INTEGRATION OF DISPERSED RENEWABLE ENERGY GENERATING IN POWER DISTRIBUTION NETWORK

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ABSTRACT

As traditional sources of energy recede and demand for energy rises at an unprecedented pace, it is difficult for the available sources to satisfy demands. As a result, this research focuses on combining conventional generation with distributed generation, each of which can be used independently. For both industrial and residential electricity suppliers, providing a secure, continuous, and safe electrical supply is a critical necessity. As we progress toward a more sustainable approach to generating electricity (both renewable and nuclear) from the currently prevalent non-renewable sources, a hybrid supply system is an intermediate phase. This project aims to simulate a three-phase power plant that incorporates a conventional steam turbine and a DC-AC inverter generation device powered by solar to produce a total of 100kW of power with a power factor of 1. The input torque to the synchronous generator and the DC voltage to the distributed system vary depending on the output power potential of each system. Both devices achieve a constant voltage at the load. When the two systems work independently, the voltages produced by both are in phase and have the same amplitude.

Index Terms: synchronous generator, power plant simulation, distributed generation, steam turbine, solar power, DC-AC inverter, low pass filter, grid simulation.

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1. INTRODUCTION

Since its discovery in the early 1900s, the electricity market has gradually increased. Electricity has progressed from a luxury to a need over the past century. Most household activities depend heavily on energy, which has helped boost industrial efficiency. Because of this reliance on energy, it has become an integral and uncompromising part of daily life. Around 2015 and 2040, the US Department of Energy expects a 28 percent rise in energy consumption. If the need for energy grows, it becomes increasingly important to satisfy it without interruption.

Non-renewable energy sources such as biomass, natural gas, and fossil fuels have been used to produce electricity for the most part. According to some estimates, these sources accounted for 78 percent of electricity production in 2007 and 71 percent in 2016. This decrease in power production from non-renewable sources is part of a broader shift toward sustainable energy. As a result, renewable energy sources such as solar, wind, and hydro have grown considerably over the same period, with some growing faster than global increases in electricity demand. Renewable energy options such as wind, solar, and hydro are seen as viable alternatives to conventional energy sources like gasoline, natural gas, and coal. As a result, distributed power generation systems (DPGSs) focused on renewable energy sources have seen tremendous growth to satisfy the ever-increasing demand for energy.

We present a simulation of a hybrid device that produces 100kW of load by evenly distributing responsibility between a synchronous generator and a DC-AC inverter in this article. A steam turbine drives the synchronous engine, which is installed in a power plant and attached to the generator by a gearbox. To limit gas emissions from the power station, a DC-AC inverter system with wind turbines and photovoltaic panels is mounted at the load side. The torque and mechanical speed of a main shaft are inputs towards the synchronous generator, while DC voltage by renewable sources is the reference to the inverter device. The voltage produced by the inverter device is in phase with the voltage just at the synchronous generator's output and has the same amplitude.

The current is coupled together at the load side due to the parallel relation between the devices. Both of these devices provide 50kW of power on their own. Finally, the outputs from both systems are wired in parallel to provide 100kW of power to the load.

The rest of this paper is organized as follows. Section II describes previous work done in this field. Section III further expands on the design process, and the results and discussion are presented in Section IV. The conclusion of this paper and future work are presented in Section V.

2. RELATED WORK

When electricity production began to satisfy demand in the last few years, the priority of energy generation changed from producing abundantly to producing efficiently. For a long time, the emphasis has been on improving the productivity of current power plants and developing new plants that are more effective than previous plants. Bugge, et al. describe the construction of Danish coal-fired power plants that began operating in the late 1990s [5]. Such power plants were more powerful than those previously used in Europe, and they generated less emission. Further, Ber, M. J. describes other improvements in power generation strategy that would increase productivity and reduce the environmental effects of electricity generation, lowering CO2 emissions [4]. When research proved the impact of global warming on the atmosphere, however, a movement toward a more environmentally conscious approach to electricity production occurred. Simultaneously, studies into green energy sources revealed the challenges of producing sustainable energy on a large scale with current technology. [6] [7]. Renewable technology has become a difficult challenge due to a shortage of initial resources, reliability, transportation, and transmission problems. Lewis, *et al.* [8] address the complexities of solar energy generation in terms of the chemistry of collecting, preserving, and distributing this energy.

Moreover, the initial capital requirements for producing power from renewable energies remained an obstacle, preventing large-scale installations of alternative energy sources. Meantime, small-scale generations focused on renewable energy continued to grow, leading to the development of hybrid or distributed generation technologies.

Electricity generation systems that would provide electricity produced via distribution networks and/or on the consumer side were described as distributed systems [9]. Even more research in the field of distributed generation systems has focused on the advantages, problems, difficulties, and potential solutions. [10] [11] [12]. Since then, distributed generation systems have grown in significance and popularity, mainly on the small and medium scale, with many businesses investing in producing, storing, handling, and regulating their electrical consumption. The inclusion of a second power generation near the load site often reduces the possibility of failure in such systems [14].

As a result, on-site (load site) production of energy from green and clean energy sources is becoming more common. Pipattanasomporn *et al.* [13] elaborate on the advantages of using distributed generation technologies in industrial and commercial settings. It also stresses the reduced operating costs and faster break-even expenses involved with distributed generation rollout. Shah et al. offer a study of different hybrid distributed energy sources used in the United States to address the issue of which distributed generation technology to use. Their findings indicate that switching to a hybrid solar model will provide enough energy to hot, cool, and cold locations throughout the United States [15]. A further promising use of a combined generation device in the residential domain is for remote islands where transmission of energy is difficult. Guerrero *et al.* [16] address this idea and the ability of a distributed generator to make a difference in such a region.

This paper aims to demonstrate through simulations that a distributed energy system can efficiently and continually supply adequate power to a three-phase RL load. We have used a permanent magnet synchronous machine that is linked to a steam turbine that serves as a prime mover for the same purpose. On the other hand, we simulate a DC-AC inverter by assuming that the DC input is provided by photovoltaic cells.

3. SYSTEM FRAMEWORK

The subsections that follow go into greater detail about the individual components of the distributed generation system (Figure-1)

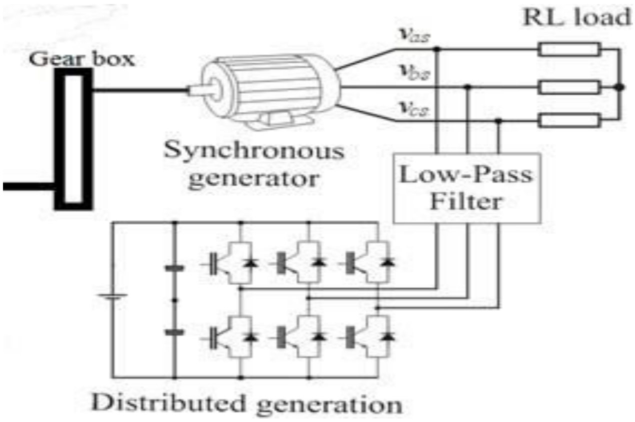

Figure-1. System framework.

A. Synchronous Generation

Synchronous generators provide a significant amount of industrial electrical capacity. They are most widely used to transform the mechanical power output of steam turbines, gas turbines, reciprocating engines, and hydro turbines into electrical power that can be supplied to the grid.

Synchronous generators are made up of two components: a rotor and a stator. The rotor is made up of ground poles, while the stator is made up of armature winding. In the vicinity of stator armature winding, the rotor field poles turn to coincide with the armature, causing an alternating voltage to be generated, which results in the production of electrical power. Many synchronous machines' electrical and electromechanical behavior can be modeled using the equations that characterize the three-phase salient-pole synchronous system. The study of the synchronous generator in the power system or electric grid setting is often carried out believing positive currents out from the device.

The permanent magnet synchronous generator is a generator that uses a permanent magnet instead of inductor coils to create an excitation field. In this project, we created a permanent magnet synchronous alternating current generator (alternator). For such purposes of that kind of simulation, we can presume that the synchronous generator is running at full power. The device is designed using the steady-state equations of a Permanent Magnet Synchronous Generator [17].

B. DC-AC Inverter

Distributed generation is a small- to medium-scale solution to producing a portion of the energy consumed near to the end consumers of power. Distributed generator systems are often made up of compact (and typically renewable energy) generators, and they have a range of possible advantages over conventional non-renewable energy generation methods. In certain ways, distributed generators may provide lower-cost energy while still improving efficiency and protection. Rather than relying on a few large-scale generating stations situated far from demand centers, a distributed generation system hires several small plants that can provide electricity on-site with less (or no) dependence on the delivery and transmission infrastructure. These technologies produce electricity in capacities ranging from a fraction of a kiloWatt to almost 100 megaWatts (MW). Utility-scale power plants have capacities that often exceed 1,000 MW.

Distributed generation occurs on two levels: the local as well as the end-point. Local energy production plants also include site-specific renewable energy technology such as wind turbines, geothermal energy processing, solar systems (photovoltaic including combustion), as well as some hydro-thermal plants. These plants are usually smaller and less concentrated than conventional power plants. They are frequently more energy and cost-effective, as well as often more reliable. As these local-scale distributed generation suppliers often consider the local context, they often generate less environmentally harmful waste or disrupt electricity than relatively large-scale power plants.

C. Low Pass Filter

A low pass filter makes signals with lower frequencies than a certain cut-off frequency and attenuates signal elements with higher frequencies than that of the cut-off frequency. We used an LCL filter in this project to attenuate higher-frequency components from the inverter stream. Figure-2 depicts the topology of the LCL filter under consideration. Even with low inductance levels, the LCL filter will attenuate current ripple. It will, however, introduce resonances and unstable states into the scheme. As a result, the filter should be specifically constructed by the parameters of the particular converter.

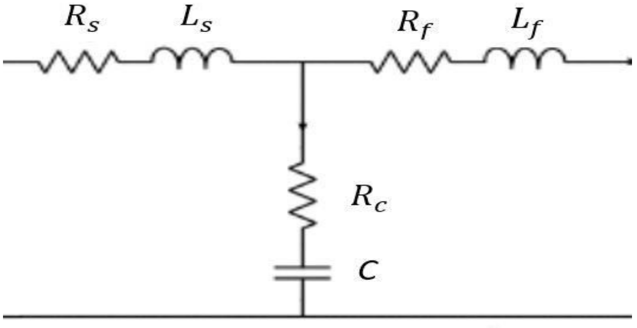

Figure-2. Configuration of an LCL low pass filter.

The cut-off frequency of the filter is the most critical parameter. Since the filter must have adequate attenuation in the context of a converter's switching frequency, the cut-off frequency of the filter must be at least one-half of the switching frequency of the converter. As shown in Figure-3, the low pass filter is implemented directly after the inverter in this project.

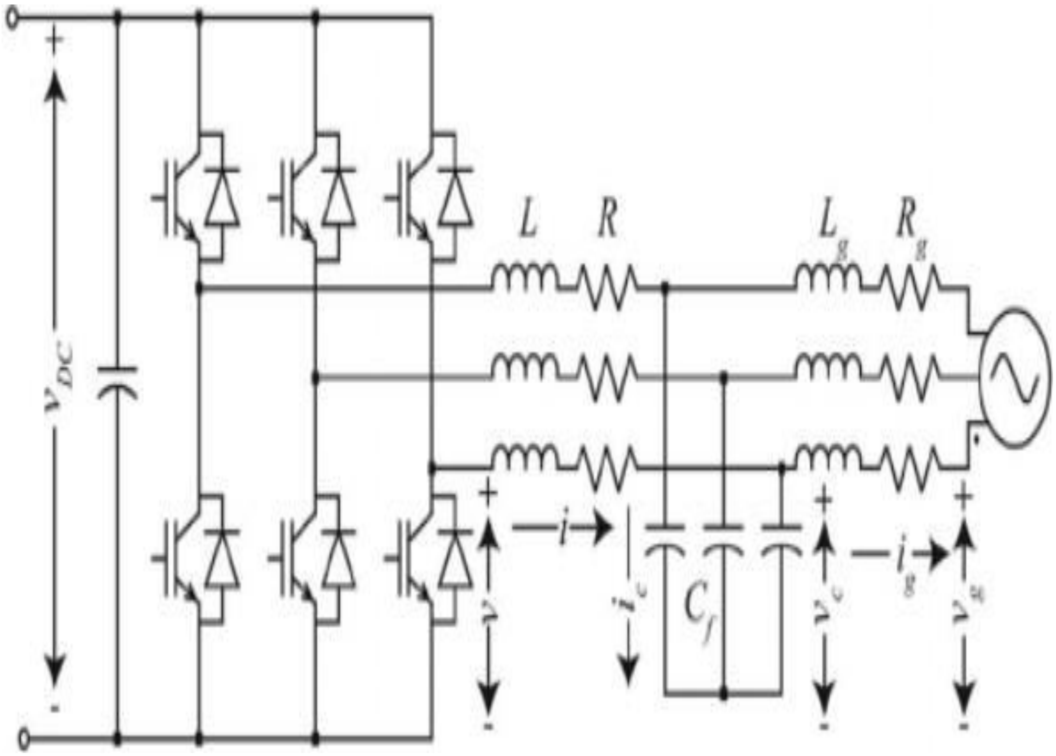

Figure-3. Three-phase inverter topology with LCL low pass filter.

4. SIMULATION RESULTS AND DISCUSSION:

In the following sections, we will go through the simulation procedure, the formulae used, and the results obtained.

A. Synchronous Generation

The inputs for the AC Generator are torque (τ) supplied to the machine and mechanical speed of the machine (ω_r). The values of (τ) and (ω_r) are estimated to produce 50kW of electricity. Provided the τ (in Nm) generator, the equation for quadrature current (I_{qs}) at steady state can be determined using the equation given by,

$$\tau = \frac{3}{2}\cdot\frac{P}{2}\cdot\left[\lambda_m \cdot I_{qs} - \left(L_q - L_d\right)\cdot I_{qs}\cdot I_{ds}\right] \qquad (1)$$

where, P = Number of Poles of the machine
λ_m = The Permanent Magnet flux linkage
I_{qs} = The quadrature axis current
I_{ds} = The direct axis current
L_q = Quadrature axis inductance
L_d = direct axis inductance

For the dynamic process, we use the T-model, as seen in Figure 4 [17].

We assume the L_d and L_q values are identical since we are using a 4-pole salient pole method. We get I_{qs} by rearranging the values in equation 1

$$I_{qs} = \frac{2}{3}\cdot\frac{2}{P}\cdot\frac{1}{\lambda_m}\cdot\tau \qquad (2)$$

The Direct voltage (V_{ds}) and Quadrature voltage (V_{qs}) are given by,

$$V_{qs} = r_s I_{qs} + \omega_r \cdot L_d \cdot I_{ds} + \omega_r \cdot \lambda_m \qquad (3)$$

$$V_{ds} = r_s \cdot I_{ds} - \omega_r \cdot L_q \cdot I_{qs} \qquad (4)$$

where, r_s = Stator resistance

The original values of quadrature and direct axis current and voltage are considered to be zero. As a result, for the first iteration of the simulation, the only voltage produced in V_{qs} and V_{ds} is by the system's speed voltage. The speed voltage is determined by ω_r The impedance matrix provides I_{ds}.

$$I_{ds} = \frac{-\lambda_m}{L_d} \qquad (5)$$

As a result, the values ofV_{qs} , V_{ds}, I_{qs}, and I_{ds} will all be non-zero after the first iteration. Figure-5 depicts the plots for I_{qs} , I_{ds} and I_{0s} , while Figure-6 depicts the plots for V_{qs} , V_{ds}, and V_{0s}

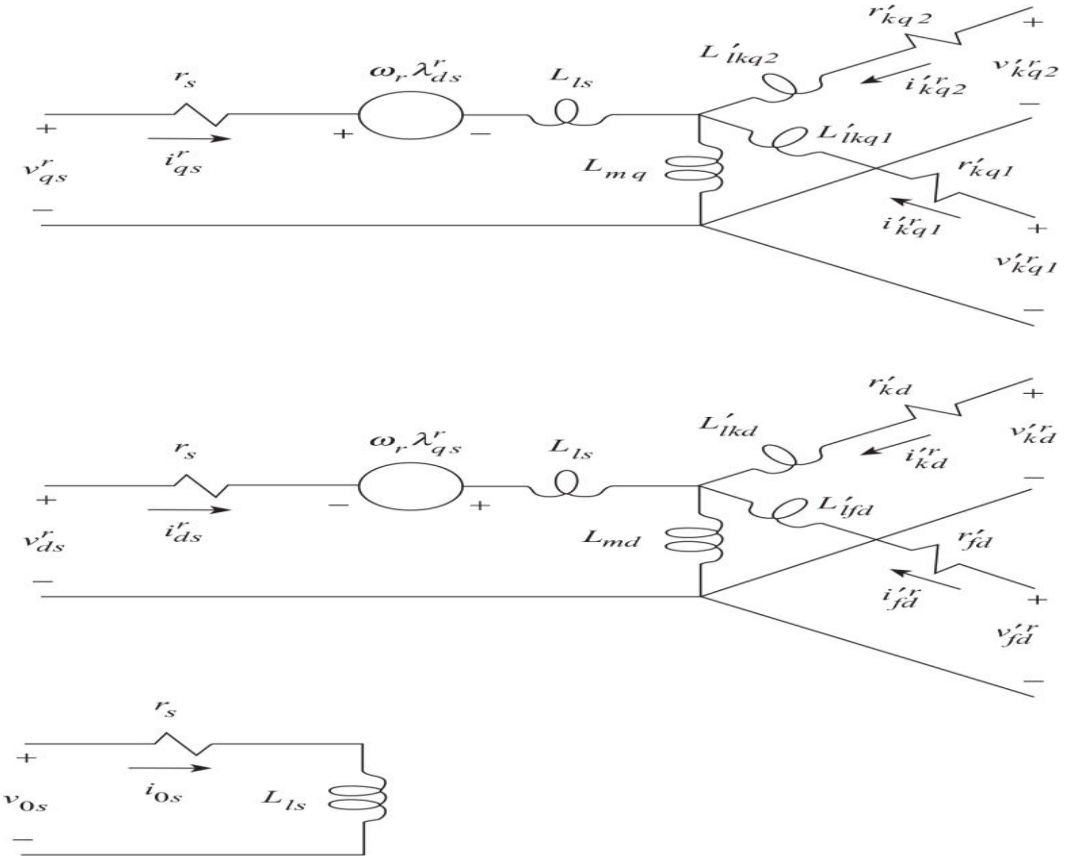

Figure-4. Three-phase synchronous machine equivalent circuit with transformed variables.

The inverse park transformation is then used to quantify phase voltages and currents (Figures 7 and 8). The inverse Park's transformation matrix [18] is given by,

$$K_s^{-1} = \begin{bmatrix} \cos\theta & \sin\theta & 0 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & \sin\left(\theta - \frac{2\pi}{3}\right) & 0 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & 0 \end{bmatrix} \quad (6)$$

$$V_{abcs} = K_s^{-1} \cdot V_{qd0s} \quad (7)$$

Likewise, the phase current is computed by using inverse Park's transformation.

$$I_{abcs} = K_s^{-1} \cdot I_{qd0s} \quad (8)$$

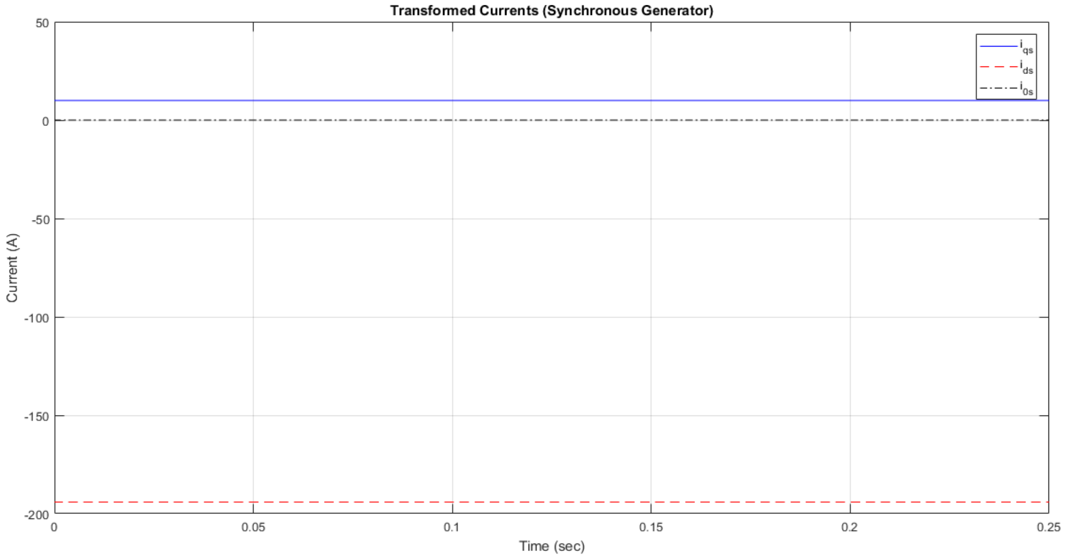

Figure-5. Currents in the reference frame.

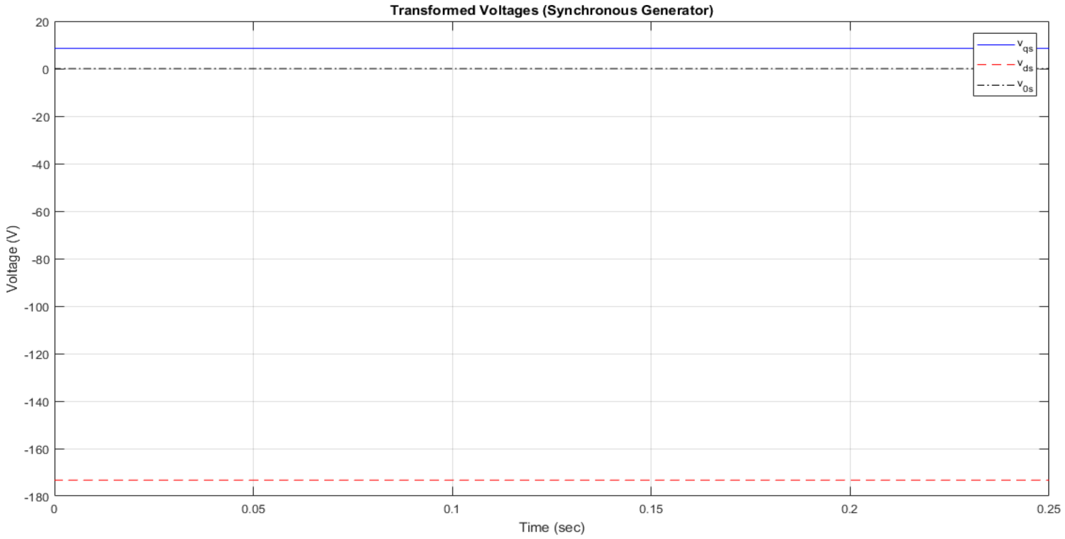

Figure-6. Voltages in the reference frame.

The synchronous generator's output power (Figure-9) is estimated as follows:

$$P_{sync} = V_{as} \cdot I_{as} + V_{bs} \cdot I_{bs} + V_{cs} \cdot I_{cs} \quad (9)$$

The synchronous generator has a power capacity of slightly more than 50kW.

B. DC-AC Inverter

The simulated DC-AC inverter is used to transform the DC voltage supplied by photovoltaic cells and wind turbines to three-phase AC power which can be transferred to the load.

An inverter with the configuration shown in Figure-10 is used for this function. It is known that the input voltage is stable at 250V DC.

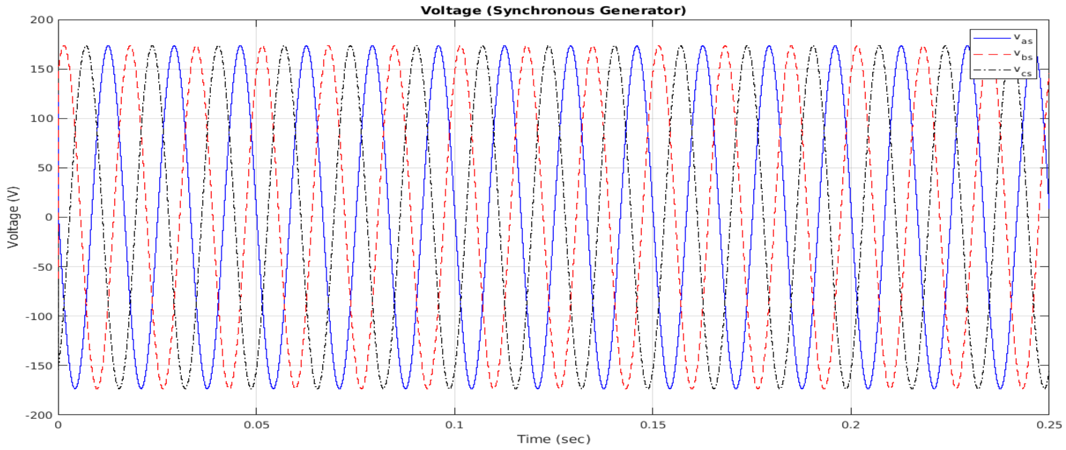

Figure-7. Output phase voltages of the synchronous generator.

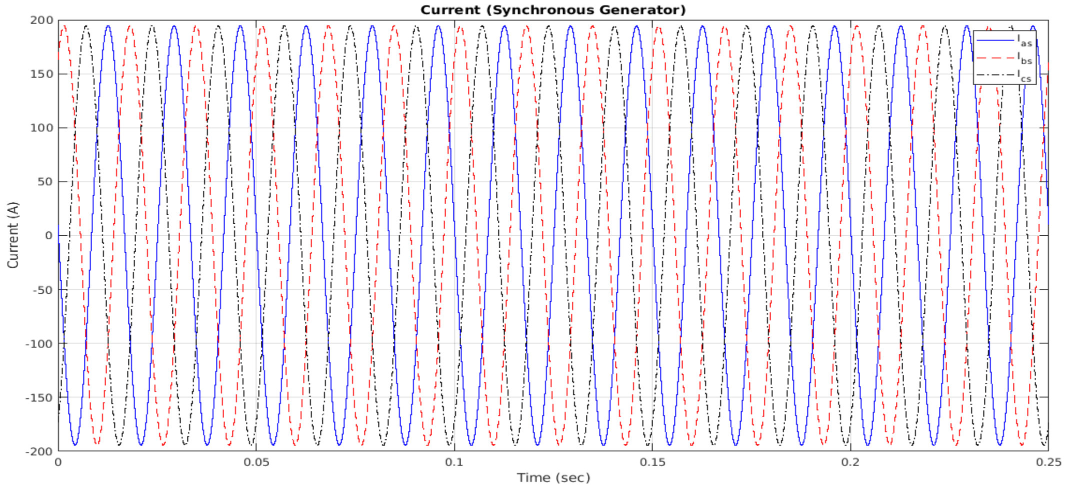

Figure-8. Output phase currents of the synchronous generator.

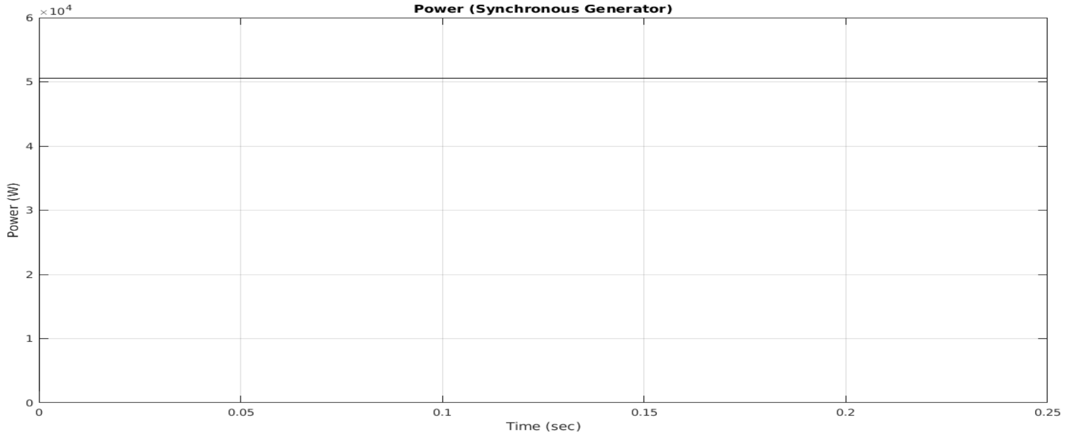

Figure-9. Output power of the synchronous generator.

MOSFET switches are used because of their benefits in low-voltage and high-frequency applications. For simulation purposes, we also presume optimal systems, i.e. no firing delay ($\alpha = 0$) and no voltage drop through the switches and diodes.

A PWM circuit connected to a sum of two signals, a three-phase reference signal, and a high frequency sawtooth, is used to control the switches. Figure-12 depicts the outcome of the switching circuit (Figure-11). Figure-13 depicts the control switch effects for each switch. The first signal (q1) is used to control switches T1 and T4, the second (q2) is used to control switches T2 and T5, and the third (q3) is used to control switches T3 and T6. Figure-14 depicts the measured pole voltages from Equations 10, 11, and 12.

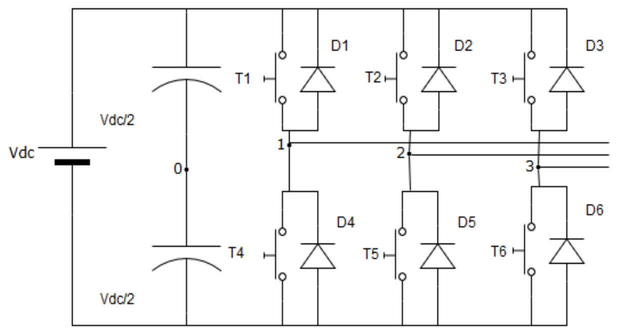

Figure-10. Configuration of three-phase DC-AC inverter used.

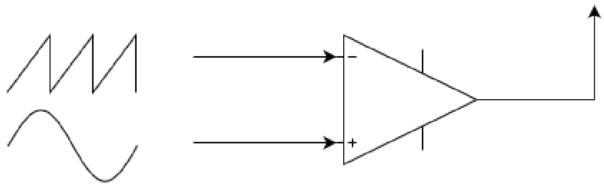

Figure-11. Configuration of PWM control circuit.

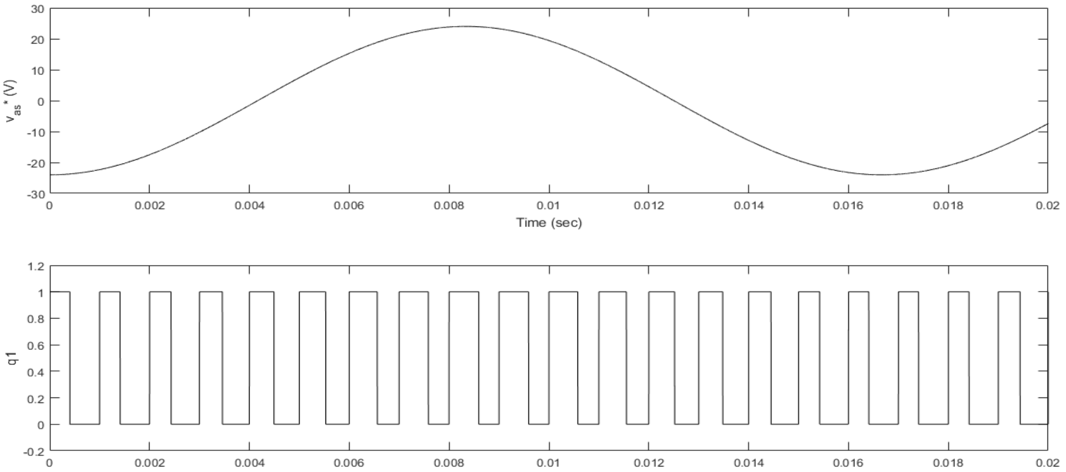

Figure-12. Output of PWM control circuit.

$$v_{10} = (2 \cdot q1 - 1) \cdot \frac{V_{dc}}{2} \tag{10}$$

$$v_{20} = (2 \cdot q2 - 1) \cdot \frac{V_{dc}}{2} \tag{11}$$

$$v_{30} = (2 \cdot q3 - 1) \cdot \frac{V_{dc}}{2} \tag{12}$$

Since the point 0 for the three phases differs from the neutral, we quantify vn0 as follows:

$$v_{n0} = \frac{1}{3} \cdot (v_{10} + v_{20} + v_{30}) \tag{13}$$

Using Equations 14, 15, and 16, the three-phase voltages v_{as}, v_{bs}, and v_{cs} are determined using the pole voltages. A trace of these phase-neutral voltages is shown in Figure-15.

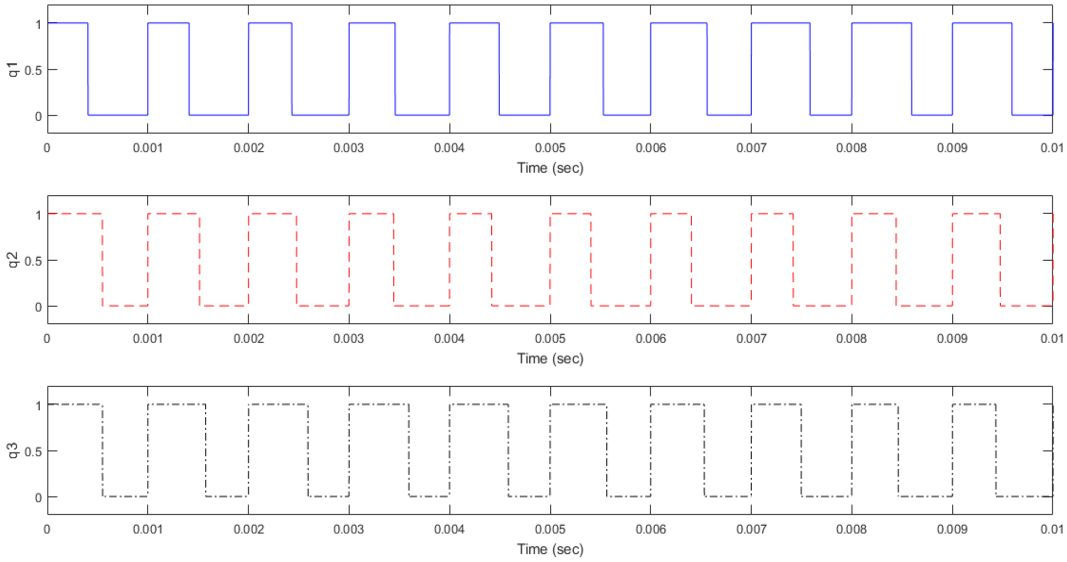

Figure-13. Outputs of PWM circuit for control of the 6 switches.

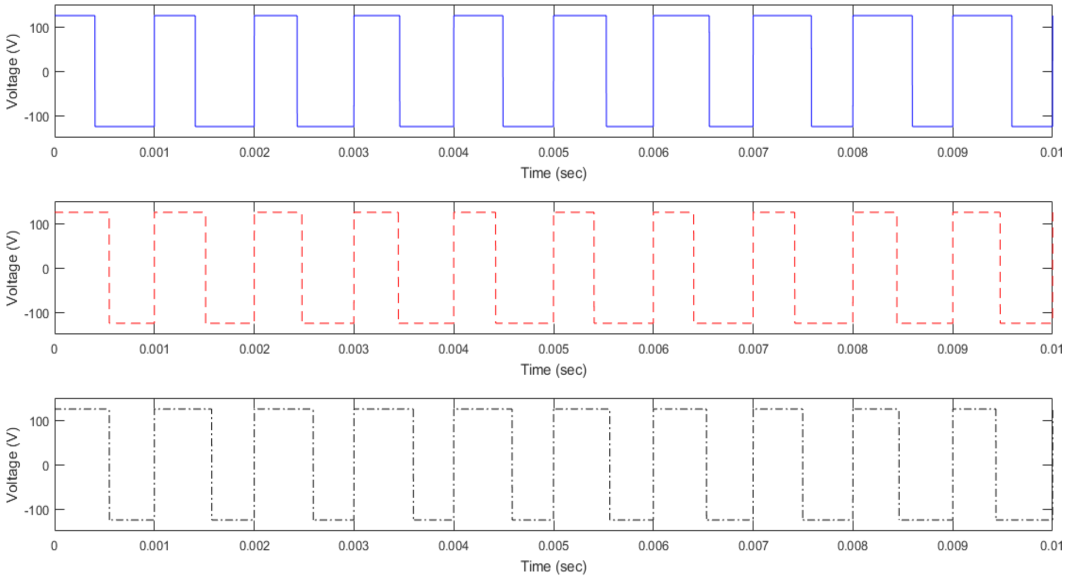

Figure-14. Pole voltages at the output of the DC-AC inverter.

$$v_{as} = v_{10} - v_{n0} \tag{14}$$

$$v_{bs} = v_{20} - v_{n0} \tag{15}$$

$$v_{cs} = v_{30} - v_{n0} \tag{16}$$

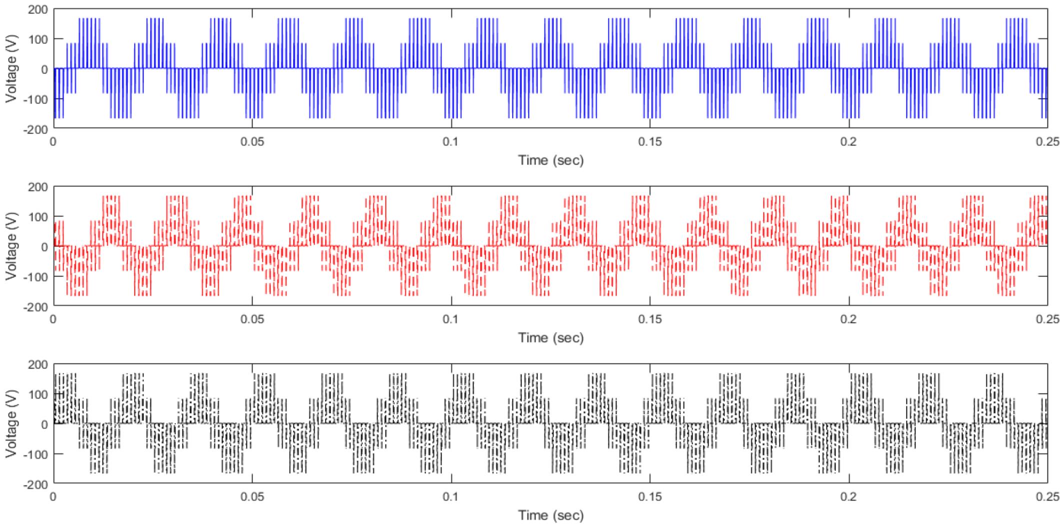

Figure-15. Phase-neutral voltages outputs of the DC-AC inverter.

This system's current output is measured as the current passing into an RL load. Figure-16 depicts these three-phase currents.

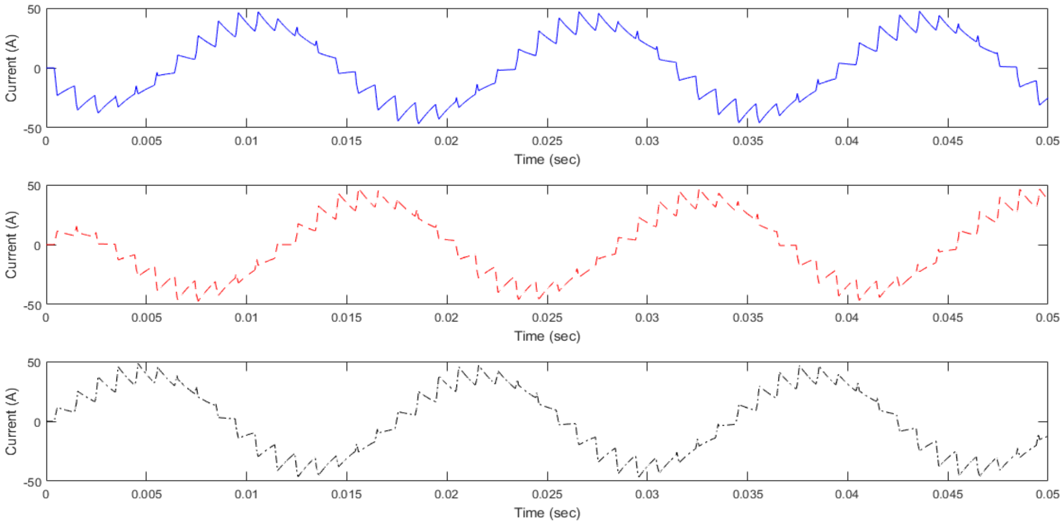

Figure-16. Phase-neutral current outputs through an RL load.

C. Low Pass Filter

These outputs, as seen in Figures 15 and 16, cannot be supplied to the load. An LCL filter in the configuration shown in Figure 2 is used to isolate the high-frequency components from the output voltage and provide a smooth, sinusoidal output. The LCL filter is configured as seen in Figure-2. Although the resistances in series with the inductors are the resistances applied by the inductors, the resistance in series with the capacitance is a damping resistance.

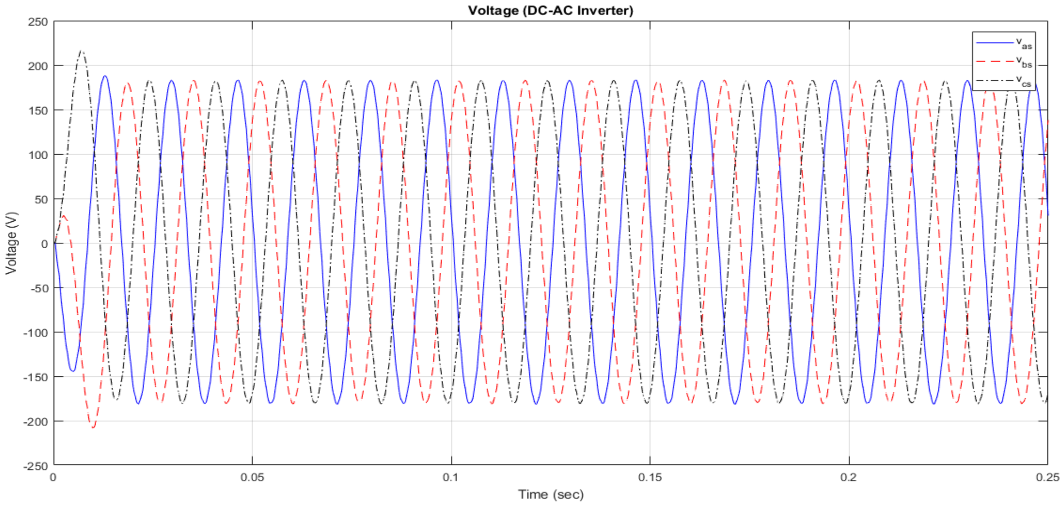

Figure-17. Output voltage of the LCL low pass filter.

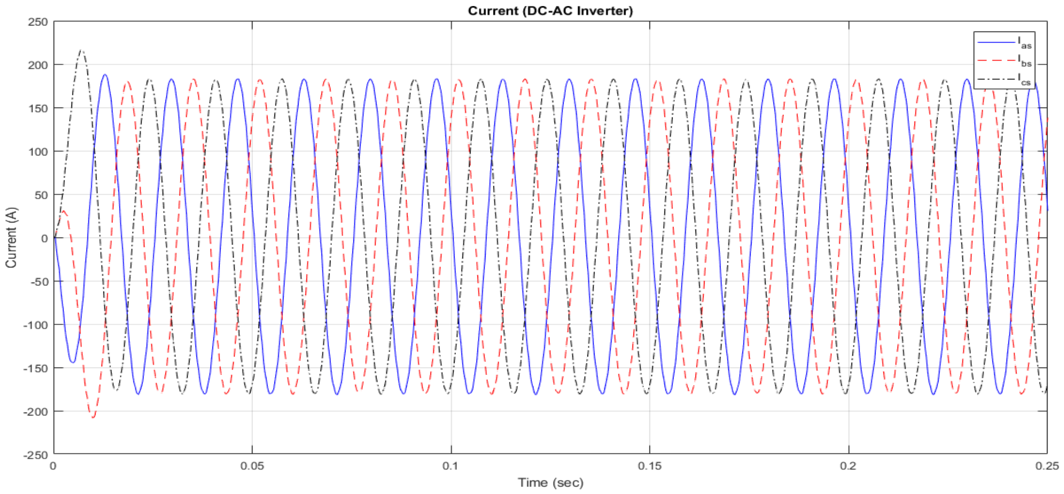

Figure-18. Output current of the LCL low pass filter.

The three-phase phase-neutral voltages are fed into the LCL low-pass filters. Finally, we connect a 1 resistance in series with the LCL filter and calculate the voltage through it as well as the current flowing through it as the output voltages (Fig 17) and currents (Figure-18). Equation 9 is used to measure the output capacity of the LCL-distributed device. Figure-19 shows that the circuit's output power reaches just under 50kW with slight ripples.

5. CONCLUSIONS

Individually generated systems are linked in parallel to form larger systems. The concurrent relation of these individual generation systems ensures that if the voltages are identical and instep, the currents are applied in parallel. The system's output voltage is 360V peak to peak (Figure-20), and the output current is 750A peak to peak (Figure-21). This generation system produces 100kW of output power (Figure-22), with the load split evenly between the two generation systems. Overall, such a device reduces reliance on the grid by supplying a consistent supply of electricity produced at the load side. The growing relevance of such distributed generation networks can be seen in the transition toward a more competitive electricity generation outlook.

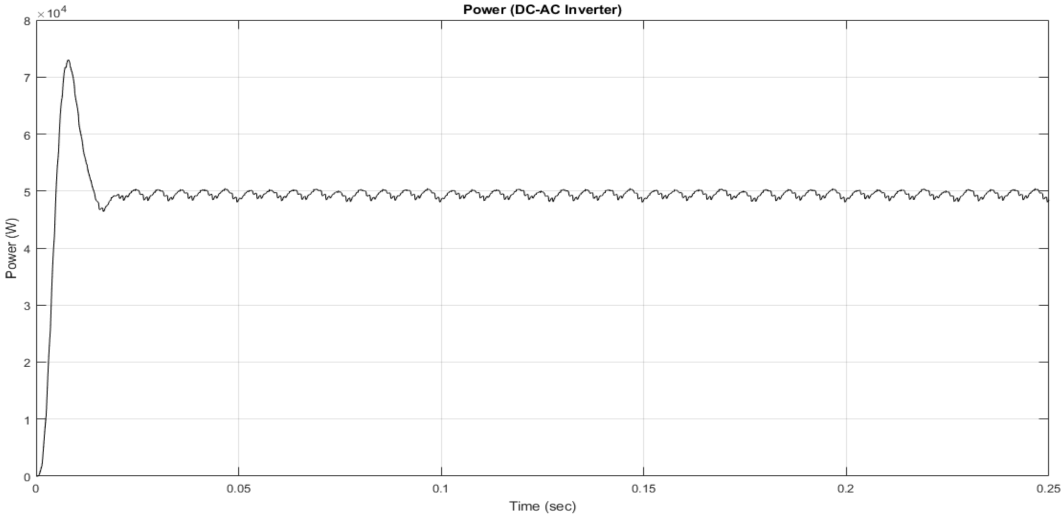

Figure-19. Output power of the distributed generator through the LCL low pass filter.

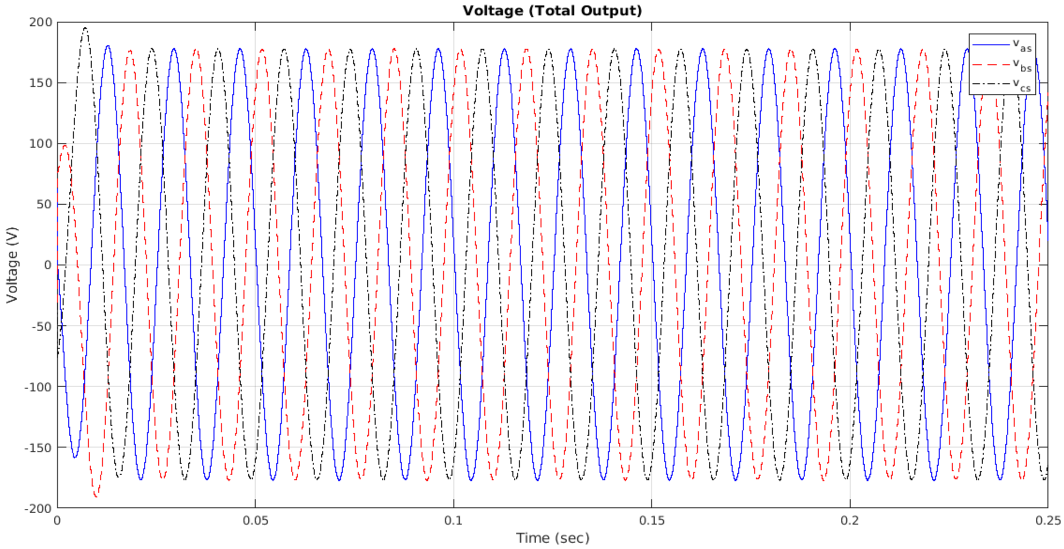

Figure-20. Total output voltage of the hybrid distributed generation system.

Previous research in the area has shown the importance of using renewable technology. To that extent, this study serves as a proof-of-concept for a hybrid power generation system that can be used by commercial and residential enterprises looking to minimize their energy costs, reduce their carbon footprints, reduce their reliance on third-party energy providers, and improve their consolidation with local electricity generation

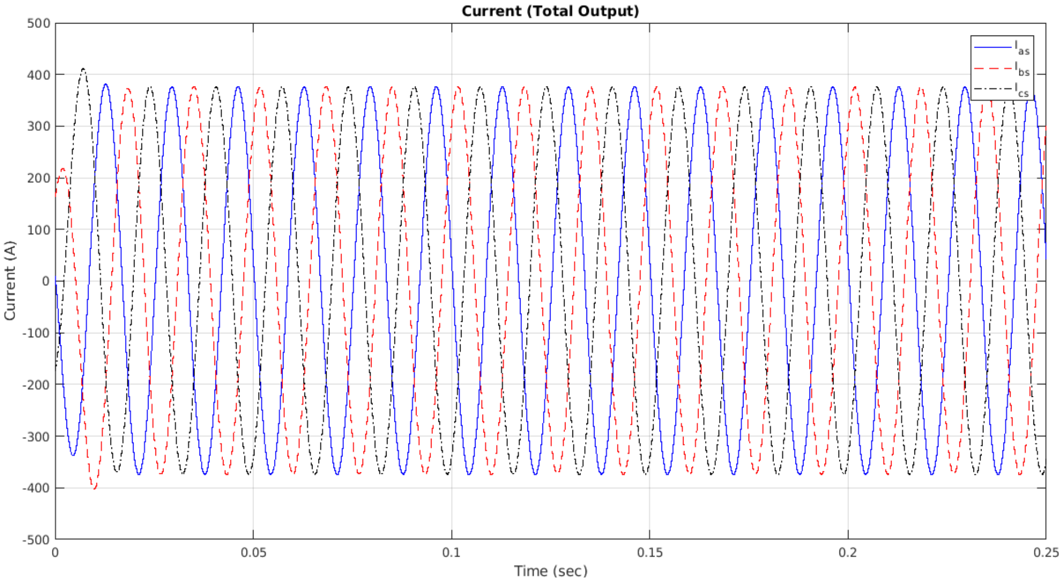

Figure-21. Total output current of the hybrid distributed generation system.

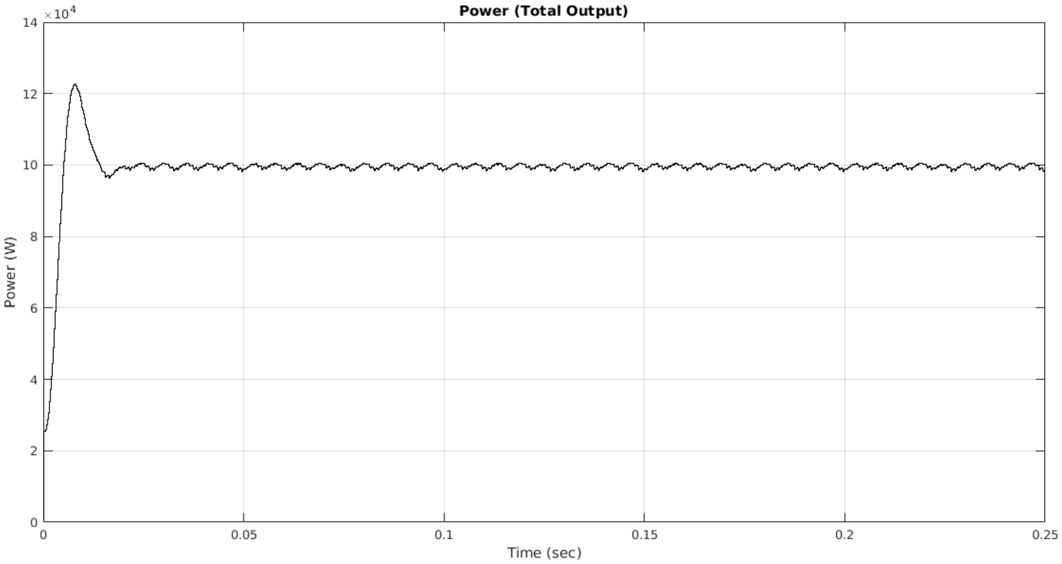

Figure-22. Total output power of the hybrid distributed generation system.

Although this system was developed to provide a significant commercial or industrial RL load, it also serves as a foundation for converting other systems to hybrid applications, such as automobile power trains, ships and airplanes, individual household energy generation systems, and so on.

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