



Development and Execution of a Two-Way DC-AC Converter for Energy Storage Applications

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Abstract

This paper presents a software-based design and simulation of a bidirectional single phase DC-AC converter intended for integration with energy storage systems. The proposed approach utilizes a triple-port converter (T-PC) topology to facilitate efficient power exchange between an energy storage device (ESD) and the grid, employing advanced modulation and control strategies to reduce switching losses and optimize efficiency. Through a MATLAB/Simulink environment, we simulate and analyze the control dynamics of the converter, showcasing improved performance under varying voltage conditions. This study excludes hardware implementation and instead emphasizes theoretical modeling and digital control algorithms suitable for real-time applications.

Keywords: Bidirectional DC-AC Converter, Energy Storage System, Triple-Port Converter (T-PC), Simulation, MATLAB/Simulink, Power Electronics, Control Strategy.

Introduction

Energy storage, such as that found in microgrids, electric cars, and uninterrupted power supplies (UPS), is a crucial component of the power system. The primary component that connects the energy storage device (ESD) to the grid is the dc-ac bidirectional converter [1]. It is difficult to swap power between the ac grid and ESD in a flexible and effective manner. As illustrated in Fig. 1, a dual-stage bidirectional dc-ac converter is frequently utilized to link a low-voltage ESD to the grid. To adopt constant VB (dc bus voltage), a bidirectional dc-dc converter is offered; the voltage is higher than the grid peak amplitude voltage VG (ac grid voltage) [2]. When the VB voltage is step-down to VESD in the ac-dc mode, a bidirectional dc-dc converter boosts the ESD voltage up to VB in the dc-ac mode. The main problem of the dual-stage conversion is more number of conversion stages because whole powers are processed double the times, which decreases the efficiency of the system. Several methods are suggested to increase the efficiency of the dc-ac bidirectional converter, but researchers are concentrating on dc-dc conversion stage or dc-ac conversion stage individually [3, 4]. Designed circuits and control strategy were applied to any one of the conversion stages to get multilevel operation or soft-switching operation losses, but overall efficiency improvement is pending due to two conversion stages [5, 6].



Fig 1: Existing dual conversion.

A bidirectional z-source or quasi-Z-source inverter can accomplish single-stage dc-ac bidirectional conversion or single-phase direct conversion, which appears to be a preferable option due to single-stage energy conversion [7, 8]. With a one-stage source impedance converter, however, maintaining high efficiency is difficult because of increased voltage/current demands on the switches, modulation index, and boost-up capacity. Bidirectional full-bridge single-phase converters are therefore the appropriate solution, and grid-side time-varying voltage is a crucial consideration [9, 10]. VB voltage is frequently chosen based on the worst-case scenario, meaning that the grid-side dc-ac converter's controlled ac current ensures the largest amplitude of the ac voltage [11, 12]. To reduce the number of conversion stages, a partial power concept of operation is proposed and supplied to a bidirectional dc-dc converter and a bidirectional dc-ac converter [13, 14]. The bidirectional single-phase dc-ac

conversion, depicted in Figs. 1 and 2, does not employ this conversion paradigm. If the immediate value of V_G is smaller than V_{ESD} , ESD low-voltage VESD can send power to the grid directly. When V_{ESD} is less than or more than V_G , ESD can also transfer power with the grid via a dc-ac converter, in accordance with the multilevel converter operating principle [15, 16]. Reducing conversion stages and improving overall efficiency are the primary goals of this suggested bidirectional converter [17, 18]. The proposed converter's advantages include a single step of power conversion that allows energy exchange between low-voltage ESD and the grid, as well as a significant reduction in downstream dc-dc converter power losses and power ratings.

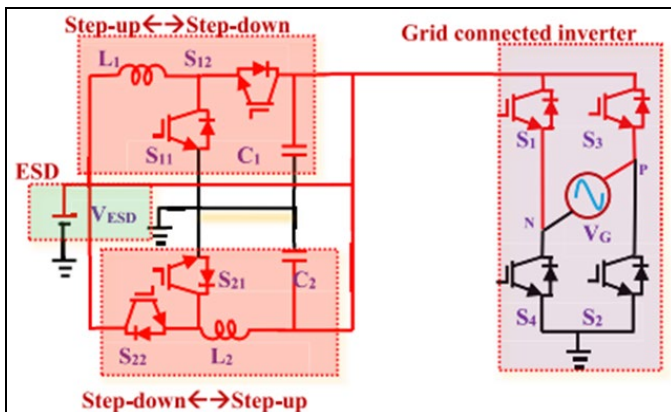


Fig 2: Existing topology

Battery

Devices called batteries store electrical energy and release it when needed. A cathode and an anode, along with an electrolyte that facilitates ion flow between the electrodes, comprise one or more electrochemical cells. When an electrical circuit is connected to a battery, chemical processes in the cells cause electrons to flow from the negative electrode to the positive electrode (cathode) via the circuit, producing an electrical current that keeps the battery charged. Batteries are used in a wide range of applications and come in different sizes, forms, and chemistries. They can power small devices like flashlights and remote controls or larger systems like electric cars and renewable energy systems.

Types of Batteries:

Batteries come in a variety of forms, each with special qualities and uses. These are a few of the most prevalent kinds:

The most traditional and popular kind of rechargeable battery is the lead-acid battery. In addition to backup power systems, they are utilized in automobiles, boats, and other vehicles.

Rechargeable, nickel-cadmium (NiCd) batteries are frequently found in cameras, portable power tools, and other electronic equipment.

Similar to NiCd batteries, nickel-metal hydride (NiMH) batteries offer a higher energy density, which makes them useful in hybrid vehicles and other uses.

Rechargeable lithium-ion (Li-ion) batteries are frequently found in laptops, cellphones, and other portable electronics.

Li-ion batteries that use a polymer electrolyte rather than a liquid electrolyte are known as lithium-polymer (Li-poly) batteries. Compared to conventional Li-ion batteries, they are lighter and more flexible, which makes them suitable for thin devices like tablets and smartphones.

Alkaline batteries are non-rechargeable and frequently found in toys, flashlights, and remote controls, among other

household gadgets.

Similar to alkaline batteries, zinc-carbon batteries are likewise non-rechargeable. They are frequently found in low-drain gadgets like radios and clocks.

Small button-cell batteries called silver oxide are frequently found in clocks, calculators, and hearing aids.

Some electric cars and other medical devices, like hearing aids, employ zinc-air batteries.

Numerous more battery types, including as solid-state, sodium-ion, and flow batteries, are still being researched and tested for a range of uses.

Advantages of Batteries

Batteries are beneficial in a variety of applications due to their many benefits. The following are a few of the biggest benefits:

- **Portable:** Because batteries are portable, they can be utilized in places without power outlets and are therefore readily carried.
- **Dependable:** Batteries can produce a steady voltage output even when the input voltage varies, making them a dependable power source.
- **Long-lasting:** Many batteries are a cost-effective option for long-term applications because of their extended lifespan, which allows them to supply power for several years.
- **Rechargeable:** Since rechargeable batteries can be used repeatedly, they cut down on waste and ultimately save money.
- **Eco-friendly:** Since many battery types may be recycled, disposing of them has less of an impact on the environment.
- **Versatile:** Batteries have many uses, ranging from storing renewable energy to powering tiny electronic devices.
- **Independent:** Batteries are helpful in distant areas or during power outages since they can supply electricity without relying on the power system.

All things considered, batteries offer a dependable and practical power source for a variety of uses, making them a necessary part of contemporary life.

Applications

Applications for batteries are numerous and range from supplying backup power for enormous buildings to powering tiny electronic devices. These are a few of the most typical uses for batteries:

- **Electronics that are Portable:** Numerous portable technologies, such as computers, smartphones, cameras, and portable game consoles, are powered by batteries.
- **Electric Vehicles:** Bicycles, buses, and cars that run on batteries are examples of electric vehicles.
- **Storage of Renewable Energy:** Energy produced by renewable sources, including solar panels and wind turbines, is stored in batteries.
- **Backup Power:** In the event of a power outage or other emergency, batteries are utilized to temporarily power houses, hospitals, and other vital infrastructure.
- **Aerospace:** Batteries power navigation systems, communication devices, and other vital systems in spacecraft, satellites, and other aerospace uses.
- **Medical Devices:** Pacemakers, hearing aids, and other implanted devices are just a few of the many medical equipment that use batteries.

- **Applications in the Military:** Radios, night vision goggles, and unmanned aerial aircraft are among the military devices that employ batteries.
- **Marine Applications:** Boats and other marine vessels, as well as undersea exploration and research, are powered by batteries.

All things considered, batteries are vital parts of contemporary life since they offer dependable, portable power for a variety of uses.

Lithium Ion Batteries

In recent years, lithium-ion batteries—a form of rechargeable battery—have grown in popularity, especially in portable electronic devices like tablets, laptops, and smartphones. They are also utilized in renewable energy storage systems and electric cars. Their high energy density, which allows them to store a significant amount of energy in a very tiny and light packaging, is the main benefit of lithium-ion batteries. Because of this, they are perfect for use in portable electronics where size and weight are crucial considerations.

Lithium ions are used in lithium-ion batteries to transfer between the anode and cathode, two electrodes that are separated by an electrolyte.

Lithium ions generate electrical energy by moving from the cathode to the anode during charging and back to the cathode during discharging.

The propensity of lithium-ion batteries to deteriorate over time and lose their energy-storage capability is one of its drawbacks. High temperatures or rapid charging rates may make this worse. However, lithium-ion batteries now operate better and last longer because to developments in battery chemistry and manufacturing techniques.

All things considered, lithium-ion batteries have gained popularity because of their high energy density, extended cycle life, and multiple recharge ability. They are anticipated to be a major factor in the shift to greener and more sustainable energy sources, and they have completely changed the way we power our modern devices.

Charging and Discharging of Lithium Ion Batteries:

Lithium ions travel through the electrolyte between the positive and negative electrodes during the charging and discharging processes of lithium-ion batteries. This is a more thorough explanation:

Getting Charged: An electric current is passed through the lithium-ion battery by a charger after it is connected to a power source.

The anode, or negative electrode, is where lithium ions are kept after being transferred from the cathode, or positive electrode, by the current.

As more lithium ions are stored in the anode, the battery's voltage rises.

The charger ceases to supply current to the battery once it is fully charged.

Discharging:

A circuit permits the electric current to move from the anode to the cathode when the lithium-ion battery is connected to a device.

Lithium ions transfer from the anode to the cathode as the current flows, producing electrical energy.

As additional lithium ions are sent to the cathode, the battery's voltage drops.

The gadget will stop working and the battery will need to be

recharged after it has been depleted to a particular level. Before their performance starts to deteriorate, lithium-ion batteries have a certain number of charge-discharge cycles. Therefore, it's crucial to utilize the right charger and charging rate and to avoid overcharging or over discharging the battery. Furthermore, the battery's performance and safety may be compromised by exposure to extreme heat or physical harm.

GRID:

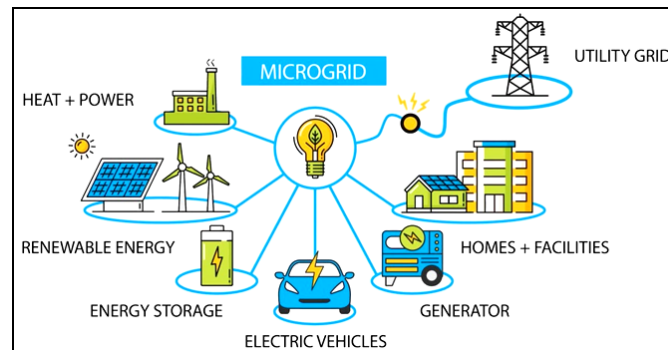


Fig 3: Microgrids

The word "grid" describes the intricate system of transmission, distribution, and power producing infrastructure that transports electricity from power plants to residences, workplaces, and other establishments.

The three primary components of the system are distribution, transmission, and power generating. Power plants use a variety of energy sources, including coal, natural gas, nuclear, wind, solar, hydro, and geothermal, to generate electricity. The transmission system is then used to move the electricity.

Transmission: High-voltage transmission lines are used to transport electricity across long distances from power plants to substations. To minimize losses and preserve a steady supply of energy, the transmission system is set up to function at voltages between 69 kV and 765 kV.

Distribution: From substations, the distribution system transports electricity to residences, workplaces, and other establishments. The distribution system is intended to give end customers dependable and effective power. It runs at lower voltages, usually between 120 and 480 volts.

Load balancing: To keep the grid's frequency and voltage steady, grid operators must continuously balance the supply and demand of power. This entails keeping an eye on power plant output and modifying generation output to correspond with the demand for electricity.

Grid Control: To guarantee the reliability and security of the grid, grid operators employ a range of control systems and technologies. These technologies and systems include Supervisory Control and Data Acquisition (SCADA) systems, which monitor and control the grid in real-time, and Automatic generating Control (AGC) systems, which modify the generating output to match the demand for power.

Grid Security: To protect the grid, several security measures are in place, such as emergency response plans, cybersecurity protections, and physical security measures. When everything is taken into account, grid operation is a complex and dynamic process that necessitates the collaboration of multiple systems and parties. However, the ultimate result is a consistent and reliable supply of electricity that powers our homes, businesses, and communities.

Utility firms, which oversee and run the grid, are in charge of upkeep of the infrastructure and guaranteeing the dependability and security of the electrical system.

Government organizations also regulate the grid to make sure it satisfies requirements and offers customers accessible and reasonably priced electricity.

Recent technological advancements, modifications to energy regulations, and the growing need for renewable energy sources have all contributed to major changes in the system. The implementation of smart grid technology, the integration of intermittent renewable energy sources like solar and wind, and the creation of energy storage systems to facilitate this integration are some examples of these changes.

Types of Grids

There are several sorts of grids depending on a number of variables, including the grid's location, size, and power source types. Here are a few examples of grid types:

The National Grid: A national grid is a vast network that links distribution networks and power plants throughout a nation. Usually, a regulated utility business or a government organization runs national grids.

Regional Grid: A regional grid is a smaller-scale network that links distribution networks and power plants in a particular area. Utility firms run regional networks, which are frequently connected to national grids. Numerous factors, such as the grid's location, size, and power source types, determine the different types of grids. Here are some grid type examples:

The National Grid The extensive network that connects electricity plants and distribution networks across a country is known as the national grid. National grids are often operated by a government agency or a regulated utility company.

Local Grid: A regional grid is a smaller-scale system that connects local power producers and distribution networks. Regional networks, often linked to national grids, are operated by utility companies.

Smart Grid: A smart grid is a contemporary grid that optimizes the grid's sustainability, dependability, and efficiency by integrating cutting-edge technology like sensors, communication networks, and data analytics.

A number of variables, including the population size, the demand for power, and the availability of resources, will determine the kind of grid that is utilized in a given area.

Grid Operation: Depending on the situation, the term "grid" can mean many various things, but generally speaking, a grid is a system of linked components that cooperate to achieve a specific objective.

When it comes to power generation and distribution, the grid is the system of power lines, substations, transformers, and other equipment that makes it possible for electricity to be produced at power plants and delivered to residences and commercial buildings. With numerous redundant paths and backup systems, the grid is built to be extremely resilient and dependable, guaranteeing that power will always be available—even in the case of equipment breakdowns or other interruptions.

The intricate system of supply and demand underpins how the grid functions. Electricity is produced by power plants and sent into the grid, where it is allocated to customers in accordance with demand.

Grid operators must constantly regulate the flow of electricity to ensure that there is always enough power to meet consumer demands without overloading the system in order to maintain a stable electrical supply. This is done by balancing supply and demand in real-time.

The term "grid" can also refer to various kinds of interconnected systems, including data, communication, and

transportation networks, in addition to electricity generation and distribution. Creating a highly dependable and efficient system that can seamlessly and effectively provide products, services, or information to users is the aim in each situation.

Inverters

Electronic devices called inverters change direct current (DC) power into alternating current (AC). They are frequently employed in many different applications when only DC power is available but AC power is required.

Pure sine wave inverters and modified sine wave inverters are the two primary categories of inverters. A clean, steady output voltage that closely resembles the AC power provided by the utility grid is produced by pure sine wave inverters. Conversely, modified sine wave inverters generate an output that is somewhat distorted but still resembles a sine wave.

Types of Inverters

Several kinds of inverters are frequently utilized, such as:

Inverters with Pure Sine Waves: As the name implies, the output of these inverters is a pure sine wave, which resembles the waveform of the electricity that utility providers provide. They work best with delicate devices and appliances including computers, audio equipment, and medical equipment.

Modified Sine Wave Inverters: These inverters generate a waveform at the output that is somewhat distorted but still resembles a sine wave. They can power simple appliances like fans, lights, and small power tools and are less expensive than pure sine wave inverters.

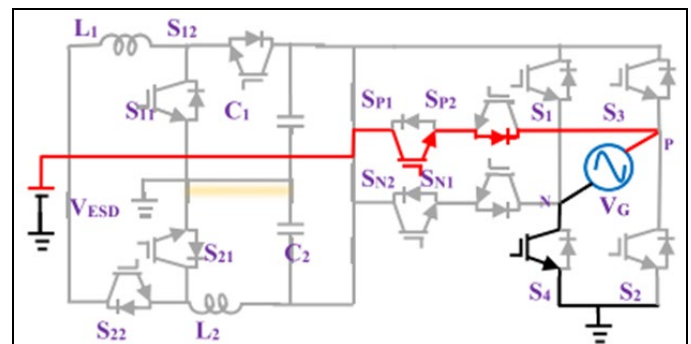


Fig 4: Direct dc-ac conversion mode

Square Wave Inverters: Most electronic equipment cannot use the square wave output that these inverters create. Because of the low quality of their output waveform, they are rarely utilized in contemporary applications.

Inverters that provide an output waveform that resembles a modified sine wave but with less distortion are known as quasi-sine wave inverters. They are less costly than pure sine wave inverters and work with the majority of modern equipment.

Grid-Tie Inverters: These inverters are utilized in utility grid-connected solar power systems. They transform solar panels' DC output into AC power that can be returned to the grid.

Working of Inverters

An inverter's fundamental operation is the use of electrical circuitry to transform DC electricity into AC power. Here is a quick rundown of how inverters operate:

Conversion from DC to DC: A DC to DC converter is used to raise the DC input voltage as the initial stage in the inverter process. The AC output voltage must be generated at this

higher voltage level.

The inverter circuitry, which is made up of electronic parts including capacitors, transistors, and diodes, receives the DC voltage after it has been applied. In order to power AC devices, the inverter circuitry transforms the DC voltage into an AC waveform.

Pulse Width Modulation

PWM is also used in some communication systems, where information is sent via a communication channel using the duty cycle. Pulse width modulation (PWM) is a type of signal modulation used in telecommunications where specific data values are encoded at the transmitter and decoded at the receiver based on the widths of the pulses. The carrier frequency of the modulation is usually pulses of different lengths supplied at regular intervals to convey the actual information.

One technique used to control the power sent to electrical components such as motors or LEDs is pulse width modulation, or PWM. The method is turning the electricity on and off quickly at a high frequency, usually in the range of several kilohertz to several megahertz.

The fundamental idea behind PWM is to produce a smooth, steady DC voltage or current by generating a variable-frequency, constant-amplitude waveform that is simple to filter. The effective voltage or current supplied to the load can be managed by varying the waveform's duty cycle.

PWM is extensively utilized in electronic systems and devices, such as audio amplifiers, power supplies, lighting control, motor control, and more. It is a particularly effective method of power regulation because it minimizes power losses in the switching devices by rapidly turning them on and off.

PWM has further uses, including servo motor control and digital signal modulation.

Types of Pulse Width Modulation

Different types of pulse width modulation (PWM) techniques manage the signal's on-time and off-time in different ways. Among the most prevalent varieties of PWM are:

A single pulse is produced for every control cycle using single-pulse width modulation, a technique that modifies the pulse's width to control the amount of power delivered to the load. Although this approach is straightforward and simple to use, it may result in significant output voltage or current ripple.

Multiple-pulse Width Modulation: This method employs several pulses with varying widths every control cycle. A steady, smooth output voltage or current can be obtained by varying the pulse widths.

Random pulse Width Modulation: This method varies each pulse's width at random within a predetermined range. The system's electromagnetic interference (EMI) is lessened as a result, but the control circuitry may become more complex.

In order to attain the required degree of control and efficiency, hybrid pulse width modulation combines two or more of the aforementioned techniques. For instance, it might employ several sinusoidally shaped pulses to accomplish smooth motor control and effective power delivery.

The particular application and system requirements will determine which PWM approach is best. Each type of PWM has pros and cons of its own.

PI Controllers

One kind of feedback control system that is frequently utilized in process control and industrial automation is the proportional-integral (PI) controller. They combine integral control and proportional control, two fundamental control strategies.

A form of control known as proportional control modifies a system's output in proportion to the discrepancy between the actual output and the intended set point. By deducting the intended set point from the actual output, the proportional controller generates an error signal, which is subsequently multiplied by a proportional gain. The proportional gain determines how much the output should be adjusted for a given error signal.

Conversely, integral control is a kind of control that modifies the output in accordance with the cumulative error over time. The integral controller increases the integral value by an integral gain after calculating the integral of the error signal over time. For a particular integral error signal, the integral gain establishes how much the output should be modified.

To create a more efficient control system, a PI controller combines integral and proportional control. When the error signal changes, the proportional component responds quickly.

System Configuration

Illustrates the proposed single-phase bidirectional dc-dc triple port converter (T-PC). The primary Figure: The suggested topology. Figure: Direct mode of dc-ac conversion. The suggested system's basic idea is to add a dc port to the dc-ac power stage so that ESD power can only be traded with the grid through T-PC in a single conversion stage. As a result, less energy will be processed in the bidirectional dc-dc converter. An ESD and dc bus are connected to a bidirectional dc-dc converter, which provides a steady dc voltage (V_B) for the dc-ac stage and can function similarly to a conventional dual stage dc-ac converter.



Fig 5: Proposed conversions

The core component of the proposed conversion is a three-port bidirectional converter. The suggested work's developed converter is based on two bidirectional switches that are added between midpoints, or terminals P and N. Bidirectional horizontal switches (SP1 and SP2 and SN1 and SN2) are necessary to manage energy exchange between ESD and the grid in a bidirectional fashion. It is crucial that the voltage of ESD V_{ESD} be greater or less than the immediate value of grid voltage. Two insulated gate pulse width modulations (IGBTs) coupled in series, two parallel opposite blocked IGBTs, or an active switch and diode combination are the sources of horizontal bidirectional. These bidirectional switches are mainly used in dc-ac and ac-dc converters; the control and implementation

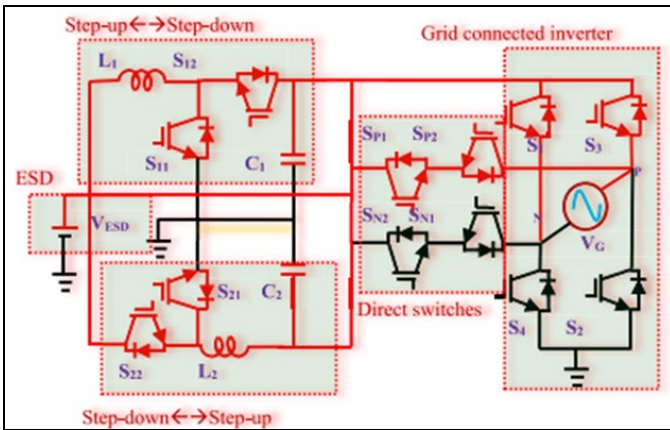


Fig 6: Proposed topology

The suggested converter can employ a sine pulse width modulation approach based on double carriers. The main T-PC waveform, where switches SP1, SN1, S1-S4 are used to acquire the converter's voltage control operation, and VPN is

the midpoint voltage of the converter switches. The suggested converter operates similarly to the conventional multilevel converter in terms of modulation approach. However, VESD and changing the state of charge (SOC) of the ESD directly determine the low difference from the same voltage levels in the conventional multilevel converter voltage level. Relationship between the suggested converter's average battery voltage (VESD) and the grid voltage instantaneous value Direct conversion mode and dual-stage conversion mode are two of T-PC's operating modes.

Regardless of the direction of energy flow, all operational switches maintain the same driving signal. The suggested bidirectional T-PC-based dc-ac converter's control block diagram. Although the suggested converter modulation is completely different, the power regulation is identical to that of a conventional converter. The rectifier stage's dc bus voltage (VB) and inverter mode are handled by the dc-dc bidirectional converter.

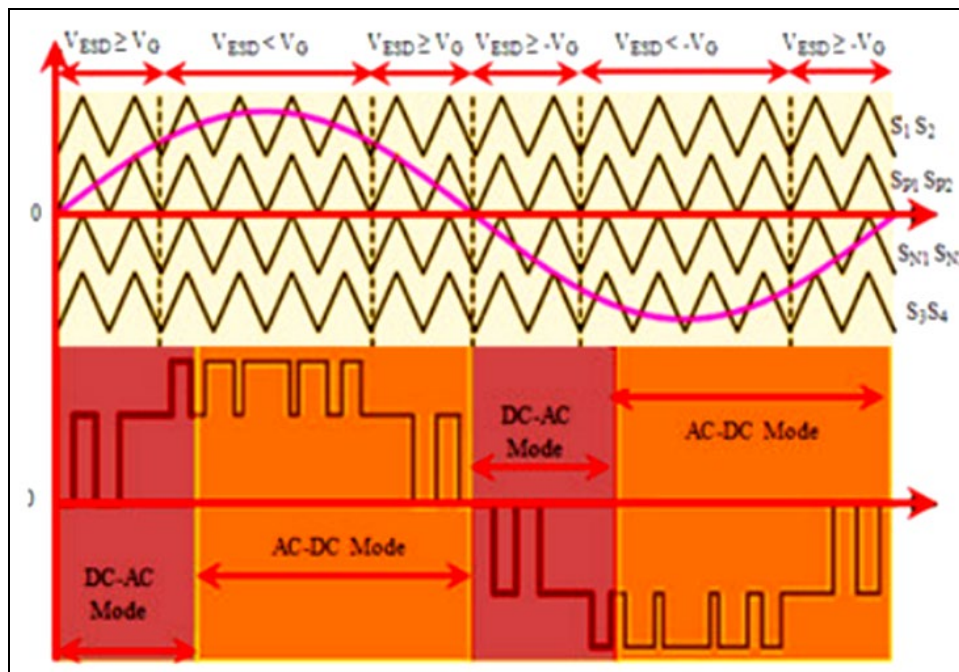


Fig 7: Main waveform of T-PC

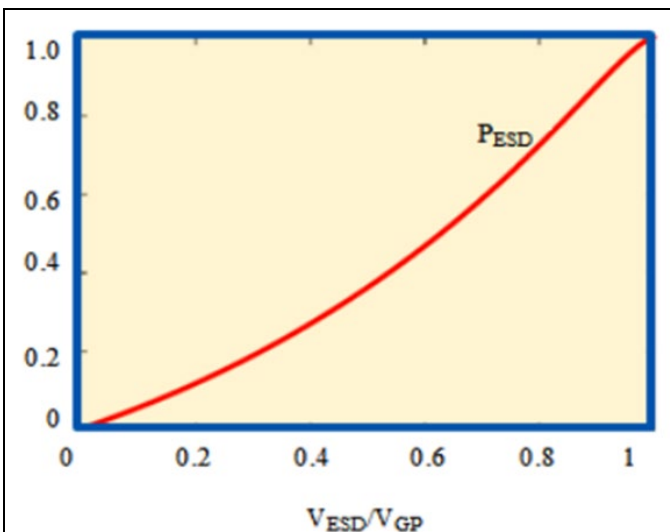


Fig 8: Normalized ESD power

Fig. 8 displays the normal average power curve. The average normal power exchange by the ESD port is represented by the curve line. ESD's energy exchange is proportional to VESD's magnitude. When $V_B > V_{GP}$, normal average power, which is the ratio of V_{ESD}/V_{GP} , is independent of V_B bus voltage. Higher VESD is therefore beneficial for reducing the number of steps of the dc-ac conversion power system in real-time applications.

Simulation Results

250 V is the VESD. Like a conventional converter, the suggested dc-ac conversion system bus voltage is chosen based on the highest values of the modulation index and grid voltage. Table I provides a comparison of parameters and components. Figure 9 displays the output waveforms of a bidirectional dc-ac converter with different ESD voltages, while Figure 10 displays the grid current, midway voltage, and switching voltage. Figure 11 displays the experimental output with energy exchanged between the grid and the dc port, while the grid voltage and current keep the same

polarity. During reactive or active power transfer, the converter's control signal stays constant, allowing for a

seamless shift from rectifier to inverter mode and vice versa.

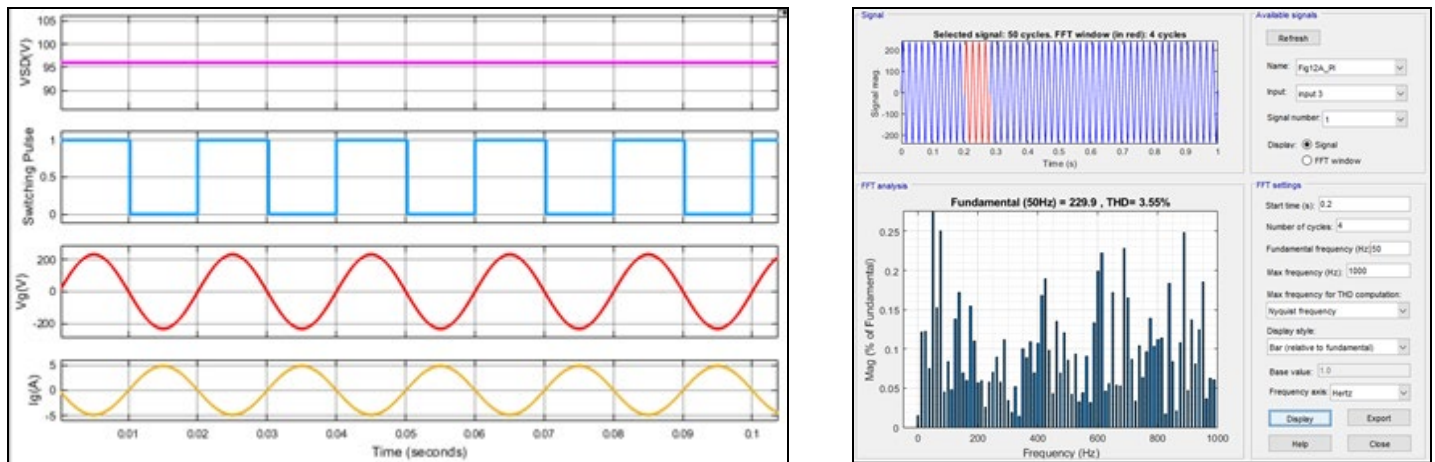


Fig 9: Steady-state waveform dc-ac mode. (a) VESD = 96 V.

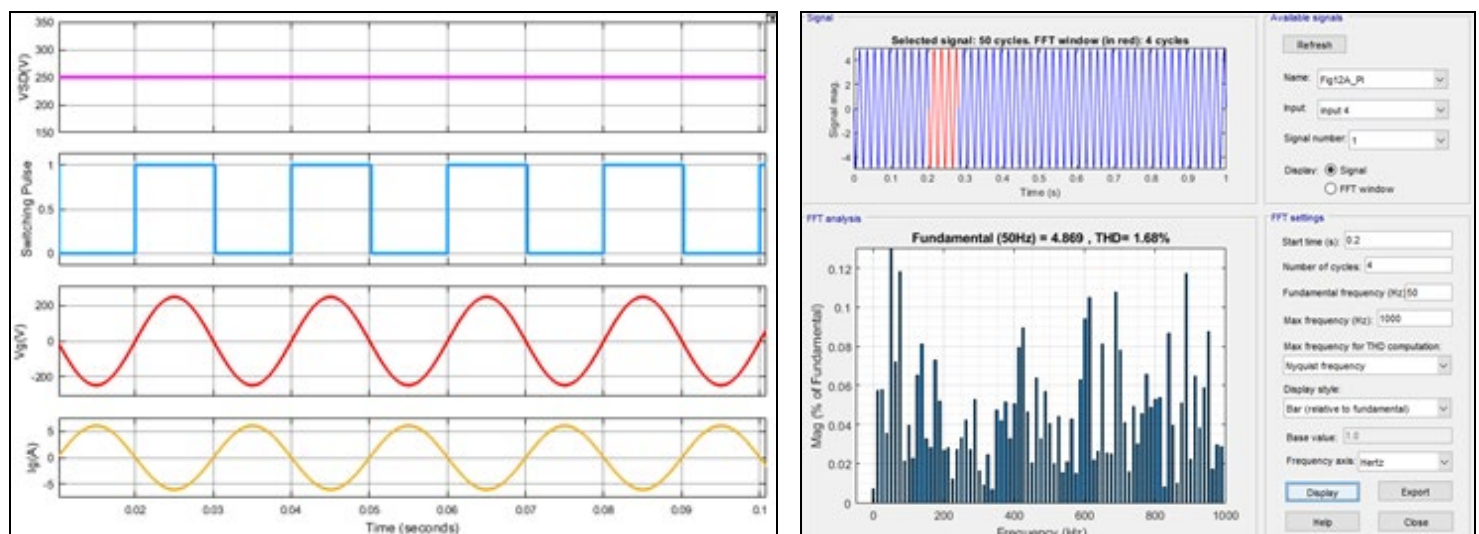
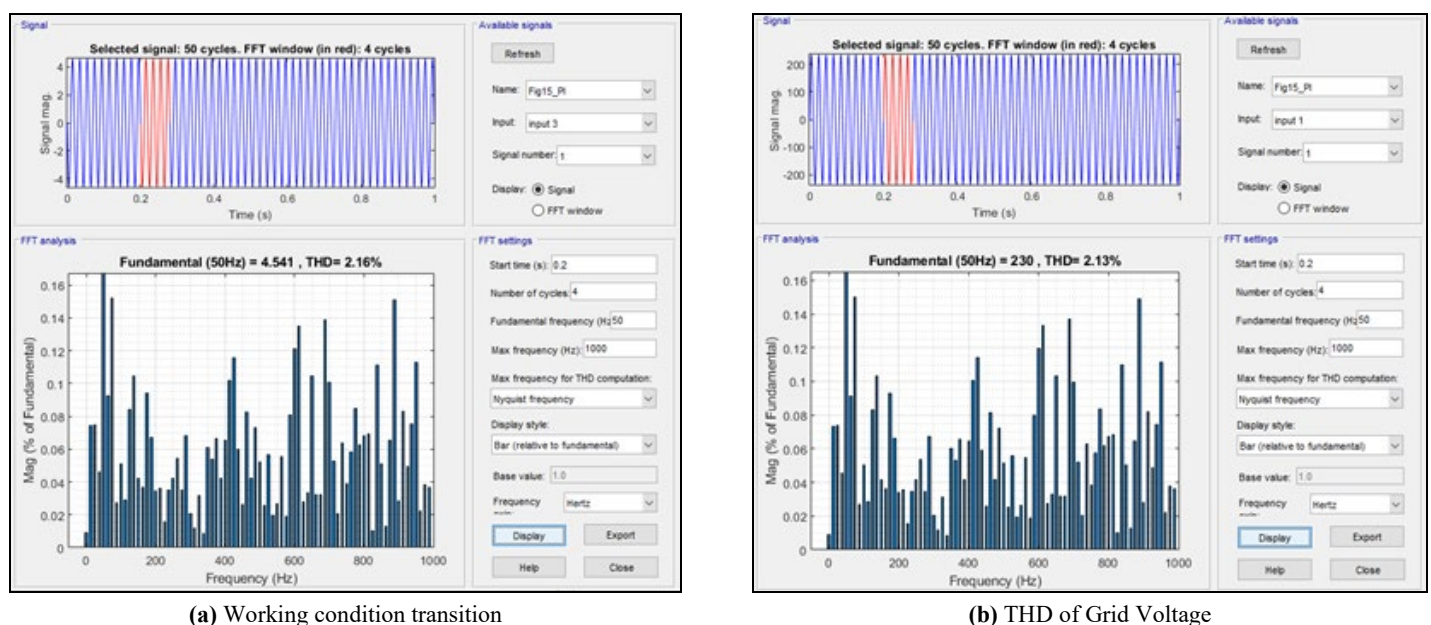


Fig 10: Steady-state waveform dc-ac mode. (b) VESD = 250 V.



(a) Working condition transition

(b) THD of Grid Voltage

Fig 11: (a) Working condition transition & (b) THD of Grid Voltage

Conclusion

For an energy storage system, a recently developed bidirectional suggested dc–ac converter is investigated. The proposed three-phase converter is used to construct the energy transfer between ESD and the grid. The only way to transfer power between ESD and the grid is through T-PC during the direct conversion phase. In the proposed energy conversion, power losses and ratings are significantly reduced, and the downstream dc–dc bidirectional converter does not require partial energy. T-PC yields theoretically evaluated switching losses because of its multilayer nature. The suggested bidirectional dc-ac converter's circuit design, fundamental concept, control, and modulation method have all been examined, and the 1.5-kW test-bench model is used to confirm the converter's viability and efficacy.

References

1. A. de Paula Dias Queiroz, Jacobina CB, de Freitas NB, Maia ACN and Melo VFMB. "Single-phase AC–DC–AC multilevel converter based on H-bridges and three-leg converters connected in series," *IEEE Trans. Ind. Appl.* 2018; 54(5):4696–4706.
2. Qin Z, Loh PC and F. "Modulation schemes with enhanced switch thermal distribution for single-phase AC–DC–AC reduced-switch converters," *Blaabjerg In April 2016, IEEE Trans. Power Electron.* 2016; 31(4):3302–3313.
3. Shahzad D, Pervaiz S, Zaffar NA and KK. "GaN-based high power-density AC–DC–AC converter for single-phase transformerless online uninterruptible power supply," *Afridi IEEE Transactions on Power Electrons.* 2010; 36(12):13968–13984
4. Sayed MA, Suzuki K, Takeshita T and Kitagawa W. *IEEE Trans. Power Electron.* "PWM switching technique for three-phase bidirectional grid-tie DC–AC–AC converter with high-frequency isolation". 2018; 33(1):845–858.
5. Kumar A and Gupta R. "Single-phase AC/DC/AC converter using cascaded multilevel inverter," in *Proceedings of the International Conference on Power and Control Embedded Systems*, 2010, 1–5.
6. Kumar A, Bhat AH and Agarwal P. "Comparative analysis of dual active bridge isolated DC to DC converter with single phase shift and extended phase shift control techniques," in *Proc. 6th Int. Conf. Comput. Appl. Electr. Eng.-Recent Adv. (CERA)*, 2017, 397–402.
7. De Freitas NB, Jacobina CB, de Moraes Lima Marinus NS and Rocha N. "AC–DC–AC single-phase multilevel six-leg converter with a reduced number of controlled switches," *IEEE Trans. Power Electron.* 2018; 33(4):3023–3033.
8. Reznikov B, Srndovic M, Familant YL, Grandi G and Ruderman A. "Simple time averaging current quality evaluation of a single-phase multilevel PWM inverter," *IEEE Trans. Ind. Electron.* 2016; 63(6):3605–3615.
9. Gehrke BS *et al.*, "Based on two-level and three-level legs, single-phase to single-phase three-wire power converters," *IEEE Trans. Ind. Appl.* 2022; 58(2):2291–2300.
10. Jacobina CB, Rocha N, De Moraes Lima Marinus NS and dos Santos Junior EC. "Single-phase to three-phase DC-link converters with reduced controlled switch count," *IEEE Trans. Ind. Appl.* 2014; 50(2):1150–1160.