Open Access Journal

Journal of Power Technologies 98 (2) (2018) 220–227

`journal homepage:papers.itc.pw.edu.pl`

Analysis and Simulation of Different Types of Power Amplifiers Used in Electromagnetic Levitation System

Sukanta Debnath[1], Pabitra Kumar Biswas[1], Upama Das[1]

Sukanta Debnath, NIT Mizoram, Chaltlang salemveng, India

Abstract

The objective of this paper is time and frequency response analysis of single quadrant and two-quadrant power amplifiers by using MATLAB SIMULINK, PSPICE and PSIM based software used in the electromagnetic levitation system. The power amplifier plays a key role in controlling the electromagnetic levitation system, controlling the current as well as the force between electromagnet and rail. Here the power amplifier is used to convert a fixed DC voltage to an adjustable DC output voltage. Different kinds of power amplifiers have been proposed for the electromagnetic levitation system. In this paper, only buck and asymmetrical converters are simulated in the simulation software. The exciting current of the electromagnet is controlled by the power amplifier, which controls the air gap and force between actuator and rail in a closed loop manner. PSPICE is an analog and digital circuit simulation software. PSIM is a general-purpose analog and digital electronic circuit simulator. It is also used for simulation and design software for power electronics, motor drives, and dynamic system simulation. SIMULINK is the graphic user interface software from MATLAB which helped us prepare the model of the various power systems, power electronics and control system.

Keywords: Electromagnetic Levitation system, Buck converter, Asymmetrical converter,Half Bridge Converter, Full Bridge converter, PSPICE, PSIM, MATLAB SIMULINK.

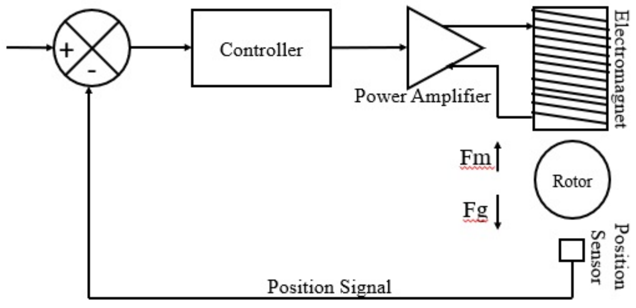


Figure 1: Block diagram of a single axis electromagnetic levitation system

1. Introduction

Suspension of an object in the air with no visible means of support due to magnetic force is known as a magnetic levitation system. The magnetic levitation system is receiving increasing attention recently due to its practical importance in many engineering systems, where it utilizes magnetic force to suspend an object in the air against gravitational force without any physical contact between the magnet and the levitated object [7, 18]. It has widespread application, like frictionless bearing (magnetic bearing), magnetically levitated trains, high-speed machine tools, levitation of molten metals in an induction furnace, etc. In any electromagnetic levitation system (EMLS) the electromagnet (actuator) has to be excited by a control voltage or current source [18]. The basic control block diagram of an EMLS is shown in Fig. 1. The power amplifier generates the desired coil current in response to a command signal from the controller in the electromagnetic levitation system. Different types of power amplifiers have been proposed for controlling the current as well as the magnetic force between the actuator and rail.

The power amplifier is central to control of the electromagnetic levitation system. Here the power amplifier is used for the DC to DC converter switch. That means the power converter conversion of fixed DC voltage to an adjustable DC output voltage. Different kinds of power amplifiers have been proposed for electromagnetic levitation. These include magnetic amplifiers (now obsolete) as well as the most modern

---

Email addresses: `sukanta.eee@nitmz.ac.in` (Sukanta Debnath), `pabitra.eee@nitmz.ac.in` (Pabitra Kumar Biswas), `upama.eee@nitmz.ac.in` (Upama Das)

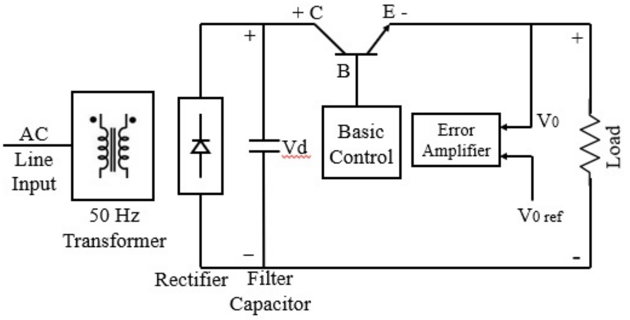


Figure 2: Schematic diagram of single switch power Amplifier

type of solid-state amplifiers. For low power application, both linear and solid-state power amplifiers have been proposed and their advantages and disadvantages discussed. Linear power supplies produce less switching noise and the overall electromagnetic interference is less when compared to that generated by the switch mode power amplifier (SMPS) circuit. However, there is some limitation in linear power supply too, as the transistor operates in its active region thereby incurring a significant amount of power loss. The overall efficiencies of linear power supply are in the range of 30% to 60%. For high power, the amplifier would be impractically large for an electromagnet-linear power setup. A combination of switched supply and a linear amplifier circuit may improve the efficiency of linear amplifier circuits further. Because of the switched mode DC to DC, power supply circuits are energy efficient (70-90% range). Increased switching speeds, higher voltage and current ratings and the relatively lower cost of power devices are the factors that have contributed to the emergence of switching power supplies. The coil current for the magnets used in levitation needs to be precisely controlled to meet the attractive force demand. The switch mode DC to DC power supply (chopper) circuit is energy efficient, but it generates electromagnetic noise which will affect the position signals. Once the decision has been taken to use the SMPS type circuit, one must design the layout of the power circuit so as to limit electromagnetic interference and an electromagnetic shield may be placed between the power amplifier circuit and the position sensor [**?**]. The other important consideration is the chopper switching frequency. The chopping frequency should be significantly higher than the frequency band of the expected position signal so as to enable effective filtering of electromagnetic interference generated by the chopper from the low-frequency position signal [3, 9]. The low pass filter cut-off frequency should be kept significantly higher than the position signal frequency, but much lower than the switching noise frequency. Due to high chopper frequency, the resulting current in the magnet coil is almost continuous, resulting in a linear transfer function for the chopper. High chopper frequency eliminates low order harmonics from the coil current, resulting in smooth current variation and less humming noise [4]. A schematic diagram of a single switch power amplifier is shown in Fig. 2.

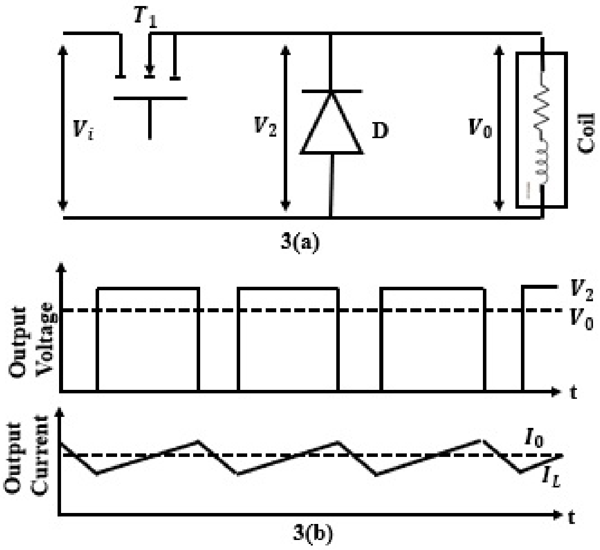


Figure 3: (a) Schematic diagram of Buck converter circuit and (b) output voltage and current waveform

2. A short description of different types of power amplifiers

A simple Buck type DC-to-DC chopper (class-D) circuit of Fig. 3(a) (using a controlled switch and a freewheeling diode) will not be suitable to feed the levitation magnet, as this chopper circuit can only apply unipolar voltage to the magnet coil. By adding the right value of series resistance to the magnet coil, one can make the coil voltage negative, as the resistance drop applies a negative voltage across the coil during the free wheeling mode of the class-D chopper [2, 13]. However, the resistance will dissipate a significant amount of power and the energy efficiency will thus be low.

The average output voltage is given by:

$$\frac{V_0}{V_i} = \frac{T_{on}}{T_{on} + T_{off}} = \frac{T_{on}}{T} = \delta \tag{1}$$

where: T—Total period = $\frac{1}{f_s}$, T_{on} –Transistor on time, δ—Transistor duty ratio

$$\begin{gathered} V_0 = T_{on} f_s V_i \\ V_0 = \delta V_i. \\ \delta = \frac{T_{on}}{T} = T_{on} f_s \end{gathered} \tag{2}$$

Thus in the ideal case, the output voltage is independent of load. When the transistor T_1 is switched on, $V_2 = V_0$, so the voltage across the inductor is:

$$V_L = L\frac{di}{dt} = V_i - V_0 \tag{3}$$

So I_L increases linearly. When the transistor T_1 is switched off, the current through the inductor L cannot instantaneously fall to zero, so the "flywheel" diode is included to provide a return path for the current to circulate through the load. During this period, $V_2 = 0$, so:

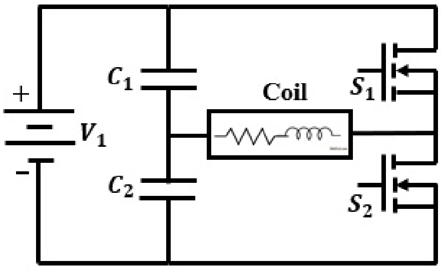


Figure 4: Half Bridge switched mode power amplifier

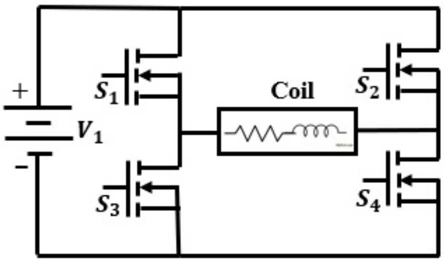


Figure 5: Full Bridge switched mode power amplifier

$$V_L = L\frac{di}{dt} = -V_0 \tag{4}$$

So I_L decrease linearly.
The peak-to-peak current ripple is

$$\triangle I = t_{on}.\left(\frac{V_i - V_0}{L}\right) = \left(\frac{V_0.T}{L}\right).(1 - \delta) \tag{5}$$

The maximum current is:

$$I_{maz} = \frac{V_0}{R} + \frac{\triangle I}{2} \tag{6}$$

The minimum current is:

$$I_{min} = \frac{V_0}{R} + \frac{\triangle I}{2} \tag{7}$$

A split DC supply (Fig. 4) for exciting the magnet-coil allows freewheeling and regeneration. It applies an equal amount (half of the input supply voltage) of positive and negative voltage to the actuator [17]. In this topology two equal capacitors are connected in series across the DC input and care has to be exercised in balancing the charge through design measures. This power amplifier has the disadvantage of de-rating the supply DC voltage by utilizing only half its value at any one time [5].

The output voltage of asymmetrical and full bridge can be written as:

$$\begin{aligned} V_0 &= \{2(T_{on}f_s) - 1\}\tfrac{V}{2} \\ &= (2\delta - 1)\tfrac{V_s}{2}. \end{aligned} \tag{8}$$

A full bridge circuit having four controlled switches (Fig. 5) can apply an equal amount of positive and negative voltage to the load (magnet coil) while allowing coil current to be bi-directional. Electromagnetic attraction force is, however, independent of the coil current direction and hence one may as well go for a cheaper asymmetrical bridge circuit that allows only one direction of the load (coil) current [15, 16]. Moreover, for the multi-magnet based levitation system the use of a full bridge circuit requires multiple isolated power supplies and gate drivers and the overall control circuit will be complicated.

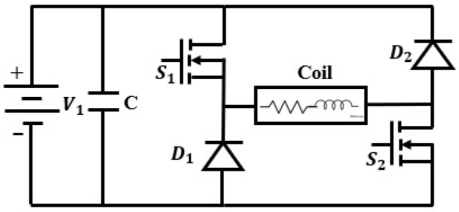


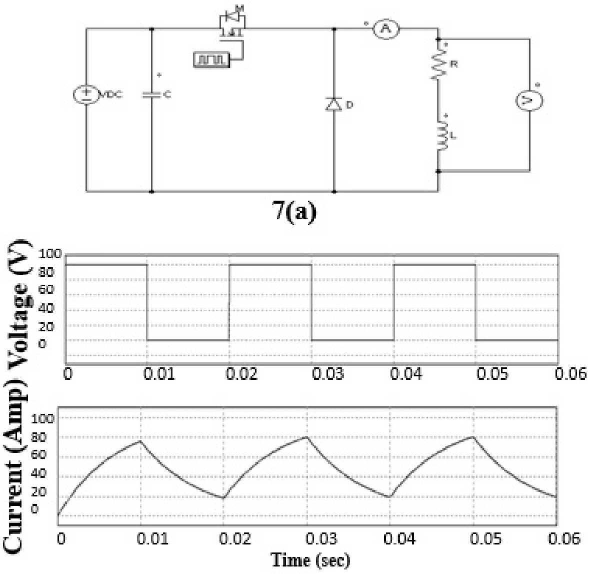
Figure 6: Asymmetrical Bridge (H-bridge) converter circuit

The asymmetrical bridge circuit shown in Fig. 6 requires only half the number of switches and diodes as the full bridge circuit and is capable of applying bi-directional load voltage similar to the full bridge circuit. Within each high-frequency cycle when the switches are ON, the positive voltage across the coil causes the coil current to rise and during OFF duration coil current decays due to the application of negative voltage [5, 13]. During current decay, through the diodes, part of the magnet energy is fed back to the supply and is not required to dissipate through any external resistance, and thus the circuit is quite energy efficient. Owing to its high energy-efficiency, this asymmetric converter is ideal for high power applications. Ohmic isolation is required between the gate drive signals of the two controlled switches and this calls for a proper isolation and amplification stage to drive each of the two switches. The output voltage of the asymmetrical and full bridge can be written as:

$$V_0 = \{2(T_{on}f_s) - 1\}V_s = (2\delta - 1)V_s \tag{9}$$

3. Introduction to PSPICE and PSIM Simulation based software

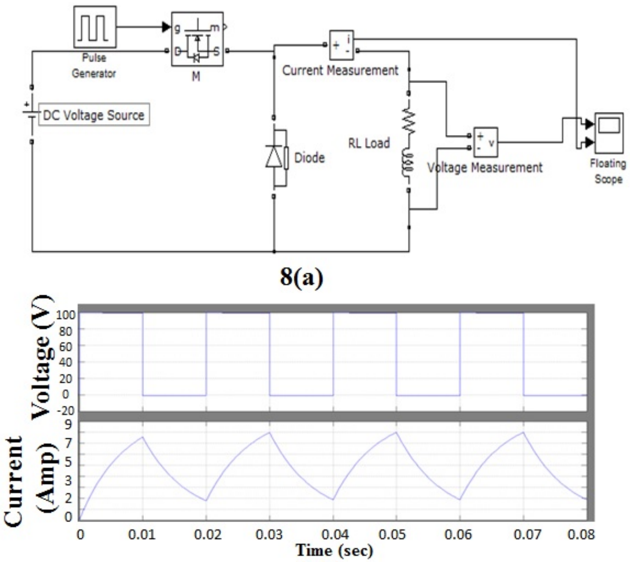
PSPICE is an analog circuit and digital logic simulation software that runs on personal computers [1]. It was developed by MicroSim and is used in electronic design automation. PSPICE, now developed for more complex industry requirements, is integrated into complete systems design flow from OrCAD and Cadence Allegro. It also supports many additional features which were not available in the original Berkeley code, such as Advanced Analysis with automatic circuit optimization, encryption, a Model Editor and support for parameterized models, and has several internal solvers, auto convergence and checkpoint restart, magnetic part editor and Tabriz core model for non-linear cores. Simulating the circuit with PSPICE is the industry-standard way to verify circuit operation at the transistor level before committing



7(a)

7(b)

Figure 7: (a) PISM circuit diagram for buck converter (b) Time response of Voltage output and current waveform of Buck Converter



8(a)

8(b)

Figure 8: (a) MATLAB circuit diagram for buck converter (b) Time response of Voltage output and current waveform of Buck Converter

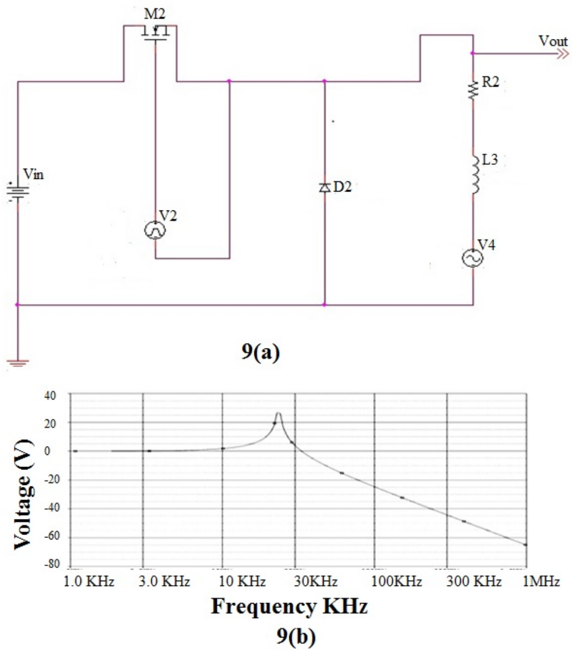
to manufacturing an integrated circuit. Board-level circuit designs can often be breadboarded for testing. Even with a breadboard, some circuit properties may not be accurate compared to the final printed wiring board, such as parasitic resistances and capacitances. These parasitic components can often be estimated more accurately using PSPICE simulation. PSIM is the leading simulation and design software for power electronics, motor drives, and dynamic system simulation. With fast simulation and easy-to-use interface, PSIM provides a powerful and efficient environment to meet your simulation needs. PSIM is simulation software specifically designed for power electronics and motor drives [8]. With fast simulation and friendly user interface, PSIM provides a powerful simulation environment for power electronics, analog, and digital control, magnetic, motor drives, and dynamic system studies.

4. Simulation Results and Discussion

Different types of simulator—like PSPICE, PSIM, and MATLAB SIMULINK—are used to simulate the time response and frequency response for various converters in which they are used to control the current or force demand of the system. The output voltage and output current have been simulated in time response for controlling the input voltage and current between the actuator and rail. The PSIM and MATLAB SIMULINK simulation circuit diagram of a buck converter or amplifier and its output voltage and current waveform are given in Fig. 7 and Fig. 8. It can be seen from Fig. 8(a) that when switch M is on and diode D, in this case, becomes reversed biased, its anode voltage is negative and cathode voltage is positive. The current will continue to flow from source to load. The voltage drops across the load, i.e. output voltage will be positive and is equal to the input voltage. When switch M is off, no current from the source is available for the load. The load terminal is completely isolated from the source. When the inductor voltage is reversed due to its property and the anode of diode D becomes positive, the cathode of D becomes negative. Therefore, the diode becomes forward biased. The stored energy of the inductor will discharge through the freewheeling diode D [2, 5, 7, 13, 18]. The load voltage will be zero, as the load terminals become short circuited. But in practice we may get a slightly negative voltage due to a small voltage drop across the diode terminals. When the switch is on current rises exponentially through the inductor, when the switch is off the current falls exponentially through the inductor, and the cycle repeats itself.

The PSPICE simulation circuit diagram and frequency response of buck converter are shown in Fig. 9. The output of the PSPICE simulation circuit gives the frequency response across the coil where the DC source is connected on the input side. In this frequency case, the response of the buck converter provides the gain cross-over frequency of 26.42 KHz as shown in Fig. 9(b). It provided quite a small bandwidth in this frequency response. Since stability is directly proportional to bandwidth, the stability of the system is also lower and has the slowest response.

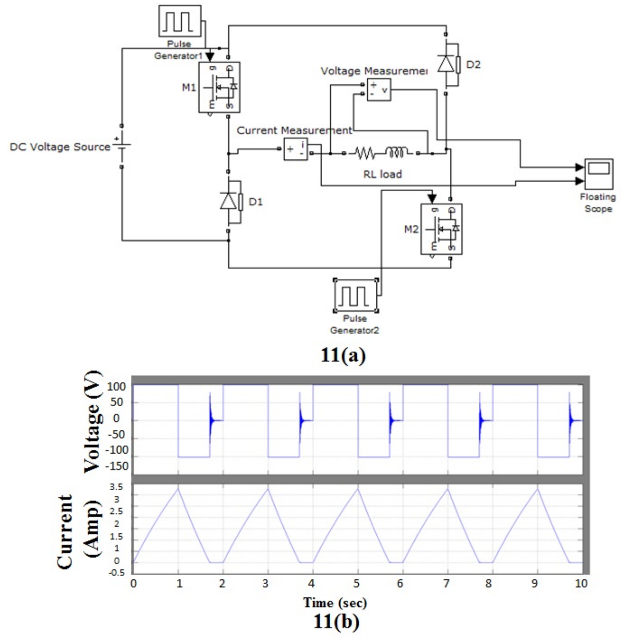
The PSIM and MATLAB SIMULINK simulation circuit diagram of the asymmetrical converter or amplifier and its output voltage and current waveform are given in Fig. 11 and Fig. 10. It can be seen in Fig. 10(a) that when both switches M1 and M2 are on, the cathode of diode D1 is more positive than its anode. So, in this case, the full voltage will appear across the load terminals. Hence, the load voltage becomes the supply voltage. When M1 and M2 are turned off, the energy stored in the coil will keep the current in the same di-



9(a)

9(b)

Figure 9: (a) PSPICE circuit diagram for buck converter (b) Frequency response of buck converter in PSPICE



11(a)

11(b)

Figure 10: (a) MATLAB circuit diagram for the asymmetrical converter (b) Voltage output and current output of MATLAB circuit diagram

rection until and unless it is depleted. Due to the property of the inductor, the coil voltage becomes reversed as soon as the supply voltage across the coil is withdrawn and M1, M2 are turned off. Here the anode of diode D2 is more positive than its cathode. Hence, diode D2 becomes forward biased. The cathode of diode D1 is more negative than its anode. Hence, diode D1 becomes forward biased, i.e., in this case the output voltage becomes negative and its magnitude is equal to the supply voltage.

The PSPICE simulation circuit diagram and frequency response of the asymmetrical converter is shown in Fig. 12. The frequency response of the asymmetrical converter gives the gain cross-over frequency of 52.675 KHz as shown in Fig. 12(b). The bandwidth of this frequency is high. Since stability is directly proportional to bandwidth, the stability of the system is quite high and gives a faster response.

The PSIM and MATLAB SIMULINK simulation circuit diagram of a half bridge converter or amplifier and its output voltage and current waveform are given in Fig. 14 and Fig. 13. Here two capacitors of this converter are used to divide the input voltage into two parts, i.e., each capacitor voltage is $V_{c1} = V_{c2} = \frac{V_i}{2}$. It can be seen that when switch M1 is on, capacitor C1 will discharge through the inductive load. In this case the upper voltage source will be operated and the voltage across the load is same as and when switch M1 is off; M2 is the voltage across the load is same and its sign will be negative. The simulation results show that the output current rises and decays exponentially, as can be seen in Fig. 13(b).

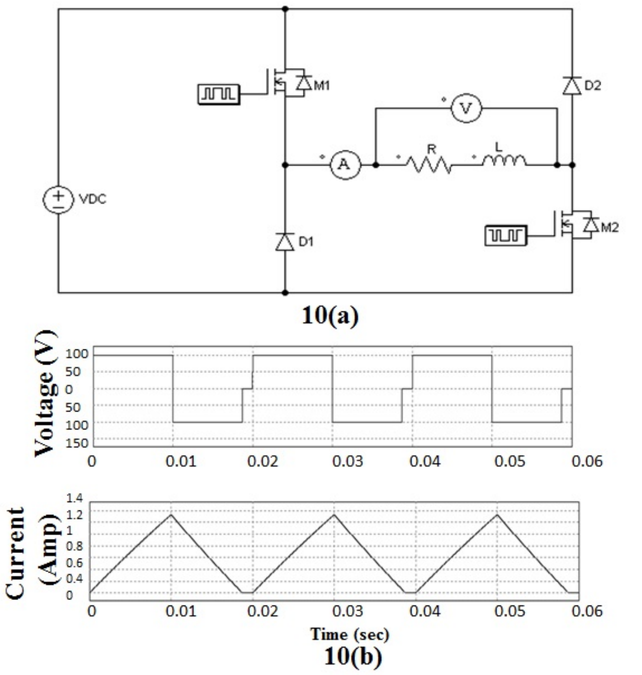
The PSPICE simulation circuit diagram and frequency response of the half bridge converter are shown in Fig. 15. As can be seen in Fig. 15(b) the frequency response of this converter gives the gain cross-over frequency of 19.582 KHz. The bandwidth of this frequency is quite good. Since stability is directly proportional to bandwidth, the stability of the system is also high, but the response is slow.

The PSIM and MATLAB SIMULINK simulation circuit diagram of the half bridge converter or amplifier and its output voltage and current waveform are given in Fig. 16 and Fig. 17. It can be seen from Fig. 17(a) when switches M1 and M2 are on, and M3 and M4 are off. In this case, the inductor charges and stores energy and full supply voltage is shown across the load and when switches M3 and M4 are on, and M1 and M2 are off the output voltage across the load is the same as supply voltage, but the direction will be the opposite, as shown in Fig. 17(b). It can be seen in Fig. 17(b) that the output current rises exponentially. But due to the connected magnetic coil and load with inductive property, the current does not change suddenly but decays exponentially, as shown in Fig. 17(b).

The PSPICE simulation circuit diagram and frequency response of the full bridge converter are shown in Fig. 18. The frequency response of this converter gives a gain cross-over frequency of 40.99 kHz. The bandwidth of this frequency is small. The stability of the system is also low and gives a good response.

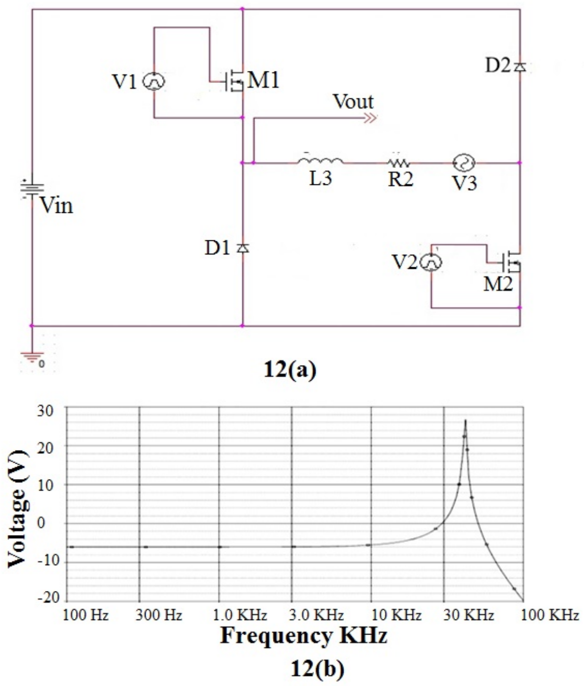
5. Conclusion

This work presents the simulation of different types of power amplifiers used in the DC electromagnetic levitation system (EMLS). The operation of power amplifiers has been discussed in this paper. The time responses were simulated


10(a)

10(b)

Figure 11: (a). PISM circuit diagram for the asymmetrical converter (b). Voltage output and current output of PSIM circuit diagram


12(a)

12(b)

Figure 12: (a) PSPICE circuit diagram for asymmetrical converter (b) Frequency response of asymmetrical converter in PSPICE

using a PSIM and a MATLAB SIMULINK based simulator. The output results of the different types of power amplifiers of these two simulators follow a similar pattern. The stability and speed of response of the power amplifier are dependent on the gain cross-overfrequency (GCF). This means that the amplifier which has high gain cross-over frequency delivers better converter stability and speed of response. This study shows that the asymmetrical converter has high gain cross-over frequency (GCF), i.e., 52.675 KHz, and the load current of the asymmetrical converter is always positive. Hence, the asymmetrical converter is selected as the power amplifier of the DC electromagnetic levitation system.

References

[1] S. Banerjee, R. Bhaduri, and P. Biswas. "frequency response based dynamic performance analysis of switched mode power amplifiers used in electromagnetic levitation systems. In *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010),Brighton, UK*, 2010.

[2] S. Banerjee, R. Bhaduri, and D. Prasad. Some aspects of switching power amplifier used in electromagnetic levitation. *International Journal of Power Electronics*, 1:33–48, 2008.

[3] P.S. Bimbhra. *Power Electronics*. Khanna Publication 5th Edition, 1995.

[4] Marty Brown. *Practical Switching Power Supply Design*. New York: Academic Press, Inc., 1990.

[5] S. Carabelli, F. Maddaleno, and M. Muzzarelli. High-efficiency linear power amplifier for active magnetic bearings. *IEEE Transactions on Industrial Electronics*, 47(1):17–24, Feb 2000.

[6] Irving M. Gottlieb. *Power Supplies, Switching Regulators, Inverters, & Converters*. New York: McGraw-Hill, 1993.

[7] B.V. Jayawant. Review lecture. electromagnetic suspension and levitation techniques. 416:245–320, 04 1988.

[8] Sameer Khader, Alan Hadad, and Akram A. Abu-aisheh. The application of psim &matlab simulink in power electronics courses. In *IEEE Global Engineering Education Conference (EDUCON), Jordan*, 2011.

[9] Philip T. Krein. *Elements of Power Electronics*. Oxford University Press, 2003.

[10] F. Maddaleno, S Carabelli, and M Muzzarelli. A modified class g amplifier for active magnetic bearing , vol.1, california, usa. In *13th annual applied power electronics conf, Proc. APEC'97*, pages 534–538, 15-19 feb 1997.

[11] D. M. Mitchell. *DC-DC Switching Regulator Analysis*. New York: McGraw-Hill, 1988.

[12] Ned Mohan, Tore M. Undeland, and William P. Robbins. *Power Electronics: Converters, Applications, and Design*. IEEE Press and John Wiley & Sons, 1996.

[13] S. Moriyama. Ac magnetic suspension using a differential feedback power amplifier. *Electrical Engg. in Japan*, 131(2):61–67, 2000.

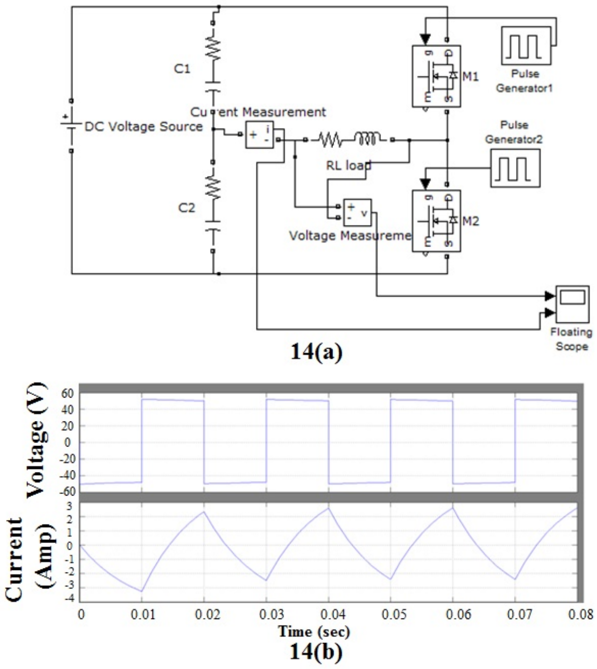
[14] M. H. Rashid. *SPICE for Circuits and Electronics Using PSpice. Englewood Cliffs*. NJ: Prentice-Hall, 1990.

[15] Muhammad H. Rashid. *Power Electronic*. Wheeler Publishing, 1998.

[16] Seguier. *Power Electronic Converters: DC-DC Conversion*. Springer-Verlag, Inc, 1993.

[17] P.C. Sen. *Thyristorised DC Drive*. New York : Wiley Interscience, 1981.

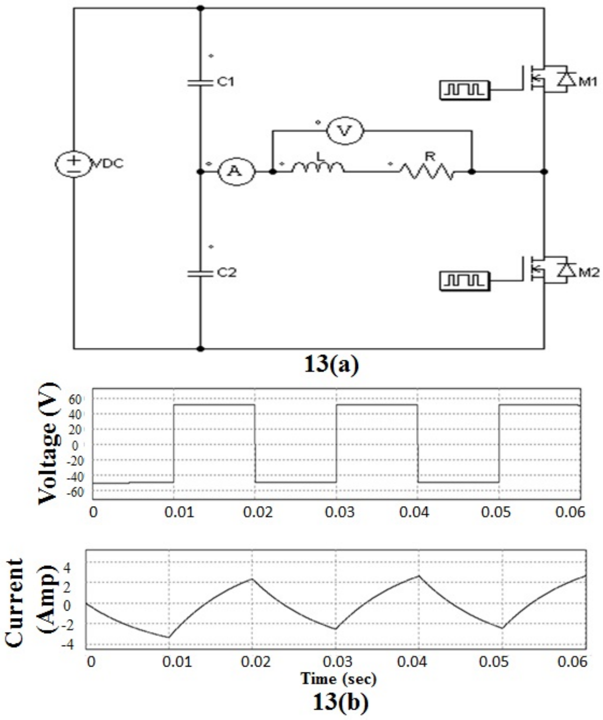
[18] P. K. Sinha. *Electromagnetic suspension : dynamics & controls*. Peter Peregrinus Ltd. : London 1987, 1987.



14(a)

14(b)

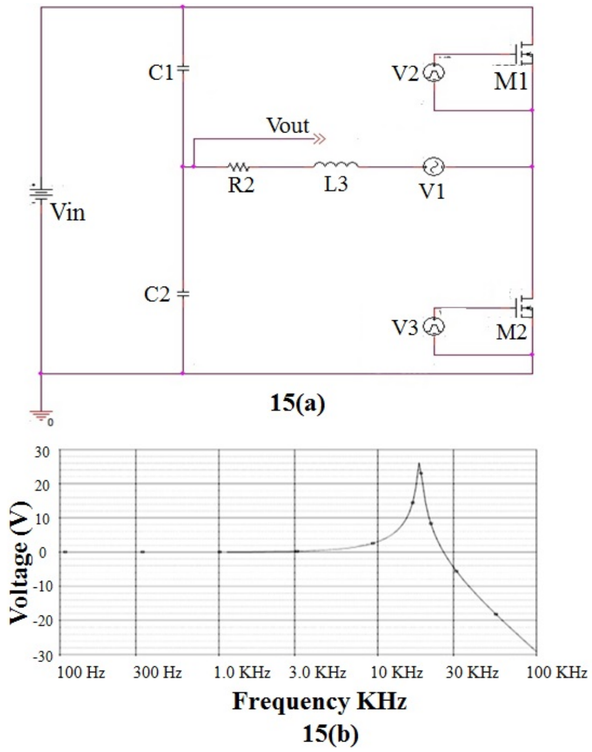
Figure 13: (a) MATLAB circuit diagram for half bridge converter (b) Voltage output and current output of MATLAB circuit diagram



13(a)

13(b)

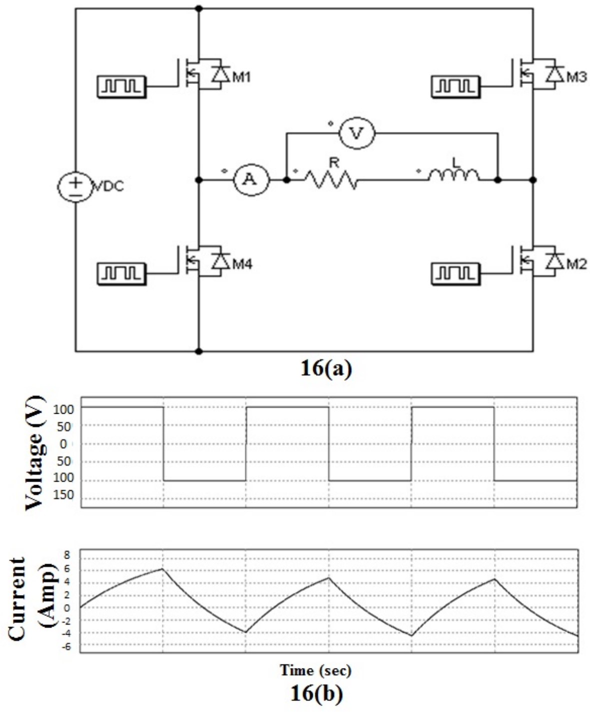
Figure 14: (a) PISM circuit diagram for half bridge converter (b) Voltage output and current output of PSIM circuit diagram



15(a)

15(b)

Figure 15: (a) PSPICE circuit diagram for half bridge converter (b) Frequency response of half bridge converter in PSPICE



16(a)

16(b)

Figure 16: (a) PISM circuit diagram for full bridge converter (b) Voltage and current output of PSIM circuit diagram

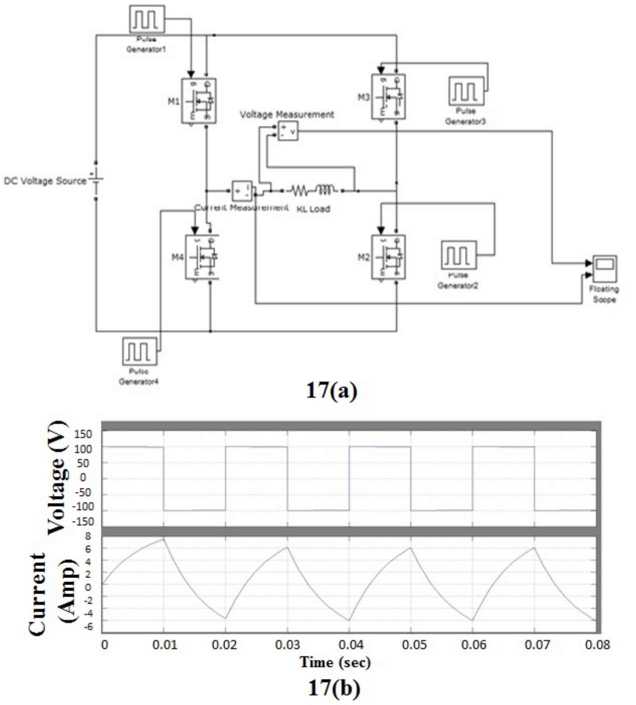


Figure 17: (a) MATLAB circuit diagram for full bridge converter (b) Voltage output and current output of MATLAB circuit diagram

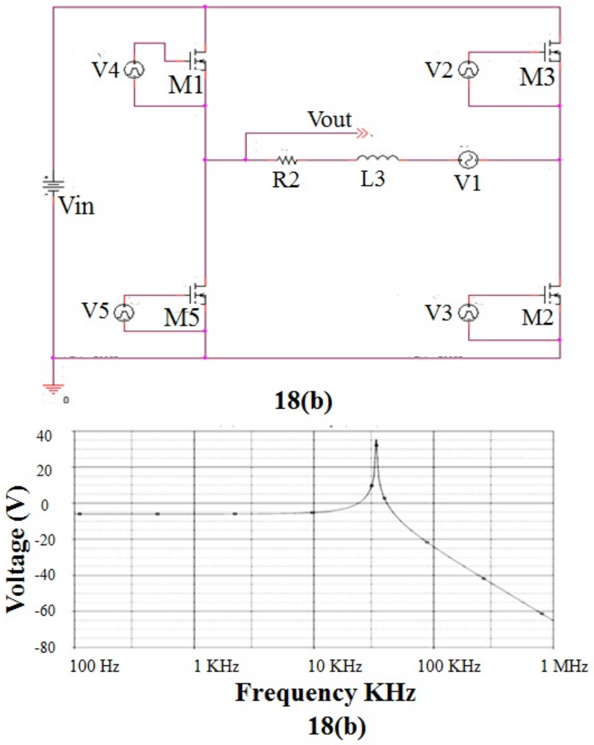


Figure 18: (a). PSPICE circuit diagram for full bridge converter (b). Frequency response of full bridge converter in PSPICE