Simulation and modeling of high voltage DC to AC PWM inverter for electrostatic generator

S. M. A. Motakabber*, M. Wahidur Rahman, and Muhammad Ibn Ibrahimy

Dept. of Electrical and Computer Engineering, Faculty of Engineering, International Islamic University Malaysia, 53100 KL, Malaysia

Abstract. This paper proposes a single-phase DC to AC inverter for ESG (electrostatic generators) that may be used in the household’s application. The electrostatic generators were developed a while ago and remained abandoned for a long time. Now, as the modern technology advanced, it’s time to utilize the ESG to power generation. A pulse width modulation (PWM) based high voltage DC to AC inverter is a suitable system for converting the EGS high electrostatic DC voltage into standard 50Hz, 220V(rms) AC. The PWM technique is used to control the inverter switches to create a pulse width modulated bi-phase square wave signal. A lowpass LC filter has been utilized to remove the higher harmonic frequencies and which is capable to reduce the total harmonic distortion (THD) around 3.5%. The proposed model showed the overall system performance in terms of efficiency is 95%. To use ESG, this inverter is an easy and cost-effective electrical device. From the result, it is observed that the output voltage of the proposed inverter is greatly improved compared to the other inverter circuits.

1 Introduction

In recent years, the power application is growing in numbers due to developments in semiconductor switch technologies. Nowadays, utilization of energy is a critical subject in the field of power systems. Most of the conventional electrical power generation is based on non-renewable energy sources such as coal, petroleum gas, oil, and nuclear, etc. Alternatively, the renewable energy sources like solar, wind, hydro etc. based technologies are rapidly evolving side by side [1]. To contribute this need, power electronics required to find innovative ways of generating power and develop affordable and dependable systems. Therefore, ESG can be utilized to generate electric power as a non-conventional way. The ESG was invented in the 18th century and used in high voltage scientific research application only, such as particle accelerators, discharge tubes. The main obstacle in ESG is that it produces only high voltage DC, so it is difficult to use in normal works. Due to the recent advancement of electronic devices and technology, it is possible to invert the DC to AC electronically.

An inverter can be characterized as a square, modified and pure sine wave due to their generated waveform [2]. Generally, a PWM technique is used for high-efficiency inverter.
The square wave is used for low power application and low cost. The main drawbacks of the high voltage systems are high harmonic frequency distortion, low efficiency and high switching loss. A modified sine wave has less switching loss and lowers harmonic distortion to compared to a square wave. However, a pure sine wave is used high voltage application because it can be generated high power, high efficiency and low harmonic frequency distortion to compare other methods. The PWM controller is used to generate an inverter gate drive signal to compare the sinusoidal wave with a triangular waveform. The control method of PWM inverter offers some significance electronic devices such as power loss in the switching, harmonics reduction, generate an AC voltage of variable magnitude as well as different frequency.

Based on the circuit topology an inverter can be worked as a half bridge or a full bridge mode [4]. They have their own merits and demerits. For simple and low-cost application generally, a half bridge inverter structure is used, whereas, in a higher power and efficiency full bridge inverter structure is used. The basic block diagram of a full bridge inverter structure is shown in figure 1. Whatever the topology of the inverters, a PWM system is widely used to generate the sinusoidal wave, to improve the power quality and to minimize frequency harmonic distortion [5].

![Fig. 1. Basic block diagram of a PWM full-bridge inverter system.](image)

Now, in the PWM technique uses insulated gate bipolar transistor (IGBT) switches and which can be operated at a low or high frequency based on the carrier signal. When the carrier signal is higher, the system frequency also increases to improve the switching efficiency, while the carrier signal is low it increases the switching delay, noise ratio and phase angle [6]. In switching operation, switching stress and electromagnetic interference occurs during the on/off time of the power devices for the change of voltage \(dv/dt\) and current \(di/dt\) [7].

A filter is utilized to convert the modulated square wave into a sine wave with the same fundamental frequency with a minimum phase shift. An LC filter can reduce harmonic reduction and make the required frequency in the range of angles which is < 5° [8]. The main advantages of LC filter are low power loss, simple, reliable and cheap, while LCL filter is complex and costly.

In this paper, focus on the modeling of a full bridge PWM inverter for high voltage static DC. The proposed system uses power IGBT as an electronic switch. Two levels PWM technique has been used to control the IGBT gate to reduce the switching losses and harmonic distortion. A microcontroller has been used to generate the gate driving pulses, which makes the controller more flexible and reliable.

2 Switching and control

Nowadays, a variety of electronic switches are available in the market. The high voltage and high current, a bipolar transistor can be accessible, while their switching speed is slow. However, a power MOSFET has higher switching speed with lower voltage and current handling capacity. A hybrid structure of a solid state switch like IGBT device consists of MOSFET and BJT, which offers to use more power than a standard bipolar transistor with
the low input at the same time higher voltage operation of the MOSFET [9]. Due to its low cost, high efficiency and reliability IGBT is most commonly used the solid-state switch in the power electronics field.

Figure 2 shows the Matlab simulation block of an IGBT diode with it's on/off characteristics. The maximum switching speed of an IGBT is controlled by its signal rising and fall time and critical to measure. The time needs to fall the collector voltage from 100% to 10% V_max is called on time, t_on, similarly, the time needs to raise the collector voltage from 10% to 100% V_max is called the off time, t_off as shown in figure 2(b). So the delay time involves in the IGBT, T_d and the maximum switching speed limit can be represented by the Equation (1)-(3).

\[ f_s = \frac{1}{T_d} = \frac{1}{t_{on} + t_{off}} \]  
\[ t_{on} = t_{dn} + t_r \]  
\[ t_{off} = t_{df} + t_{f1} + t_{f2} \]

Fig. 2. IGBT equivalent circuit, (a) Matlab block and (b) on/off characteristics.

3 Electrostatic generator and inverter

Electrostatic generators are mechanical devices that generate high voltage DC from mechanical energy. The output voltage and current depend on the generator size and speed of the disk. The principle of generating the electrical power of an ESG is completely different than the electrical power generated by the conventional magnetic induction theory. The construction of a Wimshurst ESG is simple as shown in figure 3, it has opposite signs rendered of two conductors, using only electric forces, and work by using moving plates, drums, or belts carry electric charge to a high potential electrode [10].
Usually, the ESG generates 4kV to 25kV DC and it is difficult to sustain a single IGBT at this high voltage level. So, to construct an inverter for ESG source required numbers of IGBTs are needed to be connected in series. For switching the individual IGBT in series connection is complex and needs special circuit arrangement as shown in figure 4. Then the electrical inverter transforms it to AC with a required frequency of 50Hz. These DC to AC power inverters are widely used for various applications like distribution system. Each voltage-mode and current-mode control has been used in sensitive applications.

![Fig. 4. IGBT application in high voltage, (a) series connection and (b) gate triggering.](image)

A full bridge switching topology of the inverter for ESG source is shown in figure 5. In this bridge configuration, 4-groups of the switch are used. Each group consists of two 2-IGBTs in the series. The high voltage DC of the ESG is divided into ±4000V and neutral (Ground) to make bipolar phase. Two opposite corners of the IGBT switching bridge are connected with the ±4000 VDC of the ESG and the AC load is connected to the other corner of the bridge.

![Fig. 5. A full-bridge inverter circuit using IGBTs for ESG.](image)

The PWM voltage for the IGBT gate control is generated by using Arduino Nano, which makes the circuit more compact, flexible and easy to programmable control without changing the hardware connection. The AC output voltage waveform is a pulse width modulated 50 Hz sinusoidal wave. An LC-lowpass power filter is used to remove the unwanted higher harmonic frequencies from the PWM output voltage and make it...
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The theory of the LC-lowpass filter is well known and needs slight adjustment for using it to the PWM signal. The capacitor and inductor values can be calculated by using equation (4) and equation (5) [11].

\[
L = \frac{2V_{dc} \times D}{\Delta I_{max} \times f_s} \quad (4)
\]

where, \( L \) is the inductance in Henry, \( V_{dc} \) is the input DC voltage in volt, \( f_s \) is the switching frequency in Hz, \( \Delta I_{max} \) is the maximum allowable ripple current and \( D \) is the duty cycle.

\[
C = \frac{\Delta I_L}{\Delta V_{out} \times f_s} + r_{ESR} \Delta I_L \quad (5)
\]

where, \( C \) is the capacitance in Farad, \( \Delta V_{out} \) is the output ripple voltage, \( \Delta I_L \) is the maximum allowable ripple current in the inductor and \( r_{ESR} \) is the equivalent series resistance of the capacitor in Ohms.

The output power quality in terms of the harmonic frequency distortion can be calculated by using the equation (6) [12]. The total harmonic distortion (THD) is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency.

\[
THD = \sum_{n=2}^{\infty} \frac{V_n^2}{V_1} \times 100 \quad (6)
\]

where, \( V_n \) is the voltage of the nth harmonic frequency and \( V_1 \) is the voltage of the fundamental frequency.

4 Result and discussion

The proposed high voltage DC to AC inverter model has been investigated by using Matlab 2017a. The simulation parameters have been considered as duty cycle \( D = 85\% \), PWM carrier frequency \( f_s = 5\) kHz, fundamental frequency \( f_1 = 50\) Hz and dual DC input voltage \( V_{DC} = \pm 5\) kV. Figure 6 shows the time domain output voltage waveform of the proposed inverter. It is observed from figure 6 that the output voltage of the inverter complied with the proposed design.

Fig. 6. Output voltage waveform of the inverter, (a) PWM output and (b) filtered output.

5 Conclusion

The proposed full-bridge inverter model can be used for the electrostatic generator to convert the high voltage DC into AC. The duty cycle and the carrier frequency of the PWM
have a significant effect on the DC to AC conversion efficiency. The LC-lowpass filter is used to reduce the THD without the losses of power.

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