Distributed Generation System

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***Abstract*— Providing a reliable, constant and stable electrical supply is an important requirement for both industrial and household electricity providers. As we move towards a more sustainable approach of generating electricity (renewable and nuclear) from the currently widespread non-renewable sources, an intermediate step is a supply system that employs a hybrid approach. To demonstrate the possibility of such a deployment, this project aims to simulate a three-phase power plant that combines a traditional steam turbine and a DC-AC inverter generation system that is driven by solar or wind energy, to deliver a total 100kW of power with a power factor of 1.**

***Index Term:* Synchronous Generator, Distributed Generator, Distributed Generation, Power Plant Simulation, Steam Turbine, Solar Power, Wind Power, DC-AC Inverter.**

I. INTRODUCTION

The demand for electricity has been increasing steadily since it was first discovered in the early 1900s. Over the last century, electricity has grown from being a luxury to a necessity. Most household tasks depend largely on electricity, and it has aided an increase of industrial productivity. This dependence on electricity has led electricity to become an important, uncompromising part of daily human life. US Department of Energy predicts a 28% increase in energy demand between 2015 and 2040 [1]. As energy demand keeps increasing, it becomes imperative to meet this demand without an interruption.

Electricity has largely been generated using non-renewable sources like coal, natural gas, and fossil fuels. Some estimates put the use of these sources in electricity generation at 78% for 2007 and 71% for 2016 [2]. This reduction in the generation of electricity using non-renewable sources is a part of a larger trend towards clean energy. Thus, over the same period, renewable energy sources like solar, wind and hydro have been increasing significantly, with some growing faster than the global increase in electricity demand [1]. Renewable energy sources like wind, sun, and hydro are seen as a reliable alternative to the traditional energy sources such as oil, natural gas, or coal. Distributed power generation systems (DPGSs) based on renewable energy sources, have thus experienced immense development to meet energy ever increasing demand needs [3].

In this paper, we present a simulation of a hybrid system that generates 100kW of load by dividing the responsibility equally among a synchronous generator and a DC-AC inverter. The synchronous generator is driven by a steam turbine, which is deployed in a power plant and connected to the generator through a gear box. A DC-AC inverter system with wind turbines and photo-voltaic panels are installed at the load side to reduce the gas emission from the power plant. Inputs to synchronous generator are torque and mechanical speed of the prime mover, whereas DC voltage from the renewable sources is the input to the inverter system. The voltage generated by the inverter system is in phase and has the same amplitude as the voltage at the output of the synchronous generator. Because of the parallel connection between the systems, the current is added together at the load side. Independently, both these systems generate 50kW of output. At the end, the output from both the systems is connected in parallel to supply the load with 100kW power.

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.

II. RELATED WORK

In the last few decades, as energy generation started meeting the energy demand, the focus of energy generation has shifted from generating plentiful to generating efficiently. For quite some time, the focus was on improving the efficiency of existing power plants and building new plants which would be more efficient than previous plants. Bugge, et al. describes the development process of Danish coal-powered power plants that started operation in the late 1990s [5]. These power plants were more efficient than the ones used in Europe before that, and operated with reduced emissions. Further, Ber, M. J. describes other changes in power generation methodology to improve efficiency and reduce the environmental impact of energy generation, and thereby reducing CO_2 emissions [4].

Over time, however, as studies proved the effects of global warming on the environment, a shift toward a more conscientious outlook of energy generation took place. At the same time, research in renewable sources of energy detailed the problems associated with the generation of clean energy at scale, with existing technology [6] [7]. Initial capital, lack of reliability, storage and transmission issues made renewable energy a challenging problem. Lewis, et al. discuss the challenges relating to solar energy generation with respect to the chemistry of capturing, storing and transmitting this energy [8].

However, the challenges pertaining to the initial capital requirement for the production of electricity using renewable sources remained, limiting large scale deployments of renewable sources of energy. Meanwhile, the interest of small-scale generation in renewable energy kept increasing, leading to an introduction of the concepts of hybrid or distributed generation systems. Distributed systems were defined as electricity generation systems that provide electricity generated within distribution networks and / or on the customer side [9]. Further research in the area of distributed generation systems emphasized the benefits, issues, challenges and proposed solutions [10] [11] [12].

Distributed generation systems have since been gaining importance and acceptance, especially at the small- and medium-scale, with a lot of establishments making investments in generating, storing, managing and controlling their electrical consumption. Such systems also reduce the probability of failure by the presence of a second generation system close to the load site [14]. Thus, on-site (load site) generation of electricity from renewable and clean sources of energy is becoming more prevalent. Pipattanasomporn, et al. further expands the benefits of using distributed generation systems at the commercial and industrial levels [13]. It also emphasizes on the lower running costs and the pace of break-even costs associated with the deployment of distributed generation.

To answer the question of which distributed generation system to use, Shah, et al. present a comparison of various hybrid distributed energy systems used in the US. Their results show that a transition to a hybrid solar model can sufficiently supply enough energy to hot, moderate and cold locations throughout the United States [15]. Another promising application of a hybrid generation system in the residential domain is to remote islands that are a challenge to transmit electricity to. This concept and the potential for a distributed generator to make a difference to such a location is presented by Guerrero, et al. [16].

The focus of this paper is to prove by simulations that a distributed generation system can provide sufficient power reliably and continuously, to a three-phase RL load. For the same, we use a permanent magnet synchronous machine connected to a steam turbine that acts as a prime mover. On the other hand, we simulate a DC-AC inverter by assuming a DC input is generated with wind turbines and / or photovoltaic cells.

III. System Framework

The following subsections describe the individual components of the distributed generation system (Figure 1) with further detail.

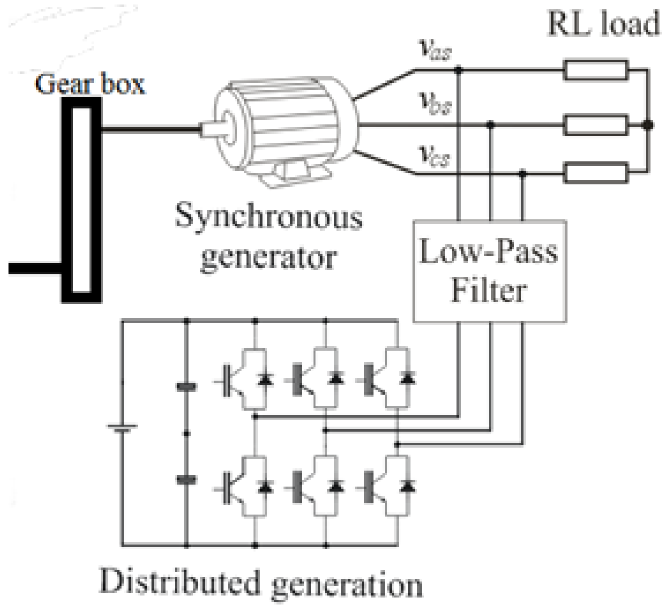

Fig. 1. System framework.

A. Synchronous Generation

Synchronous generators are a major source of commercial electrical energy. They are most commonly used to convert mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for supplying to the grid.

Synchronous generators consist of two parts: a rotor and a stator. The rotor consists of field poles, whereas the stator consists of armature conductors. In the presence of stator armature conductors, the rotor field poles rotate to align with the armature, inducing an alternating voltage, which in turn results in electrical power generation.

The electrical and electromechanical behavior of most synchronous machines can be predicted from the equations that describe the three-phase salient-pole synchronous machine. In the power system or electric grid environment, the analysis of the synchronous generator is often carried out assuming positive currents out of the machine. A generator in which a permanent magnet is used instead of inductor coils to provide excitation field is termed as a permanent magnet synchronous generator. In this project, we have designed a permanent magnet synchronous AC generator (alternator). For the purposes of this simulation, we assume that the synchronous generator is rotating at the rated speed. The machine is designed based on the steady state equations of a Permanent Magnet Synchronous Machine [17].

B. DC-AC Inverter

Distributed generation is an approach employed at the small- and medium-scale to produce a part of the electricity consumed close to the end users of power. Distributed generator technologies often consist of modular (and usually renewable energy) generators, and they offer a number of potential benefits over traditional non-renewable methods of energy generation. In many cases, distributed generators can provide lower-cost electricity, better reliability and more security.

Instead of using a few large-scale generating stations located far from load centers, a distributed generation system employs numerous small plants that can provide power on-site with limited (or no) reliance on the distribution and transmission grid. Such technologies yield power in capacities that range from a fraction of a kiloWatt to about 100 megaWatts (MW). Utility-scale generation units generate power in capacities that often reach beyond 1,000 MW.

Distributed generation takes place on two-levels: the local level and the end-point level. Local level power generation plants often include renewable energy technologies that are site specific, such as wind turbines, geothermal energy production, solar systems (photovoltaic and combustion), and some hydro-thermal plants. These plants tend to be smaller and less centralized than the traditional power plants. Frequently, they are more energy and cost efficient, and much more reliable. Since these local level distributed generation producers often take into account the local context, the usually produce less environmentally damaging pollution or disrupting energy than the larger central model power plants.

C. Low Pass Filter

A low pass filter allows the signals which have lower frequencies than a certain cutoff frequency and attenuates signal components of frequencies higher than the cutoff frequency. For this project we have used an LCL filter to attenuate higher frequency components from the output of the inverter. The topology of the considered LCL filter is as shown in Figure 2.

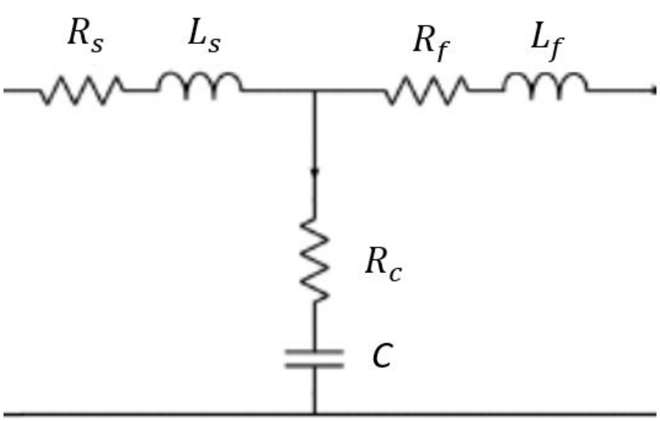

Fig. 2. Configuration of an LCL low pass filter.

The LCL filter has the ability to attenuate current ripple even with small inductance values. However, it can also bring resonances and unstable states into the system. Therefore, the filter should be designed precisely according to the parameters of the specific converter. The most important parameter of the filter is its cut-off frequency. The cut-off frequency of the filter must be minimally one half of the switching frequency of the converter, because the filter must have enough attenuation in the range of the converter's switching frequency. In this project the low pass filter is implemented directly after the inverter as shown in Figure 3.

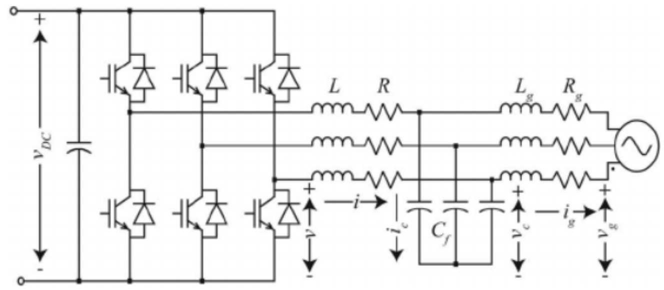

Fig. 3. Three-phase inverter topology with LCL low pass filter

IV. Simulation Results and Discussion

In the following subsections, we discuss the process of simulation, the formulae used and the results obtained.

A. Synchronous Generation

For the AC Generator, the inputs given are torque (τ) supplied to the machine and mechanical speed of the machine (ω_r). The values of τ and ω_r are calculated to give a power output of 50kW. Given the τ (in Nm) of the generator, the equation for quadrature current(I_{qs}) can be calculated at steady state using the equation given by,

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

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

As a reference, we rely on the T-model for the transformed variables, as shown in Figure 4 [17].

Because we use a 4-pole salient pole system, we assume the L_d and L_q values are equal. Rearranging the values in equation 1, we get I_{qs} as,

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

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

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

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

where, r_s = Stator resistance.

The initial values of the quadrature and direct axis current and voltage are assumed as 0. Thus, for the first iteration of the simulation, the only voltage generated in V_{qs} and V_{ds} is by speed voltage of the system. The speed voltage depends on ω_r. I_{ds} is given by the impedance matrix,

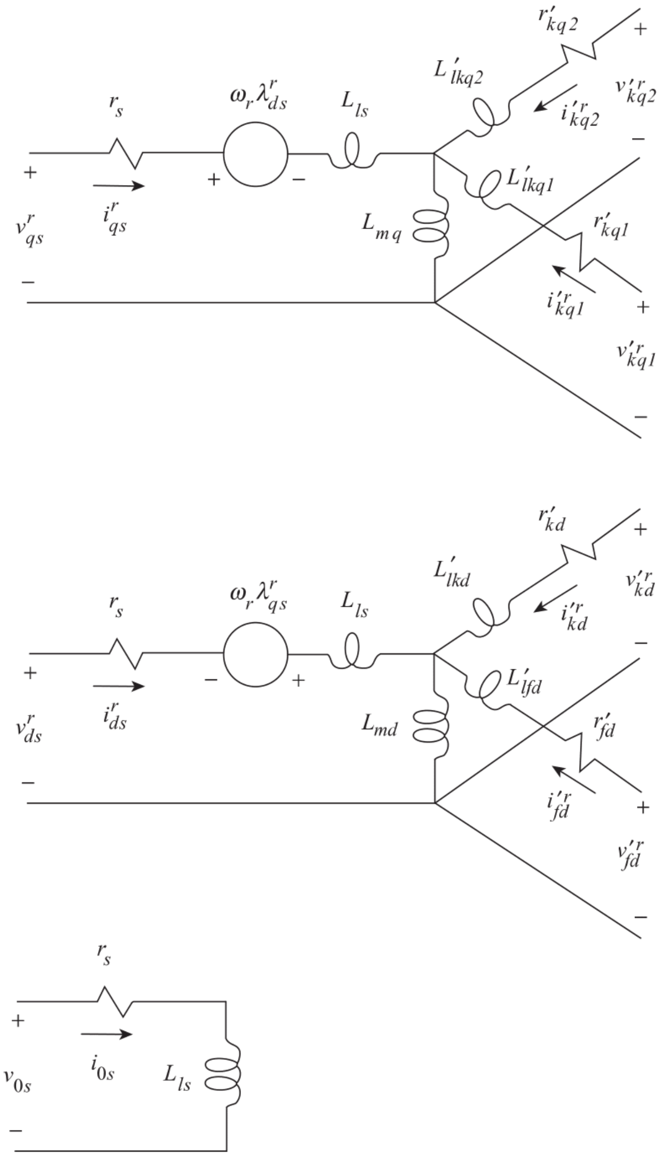

Fig. 4. Equivalent circuit of a three-phase synchronous machine with transformed variables.

$$I_{ds} = \frac{-\lambda_m}{L_d} \tag{5}$$

Thus after the first iteration, the values of V_{qs}, V_{ds}, I_{qs} and I_{ds} will all be non-zero. The plots for I_{qs}, I_{ds} and I_{0s} are shown in Figure 5, whereas the plots for V_{qs}, V_{ds} and V_{0s} are shown in Figure 6.

We then calculate phase voltages and currents using the inverse park transformation (Figures 7 and 8). The matrix for inverse Park's transformation [18] is given by,

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

$$V_{abcs} = K_s^{-1} \cdot V_{qd0s} \tag{7}$$

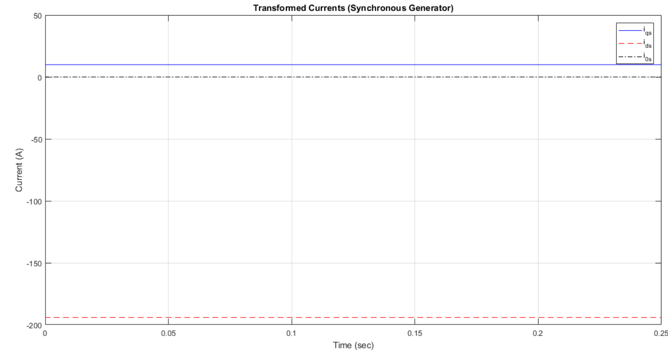

Fig. 5. Currents in the reference frame.

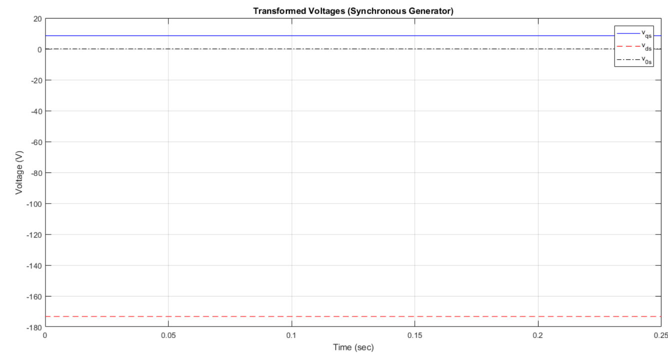

Fig. 6. Voltages in the reference frame.

Similarly, the phase current is calculated by using inverse Park's transformation,

$$I_{abcs} = K_s^{-1} \cdot I_{qd0s} \tag{8}$$

The output power of the synchronous generator (Figure 9) is calculated as,

$$P_{sync} = V_{as} \cdot I_{as} + V_{bs} \cdot I_{bs} + V_{cs} \cdot I_{cs} \tag{9}$$

It can be observed that the power output of the synchronous generator is just over 50kW.

B. DC-AC Inverter

The DC-AC inverter simulated is used to convert the DC voltage supplied by the photovoltaic cells and wind

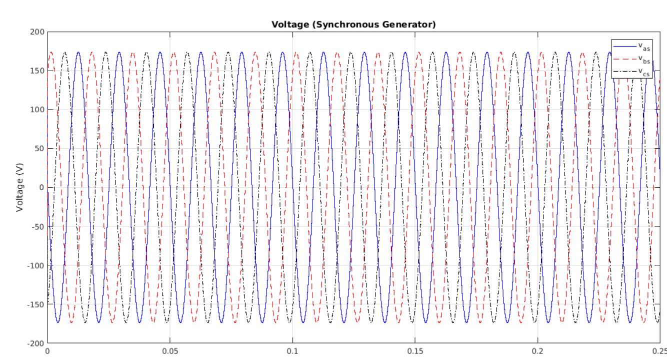

Fig. 7. Output phase voltages of the synchronous generator.

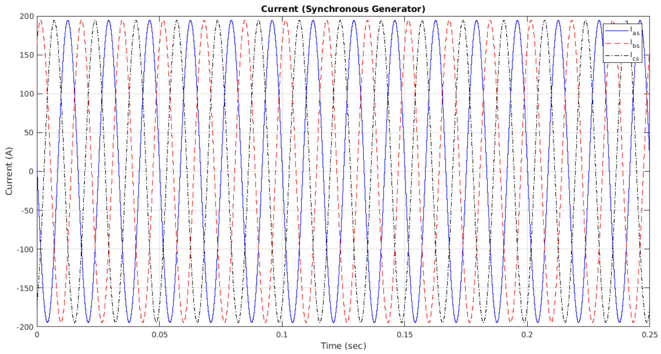

Fig. 8. Output phase currents of the synchronous generator.

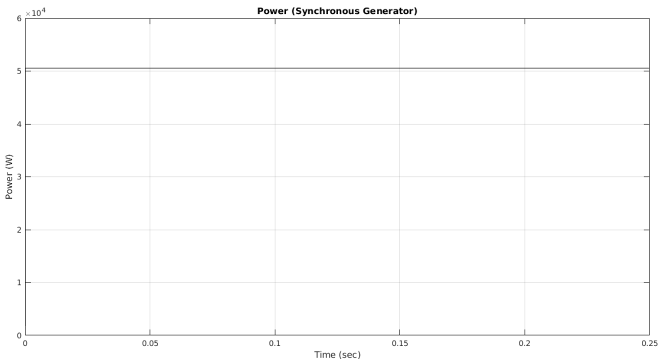

Fig. 9. Output power of the synchronous generator.

turbines to AC three-phase that can be supplied to the load. For this purpose, a inverter of the configuration shown in Figure 10 is used. A constant input of 250V DC is assumed. We use MOSFET switches because of their advantages in applications that involve low voltages and high frequencies. For the purposes of simulation, we also assume ideal devices, i.e. 0 firing delay ($\alpha = 0$) and no voltage drop across the switches and diodes.

To control the switches, a PWM circuit connected to a sum of 2 signals, three-phase reference signal and a high-frequency sawtooth, is used. The result of the switching circuit (Figure 11) used is shown in Figure 12. Figure 13 shows the control switch results for all the switches. The first signal ($q1$) is applied to control switches T_1 and $\bar{T}_4$, second ($q2$) is used to control switching of T_2 and $\bar{T}_5$, and third ($q3$) is used to control T_3 and $\bar{T}_6$. The pole voltages calculated from Equations 10, 11 and 12, and are shown in Figure 14.

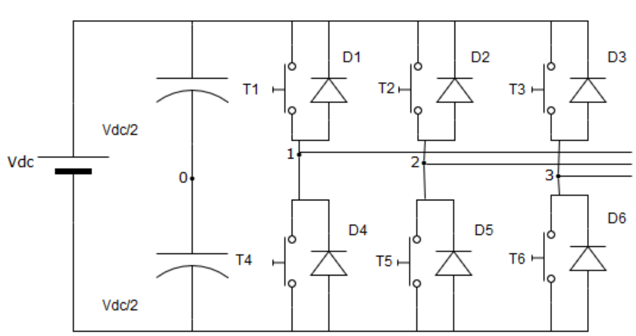

Fig. 10. Configuration of three-phase DC-AC inverter used.

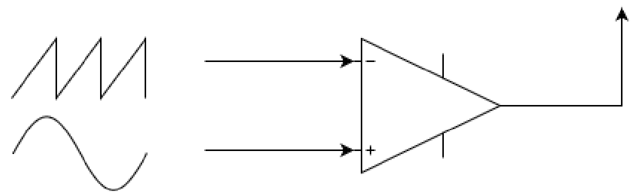

Fig. 11. Configuration of PWM control circuit.

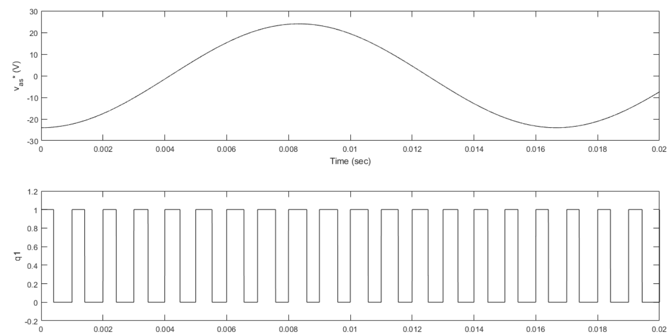

Fig. 12. Output of PWM control circuit.

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

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

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

Because the point 0 is different from the neutral for the three-phases, we calculate v_{n0} as,

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

Thus, with the pole voltages, the three phase voltages v_{as}, v_{bs} and v_{cs} are then calculated using Equations 14, 15 and 16. Figure 15 shows a plot of these phase-neutral voltages.

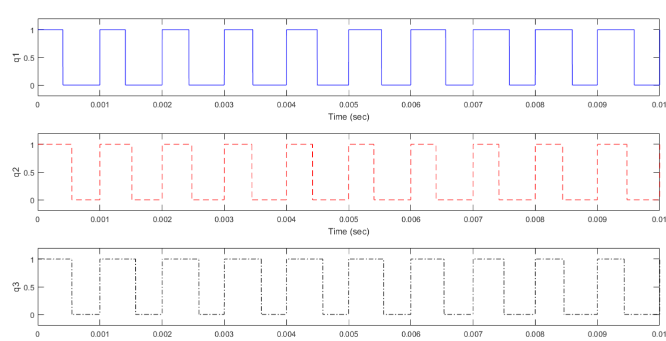

Fig. 13. Outputs of PWM circuit for control of the 6 switches.

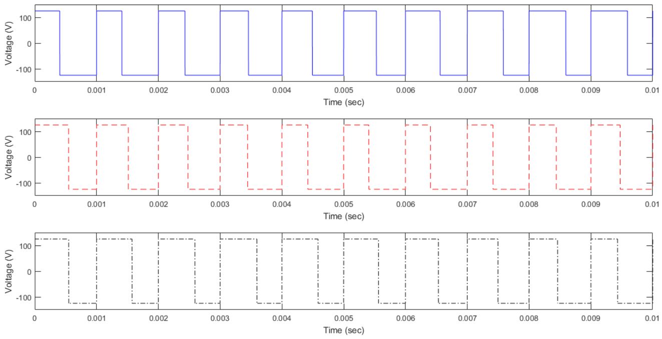

Fig. 14. Pole voltages at the output of the DC-AC inverter.

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

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

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

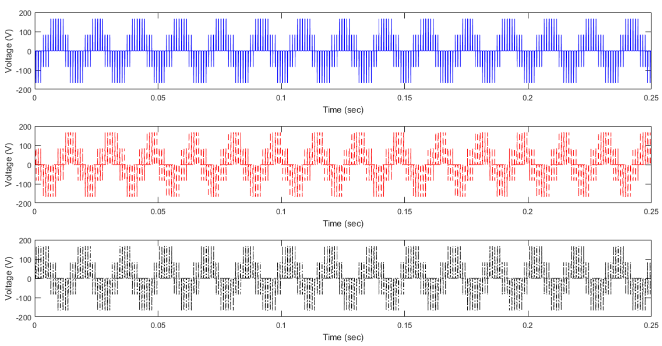

Fig. 15. Phase-neutral voltages outputs of the DC-AC inverter.

The current output of this system is observed as the current passing through an RL load. These three-phase currents are shown in Figure 16.

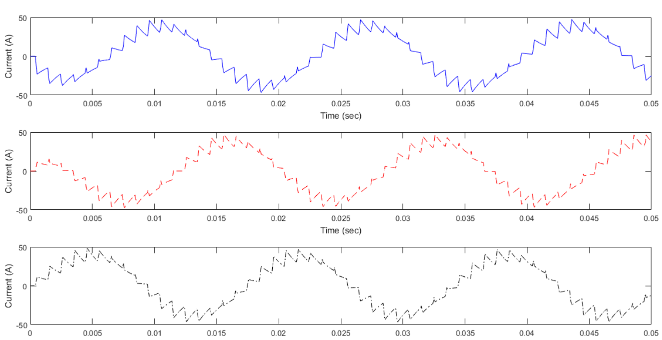

Fig. 16. Phase-neutral current outputs through an RL load.

C. Low Pass Filter

As can be seen from Figures 15 and 16, these outputs cannot be supplied to the load. To remove the high frequency components from the output voltage and to provide a smooth, sinusoidal output, an LCL filter of the configuration shown in Figure 2 is used. The configuration of the LCL filter is as shown in Figure 2. While the resistances connected in series with the inductances are the resistances added by the inductances, the resistance connected in series with the capacitance is a damping resistance.

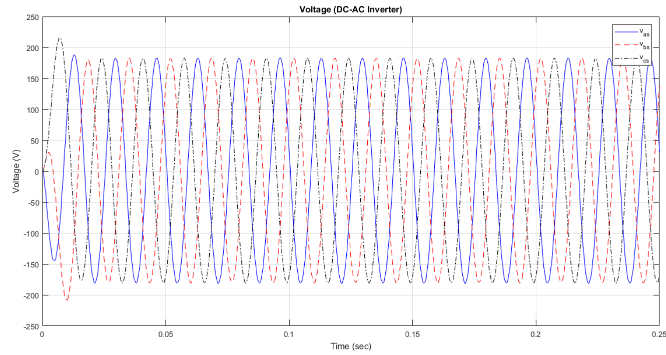

Fig. 17. Output voltage of the LCL low pass filter.

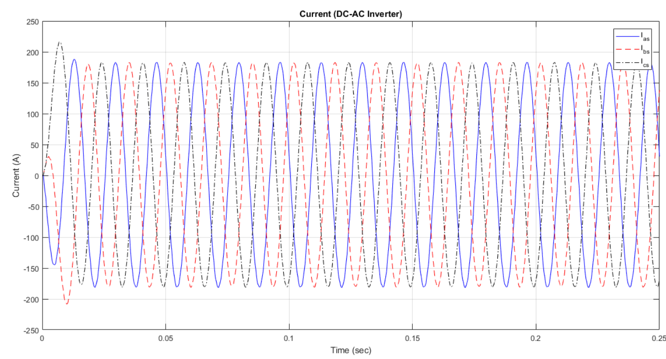

Fig. 18. Output current of the LCL low pass filter.

The input to the LCL low pass filters are the three-phase phase-neutral voltages. At the end, we assume a 1Ω resistance in series with the LCL filter, and measure the voltage across it, and current flowing through it as the output voltages (Figure 17) and currents (Figure 18) respectively. The output power of the LCL distributed system is calculated by Equation 9. As can be seen from Figure 19, the output power of the circuit averages to just under 50kW, with minor ripples.

V. Conclusion and Future Work

Individually generated systems are combined together by connecting them in parallel. The parallel connection of these individual generation systems means that the currents get added in parallel if the voltages are equal and in phase. The output voltage of the system thus generated is 360V peak-to-peak (Figure 20), and the output current is 750A peak-to-peak (Figure 21). The output power that this generation system delivers is 100kW (Figure 22), with the load shared equally among both the generation systems.

On the whole, such a system helps reduce the dependence on the grid by providing a stable source of electricity generated at the load side. The growing importance of such

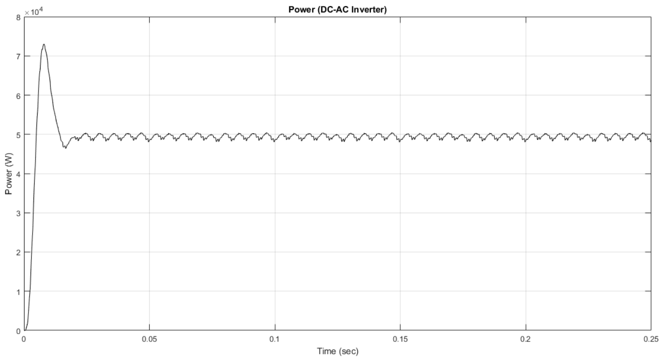

Fig. 19. Output power of the distributed generator through the LCL low pass filter.

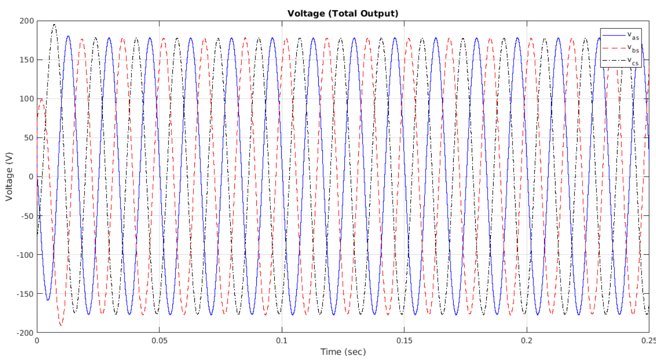

Fig. 20. Total output voltage of the hybrid distributed generation system.

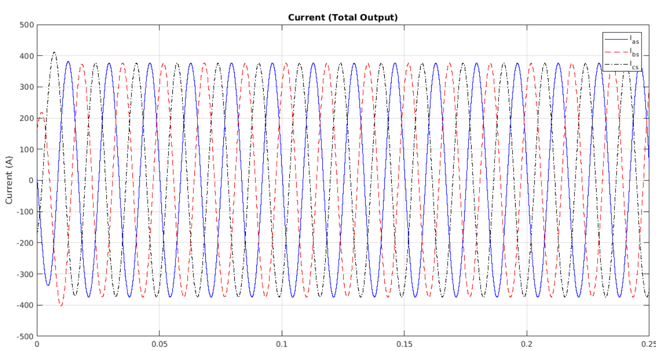

Fig. 21. Total output current of the hybrid distributed generation system.

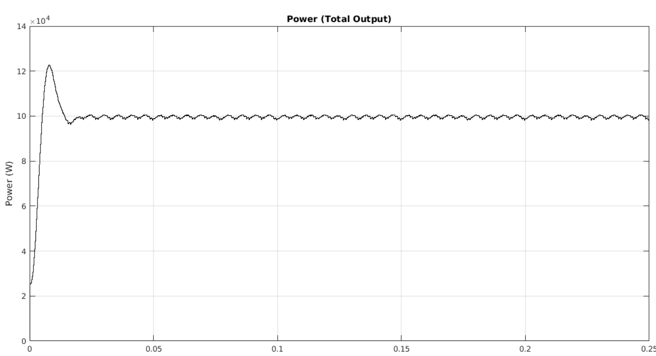

Fig. 22. Total output power of the hybrid distributed generation system.

distributed generation systems has been visible in the shift toward a more sustainable outlook of energy generation. Previous work in the field has established the need for resorting to clean energy. To that end, this research serves as a proof-of-concept for a hybrid power generation system that can be employed by commercial and industrial establishments intending to reduce their energy costs, reduce their carbon footprints, reduce their dependence on third-party energy provisions, and also increase their vertical integration with local electricity generation.

While this system has been designed for supplying a large commercial or industrial RL load, it also serves as a baseline for converting other systems to hybrid applications including automotive powertrains, engines for ships and airplanes, individual household electricity generation systems, etc.

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