Optimization of Three-Phase Grid-Tie Inverter Systems

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Abstract:

The aim of this project was to design, simulate, and analyze three-phase grid-tie inverter systems used by Bloom Energy for DC/AC power conversion. Analyzing and simulating the control structure of these inverters helps in learning how to increase efficiency of the DC/AC conversion process to minimize power loss. Specifically, the fundamental objective of the project was to develop a theoretical model of the three-phase grid-tie inverter systems and study how real and reactive power (P and Q) are varying based on the inverter output voltage and frequency. The theoretical model for a single inverter system could then be applied to designing a controller for multiple inverter systems connected in parallel, using the droop control structure.

The theoretical modeling was performed using MATLAB/Simulink. The single grid-tie inverter systems were monitored using these tools and the power outputs, both real and reactive, were measured with respect to changes in load. Based on the controller used in these simulations, it was found that real and reactive power stabilized over time after an initially high transient response. Future work for this project involves implementing the theoretical models developed in the scope of this project onto hardware provided by Bloom Energy and applying the theoretical models for single three-phase grid-tie inverter systems to multiple systems connected in parallel.
**Introduction:**

Bloom Energy is a company headquartered in Sunnyvale, California which strives to power commercial structures and campuses in a more environmentally friendly, economical way. This company has created on-site power generation servers called Bloom Boxes, which can use either traditional or renewable fuels to locally generate power. Fuel cells, which are a distributed energy resource, can be used to generate power to be shared. Bloom Energy has created a cutting-edge type of fuel cell using sheets of a chemical resembling beach sand (scandia stabilized zirconia) bordered with a specially formulated paint. When multiple sheets are stacked together, oxygen interacts with the fuel cells in order to convert chemical energy into electrical energy. The Bloom Box implements this on a large scale in order to harness enough electrical energy to supply power to the customer. This power can then be delivered back into the electric grid using grid-tie inverters. This design is beneficial to both the environment and the customer, since Bloom Boxes prevent the need for power lines from an outside source, combustion, or the burning of fossil fuels.

**Figure 1: Diagram Illustrating the Process of How a Bloom Box Works**

There are some obstacles to be faced with tying multiple inverter systems to an electric grid. Increasing efficiency of these inverter systems to minimize power losses during the DC/AC
power conversion process is a great challenge for energy companies such as Bloom Energy and is the basis of this project. The DC/AC conversion process allows for power to be shared as needed in a reliable and redundant way. Challenges arise when synchronizing multiple DC sources connected with AC components to the electric grid. If synchronization of the AC elements does not occur properly, the system’s integrity is lost and the system is at risk of overloading due to high level currents being created by the changes of the AC elements’ voltages. Optimizing the efficiency of the grid-tie inverter also minimizes power loss in the system. Using droop control is essential for synchronization and optimization of the grid-tie inverter systems.

The primary objective of this project was to create and implement a theoretical model of a single three-phase grid-tie inverter control system from a real and reactive power feeding perspective. Also, a controller was designed in order to minimize power loss during the DC/AC conversion process. These theoretical findings are fundamental to the design of a controller for multiple grid-tie inverters. It is important to consider this system on a larger scale, since power can be supplied to an electric grid using various forms of alternative energy resources, such as solar energy (photovoltaics), et cetera, in addition to distributed energy resources. For the purposes of sustainability, the system was designed using solid-oxide fuel cells (SOFC) as the input, since its carbon footprint is much less than those of proton exchange membrane fuel cells (PEMFC). Although it takes approximately 24 hours for the SOFCs to begin running, PEMFCs are relatively reserved for automobiles, making SOFCs a better choice.

Bloom Energy’s hardware links to the microgrid rather than macrogrid. This essentially allows for local power generation versus centralized power generation that occurs in the traditional power grid. In a traditional power grid (macrogrid), power is generated in some kind of power plant (whether it is fueled by fossil fuels, geothermal energy, nuclear energy etc.) and transmitted in one direction to the customers. In contrast, a microgrid is a small, independent power system, typically producing power less than 60 MW that can generate, utilize and/or store power locally. A microgrid must contain both sources (generation) and sinks (loads) under local control and can function either by being connected to the macrogrid or islanded. Power is generated, used, and stored within the microgrid. Power can also be sent back into the macrogrid from a microgrid. There are several benefits to the microgrid over the macrogrid. Microgrids can
provide clean, affordable energy locally and they provide the opportunity to control power quality and reliability (PQR) locally to meet the load requirements of the area being powered.

**Figure 2: Bloom Energy’s Bloom Boxes for Commercial Applications**

The simulation and analysis of the single grid-tie inverter system currently being used by Bloom Energy was simulated through MATLAB/Simulink software. A model of the system was developed to collect data concerning real and reactive power behavior with frequency and power parameters. The model was then tested using different loads and recording changes in power outputted based on load variations.
Related standards and regulation:

Utilities were not designed to accommodate active generation and storage at the distribution level. This resulted in delays in using and integrating distributed power resources with the grid, such as the fuel cells. Several standards have established the requirements for grid-tied distributed energy resources such as fuel cells, The IEEE 2030 and the IEEE 1547 ([21] and [22])

--- IEEE Std 2030 establishes the smart grid interoperability reference model (SGIRM) and addresses terminology, characteristics, functional performance and evaluation criteria, and the application of engineering principles for smart grid interoperability of the electric power system with end-use applications and loads. The IEEE Std 2030 allows for extensibility, scalability, and upgradeability. The IEEE 2030 SGIRM defines three integrated architectural perspectives: power systems, communications technology, and information technology. Also defining design tables and the classification of data flow characteristics necessary for interoperability.

--- The IEEE Std 1547 provides the requirements for operation, testing, safety considerations, and maintenance of interconnecting distributed energy resources. It includes general requirements, response to abnormal conditions, power quality, islanding, and test specifications and requirements for design, production, installation evaluation, commissioning, and periodic tests. The stated requirements include the synchronization of distributed resources (DR), or power inverters/converters, such as the fuel cells, to grid-tied DR. The Energy Policy Act of 2005 established IEEE 1547 as the national standard for the interconnection of distributed generation resources in the USA.
Design & Analysis:

The theoretical model for the project was created using various MATLAB/Simulink simulations, the most important of which, the single grid-tie inverter system. In this project, a model was built that can simulate the effects of load changes on our inverters. The objective is then to develop a controller that uses the feedback from the utility side and from the output of the inverters, to change the simulation characteristics of the inverters, to avoid a loss in transmission. The theoretical basis of the model generated is shown below.

Figure 3: Theoretical basis of Simulations

![Figure 3: Theoretical basis of Simulations](image)

Figure 4: Schematic of the Simulation

![Figure 4: Schematic of the Simulation](image)
For the purposes of this project, a solid oxide fuel cell (SOFC) Simulink model has been used to generate the DC input. These act as the Bloom Box in the simulation and operate the same way as Bloom Boxes do. Solid oxide fuel cells are devices that produce energy based off of oxidizing the fuel from the cells equipped. The SOFCs are an efficient use of power generation, as they have a low cost and are considered clean energy. The fuel cells to the left of the simulation in Figure 4 serve as the DC input (5 kW each, 8 stack resulting in 40 kW input). The power from these fuel cells enters the 12 DC/DC converters in parallel, from which the output enters the pulse-width modulated (PWM) IGBT inverters.

The inverters complete the DC/AC conversion process, after which the AC output is fed into the utilities and measured at the 12.5 kW load (to the right). Real and reactive power (P and Q respectively) are measured and compared to the inputted DC value and then, measured at the load.

\[
P = \frac{E^2 \cos \phi_e - EV \cos (\phi_e - \phi_v + \phi_z)}{Z} \quad P = \frac{EV \sin (\phi_e - \phi_v)}{X} \quad P = \frac{EV \delta}{X}
\]

\[
Q = \frac{E^2 \sin \phi_e - EV \sin (\phi_e - \phi_v + \phi_z)}{Z} \quad Q = \frac{E^2 - EV \cos (\phi_e - \phi_v)}{X} \quad Q = \frac{E(E-V)}{X}
\]

The controller is designed to minimize power losses caused by changes in load. In the model, the control system is an open loop feedback system, where the controller is a three-arm bridge, which has six pulses with a 4860 Hertz frequency. Outputs of the real and reactive power at the load are visually depicted below:
Figure 5: Real Power

![Real Power Graph](image1)

Figure 6: Reactive Power

![Reactive Power Graph](image2)
Figure 7 shows the Simulink diagram of the controller implemented. The graphs below the Simulink diagram in Figure 8 show voltage, current, and real and reactive power as outputted when the controller is implemented. The appendix shows the Matlab code corresponding to the voltage, current and power representations shown in Figure 7. Real and reactive power measurements indicate that the output stabilizes after a certain amount of time. This is most likely due to the fact that the controller is stabilized in this system.

**Figure 7: Simulation Schematic of the Controller**
Figure 8: Output Data of the Controller

(a)

(b)
Controller Design Principles:

State Space Representation:

The internal state of the inverter system can be determined by the use of state equations. The state space is made up of the vector space which contains the various possibilities for internal states of the system. In order for a system to be able to utilize state-space equations, it is necessary for the system to be lumped. The system in this model, the system is lumped, which means that the state and output equations satisfy the superposition principle, and the state space is linear. The state of a system is determined by the values of the elements of the system and how they change on their own. In other words it demonstrates, how the elements of the system behaved before the droop control method was used.

The general form of state space representation for a system with p inputs, q outputs and n state variables is shown below:

\[ \dot{x}(t) = A(t)x(t) + B(t)u(t) \]
\[ y(t) = C(t)x(t) + D(t)u(t) \]

In this representation, \( x(t) \) is the state vector, \( y(t) \) is the output vector, \( u(t) \) is the control, or input vector, \( A \) is the system matrix with dimensions \( n \times n \), \( B \) is in the input matrix with dimensions \( n \times p \), \( C \) is the output matrix with dimensions \( q \times n \) and \( D \) is the feed through matrix with dimensions \( q \times p \). The first equation above is to determine derivative of state vector \( x(t) \) with respect to time, or the change in state vector \( x(t) \).

For this project, state space with a feedback loop was implemented. This can be modeled as follows:

Figure 9: Theoretical basis of state space model with feedback
In the above diagram, the output is multiplied by a matrix $K$ and this product is set as the input to the system:

$$u(t) = Ky(t).$$

The state space equations earlier described then get changed to the following, by substituting the above value for vector $u(t)$:

$$\dot{x}(t) = Ax(t) + BKy(t)$$
$$y(t) = Cx(t) + DKy(t)$$

State space representation was heavily implemented in the design of the control of this project. State space representation shows the state of the system at hand, and this is crucial to know before implementing DQ transformations to develop a controller for the system.
DQ Transformations:

The control of the single three-phase inverter system was derived using DQ transformations. DQ transformations were used in this project to rotate the reference frame of the three-phase inverter systems to simplify the calculations done to eventually model the controller. DQ transformation is a transformation of coordinates from the three-phase stationary coordinate system to the DQ rotating coordinate system. First, a transformation from the three-phase stationary coordinate system to the two-phase AB stationary coordinate system is made. Next, the AB stationary coordinate system values are transformed to the rotating DQ coordinate system.

A vector can be represented in any n-dimensional space by multiplying the transpose n-dimensional base vector by its normalized unit vector. In the normalized unit vector, the elements are the corresponding projections of the base vector on each axis of the n-dimensional coordinate system, normalized by their unit values. In three-phase space, it can be shown as follows:

\[
\mathbf{x}_{abc} = \begin{bmatrix}
\alpha_u & b_u & c_u \\
\end{bmatrix}
\begin{bmatrix}
x_a \\
x_b \\
x_c
\end{bmatrix}
\]

For a balanced three-phase system, the DQ transform can be performed by multiplying vector \(\mathbf{x}_{abc}\) with matrix \(T\), where \(T\) is defined to be:

\[
T = \frac{2}{3}
\begin{bmatrix}
cos(\omega t) & cos(\omega t - \frac{2}{3} \pi) & cos(\omega t + \frac{2}{3} \pi) \\
-sin(\omega t) & -sin(\omega t - \frac{2}{3} \pi) & -sin(\omega t + \frac{2}{3} \pi)
\end{bmatrix}
\]

Performing the multiplication \(\mathbf{x}_{dq} = T\mathbf{x}_{abc}\) results in the coordinates being transformed from the three-dimensional space to the two-dimensional DQ reference system, where the coordinates take the form:
\[ X_{dq} = \begin{bmatrix} X_d \\ X_q \end{bmatrix} \]

This transform was used in the design of the controller for our inverter system in order to simplify the three-phase element calculations. Then, the inverse calculations were performed to return back the \( X_{abc} \) vector values (in three-dimensional space) using the inverse matrix of \( T \), defined as:

\[
T' = \begin{bmatrix}
\cos(\omega t) & -\sin(\omega t) \\
\cos(\omega t - \frac{2\pi}{3}) & -\sin(\omega t - \frac{2\pi}{3}) \\
\cos(\omega t + \frac{2\pi}{3}) & -\sin(\omega t + \frac{2\pi}{3})
\end{bmatrix}
\]

This was used to calculate the vector \( X_{abc} \), using the equation:

\[ X_{abc} = T' X_{dq} \]

The DQ coordinate system is only used to simplify calculations in design of the controller. The controller specifications themselves must be represented in three-dimensional coordinates, which are in turn representative of the phases of the three-phase inverter systems. For this reason, the transform using the inverse \( T \) matrix is a crucial step.

The controller’s design relied heavily upon DQ transforms. Implementing the DQ mathematical transform, the control system is designed to be an open loop feedback system, where the controller is a three-arm bridge, which has six pulses with a 4860 Hertz frequency. A schematic of the system, including where DQ transforms would be performed, is shown below:

**Figure 10: Control topology for grid connection of an inverter system**
**Droop Control:**

The droop control method distributes power efficiently between inverters without external communication. It uses only local power to detect changes and adjust the operating points in the system accordingly. Inverters are connected in parallel to provide system redundancy and high reliability for high power and/or low cost applications. The main problem with inverters connected in parallel involves the load sharing. When there is an increase in a load, this slows down the frequency. This is due to unshared reactive power and constant changes in the voltage amplitude. The droop control method effectively limits the deviations in frequency, and the voltage amplitude is regulated within a certain margin. This allows real and reactive power to be shared equally.

Figure 11: Microgrid: Voltage and frequency regulation by imposing appropriate level of active and reactive power

Droop control is heavily influenced by real and reactive power. The reactive power of the system impacts the difference in voltage, whereas active power can affect the power angle. These parameters form a relation for the power angle of the line. Active and reactive power can be adjusted and corrected accordingly so as to vary the voltage and frequency of the system. In the frequency droop characteristic, as frequency decreases, it is evident that there is more need for active power. This increase in active power will compensate for the decrease in frequency, which allows the system to reach its steady state.

This concept allows for multiple generators to be tied to the grid with reliable and uniform load sharing. Similarly, in the voltage droop characteristic, as voltage decreases, reactive power must increase to make up for the loss. A droop control calculates a reference voltage. It compares this operating point with the current operating conditions to create an error signal. This
error signal is then used by the controller to adjust the PWM signal for driving a full-bridge inverter.

There are some limitations when utilizing the droop control method that concerns the frequency variation with the normal load changes being higher than the grid frequency variation. One of the concepts used to avoid this issue is to use low droop coefficients, but this may end up resulting in inaccurate power sharing as well as slow system response. On the other hand, with high values of droop gains, the system can tend to be unstable.

Droop control will make the Bloom Boxes more easily controllable and make their systems more redundant. The power dissipated by the Bloom Boxes can be varied automatically as the load varies dynamically. Likewise, if multiple generators are arranged in parallel and one was to stop functioning, the rest of the generators will compensate for this loss and automatically ensure that the desired amount of power is still generated. The droop control method helps oversee the smooth and dependable operation of generators tied to the grid as it eliminates the concern for power loss.
Cost, Budget & Sustainability Analysis:

The costs incurred in the scope of the project were minimal, seeing how the retrofit of the Bloom Box is very low as there is in practice, no changes made to the hardware in this project, but to the control algorithm. For this reason, the main expenses were of the simulation software and research material. These expenses are listed below:

<table>
<thead>
<tr>
<th>Item</th>
<th>Purpose</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Matlab software from Mathworks (Education version)</td>
<td>To simulate the theoretical model derived in the scope of this project and generate visual depictions of controller output for current, voltage, and real/ reactive power</td>
<td>$500.00</td>
</tr>
<tr>
<td>Simulink library with Matlab software (Education version)</td>
<td>To simulate the theoretical inverter system and controller model derived in the scope of this project</td>
<td>$500.00</td>
</tr>
<tr>
<td>“Modeling and Control of Fuel Cells” by M. Hashem Hehrir and Caisheng Wang-research material</td>
<td>To understand fundamentals needed to derive a theoretical model, which was then implemented in Matlab and Simulink</td>
<td>$96.40</td>
</tr>
</tbody>
</table>

Due to the nature of the work performed for this project, there were significantly less expenses. The fact that the group did not get to implement this theoretical model on actual hardware resulted not having any kind of cost associated with hardware. Furthermore, the fact that Matlab and Simulink are provided in Rutgers University’s facilities resulted in not having to spend money from the budget on these either. If and when the theoretical modeling developed for the scope of this project is implemented with Bloom Energy’s physical hardware, the following cost sustainability analysis applies:

The Bloom Box is comprised of many fuel cells stacked in parallel. One single cell is made of 100 x 100 mm metal alloy plates between two ceramic layers, which results in the production of 25 watts. These ceramic plates are made of scandia stabilized zirconia, otherwise known as “beach sand.” The ceramic plates are covered with green nickel oxide-based ink on one side which acts as an anode and Lanthanum strontium manganite ink on the other side as a cathode. In order to save money, Bloom Energy has implemented inexpensive metal alloy plates to receive electric conduction in between plates. Since solid oxide fuel cells usually run at a
temperature between 500 to 1000 degrees Celsius, it is necessary to use platinum as the cathode, in order to lower the temperature.

With all of these different products used in order to create a Bloom Box Server, a 100 kW server has a price range of $700,000 to $800,000. In the future, Bloom Energy hopes to produce a smaller scale model for residential homes, running at 1 kW for $3,000, leading to a capital cost $7 to $8 per watt. According to CEO K.R. Sridhar, the servers are creating natural gas electricity at $0.08 to $0.10 per kWh, which is a reduced cost compared to the price of electricity in California. Large corporate campuses such as Google, eBay, Staples, Wal-Mart, FedEx, The Coca-Cola Company, and Bank of America have purchased Bloom Box Servers in order to save costs on electricity. With eBay having 15% of their power produced from the servers, the company can expect a three-year payback time. The ultimate goal of Bloom Energy is to have their servers installed in third world countries. Although these servers are quite expensive at the time, the amount of money saved in the long run makes the concept of Bloom Boxes appealing.
Conclusion

The project is successful in clearly defining a grid-tie inverter system model and relationships for the parameters specified by Bloom Energy in it. In the future, this theoretical control system model can be implemented physically, using hardware provided by Bloom Energy. Also, the relationships discovered in this theoretical modeling process can be used to create a model for multiple grid-tie inverter systems with inverters in parallel on a single output using the droop control structure. The goal of this would be to make the DC/AC conversion more cost effective and energy efficient. These factors are important for the long term development of microgrid control structures and on-site power generation units in their entirety. By having a further understanding of the behavior of the two independent stand-alone inverters working in parallel on a single output would aid in the long term development of the microgrid control infrastructure. The control of this future inverter system will be able to measure the first two inverters individually in order to receive the total power requirements of the load and hold the proper output voltage.

The equations below show how the real and reactive powers are added up easily when placed in parallel for the output power, even if they are not of the same value.

\[ P = P_1 + P_2 \]
\[ Q = Q_1 + Q_2 \]

Below, the \( P \) and \( Q \) values represent the attempted active and reactive powers, while \( \omega \) is the frequency and \( E \) acts as the magnitude of converter output voltage. Finally, \( m \) and \( n \) are the droop coefficients.

\[ \omega = \omega^i - m(P^i - P^j) \]
\[ E = E^i - n(Q^i - Q^j) \]

With all of these equations, two independent stand-alone inverters can be placed in parallel in order to result in a single output.

This project has taught the group extensive knowledge on the process of sending power to the microgrid. However, there were many challenges encountered throughout the completion of the project. Due to time constraints, a theoretical model was created without a hardware implementation that represents the findings. If provided more time to devote to this project, the
findings could be demonstrated using a physical model of Bloom Energy’s hardware, where DC/AC conversion tests could be completed. Fortunately, this hardware will be utilized for future research and use within a Microgrid Lab being developed by Dr. Hana Godrich. A picture of it can be seen below:

Figure 12: Bloom Box Internal Hardware

The theoretical model developed in the scope of this project is an exemplar for research and educational purposes, in which the knowledge gained from this project will become the fundamentals for a new area of study within the Electrical and Computer Engineering department. Specifically, the single inverter system that was developed and modeled in the scope of this project can be applied to developing a multiple inverter system in parallel by using a droop control system. The single inverter system will provide a foundation for this new system. The findings from this project can help foster more breakthroughs and innovative solutions in the areas of power electronics, electrical energy conversion, and control system design while also
allowing for growth within the Electrical and Computer Engineering department at Rutgers University.
Appendix

% Vdcdc

x = length(Vdcdc);
y = 1:1:x;
figure(1);
subplot(2,2,1);
plot(y,Vdcdc);
title('Voltage Output DC to DC converter');
xlabel('Time');
ylabel('Voltage');

% Idc

x10 = length(Idc);
y10 = 1:1:x10;
figure(1);
subplot(2,2,2);
plot(y10,Idc);
title('Current Output from Dc to Dc converter');
xlabel('Time');
ylabel('Amps');

% % Vfc

x1 = length(Vfc);
y1 = 1:1:x1;
figure(1);
subplot(2,2,3);
plot(y1,Vfc);
title('Voltage Output Fuel Cells');
xlabel('Time');
ylabel('Voltage');

% IFC

x9 = length(IFC);
y9 = 1:1:x9;
figure(1);
subplot(2,2,4);
plot(y9,IFC);
title('Current Output from Fuel Cells');
xlabel('Time');
ylabel('Amps');

% P

x2 = length(P);
y2 = 1:1:x2;
figure(2);
subplot(2,2,1);
plot(y2,P);
title('Real Power Under Load')
xlabel('Time');
ylabel('Watts');

% Q
x3 = length(Q);
y3 = 1:1:x3;
figure(2);
subplot(2,2,2);
plot(y3,Q);
title('Reactive Power Under load')
xlabel('Time');
ylabel('VAR');

% Udq
x4 = length(Udq);
y4 = 1:1:x4;
figure(3);
subplot(2,2,1);
plot(y4,Udq);
title('Voltage DQ transform Control')
xlabel('Time');

% Idq
x11 = length(Idq);
y11 = 1:1:x11;
figure(3);
subplot(2,2,2);
plot(y11,Idq);
title('Current DQ transform Control')
xlabel('Time');

% Vctrl_out
x6 = length(Vctrl_out);
y6 = 1:1:x6;
figure(3);
subplot(2,2,3);
plot(y6,Vctrl_out);
title('Voltage Control Output')
xlabel('Time');
ylabel('Voltage');

% Ictrl_out
x13 = length(Ictrl_out);
y13 = 1:1:x13;
figure(3);
subplot(2,2,4);
plot(y13,Ictrl_out);
title('Current Control Output')
xlabel('Time');
ylabel('Amps');

%Vinv
x5 = length(Vinv);
y5 = 1:1:x5;
figure(4);
subplot(2,2,1);
plot(y5,Vinv);
title('Voltage Output from Inverters')
xlabel('Time');
ylabel('Voltage');

%Iinv
x8 = length(Iinv);
y8 = 1:1:x8;
figure(4);
subplot(2,2,2);
plot(y8,Iinv);
title('Current Output from Inverters')
xlabel('Time');
ylabel('Amps');

%mIndex
x7 = length(mIndex);
y7 = 1:1:x7;
figure(4);
subplot(2,2,3);
plot(y7,mIndex);
title('Control m index')
xlabel('Time');
References


[21] IEEE 1547 standard for interconnecting distributed resources with electric power systems
