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Development of multi-input multi-output converter for decarbonization energy system

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ABSTRACT

Decarbonization energy systems include a range of renewable energy sources, such as solar, wind, hydro, and geothermal. These sources generate electricity with minimal carbon emissions and can be used in various applications, including power generation, heating, and transportation. Therefore, the use of a multi-input multi-output (MIMO) converter is becoming increasingly important in decarbonization energy systems. This is because the integration of multiple renewable energy sources, requires a power converter that can manage multiple inputs and outputs efficiently. This paper presents the development of a MIMO converter using a single-phase matrix converter for decarbonization energy systems. The proposed converter is capable of integrating multiple renewable energy sources and can be used in a microgrid application, thus removing the need of multiple converters. The design and analysis of the converter are presented, including the selection of power switches and control strategy. The performance of the converter is evaluated through experimental results, demonstrating its effectiveness in managing multiple inputs and outputs using a single power converter circuit. The results indicate that the proposed converter is a promising solution for decarbonization energy systems, contributing to the development of sustainable energy systems.

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1. INTRODUCTION

Decarbonization energy systems refer to the shift towards using renewable energy sources and reducing the reliance on fossil fuels in order to mitigate the impacts of climate change. These systems are designed to reduce carbon emissions and promote sustainable energy sources that have minimal impact on the environment. The implementation of decarbonization energy systems requires a significant investment in research and development to improve the efficiency and effectiveness of renewable energy sources. It also requires the integration of different technologies, such as energy storage systems, smart grids, and power electronics, to enable the reliable and stable supply of renewable energy to the grid [1]–[5]. The multi-input multi-output (MIMO) are critical components in decarbonization energy systems, enabling the efficient and flexible integration of multiple energy sources and loads. They help optimize energy utilization, enhance grid stability, and contribute to the transition towards a low-carbon future.

The use of a MIMO converters is becoming increasingly important in decarbonization energy systems. This is because integrating numerous renewable energy sources, including wind and solar, need a power converter that can effectively handle numerous inputs and outputs. A MIMO converter can integrate multiple renewable energy sources into a single system, which can be used to supply power to a microgrid or the main grid. This allows for a more stable and reliable power supply, reducing the reliance on traditional fossil fuel-based energy sources. One of the advantages of using a MIMO converter is its ability to manage power flow in both directions, which is important for renewable energy systems that generate intermittent power. Accordingly, excess electricity produced by sources of clean energy can be stored in energy storage devices like batteries or capacitors and utilised later. Additionally, the usage of a MIMO converter can result in a system that is more compact and effective by reducing the size and weight of the power electronics. This is particularly important for small-scale renewable energy systems, where space and weight constraints are a major factor. The development of MIMO converters is crucial for the further integration of renewable energy sources into the grid, contributing to the development of sustainable energy systems and the reduction of carbon emissions [6]–[9].

There are several different circuit topologies that can be used for MIMO converters, including matrix converters, full-bridge converters, and dual-active-bridge converters. The choice of circuit topology depends on the specific application and system requirements. The control strategy for a MIMO converter involves coordinating the power flow between the inputs and outputs to ensure that the output voltage and frequency are within the required range. This control strategy can be achieved using different modulation techniques, such as space vector modulation, selective harmonic elimination, and pulse pattern modulation. The use of MIMO converters is becoming increasingly important as renewable energy systems continue to be integrated into the power grid. MIMO converters offer a versatile and efficient solution for the management of multiple energy sources, contributing to the development of sustainable energy systems and the reduction of carbon emissions.

A basic multiple-input converter (MIC) concept has been proposed to provide low manufacturing cost, small size, simple circuit topologies, high reliability, and centralized control [10]. For the purpose of supporting energy sources like photovoltaics (PV) and wind turbines, previous works [11]–[14] established systematic techniques to generating and synthesising MICs that have been built by taking into consideration the DC voltage sources at their input ports. Because the output of the current MICs may be controlled to produce either AC or DC, they are separated into DC-AC MICs and DC-DC MICs. The three multi-input DC-DC MICs established in [15]–[19] each have one input. These converters, which are based on the DC-DC boost converter, have a number of benefits, including the need for fewer power switches and simpler circuitry. Another design of multi-input DC-DC converters that was presented in [19] makes use of the magnetic coupling of the half-bridge boost circuit in conjunction with DC-link voltages. Qian *et al.* and Wu *et al.* in [20], [21] introduced hybrid DC-DC converters, and cross-coupled control loops were compensated independently using decoupling technique control strategies. Chen *et al.* [22], a systematic method for generating non-isolated three-port converter topologies was suggested. A three-input DC-DC converter incorporating PV and battery powers was proposed in [23] for high step-up applications.

A bidirectional multi-input converter using the input-output feedback linearization-controlled approach was proposed in [24] for an isolated DC-AC MIC. An isolated three-input full-bridge circuit topology for a hybrid fuel cell (FC) and battery system with a small autonomous load has been given in [25]. Chen *et al.* in [12], a multi-input inverter topology was presented. The study showed a line-interactive FC power supply that can run in both DC and AC for stand-alone and grid-connected modes. Zhou and Huang [26] describes a grid-connected multi-input inverter-based hybrid PV/wind power system.

Despite the fact that each DC-AC MIC has unique advantages, they all require at least two stages of conversion and an output filter in order to operate with AC loads. Multiple power conversion stages can also increase the number of devices, size, weight, cost, and system power losses of hybrid systems for all MICs. In addition, the options for a floating production platform with high reliability requirements can be limited by space constraints. Single-stage topologies, which incorporate the effectiveness of each level of multi-stage power converters, are gaining popularity in this area. Despite the possibility of increasing control complexity, they provide greater efficiency and dependability at a lower cost and smaller size.

In this paper, a MIMO converter that uses a single-phase matrix converter that can manage multiple inputs and outputs is proposed. This type of converter is particularly useful for renewable energy systems that require the integration of multiple energy sources into a single system. The proposed MIMO converter can effectively manage multiple inputs and outputs using a single power converter circuit, resulting in low power losses, reducing circuit complexity, and improving the power density of the power supply system. The results indicate that the proposed converter is a promising solution for decarbonizing energy systems and contributing to the development of sustainable energy systems.

2. THE PROPOSED MIMO CONVERTER USING MATRIX CONVERTER

It is appropriate for MIMO converter applications because the matrix converter topology in Figure 1 is a direct AC-AC converter that can execute AC-to-AC power conversion without a DC-link capacitor.

Figure 2 illustrates the matrix converter topology, which uses pulse-width modulation (PWM) to operate a matrix of power switches. The matrix is capable of generating any output voltage and frequency, given that the input voltages and frequencies are within the converter's rating. The matrix converter can also operate in both motoring and generating modes, allowing bidirectional power flow between the input and output sides.

In a proposed MIMO converter that uses the matrix converter topology, the inputs are connected to the input side of the matrix converter and the outputs are connected to the output side. The matrix converter controls the power flow between the inputs and outputs, allowing for efficient power management of multiple renewable energy sources. The control strategy of a MIMO converter using the matrix converter topology involves coordinating the power switches' operation to ensure that the output voltage and frequency are within the required range. This control strategy can be achieved using different modulation techniques, such as Arduino, active power filter function, and pulse pattern modulation. The matrix converter topology is a versatile and efficient solution for MIMO converter applications, providing a compact and reliable converter for integrating multiple renewable energy sources into a single system.

A single-phase matrix converter is a power electronic device that can perform AC-to-AC conversion without using a bulky and expensive DC-link capacitor. The matrix converter can be used in decarbonization energy systems to integrate multiple renewable energy sources, such as solar and wind, and provide a stable and reliable output to the grid. Compared to traditional AC-DC-AC converters, the single-phase matrix converter has several advantages, including improved efficiency, reduced size and weight, and increased flexibility.

In a decarbonization energy system, the single-phase matrix converter can be used to manage multiple inputs and outputs from renewable energy sources, such as solar and wind. The converter can be integrated with a microgrid system to provide stable and reliable power supply to a local area. The use of the single-phase matrix converter in decarbonization energy systems can contribute to the reduction of carbon emissions and the development of sustainable energy systems.

2.1. AC-AC converter operation

An AC-AC converter is a device used to regulate the output voltage of an alternating current (AC) power source. A matrix converter is a type of AC-to-AC power converter that is capable of converting one AC voltage to another AC voltage without the need for an intermediate DC link. To operate an AC regulator using a single-phase matrix converter, the matrix converter is connected between the AC power source and the load, with the input voltage and output voltage of the regulator connected to the input and output of the matrix converter, respectively. The matrix converter then uses its switching pattern to control the voltage and frequency of the output voltage, which in turn regulates the voltage of the load. The desired output voltage waveform, which can be altered to provide the necessary voltage regulation, determines the switching pattern used by the matrix converter. The matrix converter can also provide additional functionality, such as reactive power compensation, by adjusting the phase angle between the input and output voltages. Overall, a single-phase matrix converter can be an effective solution for operating an AC regulator, providing precise voltage regulation without the need for an intermediate DC link.

An essential component of decarbonizing energy systems is the employment of single-phase matrix converters as AC regulators. This is due to the fact that AC regulators are frequently used to regulate the output voltage of many sorts of loads, such as electric vehicles, home appliances, and industrial machinery. By increasing the efficiency and dependability of these regulators, energy waste and carbon emissions can be decreased. A matrix converter can provide several advantages when used as an AC regulator. One of the most important benefits is the ability to control the output voltage waveform. This can lead to a higher power quality, with less harmonic distortion and less electromagnetic interference, which can improve the efficiency and reliability of the power system. Another advantage of using a matrix converter as an AC regulator is its ability to provide reactive power compensation. This feature can help to improve the power factor of the load and reduce the amount of reactive power drawn from the grid, which can lead to energy savings and a reduced carbon footprint. Matrix converters can also be used to regulate the voltage of renewable energy sources, such as solar or wind generators. This is important because renewable energy sources often produce variable output voltages that can fluctuate depending on weather conditions. By using a matrix converter to regulate the output voltage of a renewable energy source, the power generated can be more reliable and easier to integrate into the grid.

2.2. AC-DC converter operation

An AC to DC converter is a device used to convert an alternating current (AC) voltage to a direct current (DC) voltage. A single-phase matrix converter can be used to operate a rectifier. To use a single-phase matrix converter as a rectifier, the AC voltage is applied to the input of the matrix converter, and the output of the matrix converter is connected to the load. The matrix converter is then used to control the output voltage to be a DC voltage. The matrix converter is designed to provide a controlled output voltage waveform, which can be used to emulate the output of a conventional diode rectifier. The matrix converter uses a set of bidirectional switches to generate the desired output waveform. By controlling the switching sequence and frequency, the matrix converter can create a DC voltage that is suitable for driving the load. The advantage of using a matrix converter as a rectifier is that it can provide a more efficient and compact solution compared to conventional diode rectifiers. The matrix converter can provide a regulated DC output voltage with low harmonic distortion, which can be especially useful in applications that require a high-quality DC voltage. Hence, a single-phase matrix converter can be an effective solution for operating a rectifier, providing a more efficient and reliable solution compared to conventional diode rectifiers.

The use of a single-phase matrix converter as a rectifier can also play an important role in the decarbonization of energy systems. This is because the matrix converter can provide a more efficient and reliable solution for rectifying AC power, which can in turn help to reduce the carbon footprint of energy generation. One of the main advantages of using a matrix converter as a rectifier is its ability to control the output voltage waveform. This allows for the generation of a DC voltage with low harmonic distortion, which is important for reducing the electromagnetic interference generated by rectifiers. By reducing electromagnetic interference, the use of matrix converters can help to improve the efficiency and reliability of power systems, reducing the need for costly and energy-intensive filtering equipment. Another advantage of using a matrix converter as a rectifier is that it can be used to support the integration of renewable energy sources, such as wind and solar. These sources of energy often generate variable output voltages, which can make it difficult to maintain a stable and reliable power supply. By using a matrix converter as a rectifier, the output voltage can be controlled and stabilized, allowing for more efficient integration of renewable energy sources. As such, the use of single-phase matrix converters as rectifiers can play an important role in the decarbonization of energy systems. By providing a more efficient and reliable solution for rectifying AC power, matrix converters can help to reduce the carbon footprint of energy generation and support the integration of renewable energy sources.

2.3. DC-AC converter operation

The DC-AC converters are widely used in decarbonized energy systems to convert direct current (DC) from sources such as photovoltaic cells or batteries into alternating current (AC) that can be used to power household appliances, electric vehicles, and industrial equipment. A single-phase matrix converter can be used as an inverter to improve the efficiency and reliability of power conversion in decarbonized energy systems. One of the main advantages of using a single-phase matrix converter as an inverter is that it can provide a regulated output voltage waveform with low harmonic distortion, which can help to reduce the electromagnetic interference generated by inverters. By reducing electromagnetic interference, the use of matrix converters can help to improve the efficiency and reliability of power systems, reducing the need for costly and energy-intensive filtering equipment.

Matrix converters can also provide a higher power factor, which can reduce the amount of reactive power drawn from the grid, leading to energy savings and a reduced carbon footprint. Another advantage of using a matrix converter as an inverter is that it can provide a higher efficiency compared to conventional inverters based on pulse-width modulation (PWM) techniques. Matrix converters use bidirectional switches to generate the desired output voltage waveform, which can lead to a lower switching frequency and lower switching losses, resulting in higher efficiency. Matrix converters can also be used to provide active power compensation to the grid, which can help to reduce the impact of renewable energy sources on the grid, making it easier to integrate them into the energy system.

2.4. DC-DC converter operation

DC-DC converters are commonly used in decarbonized energy systems to efficiently convert DC voltages from renewable energy sources or energy storage systems into the desired voltage level for specific loads. A single-phase matrix converter can be used as a DC-DC converter to improve the efficiency and reliability of power conversion in decarbonized energy systems. One of the main advantages of using a single-phase matrix converter as a DC-DC converter is that it can provide a regulated output voltage waveform with low harmonic distortion. This can help to reduce the electromagnetic interference generated by DC-DC converters, improving the efficiency and reliability of power systems and reducing the need for costly and energy-intensive filtering equipment.

Matrix converters can also provide a high-power density and high efficiency compared to conventional DC-DC converters. The use of a matrix converter for DC-DC conversion can lead to a lower switching frequency and lower switching losses, resulting in higher efficiency and a smaller form factor. These characteristics are important for energy storage applications such as electric vehicles or portable devices. Another advantage of using a matrix converter as a DC-DC converter is that it can provide a bidirectional power flow, allowing for energy to be transferred in both directions between the input and output. This can be useful for energy storage applications where energy needs to be stored in a battery or released from a battery as required. Matrix converters can also provide reactive power compensation, which can improve the power factor of the load and reduce the amount of reactive power drawn from the grid, leading to energy savings and a reduced carbon footprint.

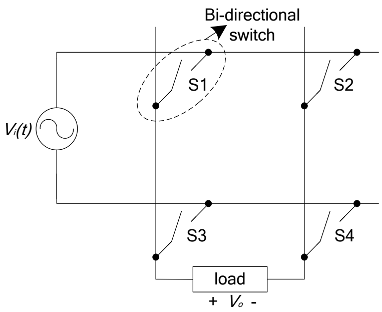


Figure 1. Circuit configuration of SPMC

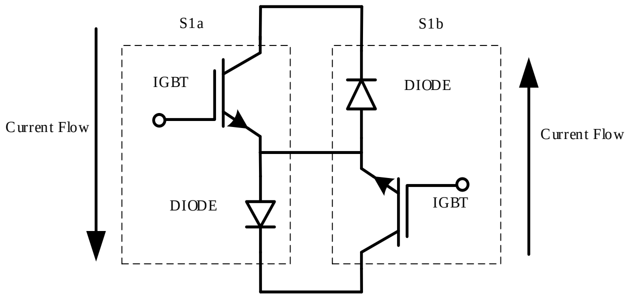


Figure 2. Bidirectional switch

3. DEVELOPMENT OF THE PROPOSED MIMO CONVERTER

The block diagram of the switching algorithm of the proposed MIMO converter with the safe-commutation technique is shown in Figure 3. All of the selector switches and the signal from the phase detector are sent to the Arduino Mega, which controls the relays and the gate driver circuit of the SPMC. In this work, the relays are used to completely separate the DC or AC voltage coming in. For the proposed MIMO converter operation, the control switching algorithm sends the input signals to the gate driver of the SPMC circuit and relays to get the desired output voltage. The flowchart of the switching algorithm for the proposed MIMO converter with the safe-commutation technique is shown in Figure 4. The flowchart for the integrated MIMO converter operation switching algorithm with a safe-commutation technique begins with checking if the rectifier switch SA is HIGH or LOW. When the switch SA is set to HIGH, the input alternating current voltage is connected to the SPMC. So, the AC-DC operation is done using the safe commutation strategy. SB is high when the AC regulator switch is set to 25 Hz. The input AC voltage is connected to the SPMC, and the AC-AC converter operation for a 25 Hz output frequency with a safe commutation strategy is executed.

If the AC regulator switch (50 Hz, SC) is turned on, the input AC voltage is connected to the SPMC, and a safe commutation strategy is used to run the AC-AC converter so that the output frequency is 50 Hz. Meanwhile, if the AC regulator switch (100 Hz) is turned on, SD is also turned on. Here, the AC voltage coming in is connected to the SPMC, and the AC-AC converter is run with a safe commutation strategy for a 100 Hz output frequency. If the inverter switch, SE, is high, then the input DC voltage is connected to the SPMC, and the DC-AC converter works with a safe commutation strategy. Furthermore, SF is high if the DC Q1 switch is high. In this case, the input DC voltage is connected to the SPMC, and the DC-DC Q1 converter operation with a safe commutation strategy is executed.

If the DC Q2 switch, SG, is turned on, the DC voltage from the input is connected to the SPMC, and the DC-DC Q2 converter works with a safe commutation strategy. If the DC Q3 switch, SH, is high, then the input DC voltage is connected to the SPMC, and the DC-DC Q3 converter operation with a safe commutation strategy is executed. Otherwise, if the DC Q4 switch, SI, is high, then the input DC voltage is connected to the SPMC, and the DC-DC Q4 converter operation with a safe commutation strategy is executed.

By determining the system requirements based on the required output voltage and frequency, power rating, and number of input sources, an experimental test rig for the proposed MIMO converter using an SPMC can be developed. The SPMC, input sources (such as solar cells and wind turbines), and output load are then chosen as the necessary power electronics components for the MIMO converter. The design of the MIMO converter's control system uses Arduino Uno microcontrollers.

The next step is to assemble the test rig by connecting the power electronics components and the control system. This involves mounting the components on a test bench and connecting the input sources and output load to the converter. Different load circumstances and input sources are applied to the proposed MIMO converter during testing to ensure that the output voltage and frequency fulfil system requirements. This involves measuring the voltage, current, power, and other parameters using test instruments such as oscilloscopes, multimeters, and power analyzers. The experimental results are evaluated to determine the efficiency, stability, and performance of the proposed MIMO converter under different load and input conditions. This can help identify areas for improvement and optimization. The test rig can be used to validate the proposed switching algorithms and study the behaviour of the MIMO converter under realistic operating conditions. The experimental results are used to optimize the design of the converter and to identify practical limitations and challenges.

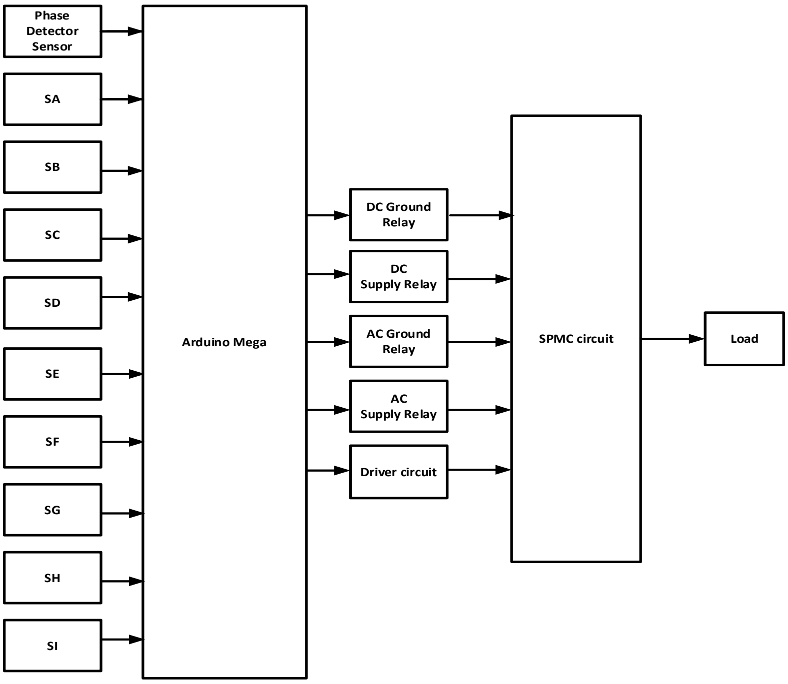


Figure 3. Block diagram for the proposed MIMO converter

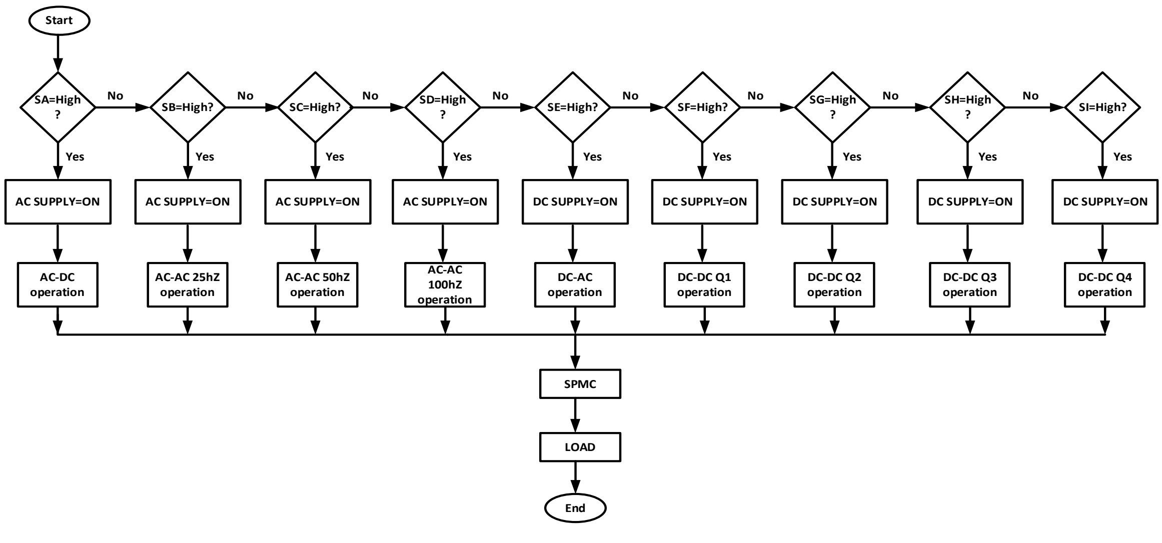
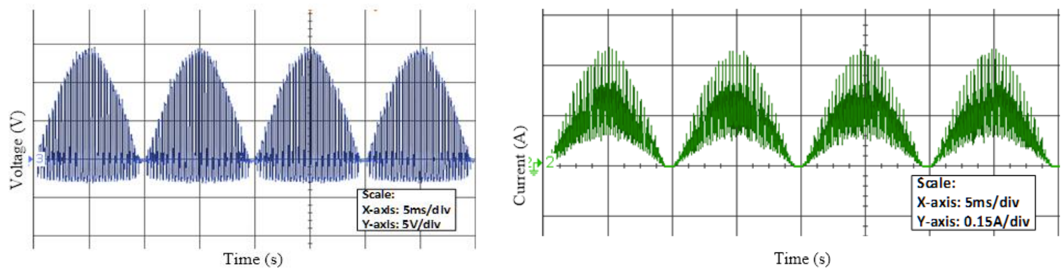


Figure 4. Flowchart of switching algorithm for the proposed MIMO converter

4. RESULTS AND DISCUSSION

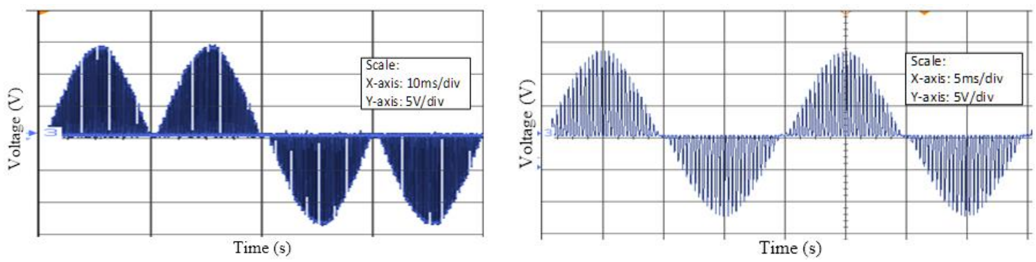
This work investigated the development of a MIMO converter using a SPMC for decarbonization energy systems. The proposed MIMO converter was designed to integrate multiple energy sources, such as DC and AC, into a single system, with the goal of reducing carbon emissions and promoting sustainable energy systems. The experimental test rig is carried out using a supply voltage, Vs of 12 Vrms with a frequency of 50 Hz and a resistive load, R of 50 ohms. This was then validated using the experimental test rig with a modulation index of 0.5 and a switching frequency of 5 kHz. The performance of the MIMO converter was evaluated through experiments, and the results and discussion are presented below.

The experimental results showed that the MIMO converter using a single-phase matrix converter was capable of managing the power flow between multiple energy sources. The matrix converter was able to generate any output voltage and frequency required by the load, given that the input voltages and frequencies were within the converter's rating. Figure 5 demonstrates the finding obtained from experimental test rig for control rectifier operation. Figure 5(a) shows the output voltage, while Figure 5(b) shows the output current waveforms. The results revealed that spikes produced by the inductive load had been successfully eliminated. The experimental results of the output voltage for the controlled AC regulator with 25 Hz, 50 Hz, and 100 Hz frequencies using an inductive load are shown in Figure 6, where Figures 6(a) to 6(c) show the output voltage for 25 Hz, 50 Hz, and 100 Hz frequencies, respectively. Figure 7 shows the experimental results of the output voltage (Figure 7(a)) and output current (Figure 7(b)) for the controlled inverter using inductive loads. The experimental results of the output voltage and output current for the controlled four quadrants DC chopper using inductive loads are shown in Figures 8 to 11. Figures 8(a) and 8(b) show the experimental results of output voltage and output current, respectively, for quadrant 1 of a DC chopper using inductive loads. The results of the output voltage and output current for quadrant 2 of a DC chopper using inductive loads are shown in Figures 9(a) and 9(b), respectively. Figures 10(a) and 10(b) show the experimental results of output voltage and output current, respectively, for quadrant 3, while the results of the output voltage and output current for quadrant 4 of a DC chopper using inductive loads are shown in Figures 11(a) and 11(b), respectively. The results of this study demonstrate the effectiveness of using a single-phase matrix converter for a MIMO converter in decarbonization energy systems. The use of a matrix converter provides a versatile and efficient solution for managing multiple renewable energy sources, enabling the development of sustainable energy systems.

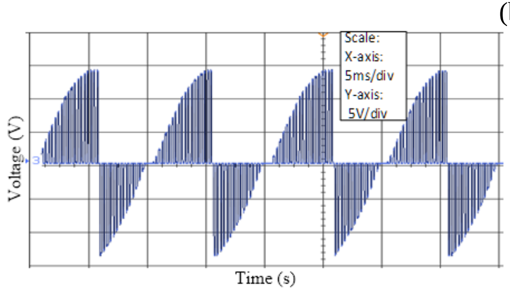


(a) (b)

Figure 5. Experimental result of controlled rectifier with Ma=0.5 using 5 kHz switching frequency (a) output voltage and (b) output current



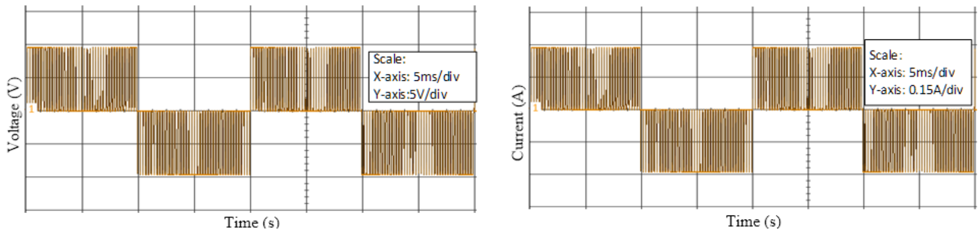
(a) (b)



(c)

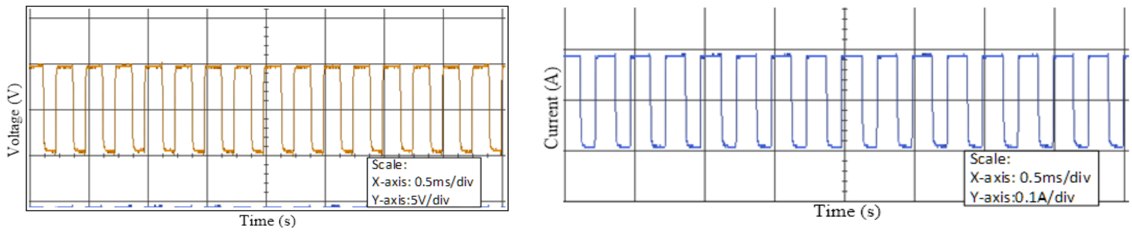
Figure 6. Experimental results of AC regulator with inductive loads (a) output voltage 25 Hz, (b) output voltage 50 Hz, and (c) output voltage 100 Hz

One of the advantages of using a single-phase matrix converter for a MIMO converter is its ability to operate with a single-phase power supply, which is often used in small-scale renewable energy systems. This can make the MIMO converter more accessible and practical for a wider range of applications. Additionally, the use of a matrix converter can reduce the size and weight of the power electronics, leading to a more compact and efficient system. Hence, the results of this work demonstrate the feasibility and effectiveness of using a MIMO converter with a single-phase matrix converter for decarbonization energy systems. The development of efficient and versatile MIMO converters is an important step towards the integration of renewable energy sources into the power grid, contributing to the development of sustainable energy systems and the reduction of carbon emissions.



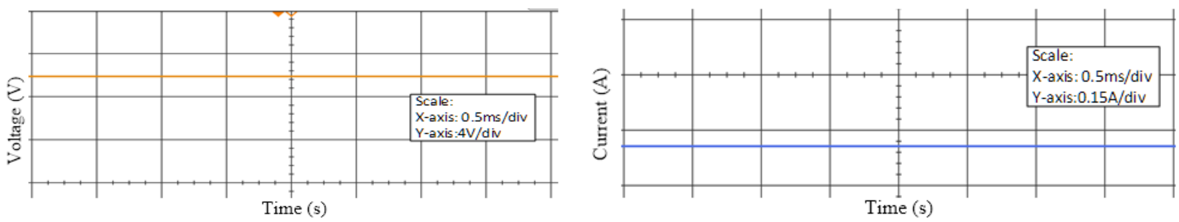
(a) (b)

Figure 7. Experimental results for inverter operation using inductive loads (a) output voltage and (b) output current



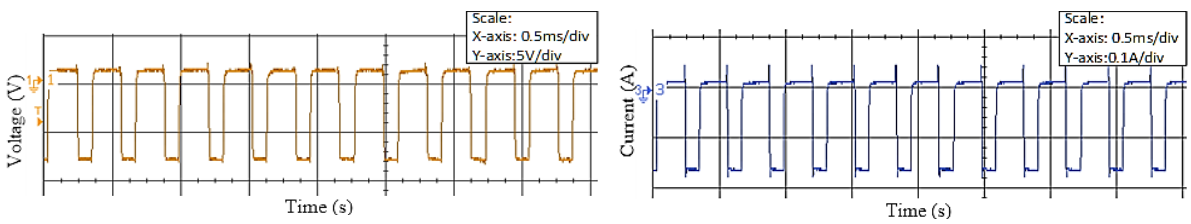
(a) (b)

Figure 8. Experimental results for quadrant 1 of DC chopper using inductive loads (a) output voltage and (b) output current



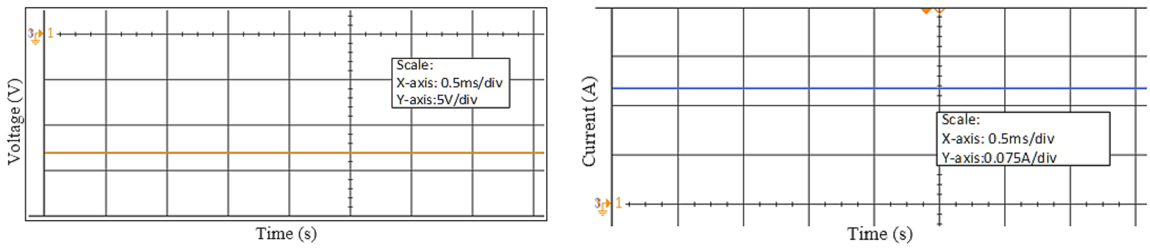
(a) (b)

Figure 9. Experimental results for quadrant 2 of DC chopper using inductive loads (a) output voltage and (b) output current



(a) (b)

Figure 10. Experimental results for quadrant 3 of DC chopper using inductive loads (a) output voltage and (b) output current



(a) (b)

Figure 11. Experimental results for quadrant 4 of DC chopper using inductive loads (a) output voltage and (b) output current

5. CONCLUSION

In conclusion, this study looked into the design of a MIMO converter for decarbonization energy systems using an SPMC. With the aim of lowering carbon emissions and developing sustainable energy systems, the MIMO converter was created to combine numerous renewable energy sources, such as solar panels and wind turbines, into a single system. The simulation and experimental findings demonstrated that the MIMO converter using an SPMC was able to control the power flow between various energy sources, generate any necessary output voltage and frequency, and operate effectively with low total harmonic distortion and high-power factor. The use of a matrix converter for the MIMO converter provides a versatile and efficient solution for managing multiple renewable energy sources, enabling the development of sustainable energy systems. One of the advantages of using a SPMC for a MIMO converter is its ability to operate with a single-phase power supply, making it more accessible and practical for a wider range of applications. Additionally, the use of a matrix converter can reduce the size and weight of the power electronics, leading to a more compact and efficient system. The design and development of effective and adaptable MIMO converters is a critical step in the integration of renewable energy sources into the power grid, assisting in the creation of sustainable energy systems and lowering carbon emissions. The results of this study demonstrate the feasibility and effectiveness of using a MIMO converter with a SPMC for decarbonization energy systems and provide a basis for further research and development in this area.

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