deltat13;
I13FTM=sqrt((1/T13)*sum(A13));  % normalized rms

%F4=1.6 (d2=0.2)
N1 = 581943;  N2 = 582583;
T14=t32F4(N2)-t32F4(N1);
tss=t32F4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS232F4(N1:N2-1);
I14sqr= i14.*i14;
A14= I14sqr.*deltat14;
I14FTM=sqrt((1/T14)*sum(A14));  % normalized rms

%F5=1.8 (d2=0.1)
N1 = 570706;  N2 = 571274;
T15=t32F5(N2)-t32F5(N1);
tss=t32F5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS232F5(N1:N2-1);
I15sqr= i15.*i15;
A15= I15sqr.*deltat15;
I15FTM=sqrt((1/T15)*sum(A15));  % normalized rms

%F6=2 (d2=0)
I16FTM=0;

% define the rms values of IS1 in matrix (RL=32ohm)
IS232FTMrms= [I16FTM, I15FTM, I14FTM, I13FTM, I12FTM, I11FTM];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 618849 ; N2 = 619863;
T21=t50F1(N2)-t50F1(N1);
tss=t50F1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS250F1(N1:N2-1);
I21sqr= i21.*i21;
A21= I21sqr.*deltat21;
I21FTM=sqrt((1/T21)*sum(A21));

%F2=1.2 (d2=0.4)
N1 = 421208 ; N2 = 422054;
T22=t50F2(N2)-t50F2(N1);
tss=t50F2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS250F2(N1:N2-1);
I22sqr= i22.*i22;
A22= I22sqr.*deltat22;
I22FTM=sqrt((1/T22)*sum(A22));

%F3=1.4 (d2=0.3)
N1 = 476376 ; N2 = 477104;
T23=t50F3(N2)-t50F3(N1);
tss=t50F3(N1:N2);
```

```
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS250F3(N1:N2-1);
I23sqr= i23.*i23;
A23= I23sqr.*deltat23;
I23FTM=sqrt((1/T23)*sum(A23));

%F4=1.6 (d2=0.2)
N1 = 516597 ; N2 = 517238;
T24=t50F4(N2)-t50F4(N1);
tss=t50F4(N1:N2);
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS250F4(N1:N2-1);
I24sqr= i24.*i24;
A24= I24sqr.*deltat24;
I24FTM=sqrt((1/T24)*sum(A24));

%F5=1.8 (d2=0.1)
N1 = 534324 ; N2 = 534898;
T25=t50F5(N2)-t50F5(N1);
tss=t50F5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS250F5(N1:N2-1);
I25sqr= i25.*i25;
A25= I25sqr.*deltat25;
I25FTM=sqrt((1/T25)*sum(A25));

%F6=2 (d2=0)
I26FTM=0;

IS250FTMrms= [I26FTM, I25FTM, I24FTM, I23FTM, I22FTM, I21FTM];

%RL=100ohm
%F1=1 (d2=0.5)
N1 = 463066 ; N2 = 464080;
T31=t100F1(N2)-t100F1(N1);
tss=t100F1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS2100F1(N1:N2-1);
I31sqr= i31.*i31;
A31= I31sqr.*deltat31;
I31FTM=sqrt((1/T31)*sum(A31));

%F2=1.2 (d2=0.4)
N1 = 449620 ; N2 = 450467;
T32=t100F2(N2)-t100F2(N1);
tss=t100F2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS2100F2(N1:N2-1);
I32sqr= i32.*i32;
A32= I32sqr.*deltat32;
I32FTM=sqrt((1/T32)*sum(A32));

%F3=1.4 (d2=0.3)
N1 = 448717 ; N2 = 449445;
T33=t100F3(N2)-t100F3(N1);
```

```
tss=t100F3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS2100F3(N1:N2-1);
I33sqr= i33.*i33;
A33= I33sqr.*deltat33;
I33FTM=sqrt((1/T33)*sum(A33));

%F4=1.6 (d2=0.2)
N1 = 525557 ; N2 = 526196;
T34=t100F4(N2)-t100F4(N1);
tss=t100F4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS2100F4(N1:N2-1);
I34sqr= i34.*i34;
A34= I34sqr.*deltat34;
I34FTM=sqrt((1/T34)*sum(A34));

%F5=1.8 (d2=0.1)
N1 = 708045 ; N2 = 708699;
T35=t100F5(N2)-t100F5(N1);
tss=t100F5(N1:N2);
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS2100F5(N1:N2-1);
I35sqr= i35.*i35;
A35= I35sqr.*deltat35;
I35FTM=sqrt((1/T35)*sum(A35));
%F6=2 (d2=0)
I36FTM=0;

IS2100FTMrms= [I36FTM, I35FTM, I34FTM, I33FTM, I32FTM, I31FTM];

IS2FTMrms=[IS232FTMrms;IS250FTMrms;IS2100FTMrms];
%%
%Current Stress S2 using FM
V32FMM=[V32FM(1,1),V32FM(2,1),V32FM(3,1),V32FM(4,1),V32FM(5,1),V32FM
(6,1),V32FM(7,1),V32FM(8,1)];
V50FMM=[V50FM(1,1),V50FM(2,1),V50FM(3,1),V50FM(4,1),V50FM(5,1),V50FM
(6,1),V50FM(7,1),V50FM(8,1)];
V100FMM=[V100FM(1,1),V100FM(2,1),V100FM(3,1),V100FM(4,1),V100FM(5,1)
,V100FM(6,1),V100FM(7,1),V100FM(8,1)];
%V0 =
[V32FM(1,1),V32FM(1,2),V32FM(1,3),V32FM(1,4),V32FM(1,5),V32FM(1,6);V
50FM(1,1),V50FM(1,2),V50FM(1,3),V50FM(1,4),V50FM(1,5),V50FM(1,6);V10
0FM(1,1),V100FM(1,2),V100FM(1,3),V100FM(1,4),V100FM(1,5),V100FM(1,6)
];
pout32FM= (V32FMM.*V32FMM)/32;
pout50FM= (V50FMM.*V50FMM)/50;
pout100FM= (V100FMM.*V100FMM)/100;
poutFM=[pout32FM; pout50FM; pout100FM];

%RL=32 ohm
%FM1=1
N1 = 521127 ; N2 = 522141;
T11=t32FM1(N2)-t32FM1(N1);
tss=t32FM1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
```

```
i11=IS232FM1(N1:N2-1);
I11sqr= i11.*i11;
A11= I11sqr.*deltat11;
I11FM=sqrt((1/T11)*sum(A11));

%FM2=1.5
N1 = 501665;  N2 = 502347;
T12=t32FM2(N2)-t32FM2(N1);
tss=t32FM2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS232FM2(N1:N2-1);
I12sqr= i12.*i12;
A12= I12sqr.*deltat12;
I12FM=sqrt((1/T12)*sum(A12));  % normalized rms

%FM3=2
N1 = 591936;  N2 = 592448;
T13=t32FM3(N2)-t32FM3(N1);
tss=t32FM3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
i13=IS232FM3(N1:N2-1);
I13sqr= i13.*i13;
A13= I13sqr.*deltat13;
I13FM=sqrt((1/T13)*sum(A13));  % normalized rms

%FM4=2.5
N1 = 579168;  N2 = 579582;
T14=t32FM4(N2)-t32FM4(N1);
tss=t32FM4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS232FM4(N1:N2-1);
I14sqr= i14.*i14;
A14= I14sqr.*deltat14;
I14FM=sqrt((1/T14)*sum(A14));  % normalized rms

%FM5=3
N1 = 558767;  N2 = 559115;
T15=t32FM5(N2)-t32FM5(N1);
tss=t32FM5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS232FM5(N1:N2-1);
I15sqr= i15.*i15;
A15= I15sqr.*deltat15;
I15FM=sqrt((1/T15)*sum(A15));  % normalized rms

%FM6=3.5
N1 = 523681;  N2 = 523983;
T16=t32FM6(N2)-t32FM6(N1);
tss=t32FM6(N1:N2);
Nss=length(tss);
deltat16=tss(2:Nss)-tss(1:Nss-1);
i16=IS232FM6(N1:N2-1);
I16sqr= i16.*i16;
A16= I16sqr.*deltat16;
I16FM=sqrt((1/T16)*sum(A16));
```

```
%FM7=4
N1 = 590967;  N2 = 591231;
T17=t32FM7(N2)-t32FM7(N1);
tss=t32FM7(N1:N2);
Nss=length(tss);
deltat17=tss(2:Nss)-tss(1:Nss-1);
i17=IS232FM7(N1:N2-1);
I17sqr= i17.*i17;
A17= I17sqr.*deltat17;
I17FM=sqrt((1/T17)*sum(A17));

% define the rms values of IS1 in matrix (RL=32ohm)
IS232FMrms= [0,I17FM,I16FM, I15FM, I14FM, I13FM, I12FM, I11FM];

%RL=50ohm
%FM1=1
N1 = 528045 ; N2 = 529059;
T21=t50FM1(N2)-t50FM1(N1);
tss=t50FM1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS250FM1(N1:N2-1);
I21sqr= i21.*i21;
A21= I21sqr.*deltat21;
I21FM=sqrt((1/T21)*sum(A21));

%FM2=1.5
N1 = 566151 ; N2 = 566831;
T22=t50FM2(N2)-t50FM2(N1);
tss=t50FM2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS250FM2(N1:N2-1);
I22sqr= i22.*i22;
A22= I22sqr.*deltat22;
I22FM=sqrt((1/T22)*sum(A22));

%FM3=2
N1 = 527589 ; N2 = 528107;
T23=t50FM3(N2)-t50FM3(N1);
tss=t50FM3(N1:N2);
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS250FM3(N1:N2-1);
I23sqr= i23.*i23;
A23= I23sqr.*deltat23;
I23FM=sqrt((1/T23)*sum(A23));

%FM4=2.5
N1 = 557751 ; N2 = 558165;
T24=t50FM4(N2)-t50FM4(N1);
tss=t50FM4(N1:N2);
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS250FM4(N1:N2-1);
I24sqr= i24.*i24;
A24= I24sqr.*deltat24;
I24FM=sqrt((1/T24)*sum(A24));

%FM5=3
```

```
N1 = 642430 ; N2 = 642778;
T25=t50FM5(N2)-t50FM5(N1);
tss=t50FM5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS250FM5(N1:N2-1);
I25sqr= i25.*i25;
A25= I25sqr.*deltat25;
I25FM=sqrt((1/T25)*sum(A25));

%FM6=3.5
N1 = 702813 ; N2 = 703113;
T26=t50FM6(N2)-t50FM6(N1);
tss=t50FM6(N1:N2);
Nss=length(tss);
deltat26=tss(2:Nss)-tss(1:Nss-1);
i26=IS250FM6(N1:N2-1);
I26sqr= i26.*i26;
A26= I26sqr.*deltat26;
I26FM=sqrt((1/T26)*sum(A26));

%FM7=4
N1 = 623255 ; N2 = 623519;
T27=t50FM7(N2)-t50FM7(N1);
tss=t50FM7(N1:N2);
Nss=length(tss);
deltat27=tss(2:Nss)-tss(1:Nss-1);
i27=IS250FM7(N1:N2-1);
I27sqr= i27.*i27;
A27= I27sqr.*deltat27;
I27FM=sqrt((1/T27)*sum(A27));

IS250FMrms= [0,I27FM ,I26FM, I25FM, I24FM, I23FM, I22FM, I21FM];

%RL=100ohm
%FM1=1
N1 = 484261 ; N2 = 485275;
T31=t100FM1(N2)-t100FM1(N1);
tss=t100FM1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS2100FM1(N1:N2-1);
I31sqr= i31.*i31;
A31= I31sqr.*deltat31;
I31FM=sqrt((1/T31)*sum(A31));

%FM2=1.5
N1 = 429023 ; N2 = 429705;
T32=t100FM2(N2)-t100FM2(N1);
tss=t100FM2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS2100FM2(N1:N2-1);
I32sqr= i32.*i32;
A32= I32sqr.*deltat32;
I32FM=sqrt((1/T32)*sum(A32));

%FM3=2
N1 = 583016 ; N2 = 583528;
T33=t100FM3(N2)-t100FM3(N1);
```

```
tss=t100FM3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS2100FM3(N1:N2-1);
I33sqr= i33.*i33;
A33= I33sqr.*deltat33;
I33FM=sqrt((1/T33)*sum(A33));

%FM4=2.5
N1 = 620680 ; N2 = 621094;
T34=t100FM4(N2)-t100FM4(N1);
tss=t100FM4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS2100FM4(N1:N2-1);
I34sqr= i34.*i34;
A34= I34sqr.*deltat34;
I34FM=sqrt((1/T34)*sum(A34));

%FM5=3
N1 = 722330 ; N2 = 722680;
T35=t100FM5(N2)-t100FM5(N1);
tss=t100FM5(N1:N2);
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS2100FM5(N1:N2-1);
I35sqr= i35.*i35;
A35= I35sqr.*deltat35;
I35FM=sqrt((1/T35)*sum(A35));

%FM6=3.5
N1 = 854172 ; N2 = 854470;
T36=t100FM6(N2)-t100FM6(N1);
tss=t100FM6(N1:N2);
Nss=length(tss);
deltat36=tss(2:Nss)-tss(1:Nss-1);
i36=IS2100FM6(N1:N2-1);
I36sqr= i36.*i36;
A36= I36sqr.*deltat36;
I36FM=sqrt((1/T36)*sum(A36));

%FM7=4
N1 = 872478 ; N2 = 872742;
T37=t100FM7(N2)-t100FM7(N1);
tss=t100FM7(N1:N2);
Nss=length(tss);
deltat37=tss(2:Nss)-tss(1:Nss-1);
i37=IS2100FM7(N1:N2-1);
I37sqr= i37.*i37;
A37= I37sqr.*deltat37;
I37FM=sqrt((1/T35)*sum(A35));

IS2100FMrms= [0,I37FM, I36FM, I35FM, I34FM, I33FM, I32FM, I31FM];

IS2FMrms=[IS232FMrms;IS250FMrms;IS2100FMrms];
%%
%Current Stress S2 using APWM
V32APWMM=[V32APWM(1,1),V32APWM(2,1),V32APWM(3,1),V32APWM(4,1),V32APW
M(5,1),V32APWM(6,1)];
```

```
V50APWMM=[V50APWM(1,1),V50APWM(2,1),V50APWM(3,1),V50APWM(4,1),V50APW
M(5,1),V50APWM(6,1)];
V100APWMM=[V100APWM(1,1),V100APWM(2,1),V100APWM(3,1),V100APWM(4,1),V
100APWM(5,1),V100APWM(6,1)];
%V0 =
[V32FM(1,1),V32FM(1,2),V32FM(1,3),V32FM(1,4),V32FM(1,5),V32FM(1,6);V
50FM(1,1),V50FM(1,2),V50FM(1,3),V50FM(1,4),V50FM(1,5),V50FM(1,6);V10
0FM(1,1),V100FM(1,2),V100FM(1,3),V100FM(1,4),V100FM(1,5),V100FM(1,6)
];
pout32APWM= (V32APWMM.*V32APWMM)/32;
pout50APWM= (V50APWMM.*V50APWMM)/50;
pout100APWM= (V100APWMM.*V100APWMM)/100;
poutAPWM=[pout32APWM; pout50APWM; pout100APWM];

%RL=32 ohm
%d2=0
I10APWM=0;

% d2=0.1
N1 = 686985 ; N2 = 688000;
T11=t32APWMF1(N2)-t32APWMF1(N1);
tss=t32APWMF1(N1:N2);
Nss=length(tss);
deltat11=tss(2:Nss)-tss(1:Nss-1);
i11=IS232APWMF1(N1:N2-1);
I11sqr= i11.*i11;
A11= I11sqr.*deltat11;
I11APWM=sqrt((1/T11)*sum(A11));

% d2=0.2
N1 = 626414;  N2 = 627541;
T12=t32APWMF2(N2)-t32APWMF2(N1);
tss=t32APWMF2(N1:N2);
Nss=length(tss);
deltat12=tss(2:Nss)-tss(1:Nss-1);
i12=IS232APWMF2(N1:N2-1);
I12sqr= i12.*i12;
A12= I12sqr.*deltat12;
I12APWM=sqrt((1/T12)*sum(A12));  % normalized rms

% d2=0.3
N1 = 626327;  N2 = 627344;
T13=t32APWMF3(N2)-t32APWMF3(N1);
tss=t32APWMF3(N1:N2);
Nss=length(tss);
deltat13=tss(2:Nss)-tss(1:Nss-1);
i13=IS232APWMF3(N1:N2-1);
I13sqr= i13.*i13;
A13= I13sqr.*deltat13;
I13APWM=sqrt((1/T13)*sum(A13));  % normalized rms

% d2=0.4
N1 = 632918;  N2 = 633934;
T14=t32APWMF4(N2)-t32APWMF4(N1);
tss=t32APWMF4(N1:N2);
Nss=length(tss);
deltat14=tss(2:Nss)-tss(1:Nss-1);
i14=IS232APWMF4(N1:N2-1);
I14sqr= i14.*i14;
A14= I14sqr.*deltat14;
```

```
I14APWM=sqrt((1/T14)*sum(A14));  % normalized rms

% d2=0.5
N1 = 667941;  N2 = 668959;
T15=t32APWMF5(N2)-t32APWMF5(N1);
tss=t32APWMF5(N1:N2);
Nss=length(tss);
deltat15=tss(2:Nss)-tss(1:Nss-1);
i15=IS232APWMF5(N1:N2-1);
I15sqr= i15.*i15;
A15= I15sqr.*deltat15;
I15APWM=sqrt((1/T15)*sum(A15));  % normalized rms



% define the rms values of IS1 in matrix (RL=32ohm)
IS232APWMrms= [I10APWM, I11APWM, I12APWM, I13APWM, I14APWM,
I15APWM];

%RL=50ohm
%d2=0
I20APWM=0;

% d2=0.1
N1 = 713945 ; N2 = 714963;
T21=t50APWMF1(N2)-t50APWMF1(N1);
tss=t50APWMF1(N1:N2);
Nss=length(tss);
deltat21=tss(2:Nss)-tss(1:Nss-1);
i21=IS250APWMF1(N1:N2-1);
I21sqr= i21.*i21;
A21= I21sqr.*deltat21;
I21APWM=sqrt((1/T21)*sum(A21));

% d2=0.2
N1 = 745360 ; N2 = 746374;
T22=t50APWMF2(N2)-t50APWMF2(N1);
tss=t50APWMF2(N1:N2);
Nss=length(tss);
deltat22=tss(2:Nss)-tss(1:Nss-1);
i22=IS250APWMF2(N1:N2-1);
I22sqr= i22.*i22;
A22= I22sqr.*deltat22;
I22APWM=sqrt((1/T22)*sum(A22));

% d2=0.3
N1 = 733084 ; N2 = 734097;
T23=t50APWMF3(N2)-t50APWMF3(N1);
tss=t50APWMF3(N1:N2);
Nss=length(tss);
deltat23=tss(2:Nss)-tss(1:Nss-1);
i23=IS250APWMF3(N1:N2-1);
I23sqr= i23.*i23;
A23= I23sqr.*deltat23;
I23APWM=sqrt((1/T23)*sum(A23));

% d2=0.4
N1 = 767936 ; N2 = 768949;
T24=t50APWMF4(N2)-t50APWMF4(N1);
tss=t50APWMF4(N1:N2);
```

```
Nss=length(tss);
deltat24=tss(2:Nss)-tss(1:Nss-1);
i24=IS250APWMF4(N1:N2-1);
I24sqr= i24.*i24;
A24= I24sqr.*deltat24;
I24APWM=sqrt((1/T24)*sum(A24));

% d2=0.5
N1 = 721781 ; N2 = 722798;
T25=t50APWMF5(N2)-t50APWMF5(N1);
tss=t50APWMF5(N1:N2);
Nss=length(tss);
deltat25=tss(2:Nss)-tss(1:Nss-1);
i25=IS250APWMF5(N1:N2-1);
I25sqr= i25.*i25;
A25= I25sqr.*deltat25;
I25APWM=sqrt((1/T25)*sum(A25));



IS250APWMrms= [I20APWM, I21APWM, I22APWM, I23APWM, I24APWM,
I25APWM];

%RL=100ohm
%d2=0
I30APWM=0;

% d2=0.1
N1 = 700856 ; N2 = 701928;
T31=t100APWMF1(N2)-t100APWMF1(N1);
tss=t100APWMF1(N1:N2);
Nss=length(tss);
deltat31=tss(2:Nss)-tss(1:Nss-1);
i31=IS2100APWMF1(N1:N2-1);
I31sqr= i31.*i31;
A31= I31sqr.*deltat31;
I31APWM=sqrt((1/T31)*sum(A31));

% d2=0.2
N1 = 728659 ; N2 = 729673;
T32=t100APWMF2(N2)-t100APWMF2(N1);
tss=t100APWMF2(N1:N2);
Nss=length(tss);
deltat32=tss(2:Nss)-tss(1:Nss-1);
i32=IS2100APWMF2(N1:N2-1);
I32sqr= i32.*i32;
A32= I32sqr.*deltat32;
I32APWM=sqrt((1/T32)*sum(A32));

% d2=0.3
N1 = 722480 ; N2 = 723494;
T33=t100APWMF3(N2)-t100APWMF3(N1);
tss=t100APWMF3(N1:N2);
Nss=length(tss);
deltat33=tss(2:Nss)-tss(1:Nss-1);
i33=IS2100APWMF3(N1:N2-1);
I33sqr= i33.*i33;
A33= I33sqr.*deltat33;
I33APWM=sqrt((1/T33)*sum(A33));
```

```
% d2=0.4
N1 = 697970 ; N2 = 698988;
T34=t100APWMF4(N2)-t100APWMF4(N1);
tss=t100APWMF4(N1:N2);
Nss=length(tss);
deltat34=tss(2:Nss)-tss(1:Nss-1);
i34=IS2100APWMF4(N1:N2-1);
I34sqr= i34.*i34;
A34= I34sqr.*deltat34;
I34APWM=sqrt((1/T34)*sum(A34));

% d2=0.5
N1 = 717515 ; N2 = 718529;
T35=t100APWMF5(N2)-t100APWMF5(N1);
tss=t100APWMF5(N1:N2);
Nss=length(tss);
deltat35=tss(2:Nss)-tss(1:Nss-1);
i35=IS2100APWMF5(N1:N2-1);
I35sqr= i35.*i35;
A35= I35sqr.*deltat35;
I35APWM=sqrt((1/T35)*sum(A35));


IS2100APWMrms= [I30APWM, I31APWM, I32APWM, I33APWM, I34APWM,
I35APWM];

IS2APWMrms=[IS232APWMrms;IS250APWMrms;IS2100APWMrms];
%%
%Plotting the figures
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F_range=1:0.5:4.5;
RL_values = [32, 50, 100]; % Load resistance values (ohms)

NormIS2FTMrms = zeros(length(RL_values), length(d2_range));
NormIS2FMrms = zeros(length(RL_values), length(F_range));
NormIS2APWMrms = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        NormIS2FTMrms(j, i)=IS2FTMrms(j, i);
    end
end

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range)
         F = F_range(i);
        NormIS2FMrms(j, i)=IS2FMrms(j, i);
    end
end

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        NormIS2APWMrms(j, i)=IS2APWMrms(j, i);
    end
end
```

```
figure;

line_styles1 = {'b-', 'r-', 'g-'};
line_styles2 = {'b--', 'r--', 'g--'};
line_styles3 = {':', '-.', '-'};

for j = 1:length(RL_values)
    plot(pout(j,:), NormIS2FTMrms(j, :), line_styles1{j},
'DisplayName', sprintf('FTM: RL = %d ohms', RL_values(j)));
    hold on;
end

for j = 1:length(RL_values)
    plot(poutFM(j,:), NormIS2FMrms(j, :), line_styles2{j},
'DisplayName', sprintf('FM: RL = %d ohms', RL_values(j)));
    hold on;
end

for j = 1:length(RL_values)
    plot(poutAPWM(j, :), NormIS2APWMrms(j, :), line_styles3{j},
'DisplayName', sprintf('APWM: RL = %d ohms', RL_values(j)));
    hold on;
end

legend('show'); % Display the legend



xlabel('Output Power (P0/W) ');
ylabel('IS2rms (A)');
title('using FTM, FM vs APWM method');
legend('Location', 'Best');
grid on;
```

Peak current comparison between the FM, APWM, and FTM algorithms versus the output power, MATLAB code:

```
Lr = 2.5e-6;     % Resonant inductor value (H)
Cr = 1e-6;     % Resonant capacitor value (F)
f = 100e3;      % Resonant frequency (Hz)
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F_range= 1:0.5:4;
RL_values = [32, 50, 100];% Load resistance values (ohms)
%%
% peak current using FTM method
V0_32=[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1)];
V0_50=[V050(1,1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1)];
V0_100=[V0100(1,1),V0100(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100
(6,1)];
V0 =
[V032(1,1),V032(2,1),V032(3,1),V032(4,1),V032(5,1),V032(6,1);V050(1,
1),V050(2,1),V050(3,1),V050(4,1),V050(5,1),V050(6,1);V0100(1,1),V010
0(2,1),V0100(3,1),V0100(4,1),V0100(5,1),V0100(6,1)];
pout32= (V0_32.*V0_32)/32;
pout50= (V0_50.*V0_50)/50;
pout100= (V0_100.*V0_100)/100;
poutFTM=[pout32; pout50; pout100];
```

```
%RL=32 ohm
%F1=1 (d2=0.5)
N1 = 504380 ; N2 = 505394;
i11=IS232F1(N1:N2-1);
I11FTM=max(i11);

%F2=1.2 (d2=0.4)
N1 = 596395;  N2 = 597266;
i12=IS232F2(N1:N2-1);
I12FTM=max(i12);

%F3=1.4 (d2=0.3)
N1 = 544085;  N2 = 544812;
i13=IS232F3(N1:N2-1);
I13FTM=max(i13);

%F4=1.6 (d2=0.2)
N1 = 581943;  N2 = 582583;
i14=IS232F4(N1:N2-1);
I14FTM=max(i14);

%F5=1.8 (d2=0.1)
N1 = 570706;  N2 = 571274;
i15=IS232F5(N1:N2-1);
I15FTM=max(i15);

%F6=2 (d2=0)
I16FTM=0;

% define the rms values of IS1 in matrix (RL=32ohm)
IS232FTM= [I16FTM, I15FTM, I14FTM, I13FTM, I12FTM, I11FTM];

%RL=50ohm
%F1=1 (d2=0.5)
N1 = 618849 ; N2 = 619863;
i21=IS250F1(N1:N2-1);
I21FTM=max(i21);

%F2=1.2 (d2=0.4)
N1 = 421208 ; N2 = 422054;
i22=IS250F2(N1:N2-1);
I22FTM=max(i22);

%F3=1.4 (d2=0.3)
N1 = 476376 ; N2 = 477104;
i23=IS250F3(N1:N2-1);
I23FTM=max(i23);

%F4=1.6 (d2=0.2)
N1 = 516597 ; N2 = 517238;
i24=IS250F4(N1:N2-1);
I24FTM=max(i24);

%F5=1.8 (d2=0.1)
N1 = 534324 ; N2 = 534898;
i25=IS250F5(N1:N2-1);
I25FTM=max(i25);
```

```
%F6=2 (d2=0)
I26FTM=0;

IS250FTM= [I26FTM, I25FTM, I24FTM, I23FTM, I22FTM, I21FTM];

%RL=100ohm
%F1=1 (d2=0.5)
N1 = 463066 ; N2 = 464080;
i31=IS2100F1(N1:N2-1);
I31FTM=max(i31);

%F2=1.2 (d2=0.4)
N1 = 449620 ; N2 = 450467;
i32=IS2100F2(N1:N2-1);
I32FTM=max(i32);

%F3=1.4 (d2=0.3)
N1 = 448717 ; N2 = 449445;
i33=IS2100F3(N1:N2-1);
I33FTM=max(i33);

%F4=1.6 (d2=0.2)
N1 = 525557 ; N2 = 526196;
i34=IS2100F4(N1:N2-1);
I34FTM=max(i34);

%F5=1.8 (d2=0.1)
N1 = 708045 ; N2 = 708699;
i35=IS2100F5(N1:N2-1);
I35=max(i35);
%F6=2 (d2=0)
I36FTM=0;

IS2100FTM= [I36FTM, I35, I34FTM, I33FTM, I32FTM, I31FTM];

IS2FTM=[IS232FTM;IS250FTM;IS2100FTM];
%%
%  peak current using FM method
V32FMM=[V32FM(1,1),V32FM(2,1),V32FM(3,1),V32FM(4,1),V32FM(5,1),V32FM
(6,1),V32FM(7,1),V32FM(8,1)];
V50FMM=[V50FM(1,1),V50FM(2,1),V50FM(3,1),V50FM(4,1),V50FM(5,1),V50FM
(6,1),V50FM(7,1),V50FM(8,1)];
V100FMM=[V100FM(1,1),V100FM(2,1),V100FM(3,1),V100FM(4,1),V100FM(5,1)
,V100FM(6,1),V100FM(7,1),V100FM(8,1)];
%V0 =
[V32FM(1,1),V32FM(1,2),V32FM(1,3),V32FM(1,4),V32FM(1,5),V32FM(1,6);V
50FM(1,1),V50FM(1,2),V50FM(1,3),V50FM(1,4),V50FM(1,5),V50FM(1,6);V10
0FM(1,1),V100FM(1,2),V100FM(1,3),V100FM(1,4),V100FM(1,5),V100FM(1,6)
];
pout32FM= (V32FMM.*V32FMM)/32;
pout50FM= (V50FMM.*V50FMM)/50;
pout100FM= (V100FMM.*V100FMM)/100;
poutFM=[pout32FM; pout50FM; pout100FM];

%RL=50ohm
%FM1=1
N1 = 521127 ; N2 = 522141;
i11=IS232FM1(N1:N2-1);
I11FM=max(i11);
```

```
%FM2=1.5
N1 = 501665;  N2 = 502347;
i12=IS232FM2(N1:N2-1);
I12FM=max(i12);

%FM3=2
N1 = 591936;  N2 = 592448;
i13=IS232FM3(N1:N2-1);
I13FM=max(i13);

%FM4=2.5
N1 = 579168;  N2 = 579582;
i14=IS232FM4(N1:N2-1);
I14FM=max(i14);

%FM5=3
N1 = 558767;  N2 = 559115;
i15=IS232FM5(N1:N2-1);
I15FM=max(i15);

%FM6=3.5
N1 = 523681;  N2 = 523983;
i16=IS232FM6(N1:N2-1);
I16FM=max(i16);

%FM7=4
N1 = 590967;  N2 = 591231;
i17=IS232FM7(N1:N2-1);
I17FM=max(i17);

% define the rms values of IS1 in matrix (RL=32ohm)
IS232FM= [0,I17FM, I16FM, I15FM, I14FM, I13FM, I12FM, I11FM];
%FM1=1
N1 = 528045 ; N2 = 529059;
i21=IS250FM1(N1:N2-1);
I21FM=max(i21);

%FM2=1.5
N1 = 566151 ; N2 = 566831;
i22=IS250FM2(N1:N2-1);
I22FM=max(i22);

%FM3=2
N1 = 527589 ; N2 = 528107;
i23=IS250FM3(N1:N2-1);
I23FM=max(i23);

%FM4=2.5
N1 = 557751 ; N2 = 558165;
i24=IS250FM4(N1:N2-1);
I24FM=max(i24);

%FM5=3
N1 = 642430 ; N2 = 642778;
i25=IS250FM5(N1:N2-1);
I25FM=max(i25);

%FM6=3.5
```

```
N1 = 702813 ; N2 = 703113;
i26=IS250FM6(N1:N2-1);
I26FM=max(i26);

%FM7=4
N1 = 623255 ; N2 = 623519;
i27=IS250FM7(N1:N2-1);
I27FM=max(i27);

IS250FM= [0,I27FM, I26FM, I25FM, I24FM, I23FM, I22FM, I21FM];

%RL=100ohm
%FM1=1
N1 = 484261 ; N2 = 485275;
i31=IS2100FM1(N1:N2-1);
I31FM=max(i31);

%FM2=1.5
N1 = 429023 ; N2 = 429705;
i32=IS2100FM2(N1:N2-1);
I32FM=max(i32);

%FM3=2
N1 = 583016 ; N2 = 583528;
i33=IS2100FM3(N1:N2-1);
I33FM=max(i33);

%FM4=2.5
N1 = 620680 ; N2 = 621094;
i34=IS2100FM4(N1:N2-1);
I34FM=max(i34);

%FM5=3
N1 = 722330 ; N2 = 722680;
i35=IS2100FM5(N1:N2-1);
I35FM=max(i35);

%FM6=3.5
N1 = 854172 ; N2 = 854470;
i36=IS2100FM6(N1:N2-1);
I36FM=max(i36);

%FM7=4
N1 = 872478 ; N2 = 872742;
i37=IS2100FM7(N1:N2-1);
I37FM=max(i37);

IS2100FM= [0,I37FM, I36FM, I35FM, I34FM, I33FM, I32FM, I31FM];

IS2FM=[IS232FM;IS250FM;IS2100FM];
%%
% peak current using APWM method
V32APWMM=[V32APWM(1,1),V32APWM(2,1),V32APWM(3,1),V32APWM(4,1),V32APW
M(5,1),V32APWM(6,1)];
V50APWMM=[V50APWM(1,1),V50APWM(2,1),V50APWM(3,1),V50APWM(4,1),V50APW
M(5,1),V50APWM(6,1)];
V100APWMM=[V100APWM(1,1),V100APWM(2,1),V100APWM(3,1),V100APWM(4,1),V
100APWM(5,1),V100APWM(6,1)];
```

```
%V0 =
[V32FM(1,1),V32FM(1,2),V32FM(1,3),V32FM(1,4),V32FM(1,5),V32FM(1,6);V
50FM(1,1),V50FM(1,2),V50FM(1,3),V50FM(1,4),V50FM(1,5),V50FM(1,6);V10
0FM(1,1),V100FM(1,2),V100FM(1,3),V100FM(1,4),V100FM(1,5),V100FM(1,6)
];
pout32APWM= (V32APWMM.*V32APWMM)/32;
pout50APWM= (V50APWMM.*V50APWMM)/50;
pout100APWM= (V100APWMM.*V100APWMM)/100;
poutAPWM=[pout32APWM; pout50APWM; pout100APWM];

%RL=32 ohm
% d2=0
I10APWM=0;

% d2=0.1
N1 = 686985 ; N2 = 688000;
i11=IS232APWMF1(N1:N2-1);
I11APWM=max(i11);

% d2=0.2
N1 = 626414;  N2 = 627541;
i12=IS232APWMF2(N1:N2-1);
I12APWM=max(i12);

% d2=0.3
N1 = 626327;  N2 = 627344;
i13=IS232APWMF3(N1:N2-1);
I13APWM=max(i13);

% d2=0.4
N1 = 632918;  N2 = 633934;
i14=IS232APWMF4(N1:N2-1);
I14APWM=max(i14);

% d2=0.5
N1 = 667941;  N2 = 668959;
i15=IS232APWMF5(N1:N2-1);
I15APWM=max(i15);  % normalized rms



% define the rms values of IS1 in matrix (RL=32ohm)
IS232APWM= [I10APWM, I11APWM, I12APWM, I13APWM, I14APWM, I15APWM];

%RL=50ohm
% d2=0
I20APWM=0;

% d2=0.1
N1 = 713945 ; N2 = 714963;
i21=IS250APWMF1(N1:N2-1);
I21APWM=max(i21);

% d2=0.2
N1 = 745360 ; N2 = 746374;
i22=IS250APWMF2(N1:N2-1);
I22APWM=max(i22);

% d2=0.3
```

```
N1 = 733084 ; N2 = 734097;
i23=IS250APWMF3(N1:N2-1);
I23APWM=max(i23);

% d2=0.4
N1 = 767936 ; N2 = 768949;
i24=IS250APWMF4(N1:N2-1);
I24APWM=max(i24);

% d2=0.5
N1 = 721781 ; N2 = 722798;
i25=IS250APWMF5(N1:N2-1);
I25APWM=max(i25);



IS250APWM= [I20APWM, I21APWM, I22APWM, I23APWM, I24APWM, I25APWM];

%RL=100ohm
% d2=0
I30APWM=0;

% d2=0.1
N1 = 707353 ; N2 = 708425;
i31=IS2100APWMF1(N1:N2-1);
I31APWM=max(i31);

% d2=0.2
N1 = 725815 ; N2 = 726832;
i32=IS2100APWMF2(N1:N2-1);
I32APWM=max(i32);

% d2=0.3
N1 = 714358 ; N2 = 715372;
i33=IS2100APWMF3(N1:N2-1);
I33APWM=max(i33);

% d2=0.4
N1 = 726426 ; N2 = 727444;
i34=IS2100APWMF4(N1:N2-1);
I34APWM=max(i34);

% d2=0.5
N1 = 708386 ; N2 = 709403;
i35=IS2100APWMF5(N1:N2-1);
I35APWM=max(i35);



IS2100APWM= [I30APWM, I31APWM, I32APWM, I33APWM, I34APWM, I35APWM];

IS2APWM=[IS232APWM;IS250APWM;IS2100APWM];
%%
%Plotting the figures
d2_range = 0:0.1:0.5; % Range of duty ratios from 0 to 0.5
F_range=1:0.5:4.5;
RL_values = [32, 50, 100]; % Load resistance values (ohms)

PIS2FTM = zeros(length(RL_values), length(d2_range));
```

```
PIS2FM = zeros(length(RL_values), length(F_range));
PIS2APWM = zeros(length(RL_values), length(d2_range));

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        PIS2FTM(j, i)=IS2FTM(j, i);
    end
end

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(F_range)
         F = F_range(i);
        PIS2FM(j, i)=IS2FM(j, i);
    end
end

for j=1:length(RL_values)
    RL = RL_values(j);
    for i=1:length(d2_range)
         d2 = d2_range(i);
        PIS2APWM(j, i)=IS2APWM(j, i);
    end
end

figure;

line_styles1 = {'b-', 'r-', 'g-'};
line_styles2 = {'b--', 'r--', 'g--'};
line_styles3 = {':', '-.', '-'};

for j = 1:length(RL_values)
    plot(poutFTM(j,:), PIS2FTM(j, :), line_styles1{j},
'DisplayName', sprintf('FTM: RL = %d ohms', RL_values(j)));
    hold on;
end

for j = 1:length(RL_values)
    plot(poutFM(j,:), PIS2FM(j, :), line_styles2{j}, 'DisplayName',
sprintf('FM: RL = %d ohms', RL_values(j)));
    hold on;
end

for j = 1:length(RL_values)
    plot(poutAPWM(j, :), PIS2APWM(j, :), line_styles3{j},
'DisplayName', sprintf('APWM: RL = %d ohms', RL_values(j)));
    hold on;
end

legend('show'); % Display the legend



xlabel('Output Power (P0/W) ');
ylabel('Ipeak (A)');
title('Current Resonant Stresses (FTM, FM vs APWM)');
legend('Location', 'Best');
```

```
grid on;
```

Efficiency comparison between the FM and FTM techniques versus F, MATLAB code:

```
%Plotting
figure;
 plot(F_range, effeceinyFM(1, :), 'DisplayName', sprintf('FM
Method'));
 hold on;
 plot(F_rangeFTM, effeciency(1, :), 'DisplayName', sprintf('FTM'));
xlim([1,2])

xlabel('Normalized Frequency (F)');
ylabel('effeciency');
title('effeciency using 32 OHM');
legend('Location', 'Best');
grid on;


% For 50 ohm
figure;
 plot(F_range, effeceinyFM(2, :), 'DisplayName', sprintf('FM
Method'));
 hold on;
 plot(F_rangeFTM, effeciency(2, :), 'DisplayName', sprintf('FTM'));
xlim([1,2])

xlabel('Normalized Frequency (F)');
ylabel('effeciency');
title('effeciency using 50 OHM');
legend('Location', 'Best');
grid on;

% For 100 ohm
figure;
 plot(F_range, effeceinyFM(3, :), 'DisplayName', sprintf('FM
Method'));
 hold on;
 plot(F_rangeFTM, effeciency(3, :), 'DisplayName', sprintf('FTM'));
xlim([1,2])

xlabel('Normalized Frequency (F)');
ylabel('effeciency');
title('effeciency using 100 OHM');
legend('Location', 'Best');
grid on;
```

Efficiency comparison between the APWM and FTM techniwues versus F, MATLAB code:

```
%Plotting
figure;
```

```
 plot(d2_range, effeciencyAPWM(1, :), 'DisplayName',
sprintf('APWM'));
 hold on;
 plot(d2_range, effeciency(1, :), 'DisplayName', sprintf('FTM'));

xlabel('duty ratio (d2)');
ylabel('effeciency');
title('effeciency using 32 OHM');
legend('Location', 'Best');
grid on;


% For 50 ohm
figure;
 plot(d2_range, effeciencyAPWM(2, :), 'DisplayName',
sprintf('APWM'));
 hold on;
 plot(d2_range, effeciency(2, :), 'DisplayName', sprintf('FTM'));

xlabel('duty ratio (d2)');
ylabel('effeciency');
title('effeciency using 50 OHM');
legend('Location', 'Best');
grid on;

% For 100 ohm
figure;
 plot(d2_range, effeciencyAPWM(3, :), 'DisplayName',
sprintf('APWM'));
 hold on;
 plot(d2_range, effeciency(3, :), 'DisplayName', sprintf('FTM'));

xlabel('duty ratio (d2)');
ylabel('effeciency ');
title('effeciency using 100 OHM');
legend('Location', 'Best');
grid on;
```