Arduino-Based Three-Phase Inverter Using Power MOSFET for Application in Microgrid Systems

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Abstract —**Rapid depletion of fossil fuel reserves, and concerns over climate change have encouraged power generation from sustainable energy based microgrids. And to address the necessity of three-phase inverters in microgrid systems or sustainable-powered households, an Arduino-based three-phase inverter using MOSFET is designed, which converts DC into three-phase AC power. The designed system generates 223V square signals at each phase from a 12V battery through switching of three stages of power MOSFETs using pulse width modulation (PWM) signals at their gates from an Arduino Uno. Each stage of power MOSFETs consists of six transistors making it eighteen in total, which are used to perform the inversion process separately for each three single-phase connections. The system is programmed using an Arduino Uno to generate PWM signals and to keep 120 degrees phase displacement among each phase. Three step-up transformers are coupled at the outputs of MOSFET stages for amplification. The system generates 386.25V of voltage for the three-phase line delivering 0.58A of current using a 60W incandescent bulb at each phase as a load. The design and simulation of the electronic circuit are done by Proteus, and the programming codes are written using Arduino IDE. The designed system is practically contrasted and verified.**

Index Terms—**Arduino Uno R3, MOSFET, PWM, Three-phase Inverter, Microgrid, Renewable Energy, Proteus**

I. Introduction

In this era of booming technology and electrification, escalated demand for electric power has put the power generation and management system in a challenging situation. And with escalated regulation on CO_2 (carbon dioxide) emission worldwide, the traditional power generation and management system will not be able to withstand the challenge [1], [2]. This is why humankind started to search for the substitution of the current power generation system [3]–[5]. Moreover, as humanity is more and more dependent on electricity, the energy demand has been increasing which creates complications for the power distribution system, like instability of the grid and power outages. The need of generating enough energy and awareness in sustainable technologies yield an accelerated improvement in power distribution systems involving renewable energy, and the microgrid system is a promising outcome of it [6], which have the potential of addressing several concerns faced by traditional power systems. A Microgrid is defined as a low-voltage (LV) distribution network that includes distributed generators (DGs), energy storage devices, and controllable loads that can be operated either interconnected or isolated from the main power grid (Fig. 1). Microgrids hold the potential of being very reliable and economically sustainable power systems that can significantly improve the eco-friendliness, efficiency, and resiliency of a system [2].

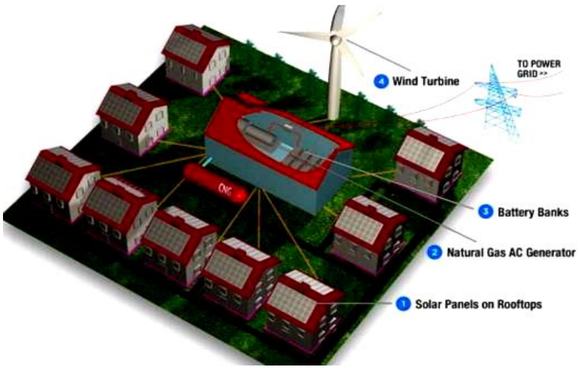

Fig. 1. A typical microgrid system [7], [8].

In comparison to traditional large power grids, microgrids require smaller investment costs that can make them easily available to a vast number of people living remotely. Besides meeting the electricity demands of the customers, microgrids improve the quality of power by reducing voltage dips, and can greatly reduce the overall energy cost. Modern microgrids can also offer some other advantages like conservation voltage regulation (CVR) and the four-quadrant operation of inverters that have the potential of further optimizing the energy. Microgrid technology is a crucial method for power distribution and management systems because every household with a renewable energy source can contribute to it, which can solve the excessive power demand issue and can bring down the electricity cost during the pick hour. Microgrids can provide a number of benefits to the energy suppliers well, such as reduced

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transmission and distribution congestion, improved grid asset utilization, and grid investment deferment [2]. Microgrids can include micro-sources like photovoltaic or solar arrays, wind generators, micro-turbines, biomass, geothermal, steam or gas turbines, fuel cells, and reciprocation internal combustion engines. Energy storage devices in microgrids may include batteries, flywheels, and energy capacitors (super-capacitors). Besides storing the energy from renewable sources, the role of the storage devices in microgrids is to keep a balance between energy generation and consumption [2]. Since storage devices store energy in the form of DC electrical power, an inversion system is required to run the AC appliances, power tools in households or industrial facilities.

An inversion system or an inverter is an electronic device that converts DC into AC power maintaining a preferred voltage and frequency [9], [10], where the output AC power can be a sine wave or other forms of the signal [11]. Inverters can be made with different numbers of output phases. However, in practice, single-phase and three-phase inverters are most commonly used [12]. Construction-wise three-phase inverters can be two types: Three-phase Bridge Inverter, and Three Single-phase Parallel Inverter. The work presented in this paper uses the second construction method. There are two types of inverter topology in general, which are Current Source Inverter (CSI), and Voltage Source Inverter (VSI) [13]. One which takes in a fixed voltage from a source like a DC power supply, and converts it to AC power with variable frequency is called a VSI. VSIs can be categorized into three types: Square-wave Inverters, Pulse-width Modulated (PWM) Inverters, and Single-phase Inverters with Voltage Cancellation. This paper describes the design of a Pulse-width Modulated VSI [12], [14]. A basic three-phase inverter is shown in Fig. 2.

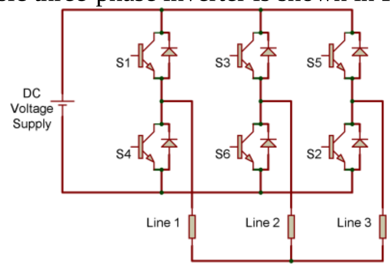

Fig. 2. A basic voltage source three-phase Inverter [9].

PWM is the method used for switching devices to produce the effect of continuously changing analog signals. This method has a very high electrical efficiency [15]. Three PWM techniques are usually seen in electronic design: Single-pulse Modulation, Multiple-pulse Modulation, and Sinusoidal Pulse-width Modulation [14]. In an Inverter, the PWM is usually done using power semiconductor switches e.g. IGBTs, MOSFETs, and BJTs; and there are several methods for doing it to get the output AC signal closely similar to a sine wave. An inverter controls only the frequency of the output whereas the input voltage controls the magnitude of the output [14]. The output voltage of an inverter can be fixed or variable at a fixed or variable frequency. If the voltage of the DC input is constant and not controllable, a variable output voltage can be achieved by varying the frequency of the inverter, which is generally done by employing PWM. The output signal of an inverter is an alternating waveform, which is not necessarily pure sinusoidal. But with various techniques, the inverter can be designed to deliver an output waveform close to a sinusoidal [12]. PWM techniques are the same for both single-phase and three-phase inverters. Except for three-phase ones, the modulation has to be done simultaneously for each phase with various angular displacements like 120 degrees, 150 degrees, or 180 degrees, etc. depending on the required electrical efficiency [9], [14]. The presented work uses Single-pulse Modulation with 120 degrees displacement, and MOSFETs to implement it.

PWM signals can be generated in different ways e.g. using op-amps, 555 timers, microcontrollers, or Arduino. Arduino is essentially also a microcontroller; it is an open-source platform that consists of a microcontroller chip. Arduino is designed to provide an inexpensive and easy way to program electronic devices that interact with their surrounding environment by using sensors or other means of input data [16]. The presented work uses Arduino Uno R3 for the required task.

In this paper, the design and prototyping of a three-phase inverter that converts DC signal into 3-phase AC signal is presented, which generates 223V square signals at each line from a 12V battery using PWM driven three stages of 18 power MOSFETs, keeping 120-degree phase displacement among the phases.

The rest of the paper is organized in the following manner. Section II of the paper describes the components and peripheral devices required for the work along with the block diagram of the system. Section III represents the design of the electronic circuits/hardware of the system. Section IV describes the programming of the Arduino Uno R3. Section V represents the results of the work. Section VI concludes the paper, and section VII describes the future scopes of the work.

II. MATERIALS & METHODS

The designed inverter involves an Arduino Uno as the brain of the system and to produce PWM signals, Power MOSFETs to create AC signals, and center-tapped step-up transformers to amplify the output. As per the focus of this paper, a brief explanation of Arduino Uno R3 (Fig. 3) and Power MOSFETs (IRF Z44N) are provided below, followed by a detailed list of system components, and the system block diagram.

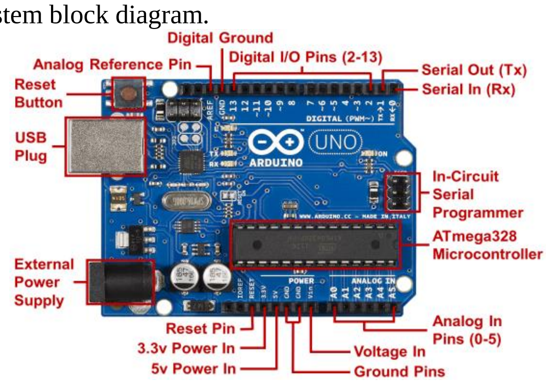

Fig. 3. Arduino Uno R3 with pin-outs.

A. Arduino Uno R3

Arduino is a single-board microcontroller-based open-source platform, developed to formulate and execute processes based on electronics to make interdisciplinary research work more accessible. The hardware of Arduino comprises an 8-bit Atmel AVR microcontroller with on-board I/O support, and the software comprises a standard language (programming C) and also the boot loader that runs on the board [17], [18].

The Arduino Uno is one of the series of Arduino, which is based on the ATmega328 microcontroller. It comprises 14 digital input/output pins (among which 6 can be used as PWM outputs), 6 analog inputs, an ICSP header, a 16 MHz crystal oscillator, a power jack, a USB connection, and a reset button. The Arduino Uno board can operate on a DC supply of 6 to 20 volts [18], [16], [19]. The Arduino Uno R3 is the latest version in the Arduino Uno series, which is used for the work in this paper. In addition to the features of the previous Arduino Uno board, the Arduino Uno R3 uses an ATmega16U2 (USB-to-Serial converter) instead of the 8U2 or FTDI found on previous versions, which permits more memory and faster transfer rates.

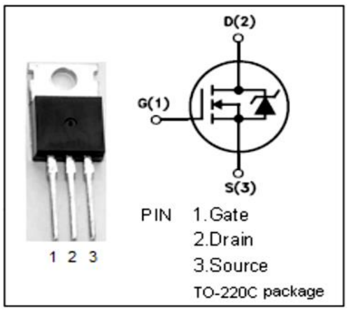

Fig. 4. IRF Z44N pin-outs [20].

TABLE I: COMPONENTS AND PERIPHERAL DEVICES

Devices	*Reference / Name*	*ID / Specification*
Battery	BATTERY	12V
Arduino	Arduino Uno R3	ATmega328P based
Capacitor	C1	4700uF, 50V
MOSFET	Q1, Q2, Q3, …, Q18	IRF Z44N (V_{DS}=55V max, I_D=49A max, ±V_{GS}=20V max, $V_{GS(TO)}$=2V min)
Transformer	Transformer 1 to 3	Primary 12V, Secondary 220V
Lamp (as load)	Lamp 1 to 3	60W, 220V

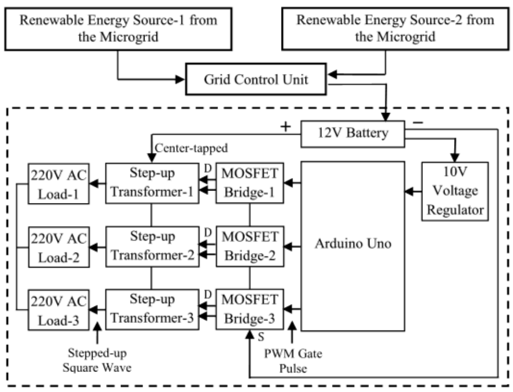

Fig. 5. Block diagram of the designed three-phase inverter system.

B. Power MOSFETs (IRF Z44N)

The Power MOSFET (Metal Oxide Semiconductor Field Effect Transistor) is built on the original field-effect transistor introduced in the 1970s. The invention and development of the power MOSFET were partly compelled by the limitations of BJTs (Bipolar Power Junction Transistors), which previously was the preferred device in most power electronics applications. Power MOSFETs are the most widely used power devices because of their fast switching speed, low gate-drive power, and superior paralleling capability [21]. They are being used in audio/radio frequency circuits, high-frequency inverters, and motor control circuits, etc. The Power MOSFET used in this work is IRF Z44N (Fig. 4) featuring 49A drain current at 25℃, 55V (Min) drain-source voltage, 0.032Ω (Max) static drain-source on-resistance, and fast switching [20].

C. Components & Peripheral Devices

Along with the Arduino Uno and Power MOSFETs, all the components and peripheral devices required to design and develop the system are listed in Table I.

D. System Block Diagram

A block diagram is very effective in having a high-level view and understanding of a system quickly. So, to provide an overall easy visualization of the whole system presented in this paper including all its peripheral devices a block diagram is provided in Fig. 5. According to the diagram, the DC power accumulated in the battery from a microgrid or renewable energy source is to be converted into AC power separately through three legs. Where each leg consists of a stage of power MOSFETs and a step-up Transformer to accomplish the inversion and amplification process respectively.

The main concept of the process or the working principle of the system can be described as following: The DC power from the battery is fed to the stage of MOSFETs, which is to be converted into AC. Since the MOSFETs are acting as switches, their gate pulses are controlled by the Arduino through PWM signals. By making the MOSFETs ON and OFF through their gate pulses the DC power is converted to AC at their outputs. The Arduino is programmed in such a way so that the output signals of the MOSFET stages have a 120 degrees phase displacement among them. Finally, the alternating output signals of MOSFET stages are amplified individually through step-up transformers to drive 220V loads. The outputs from the secondary winding of the transformers are square waves according to the design.

III. ELECTRONIC CIRCUIT / HARDWARE DESIGN

As mentioned above, a three-phase inverter can be built by inverting three single-phase connections separately, as long as they have a certain phase displacement among them [12]. The three-phase inverter in Fig. 6 is designed with 120 degrees phase displacement with PWM applied to each phase separately by the Arduino.

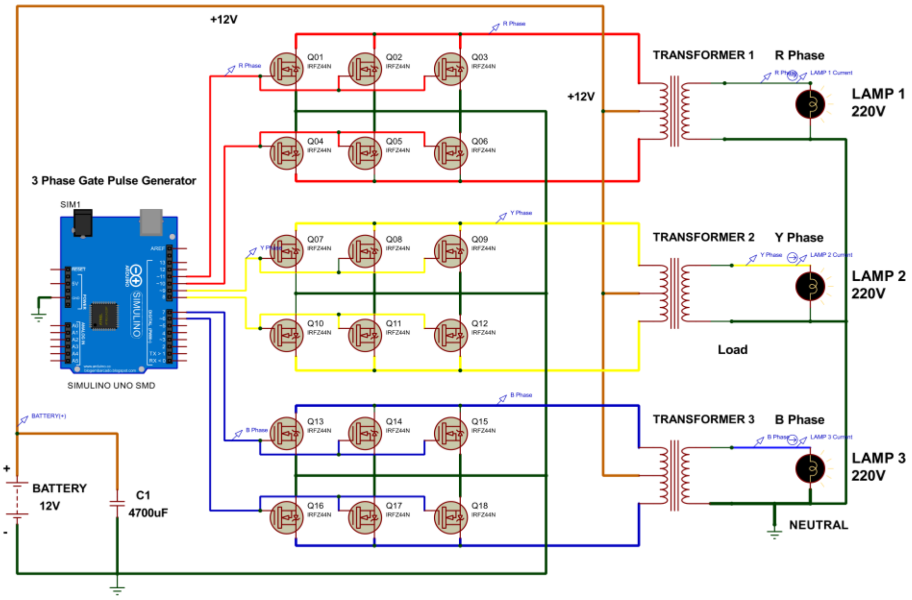

Fig. 6. The whole schematic of the Arduino-based three-phase inverter.

In Fig. 6, each single-phase connection is called a leg for simplicity; where each leg contains 6 (six) power MOSFETs (nMOS) connected to the Arduino to do the inversion through switching. The number of MOSFETs can vary depending on the power requirement. The presented work uses 6 of them in parallel because the model of MOSFET (IRF Z44N) used in the implementation has a comparatively low power rating. Each leg incorporates a center-tapped step-up transformer coupled with the output of MOSFETs to amplify the voltage to 223V from an input voltage of 12V.

All the circuit components like the battery, Arduino, MOSFETs, and transformers, in Fig. 6, are shown with their interconnection in different colors for easier understanding. 3 (three) 220V lamps/bulbs are used as loads to simulate the three-phase functionality. The center wire of the transformer is connected to the positive terminal of the battery and the other two wires are connected to the drains of the six-MOSFET bridge. The sources of each three MOSFET bridges are connected to the negative terminal of the battery and the gates of the MOSFETs are connected to the digital output (PWM) of the Arduino. When Arduino generates gate pulses, the MOSFETs convert direct current (DC) to alternative current (AC) through switching, and current starts to rise in the MOSFETs which makes each transformer to generate EMF, opposing the EMF of the battery. Both transformers and loads are connected in ‘Y’ configuration, and impedances of the transformers are kept as 5.7mH and 1000mH for primary and secondary respectively. The design of the electronic circuit is done by Schematic Capture of Proteus 8.9 Professional.

IV. Arduino Programming

Arduino board is a microcontroller-based platform for programming electronic devices. The microcontroller used in an Arduino Uno R3 is ATmega328P from Atmel. Therefore, the functionality of an Arduino depends on the programming that follows the general attributes of Atmega programming [22], [23]. To generate the PWM signal to feed into the three MOSFET bridges for the inversion process with 120 degrees phase displacement, the PIN 6 to 11 of the Arduino are taken as output pins [24]. Arduino IDE is used to write the programming codes. Table II enlists the actual programming code.

TABLE II. PROGRAMMING CODE OF THE INVERSION SYSTEM

```
void setup() {
pinMode(11, OUTPUT);
pinMode(10, OUTPUT);
pinMode(9, OUTPUT);
pinMode(8, OUTPUT);
pinMode(7, OUTPUT);
pinMode(6, OUTPUT);
}
void loop() {
int var=0;
digitalWrite(11, HIGH);
digitalWrite(7, LOW);
digitalWrite(9, LOW);
digitalWrite(10, LOW);
digitalWrite(6, HIGH);
digitalWrite(8, HIGH);
delay(6.67);
digitalWrite(9, HIGH);
digitalWrite(8, LOW);
while(var==0){
delay(3.33);
digitalWrite(11, LOW);
digitalWrite(10, HIGH);
delay(3.33);
digitalWrite(7, HIGH);
digitalWrite(6, LOW);
delay(3.34);
digitalWrite(9, LOW);
digitalWrite(8, HIGH);
delay(3.33);
digitalWrite(11, HIGH);
digitalWrite(10, LOW);
delay(3.33);
digitalWrite(7, LOW);
digitalWrite(6, HIGH);
delay(3.34);
digitalWrite(9, HIGH);
digitalWrite(8, LOW);
}
}
```

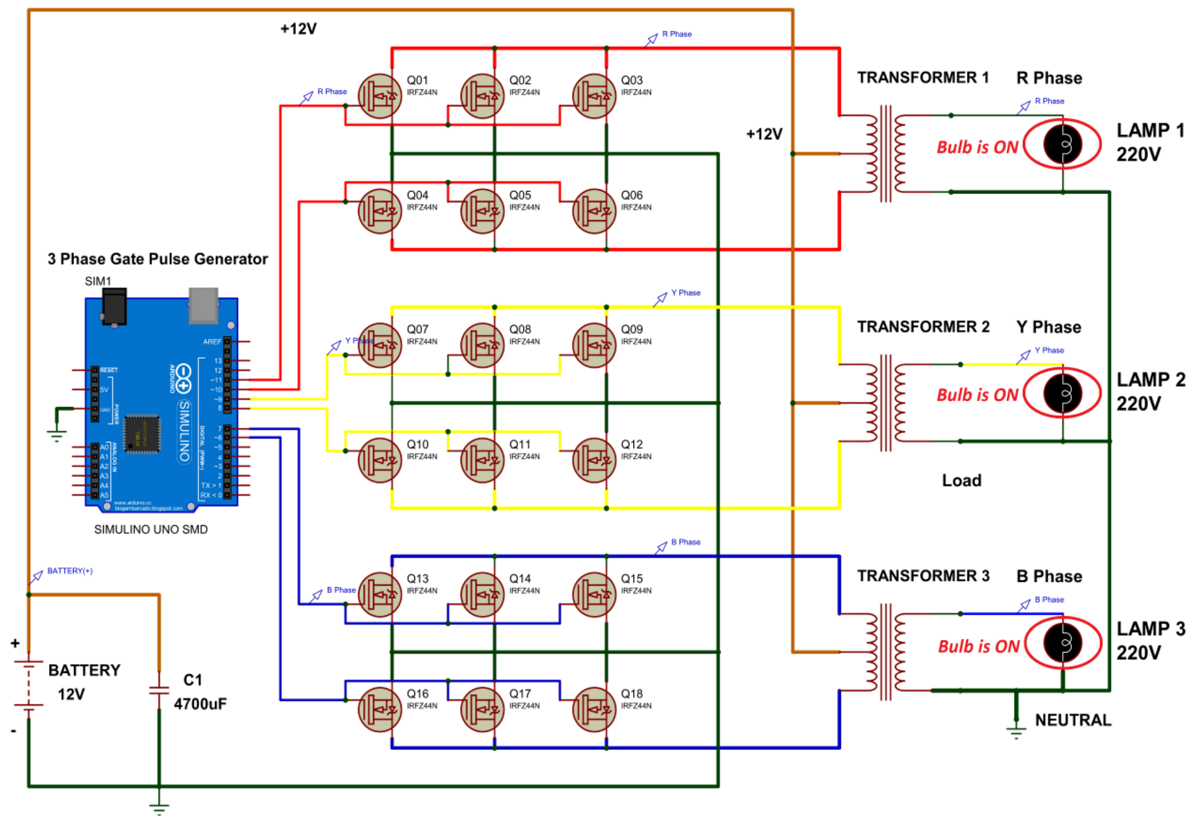

Fig. 7. Operational simulation result of the three-phase inverter.

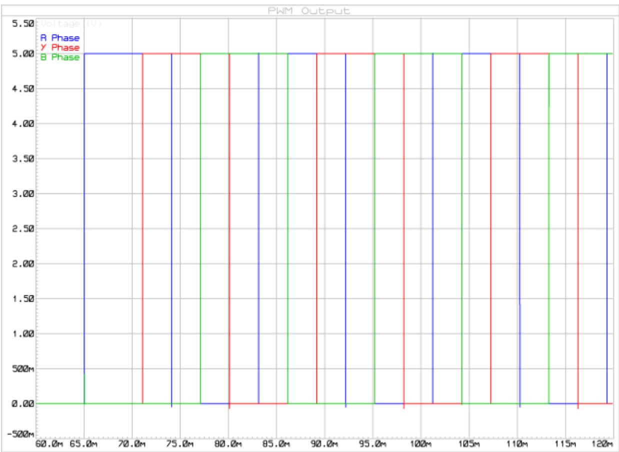

Fig. 8. PWM voltages from Arduino with 120 °phase displacement.

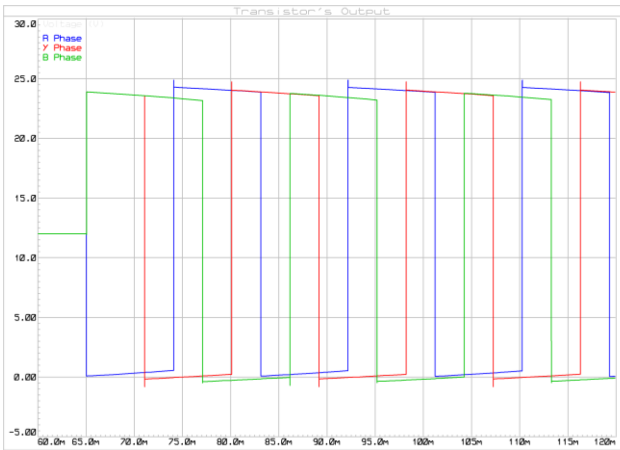

Fig. 9. Output voltages at the three stages of transistors.

V. Results and Discussion

A. Simulation Results

To verify and investigate the operation of the system, the designed system is simulated in Proteus 8.9 Professional. The results are verified according to the written program codes and their working principle, which satisfy the expected outcome. The screenshot of the simulation that represents the operational analysis is provided in Fig. 7, which shows the 3 (three) lamps/bulbs are illuminating justifying the individual inversion processes are working.

Besides operational analysis, the transient responses of the system are also checked and verified in Proteus to make sure the signals response is as per the design. The obtained results are shown in Fig. 8 through Fig. 13, justifying the transistors are making square (AC) waves from DC input keeping 120 degrees phase displacement among the individual three phases. The resultant current-voltage parameters obtained from the Proteus simulation are provided in Table III.

TABLE III. Resultant Current-Voltage Parameters

Parameters / Phase	Single-phase	Three-phase
Voltage	223 V	223 V $\times \sqrt{3}$ = 386.25 V
Current	0.58 A	0.58 A
Apparent Power	75 VA	75 VA × 3 = 225 VA
Active Power/ Load Power	60 VA	60 VA × 3 = 180 VA
Power Factor	60 VA ÷ 75 VA = 0.8	180 VA ÷ 225 VA = 0.8

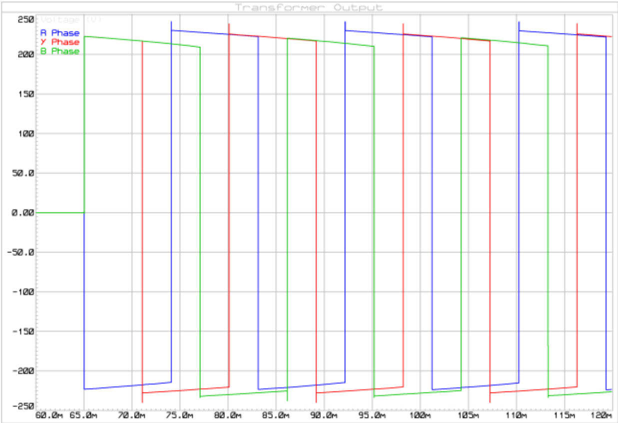

Fig. 10. Converted AC voltages at the outputs of three transformers.

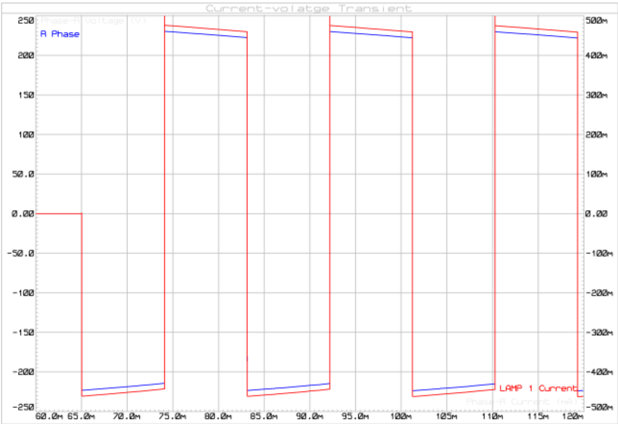

Fig. 11. Voltage vs current transient response at Phase-R.

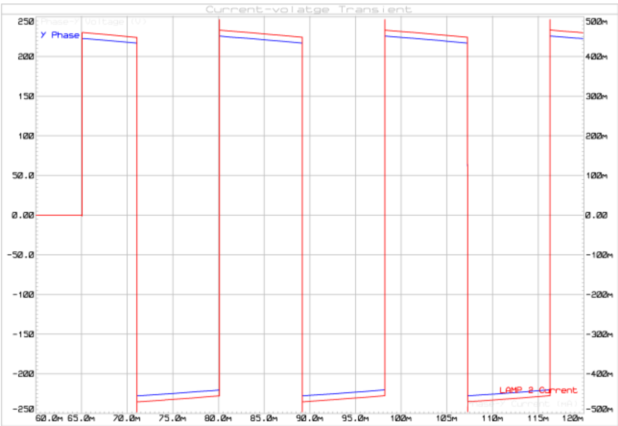

Fig. 12. Voltage vs current transient response at Phase-Y.

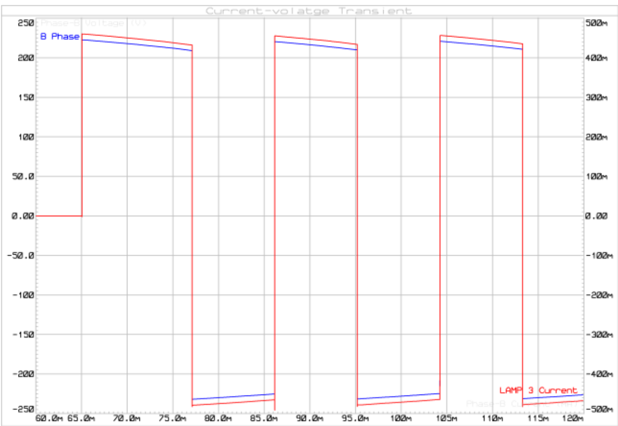

Fig. 13. Voltage vs current transient response at Phase-B.

B. Implementation/Prototype & Results

The designed three-phase inverter system is practically implemented with the components and peripheral devices as per the Proteus design, which is shown in Fig. 14. Fig. 15 represents the implemented system ON condition, where the illuminating bulbs are justifying that each single-phase inverters are working as designed and simulated.

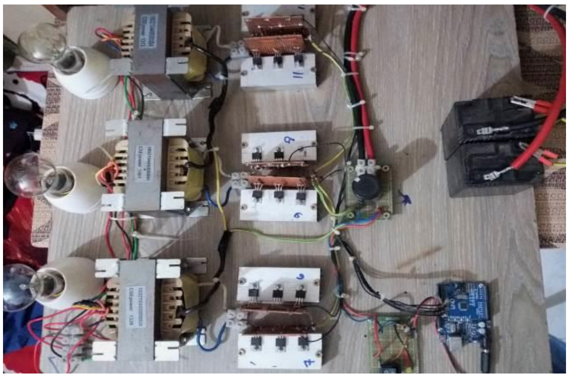

Fig. 14. Practical setup of the designed three-phase inverter.

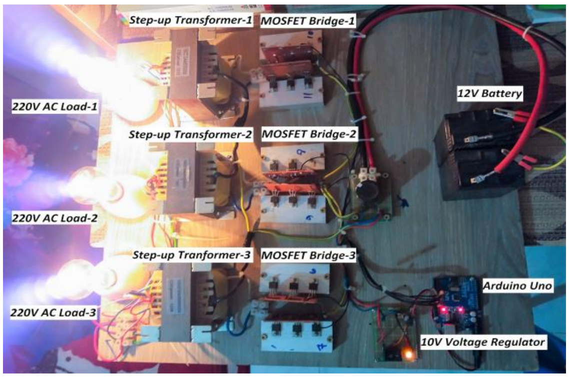

Fig. 15. Practical implementation of the designed three-phase inverter in its ON condition.

C. Discussion

A series of researches on the similar area of interest have been conducted in [25]–[41]. Among which, in [34], an 8051 microcontroller-based three-phase Inverter is designed with 6 (six) MOSFETs using PWM technique and achieved close to pure sinusoidal signal, where the fundamental principle is presented well mathematically; but hardware implementation is not shown, results are inadequate, and the maximum output voltage is not provided. In [40], a PIC microcontroller-based three-phase Inverter is designed and practically constructed with 6 (six) MOSFETs using SPWM modulation technique and achieved somewhat noisy sinusoidal signal, where mathematical modeling is shown; but output electrical parameters are inadequate. A complete discrete circuit-based transformer-less single-phase Inverter is designed with 4 (four) MOSFETs using SPWM modulation technique and achieved close to pure sinusoidal signal with 230V maximum line voltage in [30], where modulation technique is presented well; but hardware implementation is not done. In [27] and [28], an Arduino Uno-based single-phase Inverter is designed and practically constructed with 4 (four) MOSFETs using

SPWM (and SHE in [27]) modulation technique. The system in [27] achieved a noisy sinusoidal signal, where fundamental principles are presented well visually and mathematically; but output electrical parameters are inadequate, and the maximum output voltage is not provided. The system in [28] achieved close to pure sinusoidal signal with 230V maximum line voltage, where programming codes are not provided. In [26] and [35], an Arduino Uno-based single-phase Inverter is practically constructed using 2 (two) MOSFETs. The system in [26] achieved close to pure sinusoidal signal, but practical circuit diagram, programming codes are not provided, and simulation is not performed. Also, the output electrical parameters are inadequate, and the modulation technique is not mentioned. The system in [35] used the PWM technique, where programming codes and calculations are elaborately presented; but output transient responses and measured output electrical parameters are not shown. In [33] and [39], an Arduino Nano-based single-phase inverter is developed with MOSFETs using the SPWM modulation technique and achieved a somewhat noisy sinusoidal signal. The system in [33] used 8 (eight) MOSFETs and achieved 230V maximum line voltage, where no-load and with-load tests are presented well with efficiency calculations; but detailed programming codes are not provided, and results of transient responses and presentation of hardware implementation are inadequate. The system in [39] achieved 220V maximum line voltage, where complete circuit and programming codes are not provided, and hardware implementation is not shown.

The work presented in this paper aimed to design and implement an Arduino-based three-phase inverter that can be applied in microgrid systems. The designed inverter system generates 223V square wave at its output as maximum line voltage, with 120 degrees phase displacement among each phase, which is capable of driving many of the three-phase home appliances or power tools in the industrial facilities. The system is verified according to the concept, practically constructed, and tested. Design details e.g. complete circuit diagram, programming codes, electrical parameters, etc. are provided clearly that can help interested researchers and students in the same field repeat the work. The work presented in this paper including its applicability is summarized in Fig. 16.

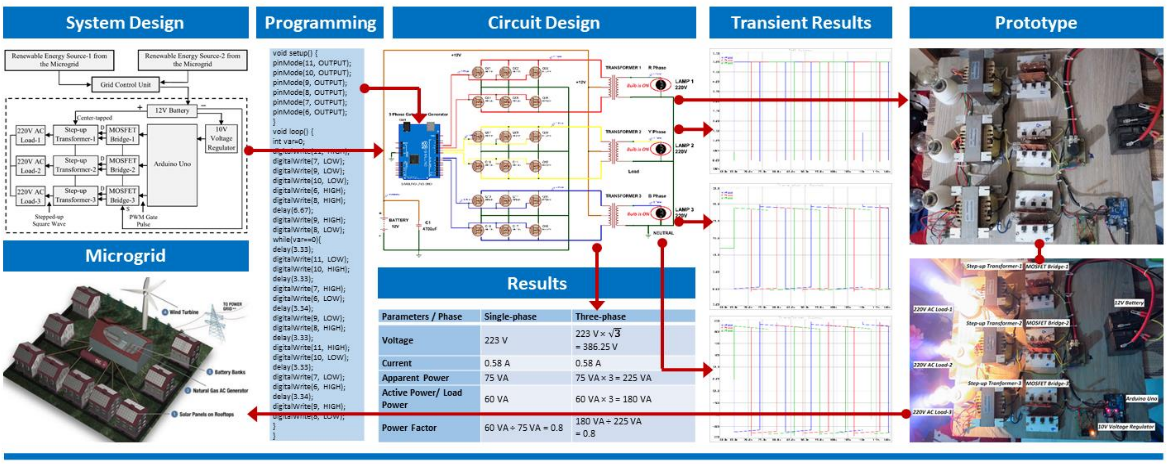

Fig. 16. A visual summary of the work done in this paper.

VI. Conclusion

An Arduino-based three-phase inverter is designed and implemented using power MOSFET, which generates 223V square signals at its output from a 12V battery. The system is verified in different ways and proven functional, and useful in the microgrid system. The designed system is also practically constructed and tested to be operational as per the concept. The system takes 12V of voltage from a battery for the inversion process, while the Arduino operates on 10V through a separate voltage regulator. The system uses a total of 18 power MOSFETs for the inversion process in three single-phase connections separately, which can be reduced to 6 if high-powered MOSFETs are incorporated. The designed system produces 386.25V of voltage for three-phase, 223V of voltage for single-phase, delivering 0.58A of current using a 60W incandescent bulb at each phase as a load. The designed inverter can be applied in a microgrid system or sustainable-powered household and small industrial facility where most electrical tools require three-phase connections.

VII. Future Scopes

Every engineering projects have some kind of scopes to improve or extend them, and the work presented in this paper is not an exception. The future scopes of this work may involve (i) changing the number of power MOSFETs and analyze the output changes or improvements, (ii) designing a filter to convert the square output signal into sinusoidal, (iii) changing the Arduino programming to generate sinusoidal output without adding a filter, (iv) designing the Grid Control Unit, according to the block diagram in Fig. 5, to complete the power management system between multiple sources.

Conflict of Interest

The authors of this paper do hereby declare that there is no conflict of interest whatsoever concerning this work.

AUTHOR CONTRIBUTIONS

Saroar Hossain and Niloy Kumar Das conducted most part of the hands-on work under the supervision of Imran Chowdhury. Taslim Ahmed and Mohammad Mahmudul Hasan provided their advice and insights into the design and prototyping and verified the results. Imran Chowdhury wrote the paper, and all the authors have approved the final version of the paper.

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