MODELING AND CONTROL OF FUEL CELL BASED DISTRIBUTED GENERATION SYSTEMS

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the
Graduate School of The Ohio State University

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* * * * *

The Ohio State University
2005

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ABSTRACT

This dissertation presents circuit models and control algorithms of fuel cell based distributed generation systems (DGS) for two DGS topologies. In the first topology, each DGS unit utilizes a battery in parallel to the fuel cell in a standalone AC power plant and a grid-interconnection. In the second topology, a Z-source converter, which employs both the L and C passive components and shoot-through zero vectors instead of the conventional DC/DC boost power converter in order to step up the DC-link voltage, is adopted for a standalone AC power supply.

In Topology 1, two applications are studied: a standalone power generation (Single DGS Unit and Two DGS Units) and a grid-interconnection. First, dynamic model of the fuel cell is given based on electrochemical process. Second, two full-bridge DC to DC converters are adopted and their controllers are designed: an unidirectional full-bridge DC to DC boost converter for the fuel cell and a bidirectional full-bridge DC to DC buck/boost converter for the battery. Third, for a three-phase DC to AC inverter without or with a Δ/Y transformer, a discrete-time state space circuit model is given and two discrete-time feedback controllers are designed: voltage controller in the outer loop and current controller in the inner loop. And last, for load sharing of two DGS units and power flow control of two DGS units or the DGS connected to the grid, real and reactive power controllers are proposed. Particularly, for the grid-connected DGS application, a
synchronization issue between an islanding mode and a paralleling mode to the grid is investigated, and two case studies are performed. To demonstrate the proposed circuit models and control strategies, simulation test-beds using Matlab/Simulink are constructed for each configuration of the fuel cell based DGS with a three-phase AC 120 V (L-N)/60 Hz/50 kVA and various simulation results are presented.

In Topology 2, this dissertation presents system modeling, modified space vector PWM implementation (MSVPWM) and design of a closed-loop controller of the Z-source converter which utilizes L and C components and shoot-through zero vectors for the standalone AC power generation. The fuel cell system is modeled by an electrical R-C circuit in order to include slow dynamics of the fuel cells and a voltage-current characteristic of a cell is also considered. A discrete-time state space model is derived to implement digital control and a space vector pulse-width modulation (SVPWM) technique is modified to realize the shoot-through zero vectors that boost the DC-link voltage. Also, three discrete-time feedback controllers are designed: a discrete-time optimal voltage controller, a discrete-time sliding mode current controller, and a discrete-time PI DC-link voltage controller. Furthermore, an asymptotic observer is used to reduce the number of sensors and enhance the reliability of the system. To demonstrate the analyzed circuit model and proposed control strategy, various simulation results using Matlab/Simulink are presented under both light/heavy loads and linear/nonlinear loads for a three-phase AC 208 V (L-L)/60 Hz/10 kVA.
Dedicated to my family and my friends
I wish to thank Prof. Ali Keyhani for providing academic guidance and an opportunity to perform this research work at Mechatronics Systems Laboratory, Department of Electrical and Computer Engineering, the Ohio State University. Without his commitment and encouragement, this dissertation would not have been possible. He has helped me to concentrate all my efforts on this work and encouraged me to have the confidence in my field of study.

I thank Prof. Donald G. Kasten and Prof. Vadim I. Utkin for being on my committee and providing valuable discussion for me.

I would like to acknowledge Dr. Mohammad N. Marwali who offered the enthusiastic help during the development of the control systems.

I also wish to thank from the bottom of my heart to Mrs. Julie Mercer and Mr. Jeff Mercer who are the best American friends and have given sincere help to acclimate my family to a new environment in America.

I should express the deepest and warmest gratitude to my parents and my parents-in-law, my wonderful lovely wife (Gum-Ja Kang) and two sons (Sung-Hoon Jung and Nick Jung) for their great sacrifices during my study at the Ohio State University.
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(Control of distributed generation systems, fuel cell systems, and UPS systems, electric machines, AC motor drives, power converters, and control)
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CHAPTER 1

INTRODUCTION

1.1 Distributed Generation Systems Background

Today, new advances in power generation technologies and new environmental regulations encourage a significant increase of distributed generation resources around the world. Distributed generation systems (DGS) have mainly been used as a standby power source for critical businesses. For example, most hospitals and office buildings had stand-by diesel generators as an emergency power source for use only during outages. However, the diesel generators were not inherently cost-effective, and produce noise and exhaust that would be objectionable on anything except for an emergency basis. On the other hand, environmental-friendly distributed generation systems such as fuel cells, micro turbines, biomass, wind turbines, hydro turbines or photovoltaic arrays can be a solution to meet both the increasing demand of electric power and environmental regulations due to greenhouse gas emission [1]-[54].

Figures 1.1 and 1.2 show future trends of electric utility industry and operating system for the DGS connected to an AC grid, respectively. As illustrated in these figures, the currently competitive DGS units will be constructed on a conventional distribution
network, instead of large central power plants because the DGS can offer improved service reliability, better economics and a reduced dependence on the local utility.

![Central Power Plants vs Distributed Generation Systems](image)

**Figure 1.1: A large central power plant and distributed generation systems**

Recently, the use of distributed generation systems under the 500 kW level is rapidly increasing due to technology improvements in small generators, power electronics, and energy storage devices. Efficient clean fossil-fuels technologies such as micro-turbines, fuel cells, and environmental-friendly renewable energy technologies such as biomass, solar/photovoltaic arrays, small wind turbines and hydro turbines, are growingly used for new distributed generation systems. These DGS are applied to a standalone [2], [4], [16], [17], [21], a grid-interconnected [3]-[6], [17], [24], [26], [41]-[45], a standby [7], [14], peak shavings [7], a cogeneration [12]-[14], etc. and have a lot of benefits such as environmental-friendly and modular electric generation, increased
reliability/stability, high power quality, load management, fuel flexibility, uninterruptible service, cost savings, on-site generation, expandability, etc.

Figure 1.2: Operating system for DGS

The major distributed generation technologies that will be discussed in this chapter are as follows: micro-turbines, fuel cells, wind turbines, solar/photovoltaic systems, and energy storage devices. Other distributed energy technologies are combustion/diesel engines. However, these technologies will not be explained due to high emissions, high operation and maintenance costs. Therefore, emerging and renewable generation technologies are described in detail in the following.
1. **Micro-turbines**, especially the small gas-fired micro-turbines in the 25-500 kW that can be mass-produced at low cost have been more attractive due to the competitive price of natural gas, low installation and maintenance costs. It takes very clever engineering and use of innovative design (e.g. air bearing, recuperation) to achieve reasonable efficiency and costs in machines of lower output. A big advantage of these systems is small-sized because these technologies mainly use high-speed turbines (50,000-120,000 RPM) with air foil bearings. Therefore, micro-turbines are one of the most promising of the DGS technologies for applications today [9], [11]-[13], [15]-[17]. Figure 1.3 shows a block diagram of micro-turbine system that consists of air compressor, recuperator, combustor, turbine, generator, and a PCU (Power Conditioning Unit) and its features are summarized below.

Figure 1.3: Block diagram of micro-turbine system
Features:

- Size: 25 – 500 kW
- Efficiency: unrecuperated (15%), recuperated (20 – 30%), with heat recovery (up to 85%)
- Installed cost ($/kW): 1,200 – 1,700
- O&M cost ($/kWh): 0.005 – 0.016
- Fuel: natural gas, hydrogen, biogas, propane, diesel
- Emission: below approximately 9 - 50 ppm NOx
- Cogeneration: yes (50 – 80°C water)
- Commercial Status: small volume production, commercial prototypes now
- Rotating speed (RPM): 50,000 – 120,000
- Maintenance interval: 5,000 – 8,000 hrs

Advantages:

- Small number of moving parts
- Compact size
- Light-weight
- Good efficiencies in cogeneration
- Low emissions
- Can utilize waste fuels
- Long maintenance intervals

Disadvantages:

- Low fuel to electricity efficiencies
- Loss of power output and efficiency with higher ambient temperatures
Future Research Issues:

- Improve the micro-turbine design
- Lowering costs
- Increasing performance
- Heat recovery/cogeneration
- Fuel flexibility
- Vehicles
- Hybrid systems (e.g., fuel cell/micro-turbine, flywheel/micro-turbine)


2. **Fuel cells** are also well used for distributed generation applications, and can essentially be described as batteries which never become discharged as long as hydrogen and oxygen are continuously provided. The hydrogen can be supplied directly, or indirectly produced by reformer from fuels such as natural gas, alcohols, or gasoline. Each unit ranges in size from 1-250 kW or larger MW size. Even if they offer high efficiency and low emissions, today’s costs are high. Phosphoric acid fuel cell is commercially available in the range of the 200 kW, while solid oxide and molten carbonate fuel cells are in a pre-commercial stage of development. The possibility of using gasoline as a fuel for cells has resulted in a major development effort by the automotive companies. The recent research work about the fuel cells is focused towards the polymer electrolyte membrane (PEM) fuel cells. Fuel cells in sizes greater than 200 kW, hold promise beyond 2005, but residential size fuel cells are unlikely to have any significant market impact any time soon [9], [15], [40]-[54]. Figure 1.4 shows a block diagram of fuel cell system which consists of a reformer, fuel
cell stack and a PCU. Also, features of four types of the fuel cells appropriate for distributed generation systems features are summarized below and overview of these types is listed in Tables 1.1 and 1.2.

Figure 1.4: Block diagram of fuel cell system

■ Types (according to electrolyte used):

- Phosphoric Acid Fuel Cell (PAFC)
- Solid Oxide Fuel Cell (SOFC)
- Molten Carbonate Fuel Cell (MCFC)
- Proton Exchange Membrane or Solid Polymer Fuel Cell (PEMFC or SPFC)
- Alkaline Fuel Cell
- Direct Methanol Fuel Cell
- Regenerative Fuel Cell
- Zinc Air Fuel Cell
- Proton Ceramic Fuel Cell
Features:

- Size: 1 kW – 10 MW
- Efficiency: electricity (30 – 60%), cogeneration (80 – 90%)
- Installed cost ($/kW): 1,000 – 5,000
- O&M cost ($/kWh): 0.0019 – 0.0153
- Fuel: natural gas, hydrogen, propane, diesel
- Emission: very low
- Cogeneration: yes (hot water, LP or HP steam)
- Commercial Status:
  - PAFC: commercially available
  - SOFC, MCFC, PEMFC: available in 2004

Applications:

- **PAFC**: medical, industrial, schools, commercial utilities, utility power plants, waste water treatment plants
- **SOFC**: residential cogeneration, small commercial buildings, industrial facilities
- **MCFC**: industrial, government facilities, universities, hospitals
- **PEMFC**:
  - Automotive
  - Residential (< 10kW), both with and without cogeneration
  - Commercial (10 – 250kW), both with and without cogeneration
  - Light industrial (< 250kW), both with and without cogeneration
  - Portable power (< several kW)

Advantages:

- **PAFC**: quiet, low emissions, high efficiency, proven reliability
- **SOFC and MCFC**: quiet, low emissions, high efficiency
- **PEMFC**: quiet, low emissions, high efficiency, synergy with automotive
Disadvantages:

- **PAFC**: high cost
- **SOFC**: high cost, planar SOFCs are still in the R&D stage but recent developments in low temperature operations show promise
- **MCFC**: high cost, need to demonstrate long term dependability
- **PEMFC**: high cost, limited field test experience, low temperature waste heat may limit cogeneration potential

Future Research Issues:

- **PAFC**:
  - Increase anode CO tolerance with operating temperature
  - Simplify reformer design, and increase the lifetime of reformate-fueled stacks
  - Lower the moderate stack temperature to allow rapid start-up and shutdown
  - Increase the temperature difference between the stack and the environment so that thermal and water management functions of the fuel cell system are greatly simplified
  - Decrease the system water requirements and increase the flexibility of operation

- **SOFC**:
  - Cost reduction
  - Identify configurations to require less stringent material purity specifications
  - Identify routes to reduce the amount of insulation in the system
  - Move manufacturing processes towards net-forming rather than machining in order to minimize scrap production
  - Use of less exotic alloys
  - Maintenance of seals and manifolds under severe thermal stresses
  - Long-term mechanical integrity of planar systems
  - Long-term material compatibility of planar systems
- **MCFC:**
  - Extend stack life
  - Increase the power density
  - Reduce the cost

- **PEMFC:**
  - Operate at pressures > 1.5 atm.
  - Guarantee long-term operation
  - Produce 10 – 20 ppm CO in long-term, real-world environments
  - Operation of fully integrated systems in a broad range of thermal environments with adequate water recovery over extended periods
  - Operation of fully integrated systems in environments like freezing temperatures

### Manufacturers:

- **PAFC:** Japan’s Fuji Electric Company, Ltd., UTC Fuel Cells, Mitsubishi Electric Corporation
- **SOFC:** Global Thermoelectric, Siemens Westinghouse Power Corporation, SOFCo, ZTEK Corporation
- **MCFC:** Fuel Cell Energy, Hitachi, Ltd., Ansaldo Ricerche Srl
<table>
<thead>
<tr>
<th>Types</th>
<th>PAFC</th>
<th>SOFC</th>
<th>MCFC</th>
<th>PEMFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>100 – 200kW</td>
<td>1kW–10MW</td>
<td>0.25–10MW</td>
<td>3 – 250kW</td>
</tr>
<tr>
<td>Fuel</td>
<td>Natural gas, landfill gas, digester gas, propane</td>
<td>Natural gas, hydrogen, landfill gas, fuel oil</td>
<td>Natural gas, hydrogen</td>
<td>Natural gas, hydrogen, propane, diesel</td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>400°F</td>
<td>1,800°F</td>
<td>1,200°F</td>
<td>200°F</td>
</tr>
<tr>
<td>Installed Cost ($/kW)</td>
<td>3,000 – 3,500</td>
<td>1,300 – 2,000</td>
<td>800 – 2,000</td>
<td>4,000</td>
</tr>
<tr>
<td>Cooling Medium</td>
<td>Boiling Water</td>
<td>Excess Air</td>
<td>Excess Air</td>
<td>Water</td>
</tr>
<tr>
<td>Environmental – friendly</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Commercially Availability</td>
<td>Yes</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Cogeneration</td>
<td>Yes (hot water)</td>
<td>Yes (hot water, LP or HP steam)</td>
<td>Yes (hot water, LP or HP steam)</td>
<td>Yes (80°C water)</td>
</tr>
<tr>
<td>Efficiency (Electricity)</td>
<td>36– 42%</td>
<td>45 – 60%</td>
<td>45 –55%</td>
<td>30 – 40%</td>
</tr>
<tr>
<td>Efficiency (Cogeneration)</td>
<td>Up to 85%</td>
<td>Up to 85%</td>
<td>Up to 85%</td>
<td>Up to 85%</td>
</tr>
</tbody>
</table>

♦ Source: Distributed Energy Resources (DER)

Table 1.1 Fuel cell overview (1)
<table>
<thead>
<tr>
<th>Types</th>
<th>Peak Power Density (mW/cm³)</th>
<th>System Efficiency (% HHV)</th>
<th>Start-up Time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PAFC</td>
<td>~200</td>
<td>36 - 45</td>
<td>1 - 4</td>
</tr>
<tr>
<td>SOFC (tabular)</td>
<td>150 - 200</td>
<td>43 - 55</td>
<td>5 - 10</td>
</tr>
<tr>
<td>SOFC (planar)</td>
<td>200 - 500</td>
<td>43 - 55</td>
<td>unknown</td>
</tr>
<tr>
<td>MCFC</td>
<td>~160</td>
<td>43 - 55</td>
<td>10+</td>
</tr>
<tr>
<td>PEMFC</td>
<td>~700</td>
<td>32 - 40</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

♦ Source: Distributed Energy Resources (DER)

Table 1.2 Fuel cell overview (2)

3. **Mixed micro-turbine and fuel cell systems** will also be available as a distributed generation source. Recently, a solid oxide fuel cell has been combined with a gas micro-turbine creating a combined cycle power plant. It has expected electrical efficiency of greater than 70 %, and the expected power levels range from 250 kW to 2.5 MW [15], [44].

4. **Wind turbines** to convert wind into electricity are also a good candidate as a clean, renewable technology for a distributed power generation. Wind power has been harnessed for centuries, and today, it is the fastest growing energy source. First of all, the wind power will play a prominent role in meeting the nation’s needs due to much stricter environmental regulations about global warming increase. Electricity capacity is limited by the amount of wind, so the wind plants should be installed in windy areas. It has expected electrical efficiency of 20 - 40 %, and the expected power sizes are in the range of 0.3 kW to 5 MW [22]-[27], [29]. Figure 1.5 illustrates a block diagram of small wind turbine system and its features are summarized below.
Figure 1.5: Block diagram of small wind turbine system

- **Features:**
  - Size: small (0.3 - 50 kW), large (300 kW – 5 MW)
  - Efficiency: 20 – 40%
  - Installed cost ($/kW): large-scale (900 - 1,100), small-scale (2,500 - 5,000)
  - O&M cost ($/kWh): 0.005
  - Fuel: wind
  - Emission: zero
  - Other features: various types and sizes
  - Commercial status: widely available
  - Wind speed: – Large turbine: 6 m/s (13 mph) at average sites
    – Small turbine: 4 m/s (9 mph) at average sites
  - Typical life of a wind turbine: 20 years

- **Advantages:**
  - Power generated from wind farms can be inexpensive
  - Low cost energy
- No harmful emissions
- Minimal land use: the land below each turbine can be used for animal grazing or farming
- No fuel required

**Disadvantages:**
- Variable power output due to the fluctuation in wind speed
- Location limited
- Visual impact: Aesthetic problem of placing them in higher population density areas
- Bird mortality

**Future Research Issues:**
- Lower the cost of energy from wind to 2.5 cents/kWh at sites with 6.7 m/s [15 mph] winds
- Reduce system cost
- Improve efficiency of wind turbine generator
- Improve power quality
- New design of the airfoils for the wind turbine blades


5. **Solar/photovoltaic systems** to transform sunlight into electricity are also a good renewable technology for DGS because sunlight is an abundant resource around the world and solar electric systems are clean, quiet and easy to use, and first of all no fuel other than sunlight is needed. Furthermore, they are durable, reliable, and easy to
maintain because they do not hold any moving parts. Solar cells, also known as photovoltaic (PV) cells, use special materials called semiconductors that produce electricity when exposed to light, and four promising types of solar electric technology are under development: crystalline silicon (a form of refined beach sand), thin films, concentrators, and thermo-photovoltaics. Photovoltaic arrays may be used in a variety of sizes from 0.3 kW to 2 MW. However, installing a large number of systems make this choice undesirable. This becomes apparent when the following factors are considered; 1) high cost of land, 2) poor solar intensity in many geographic areas, and 3) climates lacking reliable sun exposure. In general, almost one acre of land would be needed to provide 150 kW of electricity [15], [28]-[31], [43], [45]. Figure 1.6 describes a block diagram of solar/photovoltaic array system and its features are abstracted in the following.

Figure 1.6: Block diagram of solar/photovoltaic array system
Features:

- Size: 0.3 kW – 2 MW
- Efficiency: 5 – 15%
- Installed cost ($/kW): 6,000 – 10,000
- O&M cost ($/kWh): 0.2
- Fuel: sunlight
- Emission: zero
- Main components: batteries, battery chargers, a backup generator, a controller
- Other features: no moving parts, quiet operation, little maintenance
- Commercial status: commercially deployed, advanced PV films under development
- An individual photovoltaic cell: 1 – 2 watts

- **Crystalline silicon:**
  - Used in more than half of all solar electric devices
  - Consists of a positive (p-type) layer and a negative (n-type) layer
  - Applications: small (watch, calculator), large (satellites, electricity for utilities)

- **Thin films:**
  - Lighter, more resilient, and easier to manufacture than crystalline silicon module
  - Materials used: amorphous silicon (best), cadmium telluride, and copper indium diselenide
  - Cost saving because of relatively little semiconductor materials
  - Flexible solar electric roofing shingles

- **Concentrators:**
  - Need optical lenses or mirrors to concentrate the sunlight
  - Components: a lens, a solar cell assembly, a housing element, a secondary concentrator, various contacts and adhesives
- Materials used: crystalline silicon, gallium arsenide, and gallium indium phosphide
- Cost saving because of using inexpensive semiconductor materials

- **Thermophotovoltaics (TPV)**
  - Convert heat into electricity
  - Advantages: cleaner, quieter, simpler, relatively maintenance free

**Advantages:**
- Work well for remote locations
- Require very little maintenance
- Environmentally friendly (No emissions)

**Disadvantages:**
- Local weather patterns and sun conditions directly affect the potential of photovoltaic system. Some locations with poor solar intensity/climates lacking reliable sun exposure and high cost of land will not be able to use solar power

**Future Research Issues:**
- Use of a concentrator technology to concentrate the solar energy over a large area onto a small area of solar cells
- Increase energy density several hundred times using a Fresnel lens or reflective surface
- Use of more exotic solar cell technology for greater efficiency
- Lower an overall cost/watt competitive with flat plate technologies
- Increase concentrator efficiency to above 30%

**Manufacturers:** AstroPower, Baekert ECD Solar Systems LLC, BP Solar, DayStar Technologies, Inc., Solec international, Inc., Xantrex Technology, Inc.
6. **Energy storage devices** such as batteries, ultra-capacitors (or super-capacitors), flywheels, Superconducting Magnetic Energy Storage (SMES), and Compressed Air Energy Storage (CAES) are one of the most critical technologies for DGS. In general, the electrochemical capacitor has high power density as well as good energy density. In particular, ultra-capacitors have several benefits such as high pulse power capacity, long lifetime, high power density, low ESR (Equivalent Series Resistance), and are very compact in size. In contrast, batteries have higher energy density, but lower power density and a shorter lifetime relative to an ultra-capacitor. A hybrid storage system, combining of ultra-capacitor and battery, is a strong recommendation that satisfies several requirements and will optimize system performance. Recent storage systems are much more efficient, economical, and perform longer than those of just five years ago. In particular, flywheel systems can generate 700 kW for 5 seconds, which outperforms a 28-cell ultra-capacitors once providing up to 12.5 kW for a few seconds [15], [32]-[39], [43]. Features of several types of energy storage devices are outlined as follows.

- **Energy storage technologies:**
  - To provide electric power over short periods of time
  - To improve the efficiency and reliability of the electric utility system
  - To accelerate adoption of renewable energy technologies
  - To correct voltage sags, flicker, and surges
  - To be used as an Uninterruptible Power Supply (UPS)

- **Types of Energy Storage Devices:**
  - Batteries, Flywheels, Ultracapacitor (Supercapacitor), Superconducting Magnetic Energy Storage (SMES), Compressed Air Energy Storage (CAES)
Features:

- **Batteries:**
  - To provide an interruptible supply of electricity to power substation
  - To start backup power systems during power outage
  - To increase power quality and reliability
  - Size: 0.14 – 2,100 kVA
  - Operating time: 5 – 60 minutes
  - Types: lead-acid (commercially available and widely used), sodium/sulfur, zinc/bromine, lithium/air
  - Uninterruptible Power Supply (UPS):
    - Cost of a complete UPS system: $200/kVA - $1,500/kVA
    - Battery cost of the complete UPS system: 60 – 70%
    - Battery replacement frequency: every 5 – 7 years

- **Flywheels:**
  - Electromechanical device: an integral motor/generator provides power for short durations such as a power outage, voltage sag, or other disturbance
  - Size: 120 – 700 kW
  - Operating time: 20 sec – 10 minutes
  - RPM: a few thousand – 60,000
  - Main components: flywheel, inverter, control system
  - Commercial Status: commercially available as individual products or integrated with prime movers such as engine

- **Ultracapacitor (Supercapacitor):**
  - To provide power during short duration interruptions and power sags
  - The life of the batteries can be extended if an ultracapacitor is combined with a battery- based UPS system
  - Commercial Status: • small ultracapacitor (commercially available)
    - large ultracapacitor (under development)
Superconducting Magnetic Energy Storage (SMES):

- To store energy in the field of a large magnetic coil with DC flowing
- To be used for short durations such as utility switching events
- Main components: SMES, inverter, control system
- Commercial Status:
  - low temperature SMES cooled by liquid helium (commercially available)
  - high temperature SMES cooled by liquid nitrogen (under development)

Compressed Air Energy Storage (CAES):

- To use pressurized air as the energy storage medium
- An electric motor-driven compressor and a modified turbine required
- Ideal location for CAES: aquifers, conventional mines in hard rock, hydraulically mined salt caverns
- Not widely utilized because of the significant space requirements

Advantages:

- Improved power quality and reliability (“premium power”)
- “Green power” dispatch/purchase options
- Reduced sizing of distributed generation systems
- Energy/demand cost saving from load leveling
- Decreased transmission and distribution infrastructure investment

Disadvantages:

- High cost for long duration storage system
- Parasite power losses to keep unit charge
- High maintenance (e.g. frequent testing, charge assessment for batteries)
Future Research Issues:

- Lower costs
- Longer life-time
- Higher efficiency

Manufacturers:

- **Flywheels**: Active Power, AFS Trinity, Beacon Power, Pentadyne, Precise Power Systems
- **Superconducting Magnetic Energy Storage (SMES)**: American Superconductor
- **Compressed Air Energy Storage (CAES)**: CAES Development Company LLC
- **Ultracapacitors**: PowerCache (Maxwell Technologies, Inc.), EPRI PEAC

A comparison of currently competitive DGS technologies mentioned above is given in Table 1.3. In the past, the electric utility industry did not offer suitable options that were suited for a wide range of consumer needs, and most utilities offered at best two or three combinations of reliability and price. However, the modern types of DGS give commercial electric consumers various options in a wider range of reliability-price combinations. For these reasons, the DGS will be very likely to thrive in the next 20 years in particular. Distributed generation technologies will have a much greater market potential in areas such as developing countries whose electricity costs are high and unreliable.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Micro-turbines</th>
<th>Fuel Cells</th>
<th>Wind Turbines</th>
<th>Photovoltaic Arrays</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Generated</strong></td>
<td>25 – 500 kW</td>
<td>1 kW – 10 MW</td>
<td>0.3 kW – 5 MW</td>
<td>0.3 kW – 2 MW</td>
</tr>
<tr>
<td><strong>Installed Cost ($/kW)</strong></td>
<td>1,200 – 1,700</td>
<td>1,000 – 5,000</td>
<td>1,000 – 5,000</td>
<td>6,000 – 10,000</td>
</tr>
<tr>
<td><strong>O&amp;M Cost ($/kWh)</strong></td>
<td>0.005 – 0.016</td>
<td>0.0019 – 0.0153</td>
<td>0.005</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Electrical Efficiency</strong></td>
<td>20 – 30%</td>
<td>30 – 60%</td>
<td>20 – 40%</td>
<td>5 – 15%</td>
</tr>
<tr>
<td><strong>Overall Efficiency</strong></td>
<td>80 – 85%</td>
<td>80 – 85%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fuel Type</strong></td>
<td>natural gas, hydrogen, biogas, propane, diesel</td>
<td>hydrogen, natural gas, propane</td>
<td>wind</td>
<td>sunlight</td>
</tr>
</tbody>
</table>

Table 1.3 Comparison of currently competitive DGS technologies

1.2 Major Technical Barriers of DGS

DGS technologies have very different research issues when compared to traditional centralized power sources. For example, they are applied to AC mains or the loads with voltage of 480 or less, and require power converters and different strategies of control and dispatch. All of these energy technologies provide a DC output requiring power electronic interfaces with the distribution power networks and its loads. To convert DC voltage to AC voltage with fixed frequency, the power conversion is performed by using a voltage source inverter (VSI) with a possibility of pulse-width modulation (PWM) that provides fast regulation for voltage magnitude [15].

Power electronic interfaces introduce new control issues, but at the same time, new possibilities. For instance, a system which consists of micro-generators and storage
devices could be designed to operate in both an autonomous mode and a grid-connected mode. One large class of problems is related to the fact that the power sources such as micro-turbines and fuel cell have a slow response and their inertia is much less. It must be remembered that the current power systems have storage in generators’ inertia, and this may result in a slight reduction in system frequency.

As these generators become more compact, the need to link them to lower network voltage is significantly increasing. However, without any medium voltage network adaptation, this fast expansion can affect the quality of supply voltage as well as the public and equipment safety because of side effects such as bidirectional power flows and increased fault current levels. Consequently, these side effects make more difficult the control, protection and maintenance of distribution systems which operate radially on the distribution line or customer side. So a new voltage control system to facilitate the connection of distributed generation resources to the distribution networks should be developed.

In many cases there are also major technical barriers to operating independently in a standalone AC system, or to connecting small generation systems to the conventional distribution networks with lower voltage, and the recent research issues to be solved are summarized as follows:

1. **Control strategy to facilitate the connection of distributed generation resources to distribution networks:** A new control scheme is required to allow more DGS sources to be connected to the distribution networks because the grid-connected DGS can have an effect on the quality of supply voltage, public safety, and equipment safety [3], [6], [18].
2. **Efficient battery control**: The efficient control of the battery for transient backup is very critical to increase the service life of the battery and lower an overall life cycle cost of energy because any errors in control that affect battery efficiency and shorten the lifetime of the batteries have a tremendous influence on total hybrid system costs [8].

3. **Inverter control based on only local information**: The control of inverters used to supply an electric power to an AC system in a distributed environment should be based on information available locally at the respective inverter because, in a system with many micro-sources, communication of information between inverter systems is impractical due to these generators being located at various distances in the distribution system. Essentially this implies that the inverter control should be based on terminal quantities [4], [15], [55]-[60].

4. **Synchronization with the utility mains**: DGS should permit each unit to synchronize with the utility grid. That is, the power generated by DGS is either generated as DC power (solar/photovoltaics and fuel cells) or AC power (small wind, micro-turbines, and micro-hydro turbines). In the case of AC power, it is again converted to DC power which is fed to the DC bus. Then the outputs of the DC power bus should be converted to AC power with the same magnitude, frequency, and phase as utility grid with the fixed voltage and frequency so that an extra power is fed back to the mains [3]-[6], [17], [24], [26], [41]-[45].
5. Compensation of the reactive power and higher harmonic components: The converter connected in parallel to AC mains can serve also as a source of reactive power and higher harmonic current components. That is, the converter system can produce not only active power but it can provide also reactive power and higher harmonic current components continuously. As a result, because this system can make a power factor of utility mains so poor, a technique which can compensate for the reactive power and higher harmonic content is required [18], [21], [55]-[60].

6. Power factor correction: In an industrial environment many loads have a poor power factor and high harmonic content of the load current. So power converters have to play a role in improving a power factor, reducing harmonic components, and functioning as a complete active filter [17].

7. System protection and safety measures: DGS need unique internal protections. The protection requirements for DGS are different compared with traditional utility considerations both at the grid interface and internally. While traditional protection schemes may be adequate at the interface, a different set of considerations may govern the internal protection to the microgrid which is highly dependent upon the short circuit currents provided by the micro-sources and power grid. For example, the micro-source can be rapidly isolated from the microgrid followed by a long restoration process. With storage on the DC bus the inverter can control the short circuit current without shutting down the microgrid while the fault is cleared. Depending on the load and generation level, and local connection conditions, the generator can provoke serious overvoltages and
undervoltages to other customers connected to the same main feeder. So these control systems have to include the protections capable of preventing system failures by overcurrent, overvoltage, and undervoltage [2]-[4], [7].

8. **Load sharing**: It is difficult for each generation unit to share loads uniformly according to its size over wide conditions. So each unit should operate in an autonomous power system and control real power (P), reactive power (Q) independently. Moreover, it should enable paralleled inverters to share linear or even nonlinear loads uniformly according to their capacities without additional interconnections, including the real power sharing, reactive power sharing, and harmonic power sharing [2], [4], [21], [55]-[60].

9. **Reliability of communication**: DGS need reliable communications for an efficient system control. That is, these generation systems were to be operated based on a communication signal between each generator and Supervisory Control Unit, and between Supervisory Control Unit and Distributed Control Center in order for DGS to decide the modes (a standalone mode or a grid-interconnection mode) or for Supervisory Control Unit to control power capacity assigned to each generator. So DGS require some means of remote monitoring and control: a RS-232 port, a local area network (LAN), or radio link. Although the radio link had reportedly been used previously for fault isolation schemes, there were still concerns about the reliability of the radio link for not working properly due to miscommunication [2], [7]-[8], [15].
10. Requirements of the customer: In the past, the electric companies did not offer various options that were suited for a wide range of consumer needs. However, the types of modern DGS can give commercial electric consumers various options in a wider range of reliability-price combinations. Therefore, the DGS should appear as an autonomous power system which meets the requirements of the customer. In addition, voltage, reliability performance, and quality of power should be those that support the customers’ objectives [7], [9], [15], [19].

As mentioned above, the DGS offer significant research and engineering challenges. Moreover, the electrical and economic relationships between customers and the distribution utility and among customers may take forms quite distinct from those we know today. For example, rather than devices being individually interconnected in parallel with the grid, they may be grouped with loads in a semi-autonomous neighborhood that could be termed a microgrid is a cluster of small sources, storage systems, and loads which presents itself to the grid as a legitimate single entity. Thus, future research work will focus on solving the above issues so that the DGS with more advantages compared with traditional large power plants can thrive in electric power industry.

1.3 Research Focus

As described in the previous sections, distributed generation systems (DGS) such as fuel cells, wind turbines, hydro turbines or photovoltaic cells will be increasingly
prosperous for power generation plants because larger central power plants are economically unfeasible in many regions due to diminishing fossil fuels, increasing fuel costs, and stricter environmental regulations about acid deposition and greenhouse gas emission [1]-[54]. As explained in Section 1.2, most DGS should be interfaced with Power Electronic systems such as DC to DC or/and DC to AC power converters to obtain a sinusoidal AC output voltage with fixed frequency from variable or high-frequency AC voltage sources or DC voltage sources. Notable progresses of Power Electronics technologies and energy storage devices for transient backup have accelerated penetration of DGS into electric power generation plants.

Among various DGS resources stated above, the fuel cells will be taken into account as an energy source of DGS in this dissertation. The fuel cells are electrochemical devices which convert chemical energy directly into electric energy by reaction of hydrogen from fuels and oxygen from air without regard to climate conditions or geographic regions, unlike hydro or wind turbines and photovoltaic arrays [40]-[54]. The fuel cells also produce water, and heat by combining hydrogen with oxygen, and have 36 – 60 % electricity efficiencies according to their types but could reach 85 % in the case of combined heat and power (CHP). Thus, the fuel cells are a safe, clean and efficient DC power source, and are one of the most attractive DGS resources for power delivery. However, in most cases, batteries or flywheels need to be placed in parallel or series with the fuel cell as a temporary energy storage element to support startup or sudden load changes because the fuel cells can not immediately respond to such abrupt load changes.
For practical realization of the fuel cell powered systems, slow dynamics of the fuel cells should be considered. Based on complicated physical and chemical processes, mathematical dynamic models of the fuel cells have been presented for design of fuel cells [61]-[67]. For a simplified dynamic analysis, a second order model [68] or a first order time delay circuit [69] has been used. However, most of papers have not addressed in detail power converter design and control. For residential applications, design and control of DC to DC boost converters and DC to AC inverters have been investigated to design low-cost and small-sized power converters [51]-[54], yet the fuel cells have been modeled by a DC voltage source and only single-phase inverters are considered. A unidirectional isolated full-bridge DC to DC power converter can be used to boost low fuel cell voltage [70]-[77]. In addition, a bidirectional full-bridge DC to DC power converter can be used for stepping up low battery voltage or stepping down high voltage side DC bus tank according to battery discharge or recharge mode [78]-[79].

Furthermore, techniques to produce a sinusoidal AC output voltage with low total harmonic distortion (THD) in a three-phase pulse-width modulation (PWM) inverter have been proposed [80]-[83]. Particularly, even if real-time deadbeat controllers [80]-[82] have low THD for linear load and a fast transient response for load disturbances, it is known that they are sensitive to parametric variations and model uncertainties as well as these techniques have a high THD under nonlinear load. On the other hand, discrete-time optimal voltage/current controllers in a rotating reference frame have been proposed for UPS applications of three-phase PWM inverter [83]. However, it does not consider a nonlinear load. Thus, a new controller is needed for the good performance such as nearly zero steady state inverter output voltage error, low THD, good voltage regulation,
robustness, fast transient response, and protection of the inverter against overload under linear/nonlinear loads.

For a parallel operation of multiple UPS systems, the advantage of the droop method [21], [55]-[60], is that it does not require communication signals among units in parallel, thereby increasing the reliability of the system. However, because of the droop characteristics, the frequency and voltage of the system drop to such a value that all units operate in a new lower frequency and smaller or bigger voltage than the nominal values. Also as in the average power method, the method only works well for linear loads, but it does not help to share the harmonics components caused by non-linear loads. Another drawback of this method is the lack of robustness toward the wiring impedance mismatch, and the differences in the wiring impedance can significantly affect the power sharing. This is due to the lack of closed loop control of the power sharing method.

In [84]-[85], a Z-source converter that can boost a DC-link voltage by employing L-C impedance components and a shoot-through without any boost converter is proposed and shows its operation under only a dynamic load, a linear/heavy load and an open-loop control without considering the dynamics of the fuel cell system.

This dissertation presents circuit models and control algorithms of fuel cell based distributed generation systems (DGS) for two DGS topologies. For the first topology, each DGS unit puts battery in parallel to the fuel cell in a standalone AC power supply and a grid-interconnection. For the second topology, a Z-source converter, which employs both L and C passive components and shoot-through zero vectors instead of the conventional DC/DC boost power converter in order to step up the DC-link voltage, is adopted for the standalone AC power supply.
In the first topology, two applications are studied: a standalone AC power supply (Single DGS Unit and Two DGS Units) and a grid-interconnection. First, dynamic model of the fuel cell is given based on electrochemical process. Second, two full-bridge DC to DC converters are adopted and their controllers are designed: a unidirectional full-bridge DC to DC boost converter for the fuel cell and a bidirectional full-bridge DC to DC boost/buck converter for the battery. Third, for a three-phase DC to AC inverter without (a single DGS unit) or with a ∆/Y transformer (two DGS units and a grid-connected DGS), a discrete-time state space circuit model is given. Two discrete-time sliding mode controllers (DSMC) are designed for a standalone single DGS unit and a grid-connected DGS: the inner loop is used for current control while the outer one is for voltage control. On the other hand, two discrete-time feedback controllers are designed for two DGS units in standalone operation: a discrete-time sliding mode controller for current control and a discrete-time optimal controller for voltage control. Last, for load sharing of two standalone DGS units and power flow control of two DGS units in standalone or the DGS connected to the grid, real and reactive power controllers are proposed.

 Particularly, for a parallel operation of two DGS units in the standalone AC power plant, proper power sharing of each DGS unit such as the real power, reactive power, and harmonic power is a big research issue, like the parallel operation of multiple UPS systems [55]-[60]. To ensure good load-sharing, the scheme combines two control methods: droop control method and average power control method [2]. Furthermore, harmonic sharing droop control method is used for each DGS unit to share harmonic components. On the other hand, for the grid-connected DGS application, a synchronization issue between an islanding mode and a paralleling mode to the grid is
investigated, and two case studies are performed. To demonstrate the proposed circuit models and control strategies, simulation test-beds using Matlab/Simulink are constructed for each configuration of the fuel cell based DGS with a three-phase AC 120 V/60 Hz/50 kVA. Space vector pulse-width modulation (SVPWM) is used as a PWM technique, and simulation results that are implemented by digital computer simulation are presented under various operating conditions.

In the second topology, this dissertation presents system modeling, modified space vector PWM implementation and control system design of the Z-source converter that uses L and C components and shoot-through zero vectors to boost DC link voltage in a standalone AC power generation [86]. For an electrical analysis of the fuel cell powered systems, the fuel cell system is modeled by an electrical R-C circuit in order to include slow dynamics of the fuel cells and a voltage-current characteristic of a cell is also considered. A discrete-time state space model is derived to implement digital control and a space vector pulse-width modulation (SVPWM) technique is modified to realize the shoot-through zero vectors that boost the DC-link voltage. Three discrete-time feedback controllers are designed: a discrete-time optimal voltage controller, a discrete-time sliding mode current controller, and a discrete-time PI DC-link voltage controller. Furthermore, an asymptotic observer which estimates load currents is used to reduce the number of sensors and enhance the reliability of the system. To demonstrate the analyzed circuit model and proposed control strategy, a system with a three-phase AC 208 V/60 Hz/10 kVA is simulated using Matlab/Simulink under heavy/light loads, linear/nonlinear loads, and load changes.
1.4 Research Contributions

In the first topology, recent research works are mostly oriented toward only one part of either dynamic modeling of the fuel cell or design of power converters with a constant DC voltage source such as a forward/push-pull DC to DC boost converter, a single unidirectional or bidirectional full-bridge DC to DC power converter as well as a DC to AC inverter. To the best of my knowledge, for the DGS with parallelly connected fuel cell and battery in a standalone AC power plant and a grid-interconnection, there has not been any paper which covers all together the slow dynamics of the fuel cell, a voltage-current polarization curve of the stack, a unidirectional full-bridge boost converter for the fuel cell, a bidirectional full-bridge buck/boost DC to DC power converter for the battery, and a three-phase DC to AC inverter. In this research, studies including both dynamic model of the fuel cell and control system design of unidirectional and bidirectional isolated full-bridge DC to DC power converters, three-phase DC to AC inverter are performed for the fuel-cell-powered DGS to place the battery in parallel to the fuel cell in both a standalone and a grid-connected power plant.

In the second topology, the previous research work shows operation of the Z-source converter under only a linear/heavy load and an open-loop control without considering the dynamics of the fuel cell system. In this dissertation, system modeling, modified space vector PWM implementation, and control system design of the Z-source converter are studied to guarantee good performance under heavy/light loads, linear/nonlinear loads, and load changes.
In consequence, this research can be effectively used to demonstrate the fuel cell based DGS illustrated in Section 1.3 for industrial applications such as stationary and distributed power generation systems that require a three-phase AC voltage output.

1.5 Thesis Organization

The dissertation is organized as follows. Chapter 2 illustrates dynamic model of fuel cell. Configurations of the DGS studied in this dissertation are presented in Chapter 3. Chapter 4 explains the circuit model of a single DGS unit and two DGS units which place the battery in parallel to the fuel cell and in a standalone AC power supply. Chapter 5 describes the circuit model and two scenarios for a grid-connected DGS. Chapter 6 presents the system modeling, modified space vector PWM implementation (MSVPWM), and feedback control system design of the Z-source converter. Control algorithms of all DGS configurations investigated in this research are proposed in Chapter 7. In Chapter 8, simulation results about each DGS configuration are demonstrated under various conditions. The conclusion is presented in Chapter 9.
CHAPTER 2

MODELING OF FUEL CELL

2.1 Introduction

This chapter will provide background and dynamic model of the fuel cell to consider dynamics of the reformer and stack that significantly affects the dynamic behavior of the fuel cell and a voltage-current polarization curve of a fuel cell stack.

2.2 Fuel Cell Background

It is known that the 19th Century was the century of the steam engine and the 20th Century was the century of the internal combustion engine. On the other hand, the 21st Century will be likely to be the century of the fuel cell, and as a result fuel cells will revolutionize the way to currently generate electric power offering the prospect of supplying the world with clean, efficient, sustainable electrical energy because they use hydrogen as a fuel.

A fuel cell is defined as an electrical cell, which unlike other storage devices can be continuously fed with a fuel in order that the electrical power can be maintained. The
Figure 2.1 shows a block diagram of basic fuel cell operation. As illustrated in this figure, the fuel such as natural gas, coal, methanol, etc. is fed to the fuel electrode (anode) and oxidant (oxygen) is supplied to the air electrode (cathode). The oxygen fed to the cathode allows electrons from the external electrical circuit to produce oxygen ions. The ionized oxygen goes to the anode through the solid electrolyte and combines with hydrogen to form water. Even though chemical reactions at anode and cathode may be a
little different according to the types of fuel cells, the overall reaction can be described as follows:

**Overall reaction:** \[ 2 \text{H}_2 \text{(gas)} + \text{O}_2 \text{(gas)} \rightarrow 2 \text{H}_2\text{O} + \text{energy (electricity, heat)} \]

Since hydrogen and oxygen gases are electrochemically converted into water and energy as shown in the above overall reaction, fuel cells have many advantages over heat engines: high efficiency and actually quiet operation and, if hydrogen is the fuel, no pollutants are released into the atmosphere. As a result, fuel cells can continuously generate electric power as long as hydrogen and oxygen are available.

Among several types of the fuel cells categorized by the electrolyte used, four types are promising for distributed generation systems: Phosphoric Acid fuel cell (PAFC), Solid Oxide fuel cell (SOFC), Molten Carbonate fuel cell (MCFC), Proton-Exchange-Membrane fuel cell (PEMFC).

All types of the fuel cells produce electricity by electrochemical reaction of hydrogen and oxygen, and the oxygen can be easily obtained from compressing air. On the contrary, hydrogen gas required to produce DC power is indirectly gained from the reformer using fuels such as natural gas, propane, methanol, gasoline or from the electrolysis of water.

A typical configuration of an autonomous fuel cell system is described in Figure 2.2. As shown in this figure, the fuel cell plant consists of three main parts: a reformer, stack, and a power conditioning unit (PCU). First, the reformer produces hydrogen gas from fuels and then provides it for the stack. Second, the stack has many unit cells in
series to generate a higher voltage needed for their applications because a single cell that consists of electrolyte, separators, and plates, produces approximately 0.7 V DC. Last, the PCU including power converters converts a low voltage DC from the fuel cell to a high voltage DC and/or a sinusoidal AC.

![Fuel Cell Diagram](image)

**Figure 2.2: Configuration of the fuel cell system**

### 2.3 Modeling of the Fuel Cell

In this section, dynamics of reformer and voltage-current polarization curve of a fuel cell stack will be discussed in detail.

#### 2.3.1 Dynamics of Reformer

For dynamic modeling of the fuel cells, the reformer and stack, which determine the dynamic response of the fuel cell system, are further described. Figure 2.3 shows a detailed block diagram of the fuel cell system to illustrate its operation.
As depicted in this figure, the fuel cell system consists of fuel cell stack and auxiliary systems such as a fuel processor controller to request the hydrogen gas, a reformer, an air compressor to provide pressurized oxygen flow through the cathode, a valve to control the hydrogen flow through the anode, a humidifier to add moisture to the hydrogen and oxygen gases, and a water-cooling system to remove heat from the stack.

Among the auxiliary systems stated above, the reformer significantly affects the dynamic behavior of the fuel cell system because it takes several to tens of seconds to convert the fuel into the hydrogen depending on the demand of the load current as
illustrated in Figure 2.4. Thus, to investigate an overall operation of fuel cell powered systems, the dynamics of the reformer need to be considered, and it may be represented by a second order transfer function model [68] or a first order time delay model [69]. In this paper, a first order transfer function is used for the dynamic model of the reformer.

2.3.2 Voltage-Current Polarization Curve of a Fuel Cell Stack

The response of the stack that produces electric DC power from hydrogen and oxygen is much faster than that of the reformer. A voltage-current polarization curve of a fuel cell stack represented in Figure 2.5 also needs to be considered for the practical model of the fuel cell. That is, cell voltage decreases as the stack current increases.

Figure 2.5 shows a static voltage-current characteristic curve of a single fuel cell. As illustrated in the figure, there exist three regions: region of activation polarization, region of ohmic polarization, and region of concentration polarization. First, in region of activation polarization, the cell voltage drops rapidly with even small current increase. Second, in region of ohmic polarization, the cell voltage linearly decreases as current increases, and the fuel cell normally operates in this region. Last, in region of concentration polarization, the voltage collapses sharply when current exceed the upper limit of safe operation, and as a consequence, operation in this region should be avoided because the fuel cell may be damaged due to primarily starvation of the hydrogen.
In this research, the Proton Exchange Membrane (PEM) fuel cells of four promising fuel cells are investigated. Based on an electrochemical process in [62], a Simulink model is developed for the V-I polarization curve of the fuel cell stack as illustrated in Figure 2.6. In this figure, the polarization curve of the fuel cell is generated using regression models with current, fuel cell temperature, vapor saturation pressure, and oxygen and hydrogen partial pressures. In particular, the oxygen and hydrogen pressures can be estimated from cathode pressure, cathode relative humidity and vapor saturation pressure.
Figure 2.6: Simulink model for V-I polarization

To obtain the voltage-current polarization curve of the fuel cell stack, the following assumptions are made:

- Fuel cell temperature is 80°C at all times.
- Gas distribution is uniform.
- Anode relative humidity is equal to cathode relative humidity and the value is 75%.
- The ratio of pressures between the interior and exterior of the channel is large enough for orifice to be choked.
- The Nernst’s equation is applied.
- The cell utilization is 85%.
Based on the above assumptions, the polarization curves of the stack of 250 cells in series for various cathode pressures [1, 1.2, 1.4, 1.6, 1.8, 2 bar] are shown in Figure 2.7. As represented in this figure, the linearized polarization curve corresponding to cathode pressure ($p_{ca}$) of 1.2 bar is selected for a 50 kW PEM fuel cell and it will be used for Simulink model of the fuel cell stack.

Figure 2.7: Voltage-current polarization curves at different cathode pressures ($p_{ca}$)

Note that the fuel cell has the slow dynamic response during transient. At initial startup, it takes 90 seconds for the fuel cell to reach steady state. Whenever there is a change in power demand, the fuel cell takes 60 seconds to reach a new steady state.
because the hydrogen flow rates can be slowly adjusted to meet the power demand [51]-[54]. To compensate for such a sluggish response of the fuel cell, an energy storage device such as a battery may be required to achieve the end-use needs. For a 50 kW PEM fuel cell, this implies that during startup (90 sec), the energy storage requirement is 4500 kJ or 1.25 kWh. Furthermore, dynamic load changes should be supported by the batteries for 60 seconds. For lead-acid batteries, about 20 % change of nominal charge state may be reasonable to avoid deep discharge and guarantee long service life as well as reserve capacity in the case of an extended fault with the fuel cell. Figure 2.8 shows a discharge curve of fuel cell and battery to determine the battery capacity. Considering only 20 % discharge of the nominal battery charge state for 90 seconds (startup), the minimum storage requirement of the batteries to support the fuel cell during all transients is about 22,500 kJ or 6.25 kWh.

Figure 2.8: Discharge curve of fuel cell and battery
CHAPTER 3

CONFIGURATIONS OF DISTRIBUTED GENERATION SYSTEMS

3.1 Introduction

This chapter will illustrate all configurations of the DGS studied in this dissertation: a standalone AC power supply (a single DGS unit and two DGS units), a grid-connected power plant, and a Z-source converter. Furthermore, all configurations are divided into two topologies. Topology 1 is the DGS with the battery in parallel to the fuel cell, and it consists of unidirectional/bidirectional DC to DC power converters and a three-phase DC to AC inverter. On the other hand, Topology 2 is the DGS with only fuel cell, and it consists of a three-phase DC to AC inverter and L-C components instead of a DC to DC boost converter to step up a low DC voltage of the fuel cell. In the following sections, each topology will be discussed in detail.

3.2 Topology 1

In this topology with the battery in parallel with the fuel cell, two DC to DC power converters are needed. Since the fuel cell can not immediately support power
demand during transient such as start-up or sudden load changes due to its slow dynamics, the remaining power is provided by energy storage elements like batteries or flywheels for the transients. Fuel cell stack voltage, battery position and topology of DC to DC boost converters can be selected variously according to the designers [51]-[54].

In this research, a low voltage DC output of the fuel cell is used along with the unidirectional boost converter to avoid reliability deterioration and increased cost caused by stacking a large number of unit cells. A low voltage battery for backup is connected in parallel to the high-side DC bus through a bidirectional buck/boost converter because difficulties in battery management can be significantly reduced. In addition, an isolated full-bridge DC to DC power converter is chosen to boost low output DC voltages of the fuel cell and battery because its topology is suitable for high power applications [70]-[79].

![Figure 3.1: Configuration for two applications in Topology 1](image)

Based on the DGS unit with the battery in parallel to the fuel cell, this dissertation focuses on two applications as illustrated in Figure 3.1: a standalone AC power supply
and a grid-interconnection. Figure 3.2 shows the network structure of multiple distributed generation systems used for the standalone AC power supply. As shown in this figure, each distributed energy system supplies electric power to the loads, like the parallel operation of UPS units in the emergency mode operation. This architecture may require for each DGS to operate independently because the distance between DGS units may make data communication impractical. As a result, the control may be based on the variables that can only be measured locally at the inverter.

Figure 3.2: Configuration for a standalone AC power supply with multiple DGS units

However, recently data communication between units can be easily realized by the rapid advances in the field of communication. Thus, a schematic diagram is depicted in Figure 3.2 for data communication between Remote Terminal Unit (RTU) and RTU
for each DGS to exchange power information (real power and reactive power). In this research, a single DGS unit and two DGS units are studied in the standalone AC power system.

Figure 3.3 shows a schematic diagram of the DGS used for a grid-connected application. In this figure, the DGS are interconnected to the conventional distribution lines in order to cover increased power required by the loads, so the distributed generation systems may spread around the distributed system that is connected to a grid system. In this application, the DGS are connected to Medium Voltage (MV) or Low Voltage (LV) Network according to power ratings or voltage ratings available for the systems. In this research, the Low Voltage Network is considered for a grid-connected DGS.

Figure 3.3: Configuration for grid-connected DGS units
3.2.1 Standalone AC Power Supply

Distributed generation systems (DGS) used for a standalone AC power plant autonomously supply electric power to local loads without power dispatch from the grid. For this application, a single DGS unit and two DGS units will be investigated in the following sections.

3.2.1.1 A Single DGS Unit

Figure 3.4 shows a configuration of a single DGS unit with parallelly connected fuel cell and battery in a standalone operation. The battery is needed to support the slow dynamic behavior of the fuel cell during transient. As shown in the figure, it consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a 3-phase DC to AC inverter, an L-C output filter, and a 3-phase local load.

![Figure 3.4: Configuration of a single DGS unit in a standalone AC power supply](image)
In this configuration, research issues are summarized below and each issue will be studied in Chapter 4:

- Dynamic modeling of fuel cell
- Unidirectional DC to DC boost power converter
  - Power flow control: From the fuel cell to the load
  - Good voltage regulation

- Bidirectional DC to DC buck/boost power converter
  - Power Flow Control:
    - Battery discharge:
      - From the battery to the load (Start-up and sudden load increase)
    - Battery charge:
      - From the fuel cell to the battery (in steady state and sudden load decrease)
  - Good voltage regulation

- DC to AC inverter:
  - Zero steady-state voltage error
  - Low THD
  - Fast transient response
  - Over-current protection
  - Good voltage regulation
3.2.1.2 Two DGS Units

Figure 3.5 depicts a configuration of two DGS units with the battery in parallel with fuel cell in a standalone application. As described in Figure 3.5, each unit consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a three-phase DC to AC inverter, an L-C output filter, a $\Delta/Y$ transformer, static power switches, and a three-phase local load. In particular, the static power switches are required to disconnect or connect each DGS unit to distribution network in the event of system failure or regular maintenance or after system recovery.

![Diagram of two DGS units](image)

Figure 3.5: Configuration of two DGS units in a standalone AC power supply
In this configuration, research issues are summarized in the following and each issue will be investigated in Chapter 4:

- Dynamic modeling of fuel cell
- Unidirectional DC to DC boost power converter
  - Power flow control: From the fuel cell to the load
  - Good voltage regulation

- Bidirectional DC to DC buck/boost power converter
  - Power Flow Control:
    ① Battery discharge:
      From the battery to the load (Start-up and sudden load increase)
    ② Battery charge:
      From the fuel cell to the battery (in steady state and sudden load decrease)
  - Good voltage regulation

- DC to AC inverter: Design of voltage/current controllers and P/Q controllers
  - Zero steady-state voltage error
  - Low THD
  - Fast transient response
  - Over-current protection
  - Good voltage regulation
  - Good load sharing of each DGS unit
  - Real and reactive power control
  - System protection
  - Synchronization between each DGS unit
3.2.2 Grid-Connected DGS

Figure 3.6 describes a configuration of a grid-connected DGS with the battery in parallel to the fuel cell, and it consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a three-phase DC to AC inverter, an L-C output filter, a ∆/Y transformer, a three-phase load, static power switches, and a grid. In the configuration, two scenarios are assumed: (a) when DGS > load, i.e., the DGS unit feeds electric power to both the local load and the grid, and (b) when DGS < load, i.e., both the DGS and the grid deliver electric power to the load. The static switches are needed to manage an islanding mode and a paralleling mode to the grid. When a fault occurs at the grid, the static switches are disconnected, and then the DGS supplies the isolated local load at an islanding mode. On the other hand, after the grid is recovered from the fault, the static switches are reconnected to operate in a paralleling mode to the grid.

Figure 3.6: Configuration for a grid-connected DGS
In this configuration, research issues are summarized as follows and each issue will be studied in Chapter 5:

- **Dynamic modeling of fuel cell**
- **Unidirectional DC to DC boost power converter**
  - Power flow control: From the fuel cell to the load
  - Good voltage regulation

- **Bidirectional DC to DC buck/boost power converter**
  - Power Flow Control:
    1. Battery discharge:
       From the battery to the load (Start-up and sudden load increase)
    2. Battery charge:
       From the fuel cell to the battery (in steady state and sudden load decrease)
  - Good voltage regulation

- **DC to AC inverter: Design of voltage/current controllers and P/Q controllers**
  - Zero steady-state voltage error
  - Low THD
  - Fast transient response
  - Over-current protection
  - Good voltage regulation
  - Power flow control: DGS > load or DGS < load
  - Real and reactive power control
  - System protection
  - Synchronization between the DGS and the grid
3.3 Topology 2 (Z-Source Converter)

In this topology with only fuel cell as an energy source, the L-C components are employed instead of a DC to DC boost converter to step up a low DC voltage of the fuel cell [84]-[85]. Figure 3.7 shows a configuration of a Z-source converter with fuel cell. As illustrated in this figure, the Z-source converter can boost the DC-link voltage used as an input of DC to AC inverter by employing L-C impedance components and a shoot-through without any boost converter. It consists of a fuel cell, a diode, impedance components (L and C), a three-phase inverter, a L-C output filter, and a 3-phase load. The diode between the fuel cell and Z-source converter is required to prevent a reverse current that can damage the fuel cell.

![Figure 3.7: Configuration of a Z-source converter](image)

In this configuration, research issues are summarized below and each issue will be discussed in Chapter 6:

- Dynamic modeling of fuel cell
- DC to AC inverter: Design of voltage/current controllers
  - PWM implementation for shoot-through zero vectors
– Zero steady-state voltage error
– Low THD
– Fast transient response
– Over-current protection
– Good observer design
– Good voltage regulation
CHAPTER 4

STANDALONE AC POWER SUPPLY

4.1 Introduction

This chapter will present detailed configurations of a single DGS unit and two DGS units with the battery in parallel with the fuel cell in the standalone AC power plant. In this topology, the battery is placed in parallel to back up the fuel cell for the transient because the fuel cell can not immediately respond to the power demand during start-up or sudden load changes due to its slow dynamics. Based on the fuel cell model described in Chapter 2, the operation of unidirectional and bidirectional full-bridge DC to DC power converters will be described and the system model of a three-phase DC to AC converter without or with a Δ/Y transformer will be given according to each application: a single DGS unit operation and a parallel operation of two DGS units. Design of closed-loop controllers will be studied in Chapter 7.
4.2 Configurations of a Single DGS Unit and Two DGS Units

In this section, the configuration of each application mentioned above will be discussed in detail, and a whole block diagram of the DGS including the fuel cell and battery will be given for each configuration.

4.2.1 A Single DGS Unit

Figure 4.1 depicts a configuration of a single DGS unit using a parallel connection of a fuel cell and battery for the standalone AC power plant. It consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a three-phase DC to AC inverter, an L-C output filter, a three-phase local load, and two controllers. Each power converter included in this configuration will be explained in the subsequent sections.

Figure 4.1: Configuration of a single DGS unit in a standalone AC power plant
Figure 4.2 shows a real system diagram of a single DGS unit that consists of a reformer, stack, a fuel processor, a unidirectional boost converter, a bidirectional buck/boost converter, a DC to AC inverter, a supervisory controller, two DSP controllers, and a 3-phase load in a standalone power generation.

As described in Figure 4.2, the fuel processor controls the reformer to produce hydrogen for the power requested from the supervisory controller, and monitors the stack current and voltage. The supervisory controller communicates with the fuel processor controller to equalize the power available from the stack to the power requested by the load, and to coordinate protections of the fuel cell. Also, it controls the DSP controller 1 and 2 for the DC and AC power regulation with sensed output voltages/currents. The
DSP controller 1 supervises the gating signals of unidirectional and bidirectional DC to DC power converters, and the DSP controller 2 regulates the gating signals of the three-phase DC to AC inverter.

4.2.2 Two DGS Units

Figure 4.3 describes a configuration of two DGS units with the battery in parallel with fuel cell in the standalone AC power supply. Similarly to Figure 4.1, each unit consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a three-phase DC to AC inverter, an L-C output filter, a ∆/Y transformer, static power switches, and a three-phase local load. Particularly, the static power switches are required to disconnect or connect each DGS unit to distribution network in the event of a system failure, regular maintenance, or after system recovery. Moreover, the ∆/Y transformer is used to protect each DGS unit by electrically isolating each other.
Figure 4.3: Configuration of two DGS units in a standalone AC power plant

Figure 4.4 illustrates a real system diagram of two DGS units in a standalone operation mode. Data communication signals between each DGS unit as well as static switch control signals are added to the configuration shown in Figure 4.2.
Figure 4.4: Detailed system diagram of two DGS units with a fuel cell and a battery

In this configuration with two DGS units, control system design of unidirectional/bidirectional isolated full-bridge DC to DC power converters and three-
phase DC to AC inverter is investigated. In particular, for the parallel operation of two DGS units, the research focuses on proper power sharing of each DGS such as the real power, reactive power, and harmonic power in a standalone AC power supply, like the parallel operation of multiple UPS systems [55]-[60]. First, good load-sharing should be maintained under both locally measurable voltages/currents, the wire impedance mismatches, and voltage/current measurement error mismatches, that significantly degrade the performance of load-sharing. Therefore, the control scheme proposed in this dissertation only uses locally measurable feedback signals (voltages/currents) and relatively low bandwidth data communication signals (respective real power and reactive power) between each generation system to overcome adverse conditions stated above.

4.3 Unidirectional/Bidirectional Full-Bridge DC to DC Power Converters

The fuel cell can not immediately respond to power demand during start-up or sudden load changes due to its slow dynamics. As a result, energy storage elements such as batteries or flywheels deliver the remaining power to the load for the transient.

In this research, a low voltage DC output of the fuel cell is used along with the unidirectional boost converter to prevent reliability deterioration by stacking a number of series cells. A low DC voltage battery for backup is connected in parallel with the high-side DC link through a bidirectional buck/boost converter because difficulties in battery management can be significantly reduced. Furthermore, an isolated full-bridge DC to DC power converter is adopted to boost low output DC voltage of the fuel cell because its topology is suitable for high power applications [70]-[79].
The fuel cell based DGS illustrated in Figures 4.1 and 4.3 is divided into two parts to investigate detailed circuit model and controller design. In this section, DC to DC power converters are explained and a three-phase DC to AC inverter will be described in the next section.

To boost low output DC voltage of the fuel cell to high DC voltage, a forward, a push-pull or an isolated full-bridge DC to DC power converter can be selected. Among these power converters, two phase-shifted full-bridge DC to DC converters, which are
one of the most attractive topologies for high power generation [70]-[79], are adopted as described in Figure 4.5: a unidirectional full-bridge DC to DC boost converter for the fuel cell and a bidirectional full-bridge DC to DC boost/buck converter for the battery.

In Figure 4.5, the unidirectional power converter system for the fuel cell consists of a fuel cell, an input filter (L₁, C₁), a full-bridge power converter (F₁ to F₄), a high frequency transformer (N₁:N₂), a bridge-diode (D₁F₁ to D₁F₄), and an output filter (L₂, C₂), while the bidirectional power converter system for the battery consists of a battery, a static switch (S₂), two full-bridge power converters (B₁ to B₄, B₁₁ to B₄₄), and a high frequency transformer (n₁:n₂).

Figure 4.6 shows power flows of DC to DC power converters for battery discharge and battery recharge. As shown in Figure 4.6, the unidirectional full-bridge DC to DC boost converter permits only one directional power flow from the fuel cell to the load because a reverse current can damage the fuel cell. In addition, response speed of the power converter should be slow enough to meet slow dynamic response of the fuel cell. On the other hand, the bidirectional full-bridge DC to DC power converter allows both directional power flows for battery discharge and recharge, and its response also should be fast to compensate for the slow dynamics of the fuel cell during start-up or sudden load changes.
Figure 4.6: Power flows of DC to DC power converters

(a) Battery discharge (b) Battery recharge
For battery discharge mode illustrated in Figure 4.6 (a), which occurs when a
startup or a sudden load increase, the fuel cell starts delivering electric power to the load
and the battery instantly provides power until the fuel cell reaches a full operation state.
After transient operation, only the fuel cell feeds electric power to the load. For battery
recharge mode shown in Figure 4.6 (b), the battery absorbs the energy overflowed from
the fuel cell to prevent DC-link voltage $V_{DC}$ from being overcharged during a sudden
load decrease, and then the battery is recharged by the fuel cell in a steady-state until it
reaches a nominal voltage.

4.4 Three-Phase DC to AC Inverter

In this section, the state space models of three-phase DC to AC inverters without
or with a $\Delta$/Y transformer will be derived for a single DGS unit and two DGS units,
respectively.

4.4.1 A Single DGS Unit

A circuit model of a three-phase DC to AC inverter with L/C output filter is
further described in Figure 4.7. As shown in the figure, the system consists of a DC
circuit model of a three-phase DC to AC inverter with L/C output filter is
further described in Figure 4.7. As shown in the figure, the system consists of a DC
circuit model of a three-phase DC to AC inverter with L/C output filter is
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further described in Figure 4.7. As shown in the figure, the system consists of a DC
circuit model of a three-phase DC to AC inverter with L/C output filter is
further described in Figure 4.7. As shown in the figure, the system consists of a DC
circuit model of a three-phase DC to AC inverter with L/C output filter is
further described in Figure 4.7. As shown in the figure, the system consists of a DC
circuit model of a three-phase DC to AC inverter with L/C output filter is
further described in Figure 4.7. As shown in the figure, the system consists of a DC
voltage source ($V_{dc}$), a three-phase PWM inverter (S1 to S6), an output filter ($L_f$ and $C_l$),
and a three-phase load ($R_L$). Note that the first stage of DGS that consists of a fuel cell, a
battery, and two full-bridge DC to DC power converters is replaced with the DC voltage
source ($V_{dc}$) because during transient the battery fully supports the fuel cell with a slow
dynamic response to keep the DC-link voltage \( (V_{dc}) \) constant and as a result, the first stage can be considered as a stiff DC energy source.

![Figure 4.7: Three-phase DC to AC inverter with L-C output filter](image)

The circuit model described in Figure 4.7 uses the following quantities. The inverter output line-to-line voltages and output currents are represented by the vectors \( V_i = [V_{iAB} \ V_{iBC} \ V_{iCA}]^T \) and \( I_i = [i_A \ i_B \ i_C]^T \). Also, the load line to neutral voltage and phase current vectors can be represented by \( V_L = [V_{LAN} \ V_{LBN} \ V_{LCN}]^T \) and \( I_L = [i_{LA} \ i_{LB} \ i_{LC}]^T \), respectively.

The L-C output filter yields the following state equations by KCL and KVL:

\[
\frac{dV_L}{dt} = \frac{1}{C_f} I_i - \frac{1}{C_f} I_L \\
T_i \frac{dI_i}{dt} = -\frac{1}{L_f} T_i V_L + \frac{1}{L_f} V_i
\]  

(4.1)
where, \( T_i = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \).

To implement the space vector PWM, the above state equations can be transformed from the \( abc \) reference frame into the stationary \( dq \) reference frame that consists of the horizontal (d) and vertical (q) axes as depicted in Figure 4.8.

From this figure, the relation between these two reference frames is below

\[
f_{dq0} = \mathbf{K}_s f_{abc} \tag{4.2}
\]

where, \( \mathbf{K}_s = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \), \( f_{dq0}=[f_d, f_q, f_0]^T \), \( f_{abc}=[f_a, f_b, f_c]^T \), and \( f \) denotes either a voltage or a current variable.

![Figure 4.8: The relationship of \( abc \) reference frame and stationary \( dq \) reference frame](image)
Using (4.2), the (4.1) can be transformed below

\[
\frac{dV_{Ldq}}{dt} = \frac{1}{C_f} I_{idq} - \frac{1}{C_f} I_{Ldq} \\
\frac{dI_{idq}}{dt} = -\frac{1}{L_f} V_{Ldq} + \frac{1}{L_f} T^{-1}_{idq} V_{idq}
\]

(4.3)

where, \( T^{-1}_{idq} = [K_s K_1]^{-1} \) is

\[
\begin{bmatrix}
\frac{1}{\sqrt{3}} \\
\frac{1}{\sqrt{3}} \\
-1
\end{bmatrix}
\]

The given plant model (4.3) can be expressed as the following continuous-time state space equation:

\[
\dot{X}(t) = AX(t) + Bu(t) + Ed(t)
\]

(4.4)

where,

\[
X = \begin{bmatrix} V_{Ldq} \\ I_{idq} \end{bmatrix}_{4 \times 1}, \quad A = \begin{bmatrix}
0_{2 \times 2} & \frac{1}{C_f} I_{2 \times 2} \\
-\frac{1}{L_f} I_{2 \times 2} & 0_{2 \times 2}
\end{bmatrix}_{4 \times 4}, \quad B = \begin{bmatrix}
0_{2 \times 2} \\
\frac{1}{L_f} T^{-1}_{idq}
\end{bmatrix}_{4 \times 2}
\]

\[
E = \begin{bmatrix}
-\frac{1}{C_f} I_{2 \times 2} \\
0_{2 \times 2}
\end{bmatrix}_{4 \times 2}, \quad u = [V_{idq}]_{2 \times 1}, \quad d = [I_{Ldq}]_{2 \times 1}
\]

Note that the load line to neutral voltage \( V_{Ldq} \) and inverter output phase current \( I_{idq} \) are the state variables, the inverter output line-to-line voltage \( V_{idq} \) is the control input \( u \), and the load phase current \( I_{Ldq} \) is defined as the disturbance \( d \).
4.4.2 Two DGS Units

The system model of a three-phase DC to AC inverter with a ∆/Y transformer will be given in this section. Also, for good load sharing of two DGS units operating in parallel, active power (P) and reactive power (Q) control will be explained.

4.4.2.1 System Modeling

Figure 4.9 shows a circuit model of a three-phase DC to AC inverter with a ∆/Y transformer. As represented in Figure 4.9, the system consists of a DC voltage source ($V_{dc}$), a three-phase PWM inverter, a L-C inverter filter ($L_f, C_f$), a ∆/Y transformer, an output filter ($C_L$), and a load ($R_L$) [2]. Notice that the first stage of DGS that consists of a fuel cell, a battery, and two full-bridge DC to DC power converters is replaced with the DC voltage source ($V_{dc}$) because during transient the battery fully supports the fuel cell with a sluggish dynamic response to keep the DC-link voltage ($V_{dc}$) constant and as a result, the first stage can be considered as a stiff DC energy source.

As shown in Figure 4.10, the three-phase ∆/Y transformer can be further modeled to simplify the circuit analysis using controlled current source, controlled voltage source, and equivalent phase impedances with the resistor $R_T$ and the inductor $L_T$.

The circuit systems defined in Figures 4.9 and 4.10 use the following quantities to describe their behavior. The inverter output line-to-line voltage and phase current are represented by the vector $\mathbf{V}_i=[V_{iAB} \ V_{iBC} \ V_{iCA}]^T$ and $\mathbf{I}_i=[i_{IA} \ i_{IB} \ i_{IC}]^T$, respectively. The line-to-line voltage and the line current vectors on the ∆-connected transformer primary side
are depicted by the vector $\mathbf{V}_p = [V_{pAB} \ V_{pBC} \ V_{pCA}]^T$ and $\mathbf{I}_p = [i_{pA} \ i_{pB} \ i_{pC}]^T$, respectively. The phase voltage and current vectors on the Y-connected transformer secondary side are denoted by $\mathbf{V}_s = [V_{sA} \ V_{sB} \ V_{sC}]^T$ and $\mathbf{I}_s = [i_{sA} \ i_{sB} \ i_{sC}]^T$. At the output terminal, the load line to neutral voltage and current vectors can be described by $\mathbf{V}_L = [V_{LA} \ V_{LB} \ V_{LC}]^T$ and $\mathbf{I}_L = [i_{LA} \ i_{LB} \ i_{LC}]^T$, respectively.

Figure 4.9: Circuit model of two three-phase DC to AC inverters
Based on Figure 4.10, the voltage relation between the two sides of the transformer can be described by

\[ V_{sA} = \frac{N_s}{N_p} V_{pAB}, \quad V_{sB} = \frac{N_s}{N_p} V_{pBC}, \quad V_{sC} = \frac{N_s}{N_p} V_{pCA} \]  

(4.5)

Similarly, the current relation is written as

\[ i_{AB} = \frac{N_s}{N_p} i_{sA}, \quad i_{BC} = \frac{N_s}{N_p} i_{sB}, \quad i_{CA} = \frac{N_s}{N_p} i_{sC} \]  

(4.6)

From Figure 4.10, it also can be observed that

\[ i_{pA} = i_{AB} - i_{CA}, \quad i_{pB} = i_{BC} - i_{AB}, \quad i_{pC} = i_{CA} - i_{BC} \]  

(4.7)
On the primary and secondary sides of the transformer, the L-C filter yields the following voltage and current equations:

\[
\frac{dV_p}{dt} = \frac{1}{3C_f} T_1 I_{i} - \frac{1}{3C_f} T_2 I_s
\]  \hspace{1cm} (4.8)

\[
T_1 \frac{dI_i}{dt} = -\frac{1}{L_f} V_p + \frac{1}{L_f} V_i
\]  \hspace{1cm} (4.9)

\[
\frac{dN_L}{dt} = \frac{1}{C_L} I_s - \frac{1}{C_L} I_L
\]  \hspace{1cm} (4.10)

\[
\frac{dI_s}{dt} = \frac{1}{L_T} T_3 V_p - \frac{1}{L_T} V_L - \frac{R_T}{L_T} I_s
\]  \hspace{1cm} (4.11)

where, \( T_i \) = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix}, \( T_2 = N_s \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}, \( T_3 = N_s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \).

To implement the space vector PWM, the above state equations (4.18)-(4.11) can be transformed from the \( abc \) reference frame into the stationary \( dq \) reference frame that consists of the horizontal (d) and vertical (q) axes shown in Figure 4.8. The relation between these two reference frames is below

\[
f_{dq0} = K_s f_{abc}
\]  \hspace{1cm} (4.12)

where, \( K_s = \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \), \( f_{dq0} = [f_d, f_q, f_0]^T \), \( f_{abc} = [f_a, f_b, f_c]^T \), and \( f \) denotes either a voltage or a current variable.
Using (4.12), the vectors $V_p$, $I_i$, $V_L$, $I_s$, $V_i$, and $I_L$ in the $abc$ reference can be transformed to $V_{pdq}$, $I_{idq}$, $V_{Ldq}$, $I_{sdq}$, $V_{idq}$, and $I_{Ldq}$ in the stationary $dq$ reference, respectively. The equations (4.8)-(4.11) can be transformed as follows

$$\frac{dV_{pdq}}{dt} = \frac{1}{3C_f} T_{idq} I_{idq} - \frac{1}{3C_f} T_{2dq} I_{sdq}$$ \hspace{0.5cm} (4.13)$$

$$\frac{dI_{idq}}{dt} = -\frac{1}{L_f} T_{idq}^{-1} V_{pdq} + \frac{1}{L_f} T_{idq}^{-1} V_{idq}$$ \hspace{0.5cm} (4.14)$$

$$\frac{dV_{Ldq}}{dt} = \frac{1}{C_L} I_{sdq} - \frac{1}{C_L} I_{Ldq}$$ \hspace{0.5cm} (4.15)$$

$$\frac{dI_{sdq}}{dt} = \frac{1}{L_T} T_{3dq} V_{pdq} - \frac{1}{L_T} V_{Ldq} - \frac{R_T}{L_T} I_{sdq}$$ \hspace{0.5cm} (4.16)$$

where,

$$T_{idq} = [K_s T_i K_s^{-1}]_{row,2} = \frac{3}{2} \begin{bmatrix} 1 & -\frac{1}{\sqrt{3}} \\ \frac{\sqrt{3}}{3} & 1 \end{bmatrix}$$,

$$T_{2dq} = [K_s T_2 K_s^{-1}]_{row,2} = \frac{N_s}{N_p} \begin{bmatrix} 3 & 0 \\ 0 & 3 \end{bmatrix}$$,

$$T_{3dq} = [K_s T_3 K_s^{-1}]_{row,2} = \frac{N_s}{N_p} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$.

All the above vectors with $dq$ subscriptions are two dimensional vectors where the 0-axis elements are not included. Since the transformer is $\Delta/Y$ type with the neutral point of the secondary side grounded, the secondary side circuit may carry unbalanced three-phase current (e.g., load unbalanced fault can cause 0-axis current). The transient behavior of the 0-axis circuit is uncontrollable in that the circuit is not accessible for the control inputs $V_{id}$ and $V_{iq}$. However, due to the existence of $R_T$, the circuit is
asymptotically stable. Therefore, the overall system is stable according to the control theory that a linear time invariant (LTI) system is stable, if its uncontrollable modes are stable.

The given plant model (4.13)-(4.16) can be expressed as the following continuous-time state space equation

\[
\dot{X}(t) = AX(t) + Bu(t) + Ed(t)
\]  

(4.17)

where,

\[
X = \begin{bmatrix} V_{pdq} \\ I_{idq} \\ V_{Ldq} \\ I_{sdq} \end{bmatrix}, \quad A = \begin{bmatrix} 0_{2\times2} & \frac{1}{3C_f} T_{1dq} & 0_{2\times2} & -\frac{1}{3C_f} T_{2dq} \\ -\frac{1}{L_f} T_{1dq}^{-1} & 0_{2\times2} & 0_{2\times2} & 0_{2\times2} \\ 0_{2\times2} & 0_{2\times2} & 0_{2\times2} & \frac{1}{C_L} I_{2x2} \\ \frac{1}{L_T} T_{3dq} & 0_{2\times2} & -\frac{1}{L_T} I_{2x2} & -\frac{R_T}{L_T} I_{2x2} \end{bmatrix}, \quad B = \begin{bmatrix} 0_{2\times2} \\ \frac{1}{L_f} T_{1dq}^{-1} \\ 0_{2\times2} \\ 0_{2\times2} \end{bmatrix},
\]

\[
E = \begin{bmatrix} 0_{2\times2} \\ 0_{2\times2} \\ -\frac{1}{C_L} I_{2x2} \\ 0_{2\times2} \end{bmatrix}, \quad u = [V_{idq}], \quad d = [I_{Ldq}].
\]

Given the sampling period \(T_s\), a discrete form of (4.17) is obtained as:

\[
X(k+1) = A^*X(k) + B^*u(k) + E^*d(k),
\]

(4.18)

where, \(A^* = e^{AT_s}\), \(B^* = \int_0^{T_s} e^{A(T_s-\tau)}Bd\tau\), and \(E^* = \int_0^{T_s} e^{A(T_s-\tau)}Ed\tau\).
Note that the state variables of the system are $V_{pdq}$, $I_{idq}$, $V_{Ldq}$, and $I_{sdq}$, the control input is the inverter output line-to-line voltage $V_{idq}$, and the disturbance is the load current $I_{Ldq}$.

4.4.2.2 Load Sharing for Parallel Operation

In general, the droop technique [21], [55]-[60] has been widely used as a load-sharing scheme in conventional power system with multiple generators. In this droop method, the generators share the system load by drooping with the frequency of each generator with the real power ($P$) delivered by the generator. This allows each generator to share changes in total load in a manner determined by its frequency droop characteristic and essentially utilizes the system frequency as a communication link between the generator control systems [21], [55]-[58]. Similarly, a droop in the voltage amplitude ($V_{\text{max}}$) with reactive power ($Q$) is used to ensure reactive power sharing.

Figure 4.11: Two DGS units connected to a load
Since this load sharing technique is based on the power flow theory in an ac system, which states that the flow of the active power \( P \) and reactive power \( Q \) between two sources can be controlled by adjusting the power angle and the voltage magnitude of each system – i.e. the active power flow \( P \) is predominantly controlled by the power angle, while the reactive power \( Q \) is predominantly controlled by the voltages magnitude, this theory is explained in Figure 4.11. Figure 4.11 indicates critical variables for load-sharing control of paralleled power converters. The figure shows two inverters represented by two voltage sources connected to a load through line impedance represented by pure inductances \( L_1 \) and \( L_2 \) for simplified analysis purpose.

The complex power at the load due to the inverter \( i \) is given by:

\[
S_i = P_i + jQ_i = V \cdot I_i^*
\]  
(4.19)

where, \( i = 1, 2 \) and \( I_i^* \) is the complex conjugate of the inverter \( i \) current and is given by:

\[
I_i^* = \left[ \frac{E_i \cos \delta_i + jE_i \sin \delta_i - V}{j \omega L_i} \right]^*
\]  
(4.20)

\[
\therefore \ S_i = V \left[ \frac{E_i \cos \delta_i + jE_i \sin \delta_i - V}{j \omega L_i} \right]^*
\]  
(4.21)

This gives the active and reactive power flowing from the inverter \( i \) as:
\[ P_i = \frac{V E_i}{\omega L_i} \sin \delta_i \] (4.22)

\[ Q_i = \frac{V E_i \cos \delta_i - V^2}{\omega L_i} \] (4.23)

From equations (4.19) through (4.23), it can be seen that, if \( \delta_1 \) and \( \delta_2 \) are small enough, then the real power flow is mostly influenced by the power angles \( \delta_1 \) and \( \delta_2 \), while the reactive power flow predominantly depends on the inverter output voltages \( E_1 \) and \( E_2 \). This means that to a certain extent the real and reactive power flow can be controlled independently. Since controlling the frequencies dynamically controls the power angles, the real power flow control can be equally achieved by controlling the frequencies of the voltages generated by the inverters.

Therefore, the power angle and the inverter output voltage magnitude are critical variables that can directly control the real and reactive power flow for proper load-sharing of the power converters connected in parallel.

In the conventional droop technique, the \( P-f \) droop and \( Q-V \) droop characteristic of each inverter \( i \) in the paralleled system can be described by:

\[ f_i = f_0 + m_i (P_i - P_{0i}) \] (4.24)

\[ V_i = V_0 + n_i (Q_i - Q_{0i}) \] (4.25)

where, \( f_i, V_i, P_i \) and \( Q_i \) denote frequency, voltage, real power and reactive power of the inverter \( i \), respectively. Also, \( f_0, V_0, P_{0i} \) and \( Q_{0i} \) represent nominal frequency, nominal voltage magnitude, nominal real power and nominal reactive power of the system, respectively, and \( m_i \) and \( n_i \) are the droop coefficients.
Based on the droop equations (4.24) and (4.25), Figure 4.12 describes a block diagram of frequency and voltage amplitude droop technique and Figure 4.13 shows $P$-$f$ droop and $Q$-$V$ droop characteristics.

Figure 4.12: Frequency and voltage amplitude droop technique

\[ m_i < 0, \quad n_i < 0 \]

Figure 4.13: $P$-$f$ droop and $Q$-$V$ droop characteristics
In the case of multiple inverters, the proportion of the load shared by each inverter can be adjusted by choosing the droop coefficient, depending on its apparent power rating as follows:

\[ m_1 \cdot S_1 = m_2 \cdot S_2 = \cdots = m_n \cdot S_n \]  
\[ n_1 \cdot S_1 = n_2 \cdot S_2 = \cdots = n_n \cdot S_n \]  

(4.26)  
(4.27)

In Figure 4.13, two inverters can be seen to share the real and reactive loads proportionally based on the chosen droop coefficients.

Figure 4.14 shows a block diagram of reference voltage by droop method. That is, the reference signal is generated with phase angle (\( \delta \)) by the real power (P) and amplitude (\( V_m \)) by the reactive power (Q), and this is used for the reference voltage of each power converter.

![Figure 4.14: Reference voltage by droop method](image)

The advantage of the droop method is that it does not require communication signals among units in parallel, thereby increasing the reliability of the system. However,
because of the droop characteristics, the frequency and voltage of the system will drop to such a value that all units will operate in a new lower frequency and smaller or bigger voltage than the nominal values. Also, as in the average power method, the method only works well for linear loads, but it does not help to share the harmonics components caused by non-linear loads. Another drawback of this method is the lack of robustness toward the wiring impedance mismatch, and the differences in the wiring impedance can significantly affect the power sharing. This is due to the lack of closed loop control of the power sharing method.

Similarly, the above control theory can be applied to a parallel operation of distributed energy systems in a standalone application. In general, there is large distance between inverter output and load bus, so each DGS is required to operate independently as using only locally measurable voltages/currents information. In addition, there is also long distance between DGS units, so data communication between DGS units may be impractical [21], [55]-[58]. However, in recent years, data communication between DGS units can easily be implemented by the rapid advances in the field of communication.

Therefore, this thesis considers the parallel operation of power converters in a standalone AC system under signal communications between units in order to ensure exact load-sharing of each DGS unit. Particularly, this research focuses on proper load-sharing between each unit, and the load-sharing should also be guaranteed under the wire impedance mismatches, voltage/current measurement error mismatches, and interconnection tie-line impedance effect that can heavily affect the performance of load-sharing [59]-[60].
Control constraints considered in this research are summarized as follows:

- Locally measurable feedback signals (voltages/currents)
- Data communications between each DGS about real power and reactive power
- Wire impedance mismatches between inverter output and load bus
- Voltage/current sensor measurement error mismatches
- Tie-line impedance between loads

To overcome the above control constraints and guarantee the good load sharing, a new droop technique using both average power method and harmonic droop control is proposed in Chapter 7 in detail [2].
CHAPTER 5

GRID-INTERCONNECTION

5.1 Introduction

This chapter will provide a configuration in detail of a grid-connected DGS unit putting the battery in parallel to the fuel cell. This configuration is similar to that of each DGS unit of two DGS units with a Δ/Y transformer, with exception that the local load is replaced with the AC grid. The fuel cell model described in Chapter 2, the operation of unidirectional and bidirectional full-bridge DC to DC power converters, and the system model of a three-phase DC to AC converter with the Δ/Y transformer illustrated in Chapter 4 can also be used in this configuration. Thus, this chapter will present two possible scenarios for the DGS unit connected to the grid and real/reactive power flow. Design of closed-loop controllers will be studied in Chapter 7.

5.2 Grid-connected Fuel Cell Based DGS

In this section, configuration and two scenarios of the DGS connected in parallel to AC grid will be investigated.
5.2.1 Configuration of the DGS connected to the Grid

Figure 5.1 illustrates a configuration of a grid-connected DGS with the fuel cell and the battery. It consists of a fuel cell, a battery, unidirectional and bidirectional isolated full-bridge DC to DC power converters, a three-phase DC to AC inverter with a $\Delta/Y$ transformer, an L-C output filter, static power switches, a wire impedance, and a grid.

![Figure 5.1: Configuration for a grid-connected DGS](Image)

Figure 5.2 describes a real system diagram of the grid-connected DGS that consists of a reformer, stack, a fuel processor, a unidirectional boost converter, a bidirectional buck/boost converter, a three-phase DC to AC inverter with a $\Delta/Y$ transformer, a supervisory controller, two DSP controllers, a static switch, and a 3-phase grid. As represented in Figure 5.2, the fuel processor controls the reformer to produce
hydrogen for the power requested from the supervisory controller, and monitors the stack current and voltage. The supervisory controller communicates with the fuel processor controller to equalize the power available from the stack to the power requested by the grid, and to coordinate protections of the fuel cell. Moreover, it controls the DSP controller 1 and 2 for the DC and AC power regulation with measured output voltages and currents.

The DSP controller 1 handles two DC to DC power converters for the fuel cell and the battery, which regulate DC-link bus voltage and compensate for the fuel cell’s slow dynamic response during transient. On the other hand, the DSP controller 2 manages the three-phase DC to AC inverter and the static switch that disconnects the DGS from the grid under a fault of the grid. Also, it controls the real power (P) and
reactive power (Q) requested from the grid as well as AC output voltage, and deals with synchronization between an islanding mode and a paralleling mode to the grid.

5.2.2 Two Scenarios of a Grid-Connected DGS

In this dissertation, two scenarios for a grid-connected fuel cell based DGS are demonstrated in Figure 5.3: (a) when DGS > load, i.e., the DGS feeds electric power to both the local load and the grid, and (b) when DGS < load, i.e., both the DGS and the grid deliver electric power to the load.

The scenario of Case 1 shown in Figure 5.3 (a) is as follows. This is the case that the power which the DGS can provide is larger than the power which the local load demands. The DGS starts up with the local load until it arrives at a steady-state. After a phase angle of the DGS output voltage is synchronized with that of the grid voltage, the static switch between the DGS and the grid is closed. Then the DGS begins to deliver P and Q to the grid as well as the local load. When a fault occurs at the grid, the static switch is disconnected, and then the DGS supplies the isolated local load at an islanding mode. After the grid is recovered from the fault, the previous process is repeated to connect the DGS to the grid.

The scenario of Case 2 depicted in Figure 5.3 (b) is in the following. It is the case that the power which the DGS can provide is smaller than the power that two local loads demand. The DGS autonomously operates with load 1 until it gets to steady-state. The phase difference between the DGS output voltage and the grid voltage decreases until the DGS output voltage is in phase with the grid voltage. After the DGS output voltage is
synchronized with the grid voltage, the static switches “1” and “2” are connected, and then the grid starts providing electric power to the load 2. The static switches “1” and “2” are disconnected under a fault of the grid, and then the DGS feeds only load 1 at an islanding mode. When the grid is recovered from the fault, a reconnected sequence with the DGS and the grid is repeated by the previous process.

Figure 5.3: New scenarios of a grid-connected DGS (a) Case 1 (b) Case 2
5.2.3 Real Power (P) and Reactive Power (Q) Control

For real power (P) and reactive power (Q) control of the DGS connected to the grid, an equivalent circuit is represented by two voltage sources through line impedance with pure inductances L in Figure 5.4. It is considered that E is the DGS output voltage and V is the grid voltage.

\[
\begin{align*}
S &= P + jQ = V \cdot I^* \\
I^* &= \left[ \frac{E \cos \delta + jE \sin \delta - V}{j\omega L} \right]^* \\
\therefore S &= V \left[ \frac{E \cos \delta + jE \sin \delta - V}{j\omega L} \right]^*
\end{align*}
\]

where, \(\delta\) denotes the phase angle between the DGS output voltage and the grid voltage.

Figure 5.4: Equivalent circuit of the DGS connected to the grid
From (5.3), the active and reactive power flowing from the DGS to the grid can be obtained below:

\[ P = \frac{EV}{\omega L} \sin \delta \]  \hspace{1cm} (5.4)

\[ Q = \frac{EV \cos \delta - V^2}{\omega L} \]  \hspace{1cm} (5.5)

From equations (5.1) through (5.5), it can be seen that, if \( \delta \) is small enough, then the real power flow is mostly influenced by the power angle (\( \delta \)), while the reactive power flow predominantly depends on the DGS output voltages E. This means that to certain extent the real and reactive power flow can be controlled independently. Since controlling the frequencies dynamically controls the power angles, the real power flow control can be equally achieved by controlling the frequencies of the voltages generated by the DGS.

Therefore, the power angle and the DGS output voltage magnitude are critical variables that can directly control the real and reactive power flow. Figures 5.5 and 5.6 show that the output active/reactive power of the DGS is a function of the power angle (\( \delta \)) along with the DGS output voltage E and line reactance X, respectively. Note that Figure 5.5 (a) and Figure 5.6 (a): \( X = 0.4363 \text{ pu}, \delta = -90^\circ \sim +90^\circ, \text{ and } E = 0.58 \sim 1.41 \text{ pu}, \)

Figure 5.5 (b): \( X = 0.21 \sim 0.87 \text{ pu}, \delta = -90^\circ \sim +90^\circ, \text{ and } E = 1 \text{ pu}, \text{ and Figure 5.6 (b): } X = 0.21 \sim 0.87 \text{ pu}, \delta = 0^\circ, \text{ and } E = 0.58 \sim 1.41 \text{ pu}. \)
Figure 5.5: Active power vs. power angle ($\delta$)

(a) Active power (P) vs. power angle ($\delta$) vs. DGS output voltage (E)

(b) Active power (P) vs. power angle ($\delta$) vs. line reactance (X)
Figure 5.6: Reactive power vs. power angle ($\delta$)

(a) Reactive power (P) vs. DGS output voltage (E) vs. power angle ($\delta$)

(b) Reactive power (P) vs. DGS output voltage (E) vs. line reactance (X)
CHAPTER 6

Z-SOURCE CONVERTER

6.1 Introduction

This chapter will present a configuration in detail of a Z-source converter that can boost a DC-link voltage by employing L-C impedance components and a shoot-through without any boost converter in a standalone AC power plant. In this chapter, a dynamic model of a fuel cell, Space Vector PWM (SVPWM) implementation, and a system model will be described. Design of closed-loop controllers will be studied in Chapter 7.

6.2 Modeling of Fuel Cell

As shown in Figure 6.1, in case that hydrogen is indirectly produced by the reformer, the fuel cell generation system consists of three parts: a reformer, stack, and power converters. The reformer produces hydrogen gas from fuels and the stack generates DC electric power by an electrochemical reaction of hydrogen and oxygen. The power converters convert a low DC voltage from the fuel cell to a high DC voltage or a sinusoidal AC voltage.
For dynamic modeling of the fuel cells, the reformer and stack are further described because a dynamic response of the fuel cell systems is determined by them. Figure 6.2 shows a block diagram of the reformer and stack to illustrate DC power generation. The reformer affects the dynamics of the fuel cell system because it takes several to tens of seconds to convert the fuel into the hydrogen, depending on the power demand. Therefore, the dynamics of the reformer may be represented by a second order model [68] or a first order time delay model [69].

The dynamic response of the stack is considered to have a faster response due to the electrochemical process of hydrogen and oxygen compared to that of the reformer. In Figure 6.2, the output of the stack shows a family of voltage-current curves for various hydrogen mass flow rates. That is, the maximum cell current and stack voltage increase as the hydrogen mass flow rate increases. As a result, the dynamic response of the reformer and stack, and a cell voltage-current curve need to be modeled for more realistic analysis of the fuel cell systems.
In this research, an R-C circuit model is used to realize slow dynamics caused by a chemical/electrical response of the reformer and stack as depicted by Figure 6.3. As represented by Figure 6.3, the reformer and stack are modeled by $R_r$ and $C_r$, and $R_s$ and $C_s$, respectively [69]. In this model, the voltage-current polarization curve of the stack is also considered. In Figure 6.2, the maximum cell current or the stack voltage for each hydrogen flow rate should be represented as a sharp drop of cell voltage due to primarily starvation of the hydrogen. However, in this study, an ohmic region of the V-I polarization curve given in Figure 2.5 is used because the fuel cell primarily operates in this region.
6.3 Configuration of Fuel Cell Based Z-source Converter

The Z-source converter is based on a new concept different from a conventional DC to DC or DC to AC power converter [84]-[86]. In the conventional 3-phase voltage source inverter (VSI), the shoot-through that both power switches in a leg are at once turned on must be avoided because it causes a short circuit. The traditional three-phase VSI has eight switching vectors that consist of six active vectors (V₁-V₆) and two zero vectors (V₀, V₇). On the other hand, the Z-source converter has one more vector (i.e., the shoot-through zero vector) besides eight switching vectors. The Z-source converter utilizes the shoot-through to directly step up a DC source voltage without a boost DC/DC power converter. Thus, a boosted voltage rate depends on total duration (Tₐ) of the shoot-through zero vectors over one switching period (Tₛ).

Figure 6.4 shows the total system diagram of a fuel cell based Z-source converter that consists of a reformer, stack, a fuel processor controller, a Z-source converter, a PWM inverter DSP controller, and a 3-phase load. As described in this figure, the fuel processor controls the reformer to produce hydrogen for power requested from the PWM inverter DSP controller. The controller monitors the stack current and voltage to assure the proper operation of the fuel cell. The PWM inverter DSP controller communicates with the fuel processor controller to equalize power available from the stack to the power requested by the load, and controls the Z-source converter, and senses output voltages/currents for a closed-loop control.
Figure 6.4: System diagram of a fuel cell based Z-source converter

Figure 6.5: Detailed configuration of the Z-source converter system

Figure 6.5 shows a detailed system configuration of the Z-source converter with fuel cell. The filter capacitors \(C_f\) to filter out harmonics of the inverter output voltage.
due to the PWM technique are added to the conventional Z-source converter. In Figure 6.5, the system consists of a fuel cell, a diode, impedance components (L_1, L_2, C_1, and C_2), a three-phase inverter, an output filter (L_f and C_f), and a 3-phase load. The diode between the fuel cell and Z-source converter is required to prevent a reverse current that can damage the fuel cell. Also, the output voltage (V_{in}) of fuel cell, capacitor voltage (V_{C2}), inverter output current (I_i), and line-to-line load voltage (V_L) are measured to implement the feedback control.

6.4 Circuit Analysis/System Modeling/SVPWM Implementation

This section will analyze the circuit model of a Z-source converter and a state space system model will be given for feedback controller design. In addition, a conventional space vector PWM technique will be modified to implement a shoot-through zero vector.

6.4.1 Circuit Analysis

The Z-source converter proposed by Peng [84] is based on a new concept completely different from a conventional DC/AC power converter. In the conventional 3-phase voltage source inverter (VSI), the shoot-through that both switches in a leg are simultaneously turned on must be avoided because it causes a short circuit and then kills power devices. Therefore, the traditional three-phase VSI has only eight basic switching vectors that consists of six active vectors V_1-V_6 (which impress the DC-link voltage on
the load) and two zero vectors $V_0, V_7$ (which do not impress the DC-link voltage on the load). However, the Z-source converter has one more vector (i.e., the shoot-through zero vector that are called the third zero state) in addition to eight basic switching vectors. That is, it utilizes the shoot-through in order to directly boost a DC source voltage without a boost DC/DC power converter because the topology of the Z-source converter makes the boost feature possible. Also, a boosted voltage rate absolutely depends on total duration ($T_a$) of the shoot-through zero vectors over one switching period ($T_z$).

To explain the operating principle of the Z-source converter in detail, the equivalent circuit model of the Z-source converter is shown in Figure 6.6 when Figure 6.5 is viewed from the DC-link. Figure 6.6 (a) shows the equivalent circuit of the Z-source converter in the shoot-through zero vectors, while Figure 6.6 (b) shows that of the Z-source converter in the non-shoot-through switching vectors [84].

![Figure 6.6: Equivalent circuit of the Z-source converter](image)

(a) In the shoot-through zero vectors (b) In the non-shoot-through switching vectors
If we assume that inductor \( L_1 \) and capacitor \( C_1 \) are equal to inductor \( L_2 \) and capacitor \( C_2 \), respectively, we can obtain the following equations from one of shoot-through zero vectors and one of non-shoot-through switching vectors.

\[
V_{C1} = V_{C2} \text{ and } v_{L1} = v_{L2} \quad (6.1)
\]

**Case 1:** one of shoot-through zero vectors (Figure 6.6 (a))

\[
v_{L1} = V_{C1}, \ v_f = 2V_{C1}, \text{ and } v_i = 0 \quad (6.2)
\]

**Case 2:** one of non-shoot-through switching vectors (Figure 6.6 (b))

**loop \( \Phi \):** \( v_{L1} = V_{in} - V_{C1} \)

**loop \( \Theta \):** \( v_{i} = V_{C1} - v_{L1} = 2V_{C1} - V_{in} \quad (6.3) \)

where, \( V_{in} \) is the output voltage of the fuel cell.

Assume that \( T_z = T_a + T_b \), where \( T_z \): switching period, \( T_a \): total duration of shoot-through zero vectors during \( T_z \), and \( T_b \): total duration of non-shoot-through switching vectors during \( T_z \). If we use the fact that the average voltage of the inductors over one switching period \( (T_z) \) is equal to zero in steady state, we can obtain the following equation from (6.2) and (6.3)
\[ V_{L1} = V_{L1} = \int_{0}^{T_z} v_{L1} dt = \frac{T_a \cdot V_{C1} + T_b \cdot (V_{in} - V_{C1})}{T_z} = 0 \]

Therefore,
\[ V_{C1} = \frac{T_b}{T_b - T_a} V_{in} = \frac{1 - \frac{T_a}{T_z}}{1 - 2 \cdot \frac{T_a}{T_z}} V_{in} \tag{6.4} \]

Also, the average DC-link voltage can be expressed as follows
\[ V_i = v_i \int_{0}^{T_z} v_i dt = \frac{T_a \cdot 0 + T_b \cdot (2V_{C1} - V_{in})}{T_z} = \frac{T_b}{T_b - T_a} V_{in} = V_{C1} \tag{6.5} \]

From (6.5), we can know that the average DC-link voltage \( V_i \) is equal to capacitor voltages \( (V_{C1} \text{ or } V_{C2}) \), so the measured \( V_{C1} \) can be used to regulate the DC-link voltage. Next, we can calculate the peak DC-link voltage using (6.3) and (6.4)

\[ V_{p_{\text{DC}}} = 2V_{C1} - V_{in} = \frac{T_z}{T_b - T_a} V_{in} = K \cdot V_{in} \tag{6.6} \]

where,
\[ K = \frac{T_z}{T_b - T_a} = \frac{1}{1 - 2 \cdot \frac{T_a}{T_z}} \geq 1 \tag{6.7} \]

\( K \) is called a boost factor and is always more than one in order to obtain the boosted DC voltage compared to the output DC voltage of the fuel cell. Using (6.6), a peak phase voltage of inverter output can be written as
\[ V_{a_p} = M \cdot \frac{V_{p_{DC}}}{2} = M \cdot K \cdot \frac{V_a}{2} \]  
\[ (6.8) \]

where, \( M \) denotes the modulation index.

Finally, from (6.8) we can know that the peak phase voltage \( (V_{a_p}) \) of the inverter output definitely depends on both the modulation index \( (M) \) and the boost factor \( (K) \), and from (6.7) the boost factor \( (K) \) is determined by a ratio \( \frac{T_a}{T_z} \).

\[ T_z = T_a + T_b \quad \Rightarrow \quad 1 = \frac{T_a}{T_z} + \frac{T_b}{T_z} (= M) \]  
\[ (6.9) \]

Moreover, sum of the modulation index \( (M=\frac{T_b}{T_z}) \) and the ratio \( \frac{T_a}{T_z} \) is always equal to unity because \( \frac{T_b}{T_z} \) is related to the non-shoot-through vectors while \( \frac{T_a}{T_z} \) is to the shoot-through zero vectors as expressed in (6.9).

6.4.2 System Modeling

Figure 6.7 shows a simplified circuit model of Figure 6.5 for an analytic modeling of the Z-source converter using fuel cells [85]-[86]. As described in Figure 6.7, the system consists of a DC voltage source, a three-phase inverter, an output filter \( (L_f \text{ and } C_f) \), and a 3-phase load. Notice that a fuel cell, a diode \( (D) \), and impedance components \( (L_1, L_2, C_1, \text{and } C_2) \) are replaced with a DC-link voltage source \( (V_{dc}) \) for circuit modeling, and \( V_{dc} \) denotes the average DC-link voltage which is also equal to the voltages \( (V_{C1} \text{ and } V_{C2}) \) of two capacitors \( (C_1 \text{ and } C_2) \).
Figure 6.7: Simplified circuit model of the Z-source converter

The simplified circuit model illustrated in Figure 6.7 uses the following quantities. The inverter output line-to-line voltage is represented by the vector \( \mathbf{V}_i = [V_{iAB} \ V_{iBC} \ V_{iCA}]^T \), and the three-phase inverter output currents are \( i_A, i_B, \) and \( i_C \). From these currents, a vector is defined as \( \mathbf{I}_i = [i_{iAB} \ i_{iBC} \ i_{iCA}]^T = [i_A-i_B \ i_B-i_C \ i_C-i_A]^T \). Also, the load line-to-line voltage and phase current vectors can be represented by \( \mathbf{V}_L = [V_{LAB} \ V_{LBC} \ V_{LCA}]^T \) and \( \mathbf{I}_L = [i_{LA} \ i_{LB} \ i_{LC}]^T \), respectively.

The L-C output filter in Figure 6.7 yields the following current and voltage equations:

\[
\begin{align*}
\frac{dV_{LAB}}{dt} &= \frac{1}{3C_f}i_{iAB} - \frac{1}{3C_f}(i_{LA} - i_{LB}) \\
\frac{dV_{LBC}}{dt} &= \frac{1}{3C_f}i_{iBC} - \frac{1}{3C_f}(i_{LB} - i_{LC}) \\
\frac{dV_{LCA}}{dt} &= \frac{1}{3C_f}i_{iCA} - \frac{1}{3C_f}(i_{LC} - i_{LA}) \\
\frac{di_{iAB}}{dt} &= -\frac{1}{L_f}V_{LAB} + \frac{1}{L_f}V_{LAB} \\
\frac{di_{iBC}}{dt} &= -\frac{1}{L_f}V_{LBC} + \frac{1}{L_f}V_{LBC} \\
\frac{di_{iCA}}{dt} &= -\frac{1}{L_f}V_{LCA} + \frac{1}{L_f}V_{LCA}
\end{align*}
\]  \hspace{1cm} (6.10)
Rewrite (6.10) into a matrix form, respectively:

\[
\frac{dV_L}{dt} = \frac{1}{3C_f} I_i - \frac{1}{3C_f} T_i I_L \\
\frac{dI_i}{dt} = -\frac{1}{L_f} V_L + \frac{1}{L_f} V_i
\]  

(6.11)

where, \( T_i = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \).

For implementation of space vector PWM (SVPWM), the above state equations (6.11) can be transformed from the \( abc \) reference frame to the stationary \( dq \) reference frame that consists of the horizontal (d) and vertical (q) axes. That is, the Clarke transformation which outputs a two coordinate time variant system (i.e., the \( abc \) system to the \( dq \) coordinate system) is given by (6.12)

\[
f_{dq0} = K_s f_{abc}
\]

(6.12)

where, \( K_s = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix} \), \( f_{dq0}=[f_d f_q f_0]^T \), \( f_{abc}=[f_a f_b f_c]^T \), and \( f \) denotes either a voltage or a current variable.
Based on the (6.12), the state equation (6.11) can be expressed as (6.13):

\[
\begin{align*}
\frac{dV_{Ldq}}{dt} &= \frac{1}{3C_f}I_{idq} - \frac{1}{3C_f}T_{idq}I_{Ldq} \\
\frac{dI_{idq}}{dt} &= -\frac{1}{L_f}V_{Ldq} + \frac{1}{L_f}V_{idq}
\end{align*}
\]  

(6.13)

where, \( T_{idq} = [K_s T K_s^{-1}]_{row, column, 1,2} = \frac{3}{2} \begin{bmatrix} 1 & -\frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & 1 \end{bmatrix} \).

Finally, we assume that the \( L_f, C_f \) parameters in the network are constant, the given plant model (6.13) can be expressed as the following continuous-time state space equation for a linear time-invariant (LTI) system

\[
\dot{X}(t) = AX(t) + Bu(t) + Ed(t)
\]  

(6.14)

where, 

\[
X = \begin{bmatrix} V_{Ldq} \\ I_{idq} \end{bmatrix}_{4 \times 1}, \quad A = \begin{bmatrix} 0_{2 \times 2} & \frac{1}{3C_f}I_{2 \times 2} \\ -\frac{1}{L_f}I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix}_{4 \times 4}, \quad B = \begin{bmatrix} 0_{2 \times 2} \\ \frac{1}{L_f}I_{2 \times 2} \end{bmatrix}_{4 \times 2}
\]

\[
u = \begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix}_{2 \times 1}, \quad E = \begin{bmatrix} -\frac{1}{3C_f}T_{idq} \\ 0_{2 \times 2} \end{bmatrix}_{4 \times 2}, \quad d = [I_{Ldq}]_{2 \times 1} = \begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix}_{2 \times 1}.
\]

Note that the line-to-line load voltage \( V_{Ldq} \) and inverter output current \( I_{idq} \) are the state variables of the system, the inverter output line-to-line voltage \( V_{idq} \) is the control input \((u)\), and the load current \( I_{Ldq} \) is defined as the disturbance \((d)\).
6.4.3 Space Vector PWM Implementation

Most of pulse-width modulation (PWM) schemes can be used to realize the Z-source converter. In this research, a space vector PWM technique (SVPWM) is chosen to implement the Z-source converter because of less harmonic distortion in the output voltages and more efficient use of supply voltage [87].

For realization of SVPWM, a three-phase voltage or current vector in the $abc$ reference frame is transformed into a vector in the stationary $dq$ coordinate frame. Figure 6.8 shows eight possible switching vectors of on and off patterns for the three upper power transistors that feed the three-phase DC to AC inverter. Six non-zero vectors ($V_1$ - $V_6$) forms the axes of a hexagonal, and two zero vectors ($V_0$ and $V_7$) are at the origin. Also, the vectors divide the plane into six sectors, and the angle between any adjacent two non-zero vectors is 60 degrees.

![Figure 6.8: Basic space vectors and switching patterns](image-url)
To generate the same voltage as $\bar{u}_{\text{ref}}$, we should determine three switching durations ($T_1$, $T_2$, $T_0$) using the most adjacent two voltage vectors within a constant period ($T_z$). Assuming the case of the sector 1 in Figure 6.8, the following equation (6.15) is derived:

$$\int_0^{T_z} \bar{V}_{\text{ref}} = \int_0^{T_1} \bar{V}_1 dt + \int_0^{T_1+T_2} \bar{V}_2 dt + \int_0^{T_2} \bar{V}_0$$

$$\therefore T_z \cdot \bar{V}_{\text{ref}} = (T_1 \cdot \bar{V}_1 + T_2 \cdot \bar{V}_2)$$

(6.15)

$$\Rightarrow T_z \cdot \bar{V}_{\text{ref}} = \begin{bmatrix} \cos(\alpha) \\ \sin(\alpha) \end{bmatrix} = T_1 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix} + T_2 \cdot \frac{2}{3} \cdot V_{dc} \cdot \begin{bmatrix} \cos(\pi/3) \\ \sin(\pi/3) \end{bmatrix}$$

(where, $0 \leq \alpha \leq 60^\circ$)

Therefore, each switching time interval can be calculated as follows:

$$T_1 = T_z \cdot a \cdot \frac{\sin(\pi/3 - \alpha)}{\sin(\pi/3)}$$

$$T_2 = T_z \cdot a \cdot \frac{\sin(\alpha)}{\sin(\pi/3)}$$

$$T_0 = T_z - (T_1 + T_2)$$

(6.16)

Based on the above conventional SVPWM technique to calculate $T_1$, $T_2$, and $T_0$, a new duration ($T = T_\alpha/3$) should be added to or subtracted from the traditional SVPWM in order to boost the DC-link voltage of the Z-source converter and to generate the sinusoid AC output voltage. As mentioned in the previous section, the rate of DC-link boosted voltage is determined by the total duration ($T_\alpha$) of shoot-through zero vectors that at once
turn on both power switches in a leg. Figure 6.9 shows both the conventional and
modified switching patterns for the Z-source converter at each sector. In Figure 6.9, each
phase leg still switches on and off once per switching cycle (Tz), and each phase has only
one shoot-through zero state (T) during one period (Tz) in any sector without the change
of total zero vectors (V0, V7, and T) and total nonzero switching vectors (V1 – V6). Even
if the output voltage of inverter and DC-link voltage can be controlled by adjusting T_a,
the maximum available shoot-through interval (T_a) to boost the DC-link voltage (v_i) is
restricted by the zero vector duration (T_0/2) which is determined by the modulation index
(m = a⋅(4/3)).
Figure 6.9: Modified SVPWM implementation (Continued)

(a) Sector 1 (b) Sector 2 (c) Sector 3 (d) Sector 4 (e) Sector 5 (f) Sector 6
Figure 6.9 continued
Figure 6.9 continued
To help understand implementation of the modified space vector PWM based on the Z-source converter, the switching time of the upper switches and the lower switches in a 3-phase inverter is summarized in Table 6.1. Note that when the shoot-through duration (T) is equal to zero, the switching time of each power switch for the Z-source converter is exactly the same as that for the conventional one.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Upper switches (S1, S3, S5)</th>
<th>Lower switches (S4, S6, S2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S1 = T1 + T2 + T0 /2 + T</td>
<td>S4 = T0 /2</td>
</tr>
<tr>
<td></td>
<td>S3 = T2 + T0 /2</td>
<td>S6 = T1 + T0 /2 + T</td>
</tr>
<tr>
<td></td>
<td>S5 = T0 /2 - T</td>
<td>S2 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td>2</td>
<td>S1 = T1 + T0 /2</td>
<td>S4 = T2 + T0 /2 + T</td>
</tr>
<tr>
<td></td>
<td>S3 = T1 + T2 + T0 /2 + T</td>
<td>S6 = T0 /2</td>
</tr>
<tr>
<td></td>
<td>S5 = T0 /2 - T</td>
<td>S2 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td>3</td>
<td>S1 = T0 /2 - T</td>
<td>S4 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td></td>
<td>S3 = T1 + T2 + T0 /2 + T</td>
<td>S6 = T0 /2</td>
</tr>
<tr>
<td></td>
<td>S5 = T2 + T0 /2</td>
<td>S2 = T1 + T0 /2 + T</td>
</tr>
<tr>
<td>4</td>
<td>S1 = T0 /2 - T</td>
<td>S4 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td></td>
<td>S3 = T1 + T0 /2</td>
<td>S6 = T2 + T0 /2 + T</td>
</tr>
<tr>
<td></td>
<td>S5 = T1 + T2 + T0 /2 + T</td>
<td>S2 = T0 /2</td>
</tr>
<tr>
<td>5</td>
<td>S1 = T2 + T0 /2</td>
<td>S4 = T1 + T0 /2 + T</td>
</tr>
<tr>
<td></td>
<td>S3 = T0 /2 - T</td>
<td>S6 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td></td>
<td>S5 = T1 + T2 + T0 /2 + T</td>
<td>S2 = T0 /2</td>
</tr>
<tr>
<td>6</td>
<td>S1 = T1 + T2 + T0 /2 + T</td>
<td>S4 = T0 /2</td>
</tr>
<tr>
<td></td>
<td>S3 = T0 /2 - T</td>
<td>S6 = T1 + T2 + T0 /2 + 2T</td>
</tr>
<tr>
<td></td>
<td>S5 = T1 + T0 /2</td>
<td>S2 = T2 + T0 /2 + T</td>
</tr>
</tbody>
</table>

Table 6.1 Switching time duration at each sector
7.1 Introduction

This chapter will present in detail design of feedback control systems about two topologies of distributed generation systems (DGS) illustrated in the previous chapters: Topology 1 (both fuel cell and battery) and Topology 2 (only fuel cell). The topology 1 is for standalone DGS and a grid-connected DGS, while the topology 2 is for Z-source converter in a standalone operation.

7.2 Topology 1

In this section, distributed generation systems with the battery in parallel with the fuel cell will be studied. Control system design of full-bridge DC to DC power converters, three-phase DC to AC inverters without or with a Δ/Y transformer will be presented for three configurations in a standalone power plant (a single DGS unit and two DGS units) and a grid-connected DGS.
7.2.1 Full-Bridge DC to DC Power Converters

Based on the circuit model in Figure 4.5, two full-bridge DC to DC power converters have to boost low DC voltage of the fuel cell and battery, and regulate tightly the DC-link voltage \( V_{dc} \) to a required voltage in spite of fuel cell output voltage fluctuating according to load. Moreover, a bidirectional DC to DC power converter for the battery should backup the fuel cell with a slow dynamic response during transient behavior.

To realize the factors above, a new topology with a static switch \( S_B \) on the side of battery which can control both directional power flows is proposed in Figure 4.5. Figure 7.1 (a) and (b) show waveforms of power transistors for battery discharge and recharge, respectively. As depicted in the figures, a phase-shifted angle (\( \delta \)) is controlled to meet the power demand and regulate DC-link voltage \( V_{dc} \) to a desired value.

During start-up or rapid load increase as shown in Figure 7.1 (a), the power converters (\( F_1 \) to \( F_4 \), \( B_1 \) to \( B_4 \)) run as a phase-shifted full-bridge converter and all power switches of the power converter (\( B_{11} \) to \( B_{44} \)) on the secondary side of battery’s transformer are turned off. Additionally, the static switch \( S_B \) is turned on for the battery to backup the fuel cell during transient.

For rapid load decrease or steady-state as illustrated in Figure 7.1 (b), the power converters (\( F_1 \) to \( F_4 \), \( B_{11} \) to \( B_{44} \)) operate as a phase-shifted full-bridge converter, whereas the power converter (\( B_1 \) to \( B_4 \)) on the primary side of battery’s transformer acts as a regular PWM full-bridge converter. Also, the static switch \( S_B \) is turned off for absorption of overcharged power or battery recharge in steady-state time.
Figure 7.1: Waveforms of power switches for DC to DC power converters

(a) Battery discharge (b) Battery recharge
Figure 7.2 shows a control block diagram of unidirectional and bidirectional full-bridge DC to DC converters. In Figure 7.2, load current $I_L$, fuel cell current $I_{F2}$ on the high voltage side, battery voltage $V_B$ and DC-link voltage $V_{dc}$ are measured to perform closed-loop control. Note that high frequency components of all measured currents are filtered out by low-pass filter for accurate voltage and current control.

As represented by Figure 7.2, control variables of two DC to DC power converters are phase-shifted angles ($\delta_f$, $\delta_b$), where $\delta_f$ is a phase-shifted angle for the fuel cell and $\delta_b$ is a phase-shifted angle for the battery, and there exist three main loops: start-up, $|e_i| > \lambda$, and $|e_i| < \lambda$, where $e_i = I_L - I_{F2}$ and $\lambda$ is a small positive value.
During start-up, phase-shifted angles ($\delta_f, \delta_b$) of two power converters are given by “Profile A” predetermined for soft starting. For $|e_i| > \lambda$, a difference between a filtered load current ($I_L$) and a filtered fuel cell current ($I_{F2}$) is used to determine either “load increase” or “load decrease”. The angles are determined by “Profile B” and “Profile C” which meet dynamic characteristics of the fuel cell and battery, depending on load increase or load decrease. If the difference is positive, “Profile B” is selected for the battery to backup the fuel cell. On the other hand, if the difference is negative, “Profile C” is chosen so that the battery can absorb electric energy overflow from the fuel cell due to abrupt load decrease.

After $|e_i|$ goes within $\lambda$, an adaptive proportional controller is used to regulate the DC-link voltage $V_{dc}$ and a discrete-time PI controller is used to recharge the battery from the fuel cell until the battery voltage $V_B$ reaches a nominal value. The adaptive controller is designed to prevent abrupt switching action which can cause a large amount of current ripple by properly adjusting the gain according to the error between reference DC-link voltage $V^*_{dc}$ and measured voltage $V_{dc}$. Also, if fuel cell stack current $I_F$ and battery current $I_B$ are above the limit which can damage cells, two power converters will shut down.

7.2.2 Three-Phase DC to AC Inverter

This section will present control system design of three applications: a single DGS unit and two DGS units in a standalone power generation, and a grid-connected DGS unit.
7.2.2.1 Standalone (A Single DGS Unit)

From the circuit model shown in Figure 4.7, to supply a qualified AC power to the local load connected to the DGS, good performance such as a low THD, a fast transient response, over-current protection should be guaranteed under linear load, nonlinear load, and even resistive load step changes.

![Figure 7.3 Control block diagram of a three-phase DC to AC inverter](image)

Figure 7.3 shows a control block diagram of a three-phase DC to AC inverter without a Δ/Y transformer. As illustrated in Figure 7.3, two discrete-time sliding mode controllers (DSMC) are proposed to perform a zero steady state tracking error, THD reduction, and fast and no-overshoot response: current controller in the inner loop and voltage controller in the outer loop. The DSMC is suitable for digital implementation since it does not exhibit the chattering phenomena due to direct digital implementation of continuous time sliding mode control [91].
A. Current Controller in the Inner Loop

For design of a discrete-time current controller, the continuous-time state space equation (4.4) of the plant can be transformed to a discrete form:

\[
\begin{cases}
X(k + 1) = A^* X(k) + B^* u(k) + E^* d(k) \\
y_1(k) = C_1 X(k) \\
e_{idq}(k) = y_1(k) - y_{1 \_ref}(k)
\end{cases}
\]  

(7.1)

where, \( y_1 = [I_{idq}] \), \( y_{1 \_ref} = [I^*_{idq}] \), \( C_1 = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \), \( d = [I_{Lqd}] \), \( A^* = e^{A T_s} \),

\[
B^* = \int_0^{T_s} e^{A (T_s - \tau)} B d \tau, \quad E^* = \int_0^{T_s} e^{A (T_s - \tau)} E d \tau.
\]

In order to control the output \( y_1(k) \) to follow the reference \( y_{1 \_ref}(k) \), a sliding mode manifold can be selected as

\[
s(k) = y_1(k) - y_{1 \_ref}(k) = C_1 X(k) - y_{1 \_ref}(k)
\]  

(7.2)

Therefore, the discrete-time sliding mode can be reached if the control input \( u(k) \) is designed as the solution of:

\[
s(k + 1) = y_1(k + 1) - y_{1 \_ref}(k + 1) \\
= C_1 A^* X(k) + C_1 B^* u(k) + C_1 E^* \dot{d}(k) - y_{1 \_ref}(k + 1) = 0
\]  

(7.3)
The control law that satisfies (7.3) and yields motion in the manifold \( s(k) = 0 \) is called ‘equivalent control’ and is given below:

\[
\mathbf{u}_{eq}(k) = \left( C_i \mathbf{B}^s \right)^{-1} \left( \mathbf{f}_d(k) - C_i \mathbf{A}^s \mathbf{X}(k) - C_i \mathbf{E}^s \mathbf{d}(k) \right)
\]  

(7.4)

If the control is limited by \( \| \mathbf{u}(k) \| \leq u_v \), then the following modified control input can be applied:

\[
\mathbf{u}(k) = \begin{cases} 
\mathbf{u}_{eq}(k) & \text{for } \| \mathbf{u}_{eq}(k) \| \leq u_v \\
\frac{u_v}{\| \mathbf{u}_{eq}(k) \|} \mathbf{u}_{eq}(k) & \text{for } \| \mathbf{u}_{eq}(k) \| > u_v
\end{cases}
\]

(7.5)

With control law (7.5), the discrete-time sliding mode can be reached after a finite number of steps and the control voltage limit \( u_0 \) is also determined by the SVPWM inverter.

B. Voltage Controller in the Outer Loop

For the dynamics of the DSMC to be included in the outer loop, its model has to be combined with the original plant. After the dynamics (7.4) of the DSMC is included in (7.1), the overall plant can be expressed as:
\[
\begin{aligned}
&\begin{cases}
X(k+1) = A_dX(k) + B_du_i(k) + E_dd(k) \\
y(k) = C_dX(k) \\
e_{vdq}(k) = y(k) - y_{ref}(k)
\end{cases} \\
&\text{(7.6)}
\end{aligned}
\]

where,
\[y = [V_{Ldq}] , \quad C_d = [I_{2\times2} \ 0_{2\times2}] , \quad A_d = A^* - B^*(C_iB^*)^{-1}C_iA^* , \quad B_d = B^*(C_iB^*)^{-1} , \]
\[E_d = E^* - B^*(C_iB^*)^{-1}C_iE^* , \quad u_i(k) = I_{cmd, idq}(k).\]

Similarly, a sliding mode manifold may be chosen in the form of:
\[s(k) = C_dX(k) - y_{ref}(k) \tag{7.7}\]

Thus, if the control input \(u_i(k)\) is designed to be the solution of \(s(k+1) = 0\), the sliding manifold can be reached after a finite time and the equivalent control \((u_{1eq})\) is given by:
\[u_{1eq}(k) = (C_dB_d^*)^{-1}(V_{Ldq}^*(k) - C_dA_dX(k) - C_dE_dd(k)) \tag{7.8}\]

If the controller gain is limited by \(|u_i(k)| \leq u_i\), then the following control law can be applied:
\[u_i(k) = \begin{cases} 
  u_{1eq}(k) & \text{for} \|u_{1eq}(k)\| \leq u_i \\
  u_0 & \text{for} \|u_{1eq}(k)\| > u_i
\end{cases} \tag{7.9}\]
7.2.2.2 Standalone (Two DGS Units)

This section will present the control system design of two three-phase PWM inverters used for two DGS units in a standalone AC power plant: P and Q controller for load-sharing, voltage and current controllers.

A. Combined Droop Control Method and Average Power Control Method for Real Power (P) and Reactive Power (Q) Sharing

To assure exact load-sharing of the real power (P) and the reactive power (Q) between DGS units, a new control method which is a combination of droop control method and average power control method is proposed [2]. In this scheme, the sharing of real and reactive powers between each DGS is implemented by two independent control variables: power angle and inverter output voltage amplitude. Especially, the reason why the average power method is used in this research is to significantly reduce the sensitivity about voltage and current measurement error mismatches. Consequently, this technique guarantees good load-sharing of the fundamental components of the load currents [59]-[60]. Furthermore, harmonic sharing control loop is proposed to share the harmonic components of the load currents based on its harmonic contents.

Figure 7.4 shows a Simulink model for an average power generation block. As shown in this figure, an average real power (P_{avg_dq}) and reactive power (Q_{avg_dq}) of each unit are used to ensure proper load-sharing. P_{Qavg_dq1} and P_{Qavg_dq2} of unit 1 and 2 can be easily obtained considering the power capability of each DGS unit. That is, when the
power rating of each unit is identical, both $P_{Q_{avg_{dq}1}}$ and $P_{Q_{avg_{dq}2}}$ are equal to $(PQ_{dq1} + PQ_{dq2})/2)$. Meanwhile, when the power rating of DGS unit 1 is twice that of DGS unit 2, $P_{Q_{avg_{dq}1}}$ and $P_{Q_{avg_{dq}2}}$ are calculated by $2 \cdot (PQ_{dq1} + PQ_{dq2})/3$) and $(PQ_{dq1} + PQ_{dq2})/3)$, respectively.

Figure 7.4: Simulink model for average power ($P_{avg_{dq}}$ and $Q_{avg_{dq}}$) generation

Figure 7.5 shows a Simulink model for the real power sharing control. In this figure, phase angle ($\Delta \theta$) is chosen as the control variable instead of frequency used as a control variable in a conventional droop method because the phase angle is not varied due to constant real power in steady-state time, and then it make the frequency remain at nominal value (60 Hz), unlike some frequency deviations of the conventional droop method.
In Figure 7.5, the difference between real-time active power ($P_\text{d}$ or $P_\text{q}$) of each unit and the rating real power ($P_{0,\text{dq}}$) of each unit is multiplied by a droop coefficient ($m_\text{1}$). In addition, the difference between the active power ($P_\text{d}$ or $P_\text{q}$) of each DGS unit and the average real power ($P_{\text{avg,}\text{dq}}$) is finally equal to zero by a discrete-time integrator in steady-state time. As a result, the active power between the DGS units is properly shared according to the power ratings of each DGS unit.
The Simulink model for the reactive power ($Q_d$ or $Q_q$) sharing control is implemented in Figure 7.6. As described in Figure 7.6, the amplitude of a reference voltage ($V_{max_{dq}}$) is decided by the average reactive power ($Q_{avg_{dq}}$) and the reactive power of each unit. The difference between real-time reactive power ($Q_d$ or $Q_q$) of each unit and the rating reactive power ($Q_{0_{dq}}$) of each unit is multiplied by a droop gain ($n_1$). In addition, by a discrete-time integrator, the reactive power ($Q_d$ or $Q_q$) of each DGS unit is also finally equal to an average reactive power ($Q_{avg_{dq}}$) in steady-state time. In order that the amplitude of the reference load voltage is generated, the nominal load voltage
(V_{nom} (120 \cdot \sqrt{2} \text{ V})) is also added to the results by the droop gains of the average reactive power (Q_{avg, dq}) and the reactive power (Q_d or Q_q).

From Figures 7.5 and 7.6 above, the phase angle and voltage amplitude of the reference load voltage are obtained from the following equations:

**D-Axis**

**Phase angle:**

\[
\phi_d(k + 1) = \phi_d(k) + m_2(P_d - P_{avg, d})
\]

\[
\Delta \theta_d(k) = \phi_d(k) + m_1(P_d - P_{0, d}) \tag{7.10}
\]

\[
\theta_d(k) = \theta_{nom}(k) + \Delta \theta_d(k)
\]

**Amplitude:**

\[
V_d(k + 1) = V_d(k) + n_2(Q_d - Q_{avg, d})
\]

\[
\Delta V_d(k) = V_d(k) + n_1(Q_d - Q_{0, d}) \tag{7.11}
\]

\[
V_{max, d}(k) = V_{nom} + \Delta V_d(k)
\]

**Voltage Reference:**

\[
V^{*}_{Ld}(k) = V_{max, d} \cdot \sin(\theta_d(k)) \tag{7.12}
\]
Q-Axis

Phase angle:

\[ \phi_q(k + 1) = \phi_q(k) + m_2 (P_q - P_{avg\_q}) \]
\[ \Delta \theta_q(k) = \phi_q(k) + m_1 (P_q - P_{0\_q}) \] (7.13)
\[ \theta_q(k) = \theta_{nom}(k) + \Delta \theta_q(k) \]

Amplitude:

\[ V_q(k + 1) = V_q(k) + n_2 (Q_q - Q_{avg\_q}) \]
\[ \Delta V_q(k) = V_q(k) + n_1 (Q_q - Q_{0\_q}) \] (7.14)
\[ V_{max\_q}(k) = V_{nom} + \Delta V_q(k) \]

Voltage Reference:

\[ V^*_{Lq}(k) = V_{max\_q} \cdot \cos(\theta_q(k)) \] (7.15)

where, \( m_1 \) and \( n_1 \): droop gain for real power and reactive power, respectively; \( m_2, n_2 \): error gain between average real power \( (P_{avg\_dq}) \) and real power \( (P_{dq}) \) of each unit, average reactive power \( (Q_{avg\_dq}) \) and reactive power \( (Q_{dq}) \) of each unit, respectively; \( P_{0\_dq}, Q_{0\_dq} \): real and reactive power rating of each unit, respectively; \( V_{nom}, f_{nom} \): nominal voltage amplitude (120\( \cdot \sqrt{2} \) V), nominal frequency (60 Hz), respectively; \( \theta_{nom} \): 2\( \cdot \pi \cdot f_{nom} \cdot t \).

Based on the above equations (7.10) to (7.15), Simulink models for the \( dq \) reference load voltages \( (V^*_{Ld} \) and \( V^*_{Lq} \)) are illustrated in Figure 7.7.
(a) $V_{Ld}^*$ reference voltage

(b) $V_{Lq}^*$ reference voltage

Figure 7.7: Reference voltage ($V_{Ld}^*$ and $V_{Lq}^*$) generation

$m_3 < 0$, $m_5 < 0$, $m_7 < 0$

Figure 7.8: Harmonic sharing droop control loop
The combined droop method and average power control method stated above does not guarantee that the harmonic components of the load current shall be shared because it affects only the phase and magnitude of the fundamental output voltage. A means is required to share the harmonic components of the load currents based on its harmonic contents. The control gains affecting the harmonics in the voltage controller that will be mentioned in the following voltage controller section can be adjusted based on the harmonic contents of the load current at that harmonic frequency. For example, the pole frequencies of the harmonic compensator can be shifted by the harmonic contents of the load current at those frequencies. This is illustrated in Figure 7.8, where $I_3$, $I_5$ and $I_7$ denote the harmonic load currents at fifth and seventh harmonics respectively, and $\omega_3$, $\omega_5$, and $\omega_7$ are the fifth and seventh harmonic frequencies of the harmonic compensator poles. First of all, the harmonic droop loop added has the advantage that it does not degrade the fundamental component; it only affects the individual harmonic when it exists.

The $\omega_3$, $\omega_5$ and $\omega_7$ are computed from the harmonic droop control loop in Figure 7.8 as follows:

$$\omega_3 = \omega_3 + m_3 I_3, \omega_3 = 2\pi \cdot 3 \cdot 60$$

$$\omega_5 = \omega_5 + m_5 I_5, \omega_5 = 2\pi \cdot 5 \cdot 60$$

$$\omega_7 = \omega_7 + m_7 I_7, \omega_7 = 2\pi \cdot 7 \cdot 60$$

So harmonic frequencies of equations (7.24) and (7.25) given in the following section need to be modified from $\omega_3$, $\omega_5$, and $\omega_7$ to $\omega_3'$, $\omega_5'$, and $\omega_7'$ in order to ensure harmonic load-sharing.
The load sharing scheme above is designed around two feedback control loops – the inner loop is used for current control while the outer one is for voltage control. A discrete-time sliding mode controller (DSMC) is applied as the current controller [1]-[2], [86], [91] and a robust servomechanism controller (RSC) is chosen to be the voltage controller [1]-[2], [86], [88], [90]. The DSMC is used in the current loop to limit the inverter current under overload condition because of the fast and no-overshoot response it provides. The RSC is adopted for voltage control due to its capability to perform zero steady state tracking error under the unknown load and eliminate harmonics of any specified frequencies with guaranteed system stability [89]-[90]. In addition, the RSC voltage control loop allows the use of a harmonic control droop scheme which ensures proper sharing of the harmonic components of the load currents.

Figure 7.9: Overall control system structure

Figure 7.9 illustrates the block diagram of the entire closed-loop system structure. In this figure, the RSC is the robust servomechanism controller, the DSMC is the discrete-time sliding mode controller, SVPWM is a three-phase space vector pulse-width
modulation inverter, $u_1$ is the current command signal ($I^*_{idq}$) outputted by the current limiter, $u$ is the inverter voltage command ($V_{idq}$), and $V_i$ is the true inverter output voltage. Quantities under $abc$ reference frame are transformed to those under stationary $dq$ reference frame as shown in the diagram.

As shown in Figure 7.9, the overall system has two feedback loops. The inner loop is the current control loop where the regulator is the DSMC and the outer loop is the voltage control loop where the regulator is the RSC. The RSC and DSMC design will be described as follows.

1) Discrete-Time Sliding Mode Current Controller in the Inner Loop

Figure 7.10 shows the block diagram of discrete-time sliding mode current controller [1]-[2], [86], [91]. As shown in Figure 7.10, the error $e_{idq}$ is used for the input signal of current controller, and the controller generates inverter output voltage command $u$ as a control signal.

Figure 7.10: Discrete-time sliding mode current controller
For the control of the inverter current in the system, only the subsystem represented by equations (4.13) and (4.14) derived in Chapter 4 needs to be considered, where \( I_{sdq} \) acts as a disturbance. Rewrite the equations in a state-space form:

\[
\begin{align*}
\dot{X}_1(t) &= A_1 X_1(t) + B_1 u(t) + E_1 d_1(t) \\
y_1(t) &= C_1 X_1(t)
\end{align*}
\]  
(7.16)

where,

\[
X_1 = \begin{bmatrix} V_{pdq} \\ I_{idq} \end{bmatrix}, \quad A_1 = \begin{bmatrix} 0_{2\times2} & \frac{1}{3C_f} T_{idq} \\ -\frac{1}{L_f} T_{idq}^{-1} & 0_{2\times2} \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0_{2\times2} \\ \frac{1}{L_f} T_{idq}^{-1} \end{bmatrix}, \quad E_1 = \begin{bmatrix} -\frac{1}{3C_f} T_{2dq} \\ 0_{2\times2} \end{bmatrix},
\]

\[
C_1 = [0_{2\times2} I_{2\times2}], \quad u = V_{idq}, \quad d_1 = I_{sdq}, \quad y_1 = I_{idq}.
\]

The 0-axis quantities are not included in the equation (7.16) because they have no impact on the primary side of the transformer. The discrete form of the system in (7.16) can be expressed as

\[
\begin{align*}
X_1(k+1) &= A_1^* X_1(k) + B_1^* u(k) + E_1^* d_1(k) \\
y_1(k) &= C_1 X_1(k) \\
e_{idq}(k) &= y_1(k) - y_{1_{\text{ref}}}(k)
\end{align*}
\]  
(7.17)

where, \( A_1^* = e^{A_1 T_s} \), \( B_1^* = \int_0^{T_s} e^{A_1 (T_s - \tau)} B_1 d\tau \), and \( E_1^* = \int_0^{T_s} e^{A_1 (T_s - \tau)} E_1 d\tau \), assuming sampling period \( T_s \).
It is desired to control the output $y_1(k)$ to follow the reference $y_{1_{\text{ref}}}(k)$. For this purpose we can choose a sliding mode manifold in the form of

$$s(k) = e_{idq}(k) = C_1X_1(k) - y_{1_{\text{ref}}}(k) \tag{7.18}$$

i.e., the tracking error, such that when the discrete-time sliding mode exists, the output $y_1(k)$ tends to the reference $y_{1_{\text{ref}}}(k)$. Discrete-time sliding mode can be reached if the control input $u(k)$ is designed to be the solution of:

$$s(k + 1) = C_1A_1^*X_1(k) + C_1B_1^*u(k) + E_1^*d_1(k) - y_{1_{\text{ref}}}(k + 1) = 0 \tag{7.19}$$

The control law satisfying (7.19) is called ‘equivalent control’ and is given by:

$$u_{eq}(k) = \left( C_1B_1^* \right)^{-1}(I_{idq}(k) - C_1A_1^*X_1(k) - C_1E_1^*d_1(k)) \tag{7.20}$$

If the control input is limited by $\|u(k)\| \leq u_v$, then the following modified control law can be obtained

$$u(k) = \begin{cases} 
    u_{eq}(k) & \text{for } \|u_{eq}(k)\| \leq u_v \\
    u_0 & \text{for } \|u_{eq}(k)\| > u_v 
\end{cases} \tag{7.21}$$
The control voltage limit $u_0$ is determined by the SVPWM inverter. With control law (7.21), discrete-time sliding mode can be reached after a finite number of steps.

2) Discrete-time RSC Voltage Controller in the Outer Loop

Figure 7.11 shows the block diagram of a discrete-time RSC voltage controller with servo-compensator and stabilizing compensator for outer loop regulation. The servo compensator is based on internal model principle, while the stabilizing compensator is based on optimal control theory [1]-[2], [86], [88], [90].

Using the internal modeling principle to a linear time-invariant (LTI) plant, asymptotic tracking of controlled variables toward the corresponding references in the presence of disturbances (zero steady state tracking error) can be achieved if the models that generate these references and disturbances are included in the stable closed loop systems. A simple form of optimal control technique – linear quadratic controller is used
to obtain the feedback gain satisfying a certainly defined optimization criterion. By
minimizing this criterion, the eigenvalues of the state space model will be automatically
placed and the feedback gains will be uniquely selected.

Based on the RSC above, the voltage controller can be designed as follows. Since
the dynamics of the DSMC is included in the inner loop, its model has to be included
together with the original plant to form the control plant for the RSC. From equation
(4.18), the original plant in a discrete form is

\[
X(k + 1) = A^*X(k) + B^*u(k) + E^*d(k) \quad (7.22)
\]

where, \( A^* = e^{AT_s} \), \( B^* = \int_0^{T_s} e^{A(T_s - \tau)} B d\tau \), and \( E^* = \int_0^{T_s} e^{A(T_s - \tau)} E d\tau \).

After the dynamics (7.20) of the DSMC is included in (7.22), the overall plant for the
RSC is:

\[
\begin{cases}
X(k + 1) = A_dX(k) + B_du_1(k) + E^*d(k) \\
y_d(k) = C_dX(k)
\end{cases} \quad (7.23)
\]

where,

\[
A_d = A^* - B^*(C_1B_1^*)^{-1}C_1(A_1^*C_{11} + E_1^*C_{12}) \quad , \quad B_d = B^*(C_1B_1^*)^{-1} \quad , \quad C_{11} = [I_{4\times4} \ 0_{4\times4}] \quad , \\
C_{12} = [0_{2\times6} \ I_{2\times2}] , \ C_d = [0_{2\times2} \ 0_{2\times2} \ I_{2\times2} \ 0_{2\times2}] , \ u_1(k) = I_{cmd,ldq}(k) , \ y(k) = V_{Ldq}(k).
\]

For the above system (7.23), once the existence of the solution to RSP is
confirmed according to the conditions in Theorem 1 [88], assuming the
tracking/disturbance poles are \( \pm j\omega_1, \pm j\omega_3, \pm j\omega_5, \ldots \) (i.e., representing sinusoidal signals with fundamental frequency \( \omega_1 \) and harmonic frequencies \( \omega_3, \omega_5, \ldots \)), the RSC can be designed in the following.

If the tracking/disturbance poles to be considered are \( \pm j\omega_1, \pm j\omega_5, \) and \( \pm j\omega_7, \) the servo-compensator is

\[
\eta = A_c \eta + B_c e_{vdq} \tag{7.24}
\]

where, \( e_{vdq} = V_{Ldq}^* - V_{Ldq} \), \( A_c = \begin{bmatrix} A_{c1} & 0_{4 \times 4} & 0_{4 \times 4} \\ 0_{4 \times 4} & A_{c2} & 0_{4 \times 4} \\ 0_{4 \times 4} & 0_{4 \times 4} & A_{c3} \\ 0_{4 \times 4} & 0_{4 \times 4} & 0_{4 \times 4} \end{bmatrix}_{16 \times 16}, \ B_c = \begin{bmatrix} B_{c1} \\ B_{c2} \\ B_{c3} \\ B_{c4} \end{bmatrix}_{16 \times 2}, \)

\[
A_{ci} = \begin{bmatrix} 0_{2 \times 2} & I_{2 \times 2} \\ -\omega_i^2 \cdot I_{2 \times 2} & 0_{2 \times 2} \end{bmatrix}, \quad B_{ci} = \begin{bmatrix} 0_{2 \times 2} \\ I_{2 \times 2} \end{bmatrix}, \quad \omega_i (i = 1, 2, 3, 4), \ \omega_1 = \omega, \ \omega_2 = 3\cdot\omega, \ \omega_3 = 5\cdot\omega, \ \omega_4 = 7\cdot\omega, \ \omega = 2\pi f, f = \text{fundamental frequency}.
\]

Notice that \( A_{ci} \) has the same poles as the given tracking/disturbance poles and only the 3 \(^{\text{rd}}\), 5 \(^{\text{th}}\) and 7 \(^{\text{th}}\) harmonics are chosen as the disturbance poles because they are the dominant harmonics.

Rewrite (7.24) in discrete form:

\[
\eta(k + 1) = A_c^* \eta(k) + B_c^* e_{vdq}(k) \tag{7.25}
\]

where \( A_c^* = e^{A_c T_s} \) and \( B_c^* = \int_0^{T_s} e^{A_c (T_s - \tau)} B_c d\tau . \)
An augmented system combining both the plant and the servo-compensator can be written as:

\[
\dot{X}(k+1) = \hat{A}X(k) + \hat{B}u_1(k) + \hat{E}_1d(k) + \hat{E}_2y_{d,\text{ref}}(k)
\]  

(7.26)

where,

\[
\begin{align*}
\dot{X}(k) &= \begin{bmatrix} X(k) \\ \eta(k) \end{bmatrix}, \\
\hat{A} &= \begin{bmatrix} A_d & 0 \\ -B_c^*C_d & A_c^* \end{bmatrix}, \\
\hat{B} &= \begin{bmatrix} B_d \\ 0 \end{bmatrix}, \\
\hat{E}_1 &= \begin{bmatrix} E^* \\ 0 \end{bmatrix}, \\
\hat{E}_2 &= \begin{bmatrix} 0 \\ B_c^* \end{bmatrix}, \\
u_1(k) &= I_{\text{cmd, idq}}(k), \\
d(k) &= I_{Ldq}(k), \\
y_{d,\text{ref}}(k) &= V^*_{Ldq}(k).
\end{align*}
\]

The stabilizing compensator, which yields the control signal \( u \) in (7.26), ensures the stability of the overall system including the modes in the plant as well as the servo-compensator and desirable performance of the system through a feedback gain \( K \) which minimizes the linear quadratic performance index (i.e., the optimization criterion) below.

\[
J_\varepsilon = \sum_{k=0}^{\infty} \dot{X}^T(k)Q\dot{X}(k) + \varepsilon u_1^T(k)u_1(k)
\]  

(7.27)

where \( Q \) is a symmetrical positive-definite matrix and \( \varepsilon > 0 \) is a small number, both of which should be selected by the controller designer according to the application.

Therefore, the control input \( (u_1) \) can be expressed by the feedback gain \( K \) obtained from Matlab function \( \text{dlqr()} \) which solves the algebraic Riccati equation for the system (7.27) such that all eigenvalues of matrix \( \hat{A} - K\hat{X} \) exist inside of unit disc. Assuming the system is a linear time-invariant (LTI), the feedback gain \( K \) is a constant.
value calculated by the Matlab function in advance. Thus, the control input ($u_1$) can be taken from the gain $K$ and state variables ($X$ and $\eta$):

$$ u_1(k) = -K \dot{X}(k) = \begin{bmatrix} K_1 & K_2 \end{bmatrix} \begin{bmatrix} X(k) \\ \eta(k) \end{bmatrix} = -K_1X(k) - K_2\eta(k) \quad (7.28) $$

Finally, since the current command signal needs to be limited to protect the system against overload, the algorithm of the current limiter is included in main program as:

$$ I_{\text{idq}}^*(k) = \begin{cases} I_{\text{cmd, idq}}(k) & \text{for } \|I_{\text{cmd, idq}}(k)\| \leq I_{\text{max}} \\ I_{\text{max}} & \text{for } \|I_{\text{cmd, idq}}(k)\| > I_{\text{max}} \end{cases} \quad (7.29) $$

To prevent servo-compensator states, which are related to the current command, from growing while the current command is saturated, the following strategy can be applied. Rewrite the servo-compensator equation as

$$ \eta(k + 1) = A^* \eta(k) + B^* e_1(k) \quad (7.30) $$

where, $e_1(k) = \begin{cases} e_v(k) & \text{if } \|I_{\text{cmd, idq}}\| \leq I_{\text{max}} \\ 0 & \text{otherwise} \end{cases}$
7.2.2.3 Grid-Interconnection

This section will present the control system design of a three-phase PWM inverter used for a grid-connected DGS unit: grid-synchronization, P and Q controller for power flow control, voltage and current controllers.

A. Grid Synchronization

To disconnect or connect the DGS and the grid according to an islanding mode or a grid-connected mode, a technique of grid synchronization needs to be considered.

Figure 7.12: Simulink model for grid synchronization

Figure 7.12 shows a Simulink model for grid synchronization which consists of synchronization start, phase-angle synchronization, and grid-side static switch signal. First, the synchronization start block generates “Synchronization Start signal” and
“Counter Clock.” Second, the phase-angle synchronization block receives the measured grid-terminal voltage \( V_{gt} \) and load phase voltage \( V_L \), the synchronization start signal and counter clock from the synchronization start block as inputs. This block outputs “lag or lead” to indicate if the DGS output voltage \( V_L \) leads or lags the grid voltage \( V_g \), “Phase-angle” that denotes the phase angle of \( V_L \) with respect to that of \( V_g \), “Sync. Starting Delay” to guarantee synchronization of all phases, and “Zero-Crossing Detection of \( V_{gt} \).” Finally, the grid-side static switch signal block produces “Static Switch Signal” to control the static switch \( S_g \) between the DGS and the grid.

![Synchronization Starting Signal](image)

![Grid Voltage \( V_{gtA} \) and DGS Output Voltage \( V_{LA} \) (V)](image)

![Grid Voltage \( V_{gtA} \) and DGS Output Voltage \( V_{LA} \) (V)](image)

Figure 7.13: Simulation results for grid synchronization
Figure 7.13 shows simulation results for grid synchronization. This figure indicates: (1) Synchronization Start Signal, (2) \( V_{gtA} \) and \( V_{LA} \) when the grid-terminal voltage (\( V_{gtA} \)) lags the DGS output voltage (\( V_{LA} \)) behind 80 degrees, and (3) \( V_{gtA} \) and \( V_{LA} \) when the grid-terminal voltage (\( V_{gtA} \)) leads the DGS output voltage (\( V_{LA} \)) by 80 degrees.

As illustrated in Figure 7.13, when the synchronization start signal is applied at 30 msec, the phase angle of the DGS output voltage (\( V_{LA} \)) synchronizes with that of the grid-terminal voltage (\( V_{gtA} \)) at about 220 msec regardless of lagging or leading phase angle.

B. Real Power (P) and Reactive Power (Q) Controller

In order to exactly control the real power (P) and the reactive power (Q) of the DGS supplied to the local load and the grid, the P and Q controllers are designed.

Figure 7.14 shows a Simulink block diagram for the real power (P) control. In this figure, power angle of a reference DGS output voltage (\( V^*_{L} \)) is determined by P. After the static switch (\( S_g \)) between the DGS and the grid is turned on, each discrete-time proportional-integral (PI) controller starts working, and the difference between reference active power (\( P_{ref} \)) and measured grid-terminal active power (\( P_{gt} \)) is used as an input of the PI controller. In Figure 7.14, an output of the PI controller is the power angle (\( \delta \)) which is chosen as the control variable instead of frequency used as a control variable in a conventional droop method. Since the phase angle is not varied due to constant real power in steady-state time, it makes the frequency remain at nominal value (60 Hz),
unlike some frequency deviations of the conventional droop method. Besides, the error between $P_{ref}$ and $P_{gt}$ eventually goes to zero by a discrete-time integrator in steady-state time. As a result, the active power between the DGS and the grid is properly controlled. However, the power angle ($\delta$) is reset to zero in the event of a grid failure.

Figure 7.14: Simulink block diagram for real power (P) control

The Simulink block diagram for the reactive power (Q) control is implemented in Figure 7.15. In this figure, the amplitude of the reference DGS output voltage ($V^*_L$) is decided by $Q$. After the static switch ($S_g$) is turned on, all discrete-time PI controllers start running, and the error between reference reactive power ($Q_{ref}$) and measured grid-terminal reactive power ($Q_{gt}$) is used for an input of the PI controller. The amplitude ($\Delta V_L$) that is an output of the PI controller is used to generate that of the reference
voltage \( (V^*_L) \). In addition, by a discrete-time integrator, the \( Q_{ref} \) is equal to the \( Q_{gt} \) in steady-state time. Meanwhile, the amplitude \( (\Delta V_L) \) is reset to zero when a fault occurs at the grid.

![Simulink block diagram for reactive power (Q) control](image)

**Figure 7.15: Simulink block diagram for reactive power (Q) control**

Based on Figures 7.12, 7.14 and 7.15, the phase angle and amplitude of the reference DGS output voltage \( (V^*_{LA}) \) are generated as follows. The phase difference \( (\theta_{sync}) \) between the DGS and the grid is added to the power angle \( (\delta) \) by the real power controller, and then the result is also added to the nominal phase angle \( (\theta_{nom}) \). On the other hand, in order that the amplitude \( (V_{L,amp}) \) of the reference DGS voltage is generated, the nominal load voltage \( (V_{nom}) \) is also added to the result \( (\Delta V_L) \) by the
reactive power controller. In consequence, the equations of the phase angle ($\theta$) and the amplitude ($V_{L\_\text{amp}}$) in phase “a” are summarized below.

**Phase angle:**

\[
\delta_i(k + 1) = \delta_i(k) + m_1(P_{\text{ref}} - P_{\text{grid}})
\]

\[
\delta(k) = \delta_i(k) + m_2(P_{\text{ref}} - P_{\text{grid}})
\]

\[
\theta(k) = \theta_{\text{nom}}(k) + \theta_{\text{sync}}(k) + \delta(k)
\]

**Amplitude:**

\[
\Delta V_i(k + 1) = \Delta V_i(k) + n_1(Q_{\text{ref}} - Q_{\text{grid}})
\]

\[
\Delta V_L(k) = \Delta V_i(k) + n_2(Q_{\text{ref}} - Q_{\text{grid}})
\]

\[
V_{L\_\text{amp}}(k) = V_{\text{nom}} + \Delta V_L(k)
\]

**Reference DGS Output Voltage:**

\[
V_{LA\_\text{amp}}(k) = V_{L\_\text{amp}} \cdot \sin(\theta(k))
\]

where, $m_1$ and $m_2$: integral gain and proportional gain for real power controller, respectively; $n_1$ and $n_2$: integral gain and proportional gain for reactive power controller, respectively; $\theta_{\text{sync}}$: phase angle between the DGS and the grid before synchronization; $\theta_{\text{nom}} = 2\pi f t$; $V_{\text{nom}}$: $120\sqrt{2}$. Note that the phase angles of the reference DGS output
voltages \((V^*_L B\) and \(V^*_L C\)) are displaced from that of \((V^*_L A)\) by 120°, 240° electrical degrees.

Finally, Figure 7.16 shows a Simulink model for the reference DGS output voltage \((V^*_L)\) generation using the above equations. Note that the magnitude \((V_{L\text{ amp}})\) of the DGS output voltage and the power angle \((\delta)\) are controlled in the range of \(V_{\text{min}} < V_{L\text{ amp}} < V_{\text{max}}\) and \(0 < \delta < 360^\circ\).

Figure 7.16: Simulink model for reference DGS output voltage \((V^*_L)\) generation
C. Voltage and Current Controllers

To provide a qualified AC power to the local load and the grid, good performance such as zero steady state tracking error, THD reduction, and fast and no-overshoot current response should be guaranteed.

Figure 7.17 shows a block diagram of the control scheme proposed for voltage and current control of the three-phase PWM inverter with a Δ/Y transformer. In Figure 7.17, the proposed control system consists of two discrete-time sliding mode controllers (DSMC) - voltage controller in the outer loop and current controller in the inner loop [91].

![Control block diagram of a three-phase DC to AC inverter](image)

Figure 7.17: Control block diagram of a three-phase DC to AC inverter

1) Discrete-time Sliding Mode Current Controller in the Inner Loop

For the current controller to generates an inverter output voltage command $V^{*}_{idq}$ as a control input ($u$), only equations (4.13) and (4.14) derived in Chapter 4 need to be considered, where $I_{idq}$ is adopted as a disturbance ($d_1$). Rewrite these two equations in a state space form:
where, $\mathbf{X}_i = \begin{bmatrix} \mathbf{V}_{\text{dq}} & \mathbf{I}_{\text{dq}} \end{bmatrix}$, $\mathbf{A}_1 = \begin{bmatrix} 0 \times 2 & \frac{1}{3C_f} \frac{T_{\text{idq}}}{L} \\ -\frac{1}{L} T_{\text{idq}}^{-1} & 0 \times 2 \end{bmatrix}$, $\mathbf{B}_1 = \begin{bmatrix} 0 \times 2 \\ \frac{1}{L} T_{\text{idq}}^{-1} \end{bmatrix}$, $\mathbf{E}_1 = \begin{bmatrix} -\frac{1}{3C_f} T_{\text{dq}} \\ 0 \times 2 \end{bmatrix}$, $\mathbf{C}_1 = [0 \times 2 \times 2]$.

The discrete form of the (7.31) can be expressed by

$$
\begin{align*}
\mathbf{X}_i(k+1) &= \mathbf{A}_1^* \mathbf{X}_i(k) + \mathbf{B}_1^* \mathbf{u}(k) + \mathbf{E}_1^* \mathbf{d}_1(k) \\
\mathbf{y}_1(k) &= \mathbf{C}_1 \mathbf{X}_i(k)
\end{align*}
$$

where, $\mathbf{A}_1^* = e^{\mathbf{A}_1 T_s}$, $\mathbf{B}_1^* = \int_0^{T_s} e^{\mathbf{A}_1 (T_s - \tau)} \mathbf{B}_1 d\tau$, and $\mathbf{E}_1^* = \int_0^{T_s} e^{\mathbf{A}_1 (T_s - \tau)} \mathbf{E}_1 d\tau$, assuming sampling period $T_s$.

To control the output $\mathbf{y}_1(k)$ to exactly follow the reference $\mathbf{y}_1_{\text{ref}}(k)$, a sliding mode manifold may be chosen in the form of:

$$
\mathbf{s}(k) = \mathbf{C}_1 \mathbf{X}_1(k) - \mathbf{y}_1_{\text{ref}}(k)
$$

i.e., the tracking error, such that when the discrete-time sliding mode exists, the output $\mathbf{y}_1(k)$ tends to the reference $\mathbf{y}_1_{\text{ref}}(k)$. Thus, the discrete-time sliding mode can be reached if the control input $\mathbf{u}(k)$ is designed to be the solution of:
\[ s(k+1) = C_1 A_1^* X_1(k) + C_1 B_1^* u(k) + E_i^* d_i(k) - y_{1_{ref}}(k+1) = 0 \] (7.34)

The control law satisfying (7.34) is called ‘equivalent control’ and is given by:

\[ u_{eq}(k) = \left( C_1 B_1^* \right)^{-1} \left( I_{idq}^* - C_1 A_1^* X_1(k) - C_1 E_i^* d_i(k) \right) \] (7.35)

If the control gain is limited by \( \|u(k)\| \leq u_v \), then the following modified control law can be applied:

\[
\begin{bmatrix}
    u_{eq}(k) \\
    u_v \\
    \|u_{eq}(k)\|
\end{bmatrix}
\begin{cases}
    u_{eq}(k) & \text{for } \|u_{eq}(k)\| \leq u_v \\
    u_v & \text{for } \|u_{eq}(k)\| > u_v
\end{cases}
\] (7.36)

Note that the control law \( u_{eq} \) is limited by the SVPWM inverter, and with control law (7.36) the discrete-time sliding mode can be reached after a finite number of steps.

2) Discrete-time Sliding Mode Voltage Controller in the Outer Loop

For the voltage controller to generate an inverter output current command \( I_{idq}^* \) as a control signal \( u_1 \), the dynamics (7.35) of the DSMC in the inner loop is included in the original plant (4.18). After the dynamics of the current controller is included in (4.18), the overall plant can be arranged:
\[
\begin{aligned}
X(k+1) &= A_d X(k) + B_d u_1(k) + E^* d(k) \\
y(k) &= C_d X(k)
\end{aligned}
\quad (7.37)
\]

where, \(A_d = A^* - B^* \left( C_1 B_1^* \right)^{-1} C_1 \left( A_1^* C_{11} + E_1^* C_{12} \right)\), \(B_d = B^* \left( C_1 B_1^* \right)^{-1}\), \(C_{11} = [I_{4 \times 4} \quad 0_{4 \times 4}]\), \(C_{12} = [0_{2 \times 6} \quad I_{2 \times 2}]\), \(C_d = [0_{2 \times 4} \quad I_{2 \times 2} \quad 0_{2 \times 2}]\), \(u_1(k) = I_{idq}^*(k)\), \(y = V_{Ldq}\).

Similarly, a sliding mode manifold may be chosen in the form of:

\[
s(k) = C_d X(k) - y_{ref}(k) \quad (7.38)
\]

Thus, if the control input \(u_1(k)\) is designed to be the solution of \(s(k+1) = 0\), the discrete-time sliding mode can be reached after a finite number of steps and the equivalent control \((u_{1eq})\) is given by:

\[
u_{1eq}(k) = \left( C_d B_d^* \right)^{-1} \left( V_{Ldq}^*(k) - C_d A_d^* X(k) - C_d E^* d(k) \right) \quad (7.39)
\]

If the control input is limited by \(\|u_1(k)\| \leq u_i\), then the following control input can be applied:

\[
u_1(k) = \begin{cases} 
u_{1eq}(k) & \text{for } \|\nu_{1eq}(k)\| \leq u_i \\ u_0 & \text{for } \|\nu_{1eq}(k)\| > u_i \end{cases}
\quad (7.40)
\]

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7.3 Topology 2 (Z-Source Converter)

In this section, a digital control strategy is proposed which can dramatically improve the performance of the fuel cell based Z-source converter under both linear and nonlinear loads.

Figure 7.18 shows a block diagram of the total control system proposed for the Z-source converter. As shown in the figure, the overall system consists of three feedback controllers, and an asymptotic observer that estimates the load current defined as the disturbance to reduce the number of sensors and to enhance reliability [86].

First, the discrete-time optimal voltage controller based on Robust Servomechanism Problem (RSP) is used for voltage tracking and THD reduction because it can eliminate any specified voltage harmonics and achieve low steady state error [1]-
Second, the DSMC is used for current regulation due to its fast tracking/no-overshoot in transient response [1]-[2], [86], [91], and third, the discrete-time PI controller performs the DC-link voltage regulation. In the following sections, design of each controller will be described in detail.

7.3.1 Discrete-Time Sliding Mode Current Controller

As depicted in Figure 7.19, a discrete-time sliding mode control (DSMC) with the asymptotic observer is used for current regulation in an inner loop because of the fast and no-overshoot response it provides [91].

Figure 7.19: Discrete-time current controller using DSMC

Figure 7.20 shows the asymptotic observer which estimates the load current \( (I_{Ldq}) \) defined as the disturbance in order to reduce the number of sensors and to enhance reliability.
Using the asymptotic observer, the load current can be estimated as follows:

\[
\frac{d\hat{V}_{Ldq}}{dt} = \frac{1}{3C_f} I_{idq} - \frac{1}{3C_f} L_1 \cdot T_{idq} \cdot (\hat{V}_{Ldq} - V_{Ldq})
\]

\[
\hat{i}_{Ldq} = L_1 (\hat{V}_{Ldq} - V_{Ldq})
\]  (7.41)

The above equation (7.41) can be rewritten as a state space equation:

\[
\dot{\hat{X}}_a(t) = A_a \hat{X}_a(t) + A_b \hat{X}_b(t) - A_a X_a(t)
\]

\[
\dot{d}(t) = \hat{i}_{Ldq}(t) = L_1 (\hat{V}_{Ldq} - V_{Ldq}) = L_1 (\hat{X}_a - X_a)
\]  (7.42)

where, \( \hat{X}_a = [\hat{V}_{Ldq}] \), \( X_b = [I_{idq}] \), \( X_a = [V_{Ldq}] \), \( A_a = \left[-\frac{L_1}{3C_f} T_{idq}\right] \), \( A_b = \left[\frac{1}{3C_f} I_{2\times2}\right] \), \( L_1 = \text{constant observer gain} \).
Given the sampling period $T_z$, the discrete form of (7.42) is

$$
\begin{align*}
\dot{\hat{X}}_a(k+1) &= A^*_a \dot{X}_a(k) + A^*_b X_b(k) - A^{**} a \hat{X}_a(k) \\
\dot{d}(k) &= \hat{I}_{Ldq}(k) = L_a \left( \dot{X}_a(k) - X_a(k) \right)
\end{align*}
$$

(7.43)

where, $A^*_a = e^{A_a T_z}$, $A^*_b = \int_0^{T_z} e^{A_a (T_z - \tau)} A_b d\tau$, $A^{**} = \int_0^{T_z} e^{A_a (T_z - \tau)} A_a d\tau$.

With the information of the disturbance obtained from the observer, the continuous-time state space equation (6.14) of the system can be expressed for design of a current controller below:

$$
\begin{align*}
\dot{X}(t) &= AX(t) + Bu(t) + Ed(t) \\
y_1(t) &= C_1X(t) \\
e_{idq}(t) &= y_1(t) - y_{ref}(t)
\end{align*}
$$

(7.44)

where, coefficients $A$, $B$, $E$ and state variables $X$ are the same as those in (6.14),

$$
\begin{align*}
u &= [V_{idq}]_{2x1} = \begin{bmatrix} V_{id} \\ V_{iq} \end{bmatrix}, \quad \dot{d} = [\dot{I}_{Ldq}] = \begin{bmatrix} \dot{i}_{Ld} \\ \dot{i}_{Lq} \end{bmatrix}, \quad y_1 = [I_{idq}] = \begin{bmatrix} I_{id} \\ I_{iq} \end{bmatrix}, \quad y_{ref} = [I^*_{idq}] = \begin{bmatrix} I^*_{id} \\ I^*_{iq} \end{bmatrix}, \\
C_1 &= \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.
\end{align*}
$$

Given the sampling period $T_z$, the (7.44) can be transformed to the following discrete-time state space equation:
\[
\begin{align*}
X(k+1) &= A^*X(k) + B^*u(k) + E^*\hat{d}(k) \\
y_1(k) &= C_1X(k) \\
e_{idq}(k) &= y_1(k) - y_{ref}(k)
\end{align*}
\] (7.45)

where, \( A^* = e^{AT_{z}} \), \( B^* = \int_{0}^{T_{z}} e^{A(T_{z}-\tau)}B \, d\tau \), \( E^* = \int_{0}^{T_{z}} e^{A(T_{z}-\tau)}E \, d\tau \).

In order to control the output \( y_1(k) \) to follow the reference \( y_{1_ref}(k) \), a sliding mode manifold can be selected in the form of

\[
s(k) = y_1(k) - y_{1\_ref}(k) = C_1X(k) - y_{1\_ref}(k)
\] (7.46)

In other words, when the discrete-time sliding mode exists, the output \( y_1(k) \) is identical to the reference \( y_{1\_ref}(k) \). Therefore, the discrete-time sliding mode exists if the control input \( u(k) \) is designed as the solution of:

\[
s(k+1) = y_1(k+1) - y_{1\_ref}(k+1) \\
= C_1A^*X(k) + C_1B^*u(k) + C_1E^*\hat{d}(k) - y_{1\_ref}(k+1) = 0
\] (7.47)

The control law that satisfies (7.47) and then yields motion in the manifold \( s(k) = 0 \) is called ‘equivalent control.’ Thus, the equivalent control \( u_{eq}(k) \) is given as follows:

\[
u_{eq}(k) = \left( C_1B^* \right)^{-1} \left( \hat{I}^*_{idq}(k) - C_1A^*X(k) - C_1E^*\hat{d}(k) \right)
\] (7.48)
Furthermore, if the control input can vary within \( \|\mathbf{u}(k)\| \leq u_0 \), then the following control input can be applied:

\[
\mathbf{u}(k) = \begin{cases} 
\mathbf{u}_{eq}(k) & \text{for } \|\mathbf{u}_{eq}(k)\| \leq u_0 \\
\frac{u_0}{\|\mathbf{u}_{eq}(k)\|} \mathbf{u}_{eq}(k) & \text{for } \|\mathbf{u}_{eq}(k)\| > u_0 
\end{cases}
\]  

(7.49)

where, \( u_0 = \frac{2}{\sqrt{3}} V_{dc} \) and the control voltage limit \( u_0 \) is also determined by the SVPWM inverter.

With the control law (7.49), the discrete-time sliding mode can be reached after a finite number of steps and first of all, the control (7.49) provides chattering-free motion in the manifold \( s(k) = 0 \) in contrast with the direct implementation of discontinuous control [89].

7.3.2 Discrete-time Optimal Voltage Controller

As shown in Figure 7.21, a discrete-time voltage controller based on the RSP that consists of a servo-compensator and a stabilizing compensator is used for voltage regulation in an outer loop. Also, the current command signal (\( I_{cmd, iqd} \)) is limited by maximum current predetermined to protect the system under overload. The theory of the robust servomechanism problem (RSP) and its solution are described in terms of mathematics in Davison’s work [88].
The goal of designing a realistic multivariable controller to solve the robust servomechanism problem is to achieve closed-loop stability and asymptotic regulation as well as fast response and robustness. In the research, a discrete-time robustness servomechanism controller (RSC) that combines both the internal model principle and the optimal control is adopted for voltage control due to its capability to perform zero steady state tracking error under unknown load and to eliminate harmonics of any specified frequencies with guaranteed system stability.

\[ X(k+1) = A^*X(k) + B^*u(k) + E^*d(k) \]  

(7.50)
After the dynamics (7.48) of the DSMC is included in (7.50), the overall plant for the RSC can be expressed:

\[
\begin{align*}
\mathbf{X}(k+1) &= \mathbf{A}_d \mathbf{X}(k) + \mathbf{B}_d \mathbf{u}_i(k) + \mathbf{E}_d \hat{\mathbf{d}}(k) \\
\mathbf{y}_d(k) &= \mathbf{C}_d \mathbf{X}(k)
\end{align*}
\tag{7.51}
\]

where, \( \mathbf{A}_d = \mathbf{A}^* - \mathbf{B}^* \left( \mathbf{C}_i \mathbf{B}^* \right)^{-1} \mathbf{C}_i \mathbf{A}^* \), \( \mathbf{B}_d = \mathbf{B}^* \left( \mathbf{C}_i \mathbf{B}^* \right)^{-1} \), \( \mathbf{E}_d = \mathbf{E}^* - \mathbf{B}^* \left( \mathbf{C}_i \mathbf{B}^* \right)^{-1} \mathbf{C}_i \mathbf{E}^* \), \( \mathbf{C}_d = \left[ \mathbf{I}_{2 \times 2} \ 0_{2 \times 2} \right] \), \( \mathbf{u}_i(k) = \mathbf{l}_{cmd,idq}(k) \), \( \mathbf{y}_d = \left[ \mathbf{V}_{Ldq} \right] \).

For the above system (7.51), once the existence of the solution to RSP is verified according to the conditions in [88], assuming the tracking/disturbance poles are \( \pm j \omega_1, \pm j \omega_2, \pm j \omega_3, \ldots \) (i.e., representing sinusoidal signals with fundamental frequency \( \omega_1 \) and harmonic frequencies \( \omega_2, \omega_3, \ldots \)), the RSC can be designed as follows. If the tracking/disturbance poles to be considered are \( \pm j \omega_1, \pm j \omega_2, \) and \( \pm j \omega_3 \), the continuous time servo-compensator is defined as

\[
\mathbf{e}_{vdq} = \mathbf{V}_{Ldq}^* - \mathbf{V}_{Ldq} \quad , \quad \mathbf{A}_c = \begin{bmatrix}
\mathbf{A}_{c1} & 0_{4 \times 4} & 0_{4 \times 4} \\
0_{4 \times 4} & \mathbf{A}_{c2} & 0_{4 \times 4} \\
0_{4 \times 4} & 0_{2 \times 2} & \mathbf{A}_{c3}
\end{bmatrix}_{12 \times 12} , \quad \mathbf{B}_c = \begin{bmatrix}
\mathbf{B}_{c1} \\
\mathbf{B}_{c2} \\
\mathbf{B}_{c3}
\end{bmatrix}_{12 \times 12},
\]

\[
\mathbf{A}_{ci} = \begin{bmatrix}
0_{2 \times 2} & I_{2 \times 2} \\
- \omega_i^2 \cdot I_{2 \times 2} & 0_{2 \times 2}
\end{bmatrix}_{4 \times 4} , \quad \mathbf{B}_{ci} = \begin{bmatrix}
0_{2 \times 2} \\
I_{2 \times 2}
\end{bmatrix}_{4 \times 2} , \quad \omega_i (i = 1, 2, 3), \omega_1 = \omega, \omega_2 = 5 \cdot \omega, \omega_3 = 7 \cdot \omega.
\]
Note that only the 5\textsuperscript{th} and 7\textsuperscript{th} harmonics are chosen as the disturbance poles because the voltage harmonics such as an odd multiple of 3 and even harmonics are suppressed in a three-phase inverter and as a consequence the dominant harmonics are the 5\textsuperscript{th} and 7\textsuperscript{th}.

The discrete form of (7.52) is:

\[ \eta(k + 1) = A^*_c \eta(k) + B^*_e e_{vdq}(k) \quad (7.53) \]

where, \( A^*_c = e^{A_c T_z} \), \( B^*_e = \int_0^{T_z} e^{A_c (T_z - \tau)} B_e d\tau \).

Therefore, an augmented system model combining both the plant (7.51) and the servo-compensator (7.53) is:

\[ \hat{X}(k + 1) = \hat{A} \hat{X}(k) + \hat{B} u_1(k) + \hat{E} \hat{d}(k) + \hat{E}_2 y_{d,ref}(k) \quad (7.54) \]

where, \( \hat{X}(k) = \begin{bmatrix} X(k) \\ \eta(k) \end{bmatrix}, \quad \hat{A} = \begin{bmatrix} A_d & 0 \\ -B^*_e C_d & A^*_c \end{bmatrix}, \quad \hat{B} = \begin{bmatrix} B_d \\ 0 \end{bmatrix}, \quad \hat{E}_1 = \begin{bmatrix} E_d \\ 0 \end{bmatrix}, \quad \hat{E}_2 = \begin{bmatrix} 0 \\ B^*_e \end{bmatrix}, \quad u_1(k) = I_{cmd,d,q}(k), \quad \hat{d}(k) = \hat{I}_{Ldq}(k), \quad y_{d,ref}(k) = V^*_{Ldq}(k). \]

The stabilizing compensator which yields the control signal \( u_1 \) in (7.54) ensures the stability and desirable performance of the overall system through a feedback gain \( K \) minimizing the discrete linear quadratic performance index (i.e., the optimization criterion):
\[
J_e = \sum_{k=0}^{\infty} \hat{X}(k)^T \hat{Q} \hat{X}(k) + \varepsilon u_1^T(k) u_1(k) \tag{7.55}
\]

where, \(Q\) is a symmetrical positive-definite matrix and \(\varepsilon > 0\) is a small number, both of which should be selected by the controller designer according to the application.

The feedback gain \(K\) can be obtained using Matlab function \(dlqr()\) which solves the algebraic Riccati equation for the system (7.54). Assuming the system is a linear time-invariant (LTI), the feedback gain \(K\) is a constant value calculated by the Matlab function in advance. Thus, control input \((u_1)\) can be taken from the gain \(K\) and state variables \((X\) and \(\eta)\):

\[
\begin{align*}
    u_1(k) &= -K \hat{X}(k) = -K_1 \begin{bmatrix} X(k) \\ \eta(k) \end{bmatrix} = -K_1 X(k) - K_2 \eta(k) \\
\end{align*}
\tag{7.56}
\]

Finally, since the current command signal needs to be limited to protect the system against overload, the algorithm of the current limiter is included in main program as:

\[
I_{\text{idq}}^*(k) = \begin{cases} 
I_{\text{cmd}, \text{idq}}(k) & \text{for } \left\| I_{\text{cmd}, \text{idq}}(k) \right\| \leq I_{\text{max}} \\
I_{\text{max}} \frac{\left\| I_{\text{cmd}, \text{idq}}(k) \right\|}{\left\| I_{\text{cmd}, \text{idq}}(k) \right\|} & \text{for } \left\| I_{\text{cmd}, \text{idq}}(k) \right\| > I_{\text{max}} 
\end{cases} 
\tag{7.57}
\]
7.3.3 Discrete-time PI DC-link Voltage Controller

Next, a discrete-time proportional-integral (PI) voltage controller is used to regulate the average voltage of DC-link as illustrated in Figure 7.22. In this research, Tustin’s method (Trapezoid Rule) is used for approximation to integration of a discrete-time PI controller.

The continuous transfer function of a conventional PI controller is given by

\[
\frac{T(s)}{E(s)} = K_p + K_i \cdot \frac{1}{s} \quad (7.58)
\]

where, \(K_p\) is the proportional gain, and \(K_i\) is the integral gain.

Equation (7.58) is equivalent to the following differential equation,

\[
\dot{T}(t) = K_p \cdot \dot{e}(t) + K_i \cdot e(t) \quad (7.59)
\]
Rearranging (7.59) in a difference equation using the trapezoidal approximation to integration

\[
\frac{T(k) - T(k-1)}{T_z} = K_p \cdot \frac{e(k) - e(k - 1)}{T_z} + K_i \cdot \frac{1}{2} (e(k) + e(k - 1))
\]  

(7.60)

So the equation (7.60) can be rewritten as follows:

\[
\begin{cases}
    e(k) = V^*_{C2}(k) - V_{C2}(k) \\
    T(k) = T(k - 1) + K_p \cdot (e(k) - e(k - 1)) + K_i \cdot \frac{T_z}{2} \cdot (e(k) + e(k - 1))
\end{cases}
\]  

(7.61)

Taking the z-transform of (7.61) yields below:

\[
\frac{T(z)}{E(z)} = K_p + K_i \frac{T_z}{2} \cdot \frac{z + 1}{z - 1}
\]  

(7.62)

As shown in Figure 7.22, one of the capacitor voltages (V_{C1}, V_{C2}) is measured for the feedback control, and an error between the desired voltage (V^*_{C2}) and sensed voltage (V_{C2}) is used as an input of the controller. Moreover, the output voltage (V_{in}) of the fuel cell is sensed, and then duration (T_{cal} = T_u/3) of shoot-through zero vectors is calculated by a look-up table according to the magnitude of the fuel cell output voltage. The equation (7.63) shows how T_{cal} is theoretically calculated assuming that a desired
capacitor voltage \( V_{C2} \) is 340 V and a switching period \( T_z = 185.2 \ \mu\text{sec} \). That is, the parameters \( K, M, a, \) and \( T \) can be calculated below:

i). When \( V_{in} = 130 \ \text{V} \) and \( P = 10 \ \text{kW} \):

\[
T_a/T_z = 0.3814, \ K = 4.2158, \ M = 0.6186, \ a = 0.4639, \ T = 23.54 \ \mu\text{sec}.
\]

ii). When \( V_{in} = 300 \ \text{V} \) and \( P = 0.5 \ \text{kW} \):

\[
T_a/T_z = 0.1053, \ K = 1.2668, \ M = 0.8947, \ a = 0.671, \ T = 6.5 \ \mu\text{sec}.
\]

\[
V_{C1} = V_{C2} = \frac{T_b}{T_b - T_a} = \frac{T_z - T_a}{T_z - 2T_a} = \frac{1 - T_a / T_z}{1 - 2T_a / T_z} \cdot V_{in}
\]

\[
\therefore \frac{T_a}{T_z} = \frac{V_{C1} - V_{in}}{2 \cdot V_{C1} - V_{in}} \quad \Rightarrow \quad K = \frac{1}{1 - 2 \cdot T_a / T_z} \quad (7.63)
\]

\[
\therefore M (= T_b / T_z) = 1 - T_a / T_z \quad \Rightarrow \quad a = 3 \cdot M / 4
\]

\[
\therefore T = T_a / 3
\]

Figure 7.23 shows the relationship between \( V_{in} \), \( T_a/T_z \), and \( K \), and as we expect, \( T_a/T_z \) and \( K \) decrease as the output voltage \( (V_{in}) \) of the fuel cell increases.

The calculated shoot-through duration \( (T_{cal}) \) is utilized in a saturation block in order to limit the final output \( (T) \) of the discrete-time PI controller. This controller should regulate the average DC-link output voltage to the desired value and the shoot-through duration \( (T) \) should be confined to a reasonable value that can guarantee accurately the
required boosted DC-link voltage. As illustrated in Table 6.1, the reference duration \( T^* = T_{z}/3 \) of shoot-through zero states is directly added to or subtracted from the conventional switching patterns of SVPWM in order to boost the average DC-link voltage.

![Figure 7.23: Relationship between \( V_{in} \), \( T_{a}/T_z \), and \( K \)](image)

**Figure 7.23: Relationship between \( V_{in} \), \( T_{a}/T_z \), and \( K \)**
CHAPTER 8

SIMULATION RESULTS

8.1 Introduction

In this chapter, simulation test beds using Matlab/Simulink will be constructed to validate the effectiveness of the system models and control algorithms proposed in the previous chapters. The chapter will show the Simulink models and simulation results for two topologies under various conditions: Topology 1 (a single DGS unit and two DGS units in a standalone AC power plant, and a grid-connected DGS) and Topology 2 (a Z-source converter in a standalone AC power plant).

8.2 Topology 1

To verify the fuel cell model and control strategies of two full-bridge DC to DC power converters and three-phase DC to AC inverters that are proposed for DGS operating in a standalone power plant and a grid-interconnection, simulation test-beds using Matlab/Simulink are built for an AC 120 V (L-n)/60 Hz/50 kVA.
In this dissertation, to overcome an excessive computation time due to three or five power converters and high PWM frequencies, the simulation test beds are divided into two parts: two full-bridge DC to DC power converters with the dynamic model of the fuel cell and a three-phase DC to AC inverter without or with a Δ/Y transformer. It is reasonable if the DC to DC power converters tightly regulate the DC-link bus voltage \(V_{dc}\) that is used as an input of the three-phase DC to AC inverter within a desired value.

8.2 1 Full-Bridge DC to DC Power Converters

To demonstrate the fuel cell model and control scheme presented for two full-bridge DC to DC power converters, a simulation test bed using Matlab/Simulink is developed.

Figure 8.1: Simulink model of the fuel cell

Figure 8.1 shows a Simulink model of the fuel cell, and it consists of a power request, a power to current conversion, a first-order transfer function for the transient
response of the reformer, a controlled current source, a linearized polarization curve for the modeling of the stack, and a controlled voltage source.

Figure 8.2: Simulink model of full-bridge DC to DC power converters with the fuel cell and battery

Figure 8.2 shows a Simulink model of two full-bridge DC to DC power converters with the fuel cell and the battery, and it consists of a fuel cell, an input filter (L₁ and C₁), a unidirectional isolated full-bridge DC to DC power converter, an output filter (L₂ and C₂), a battery, a static switch (S_B), a bidirectional isolated full-bridge DC to
DC power converter, two PWM controllers, and a load. The system parameters are given in Table 8.1.

<table>
<thead>
<tr>
<th>Fuel Cell Output Voltage</th>
<th>88 ∼ 200 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal Battery Voltage</td>
<td>120 V</td>
</tr>
<tr>
<td>Turn Ratios (N₁:N₂, n₁:n₂)</td>
<td>1:6.5, 1:6</td>
</tr>
<tr>
<td>Input Filters</td>
<td>L₁ = 20 µH, C₁ = 1000 µF</td>
</tr>
<tr>
<td>Output Filters</td>
<td>L₂ = 150 µH, C₂ = 10000 µF</td>
</tr>
<tr>
<td>Switching Frequency</td>
<td>fₚ = 10 kHz</td>
</tr>
<tr>
<td>Desired DC Output Voltage</td>
<td>Vₚₜ = 500 V</td>
</tr>
</tbody>
</table>

Table 8.1 System parameters for DC to DC power converters

Assume that it takes 12 msec for the fuel cell to reach from no-load to 40 kW and takes 4 msec (1/3 of the increasing time), and vice versa. Figures 8.3 to 8.5 show the results for startup, a sudden load increase, and a sudden load decrease, respectively.

In Figure 8.3, each figure indicates: (1) Fuel cell output voltage Vₘ₁, (2) Fuel cell stack current Iₘ, (3) Filtered output current Iₘ₂ of fuel cell on the DC-link side, (4) Filtered output current Iₜ₂ of battery on the DC-link side, and (5) High-side DC-link voltage Vₚₜ.

In Figures 8.4 and 8.5, each figure indicates: (1) Power request P, (2) Fuel cell output voltage Vₘ₁, (3) Fuel cell stack current Iₘ, (4) Filtered output current Iₘ₂ of fuel cell on the DC-link side, (5) Filtered output current Iₜ₂ of battery on the DC-link side, and (6) High-side DC-link voltage Vₚₜ.
Figure 8.3: Simulation waveforms during start-up

Figure 8.4: Simulation waveforms under a sudden load increase
In Figure 8.4, a power request signal is changed from 0 to 20 kW at 42 msec, and then 20 kW to 40 kW at 62 msec. In Figure 8.5, the power request signal is changed from 0 to 40 kW at 42 msec, and then dropped to 20 kW at 62 msec.

As depicted in Figures 8.3 to 8.5, the fuel cell current ($I_F$) has some delay because it takes some time for the fuel to be converted to the hydrogen, which is demanded for the power request, and the fuel cell voltage and stack current depend on each other as voltage-current polarization curve of the stack.

Also, the DC-link bus ($V_{dc}$) is nearly constant during the transients because the battery appropriately backs up the fuel cell. The battery is discharged during startup and abrupt load increase, while it slowly recharged by the fuel cell to reach a nominal value during rapid load decrease or in steady-state time.
8.2.2 Three-Phase DC to AC Inverter

This section will present the control algorithms of three-phase DC to AC PWM inverters described for three applications such as a standalone single DGS unit, standalone two DGS units, and a grid-connected DGS unit in Topology 1.

8.2.2.1 Standalone AC Power Supply

A. A Single DGS Unit

To verify the control strategy proposed for a three-phase DC to AC inverter, a simulation test bed using Matlab/Simulink is constructed as illustrated in Figure 8.6, and the system parameters for a single DGS unit are given in Table 8.2.

Figure 8.6: Simulink model for a single DGS unit in a standalone operation


<table>
<thead>
<tr>
<th>DC Bus Voltage</th>
<th>$V_{dc} = 500$ V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power Rating</td>
<td>$P_{out} = 50$ kVA</td>
</tr>
<tr>
<td>AC Output Voltage</td>
<td>$V_{L, RMS} = 120$ V (L-N), $f = 60$ Hz</td>
</tr>
<tr>
<td>Inverter Filters</td>
<td>$L_f = 250 , \mu$H, $C_f = 580 , \mu$F</td>
</tr>
<tr>
<td>Switching/Sampling Frequency</td>
<td>$f_s = 9$ kHz</td>
</tr>
</tbody>
</table>

Table 8.2 System parameters for a single DGS unit

Figures 8.7 and 8.8 show the results under a linear load (p.f. = 0.8) and a nonlinear load with a three-phase diode bridge, respectively. In Figures 8.9 and 8.10, the simulation results show a resistive load step change at 50 msec from 0 to 40 kW, and vice versa. Figure 8.11 shows simulation results under a resistive unbalanced load, i.e., the phase A and B are normal, while the phase C is open at 50 msec.

In Figures 8.7 through 8.11, each figure indicates: (1) Inverter output line-to-line voltage ($V_{LAB}$), (2) Load phase voltages ($V_{LAN}$, $V_{LBN}$, $V_{LCN}$), (3) Inverter output phase currents ($i_A$, $i_B$, $i_C$), (4) Load phase currents ($i_{LA}$, $i_{LB}$, $i_{LC}$), and (5) Load active power ($P_L$) and reactive power ($Q_L$).
Figure 8.7: Simulation results under a linear load (p.f. = 0.8)

Figure 8.8: Simulation results under a nonlinear load
Figure 8.9: Simulation results under a resistive balanced load step change (0 to 40 kW)

Figure 8.10: Simulation results under a resistive balanced load step change (40 kW to 0)
From Figures 8.7 to 8.11, the proposed control method demonstrates the good performance such as a low THD, a fast transient response, and over-current protection under the linear load, nonlinear load, and even resistive load step changes. Note that it takes 1/60 seconds for the $P_L$ and $Q_L$ to be accurately calculated using Simulink model in the figures and the $Q_L$ is nearly equal to zero under a resistive balanced load step change as illustrated in Figures 8.9 and 8.11.
B. Two DGS Units

Figure 8.12 shows configuration of the system simulated for two DGS units operating in parallel. This configuration consists of two DGS units and two loads. In real circuit model, wire impedances \((Z_1 \text{ and } Z_2)\) and interconnected tie-line impedance \((Z_t)\) are modeled because these can significantly affect load-sharing between the DGS units.

Figure 8.12: Configuration of the system simulated for two DGS units

To simulate Figure 8.12 with Matlab/Simulink, the configuration is modeled as Figure 8.13. This model is also composed of two DGS units, two loads, wire impedances \((Z_1 \text{ and } Z_2)\), and tie-line impedance \((Z_t)\). In particular, power information \((PQ_{dq1} \text{ and } PQ_{dq2})\) such as the real power \((P)\) and the reactive power \((Q)\) is exchanged between two DGS systems to ensure proper load-sharing.
Simulations were performed using Matlab/Simulink v6.1 with Power System Blockset (PSB). For speed of simulations, the PWM Bridge IGBT inverter has been modeled as an ideal voltage controlled source with a delay of half the sampling time of the actual PWM signal. Two linear transformers are used for the isolation transformers, and a series inductance and resistance representing the leakage impedance and losses of each transformer are respectively 3 % p.u. The series inductance and resistance of the transformers are denoted as $L_T$ and $R_T$, respectively. The circuit parameters for simulations are given in Table 8.3.
### Table 8.3 System parameters for two DGS units

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC Bus Voltage</strong></td>
<td>$V_{dc} = 500 \text{ V}$</td>
</tr>
<tr>
<td><strong>Rated Output Power of Each DGS</strong></td>
<td>50 kVA</td>
</tr>
<tr>
<td><strong>AC Output Voltage</strong></td>
<td>$V_{L, \text{RMS}} = 120 \text{ V (L-N)}, \ f = 60 \text{ Hz}$</td>
</tr>
<tr>
<td><strong>Inverter Filters</strong></td>
<td>$L_f = 2 \text{ mH}, \ C_f = 300 \mu \text{F}$</td>
</tr>
<tr>
<td><strong>Output Filter</strong></td>
<td>$C_l = 120 \mu \text{F}$</td>
</tr>
<tr>
<td><strong>$\Delta$/Y Transformer</strong></td>
<td>50 kVA, $N_p = 240, \ N_s = 120, \ R_T = L_T = 0.03 \text{ p.u.}$</td>
</tr>
<tr>
<td><strong>Switching (Sampling) Frequency</strong></td>
<td>$f_s = 6.6 \text{ kHz}$</td>
</tr>
</tbody>
</table>

As explained in previous section, each PWM inverter’s output voltage and current are controlled using dual loop control system, with outer loop (RSC) controlling the output voltage and the inner loop (DSMC) controlling the inverter current.

The droop coefficients are given as follows:

$$m_1 = -20e-6 \text{ rad/watt}$$

$$m_2 = -20e-6 \text{ rad/watt}$$

$$n_1 = -20e-4 \text{ V/var}$$

$$n_2 = -20e-4 \text{ V/var}$$

$$m_3 = m_5 = m_7 = -2e-2$$
In this study, two PWM inverters are assumed to have identical characteristics i.e. they have matched circuit components equal to their nominal values. To verify the performance of the proposed droop method for load-sharing control, tie-line impedance, wire impedances mismatches and voltage/current sensor measurement error mismatches are considered in this simulation.

The following cases are simulated:

**All Cases:**

Unit 1: \( Z_1 = R_1 + jX_1 \) (\( R_1 = 0.01 \, \Omega \), \( L_1 = 0.2 \, \text{mH} \))

Voltage measurement error: \( V_p \) \([-0.1\%, +0.1\%, -0.1\%]\), \( V_L \) \([+0.1\%, +0.1\%, -0.1\%]\)

Current measurement error: \( I_i \) \([+0.1\%, -0.1\%, -0.1\%]\), \( I_L \) \([+0.1\%, -0.1\%, -0.1\%]\)

Unit 2: \( Z_2 = R_2 + jX_2 \) (\( R_2 = 0.02 \, \Omega \), \( L_2 = 0.4 \, \text{mH} \))

Voltage measurement error: \( V_p \) \([+0.1\%, -0.1\%, +0.1\%]\), \( V_L \) \([-0.1\%, -0.1\%, +0.1\%]\)

Current measurement error: \( I_i \) \([-0.1\%, +0.1\%, +0.1\%]\), \( I_L \) \([-0.1\%, +0.1\%, +0.1\%]\)

\( Z_t = R_t + jX_t \) (\( R_t = 0.01 \, \Omega \), \( L_t = 0.2 \, \text{mH} \))

**Case 1:**

Power Ratings of DGS unit 1 and 2: 50 kVA, respectively

Load 1: \( P_{\text{load1}} = 40 \, \text{kW} \) and \( Q_{\text{load1}} = 30 \, \text{kVar} \) (p.f = 0.8)

Load 2: \( P_{\text{load2}} = 40 \, \text{kW} \) and \( Q_{\text{load2}} = 30 \, \text{kVar} \) (p.f = 0.8)
Case 2:

Power Ratings of DGS unit 1 and 2: 50 kVA, respectively

Load 1: \( P_{\text{load1}} = 40 \text{ kW} \) and \( Q_{\text{load1}} = 30 \text{ kVar} \) (p.f = 0.8)

Load 2: \( P_{\text{load2}} = 20 \text{ kW} \leftrightarrow 40 \text{ kW} \) and \( Q_{\text{load2}} = 15 \text{ kVar} \leftrightarrow 30 \text{ kVar} \) (at 3 sec)

Case 3:

Power Ratings of DGS unit 1 and 2: 50 kVA, respectively

Load 1: \( P_{\text{load1}} = 40 \text{ kW} \) and \( Q_{\text{load1}} = 30 \text{ kVar} \) (p.f = 0.8)

Load 2: \( P_{\text{load2}} = 40 \text{ kW} \leftrightarrow 20 \text{ kW} \) and \( Q_{\text{load2}} = 30 \text{ kVar} \leftrightarrow 15 \text{ kVar} \) (at 3 sec)

Case 4:

Power Ratings of DGS unit 1 and 2: 50 kVA, 25 kVA, respectively

Load 1: \( P_{\text{load1}} = 20 \text{ kW} \) and \( Q_{\text{load1}} = 15 \text{ kVar} \) (p.f = 0.8)

Load 2: \( P_{\text{load2}} = 40 \text{ kW} \) and \( Q_{\text{load2}} = 30 \text{ kVar} \) (p.f = 0.8)

Case 5:

Power Ratings of DGS unit 1 and 2: 50 kVA, 25 kVA, respectively

Load 1: \( P_{\text{load1}} = 20 \text{ kW} \) and \( Q_{\text{load1}} = 15 \text{ kVar} \) (p.f = 0.8)

Load 2: \( P_{\text{load2}} = 20 \text{ kW} \leftrightarrow 40 \text{ kW} \) and \( Q_{\text{load2}} = 15 \text{ kVar} \leftrightarrow 30 \text{ kVar} \) (at 3 sec)
Case 6:

Power Ratings of DGS unit 1 and 2: 50 kVA, 25 kVA, respectively

Load 1: $P_{load1} = 20 \text{ kW}$ and $Q_{load1} = 15 \text{ kVar}$ (p.f = 0.8)

Load 2: $P_{load2} = 40 \text{ kW}$ ⇒ $20 \text{ kW}$ and $Q_{load2} = 30 \text{ kVar}$ ⇒ $15 \text{ kVar}$ (at 3 sec)

Case 7:

Power Ratings of DGS unit 1 and 2: 50 kVA, respectively

Load 1: Three-Phase Bridge Diode ($C_{DC1} = 3000 \mu\text{F}$ and $R_{L1} = 1.3 \Omega$)

Load 2: Three-Phase Bridge Diode ($C_{DC2} = 3000 \mu\text{F}$ and $R_{L2} = 1.3 \Omega$)

Case 8:

Power Ratings of DGS unit 1 and 2: 50 kVA, 25 kVA, respectively

Load 1: Three-Phase Bridge Diode ($C_{DC1} = 3000 \mu\text{F}$ and $R_{L1} = 2.6 \Omega$)

Load 2: Three-Phase Bridge Diode ($C_{DC2} = 3000 \mu\text{F}$ and $R_{L2} = 1.3 \Omega$)

All cases are assumed that $Z_2$ is twice of $Z_1$, the signs of voltage/current sensor errors of DGS unit 1 are opposite to those of DGS unit 2. In Case 1, 2, 3 and 7, power rating of DGS unit 1 is equal to that of DGS unit 2. Case 4, 5, 6, and 8 are supposed that power rating of DGS unit 1 is twice that of DGS unit 2. Case 2 and 5 are assumed that load 2 becomes twice after 3 seconds, while Case 3 and 6 are supposed that load 2 becomes half after 3 seconds. Finally, Case 7 and 8 are simulated under non-linear loads with a three-phase bridge diode.
Figure 8.14: Simulation results for Case 1

Figure 8.15: Simulation results for Case 2
Figure 8.16: Simulation results for Case 3

Figure 8.17: Simulation results for Case 4
Figure 8.18: Simulation results for Case 5

Figure 8.19: Simulation results for Case 6
Figure 8.20: Simulation results for Case 7

Figure 8.21: Simulation results for Case 8
In this simulation, the first six cases (Figures 8.14 through 8.19) were done for linear loads, while the last two cases (Figures 8.20 through 8.21) were simulated under nonlinear loads. Figure 8.14 shows very good load-sharing of the real and the reactive powers under the conditions that both units and loads are identical. Figure 8.17 shows the results under different power ratings and loads, and these results also show that the loads are properly shared according to the power capability of each unit.

As shown in Figures 8.15 to 8.16 and 8.18 to 8.19, even when the load 2 is increased suddenly to twice or half its value after 3 seconds, respectively, the results definitely show so good a power sharing. Two nonlinear loads that consist of a three-phase bridge, a large capacitor, and a small resistor are implemented, and the results demonstrate good load sharing depending on the power rating of each unit as given in Figures 8.20 and 8.21.

8.2.2.2 Grid-Interconnection

To demonstrate the effectiveness of the control strategy proposed for a three-phase PWM inverter of a grid-connected DGS with the fuel cell and battery, a simulation test bed using Matlab/Simulink is developed for an AC 120 V (L-n)/60 Hz/50 kVA as illustrated in Figure 8.22. The system parameters for a grid-connected DGS unit are given in Table 8.4.
**Figure 8.22: Simulink model for a grid-connected DGS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DC Bus Voltage</strong></td>
<td>$V_{dc} = 500$ V</td>
</tr>
<tr>
<td><strong>Output Power Rating</strong></td>
<td>$P_{out} = 50$ kVA</td>
</tr>
<tr>
<td><strong>AC Output Voltage</strong></td>
<td>$V_{L, RMS} = 120$ V (L-N), $f = 60$ Hz</td>
</tr>
<tr>
<td><strong>Inverter Filters</strong></td>
<td>$L_f = 300$ $\mu$H, $C_f = 540$ $\mu$F</td>
</tr>
<tr>
<td><strong>Output Filter</strong></td>
<td>$C_L = 10$ $\mu$F</td>
</tr>
<tr>
<td><strong>$\Delta$/Y Transformer</strong></td>
<td>$50$ kVA, $N_p = 240$, $N_s = 120$, $R_T = L_T = 0.03$ pu</td>
</tr>
<tr>
<td><strong>Switching (Sampling) Frequency</strong></td>
<td>$f_s = 7$ kHz</td>
</tr>
<tr>
<td><strong>Line reactance</strong></td>
<td>$X = 0.43$ pu ($L = 2$ mH)</td>
</tr>
</tbody>
</table>

Table 8.4 System parameters for a grid-connected DGS
A. Case 1

Based on Figure 5.3 (a), Case 1 which denotes DGS > load is implemented. That is, the DGS autonomously feeds electric power to the local load and after grid synchronization it provides extra power to the grid. When a fault occurs at the grid, the DGS operates at an islanding mode. Figures 8.23 and 8.24 show the simulation results of Case 1.

![Simulation waveforms for Case 1](image)

Figure 8.23: Simulation waveforms for Case 1
In Figures 8.23 and 8.25, each figure indicates: (1) Inverter output line-to-line voltage \(V_{\text{IAB}}\), (2) Load phase voltages \(V_{\text{LA}}, V_{\text{LB}}, V_{\text{LC}}\), (3) Inverter output phase currents \(i_{\text{IA}}, i_{\text{IB}}, i_{\text{IC}}\), (4) Grid-side currents \(i_{\text{gA}}, i_{\text{gB}}, i_{\text{gC}}\), and (5) Synchronization starting signal \(S_{\text{sync}}\) and synchronization gating signal \(S_{g}\).

![Graph showing various voltage and current waveforms](image)

Figure 8.24: Simulation waveforms for Case 1

In Figures 8.24 and 8.26, each figure denotes: (1) Load phase voltage \(V_{\text{LA}}\) and Grid voltage \(V_{\text{gA}}\), (2) Grid voltage \(V_{\text{gA}}\) and Grid-side current \(i_{\text{gA}}\), (3) DGS active power \(P_{\text{DGS}}\) and reactive power \(Q_{\text{DGS}}\), (4) Load active power \(P_{\text{L}}\) and reactive power \(Q_{\text{L}}\), and (5) Grid-terminal active power \(P_{t}\) and reactive power \(Q_{t}\).
As represented in Figures 8.23 and 8.24, the DGS starts up with the local load (P_L = 30 kW, Q_L = 20 kvar). After the DGS reaches steady-state, a synchronization start signal (S_{sync}) is applied at 30 msec, and a synchronization gating signal (S_g) is high when phase angle of V_L synchronizes with that of V_g at 170 msec. Then the DGS supplies extra power (10 kW) to the grid as well as P_L (30 kW) and Q_L (20 kvar) to the local load. The DGS feeds only local load after the grid fails at 300 msec.

Thus, a sequence for P/Q control and grid synchronization is in the following:

1) Initially, DGS independently runs with a local load.
2) After the DGS arrives at steady-state, a synchronization start signal is sent to the DGS.
3) DGS controller starts calculating the phase difference between DGS voltage and grid voltage, and the phase difference between them decreases until the DGS output voltage (V_L) is in phase with the grid voltage (V_g).
4) After the DGS output voltage (V_L) synchronizes with the grid voltage (V_g), a synchronization gating signal is sent to the switch (S_g) for grid connection in Figure 8.22.
5) P and Q control between the DGS and the grid starts. That is, the DGS provides extra power for the grid.
6) The switch S_g is disconnected when a fault occurs at the grid, and then the DGS supplies an isolated load at an islanding mode.
7) When the grid is recovered from the fault, a reconnection sequence with the DGS and the grid is repeated as 1) to 5).
B. Case 2

Based on Figure 5.3 (b), Case 2 which means DGS < load is simulated. That is, the DGS first supplies electric power to the local load 1, and after grid connection the grid as well as the DGS begins delivering power to the load augmented by the load 2. When a fault happens at the grid, the DGS is separated from the grid and the load 2, and it feeds only the load 1 at the isolated mode. Figures 8.25 and 8.26 show the simulation results of the Case 2.

![Simulation waveforms for Case 2](image)

Figure 8.25: Simulation waveforms for Case 2
From Figures 8.25 and 8.26, initially the DGS delivers electric power to the load 1 \((P_L = 40\ kW, Q_L = 30\ kvar)\). After \(V_L\) is in phase with \(V_g\) at 170 msec, both the DGS and the grid feed the local load 1 \((P_L = 40\ kW, Q_L = 30\ kvar)\) and 2 \((P_L = 20\ kW, Q_L = 10\ kvar)\). The DGS supplies electric energy to only the local load 1 after a grid-fault occurs at 300 msec.

Thus, a sequence for real/reactive power control and grid synchronization is as follows:

1) Initially, DGS autonomously operates with a load 1.

2) After the DGS reaches at steady-state, a synchronization start signal is sent to the DGS.
3) DGS controller starts tracking the phase difference between DGS voltage and grid voltage, and the phase difference between them decreases until the DGS output voltage ($V_L$) is in phase with the grid voltage ($V_g$).

4) After the DGS output voltage ($V_L$) synchronizes with the grid voltage ($V_g$), a synchronization gating signal is sent to both the switch “1” for grid connection and the switch “2” for the load 2 connection in Figure 5.3 (b).

5) P and Q control between the DGS and the grid starts. That is, the grid delivers electric power to the load 2.

6) The switches “1” and “2” are disconnected when a fault happens at the grid, and then the DGS feeds only load 1 at an islanding mode.

7) When the grid is recovered from the fault, a reconnection sequence with the DGS and the grid is repeated as 1) to 5).

8.3 Topology 2 (Z-Source Converter)

To validate the effectiveness of the circuit model and control strategy proposed for a Z-source converter, a simulation test bed using Matlab/Simulink is constructed for an AC 208 V (L-L)/60 Hz/10 kVA. The system parameters for the Z-source converter are given in Table 8.5.
### Table 8.5 System parameters for the Z-source converter

<table>
<thead>
<tr>
<th>Fuel Cell Output Voltage</th>
<th>$V_{in} = 130 \sim 300$ V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desired Average DC-link Voltage</td>
<td>$V_{C1} = V_{C2} = 340$ V</td>
</tr>
<tr>
<td>Output Rated Power</td>
<td>$P_{out} = 10$ kVA</td>
</tr>
<tr>
<td>Impedance Components</td>
<td>$L_1 = L_2 = 200$ µH,</td>
</tr>
<tr>
<td></td>
<td>$C_1 = C_2 = 1000$ µF</td>
</tr>
<tr>
<td>Inverter Output Filters</td>
<td>$L_f = 1000$ µH, $C_f = 200$ µF</td>
</tr>
<tr>
<td>AC Output Voltage</td>
<td>$V_{L,RMS} = 208$ V (L-L),</td>
</tr>
<tr>
<td></td>
<td>$f = 60$ Hz</td>
</tr>
<tr>
<td>Switching/Sampling Period</td>
<td>$T_z = 1/(5.4$ kHz)</td>
</tr>
</tbody>
</table>

In this topology, the simulations are implemented under various conditions such as heavy/light loads, linear/nonlinear loads, and sudden load changes. In the case of the heavy load (10 kW), we assume that the output voltage of fuel cell is 130 V, while in the case of the light load (0.5 kW) that of fuel cell is 300 V. The linear load consists of a resistor, whereas the nonlinear load is composed of an three-phase inductor (2 mH), a three-phase diode bridge, a DC-link capacitor (800 µF), and a resistor (7 Ω). From Figure 2.5, when the load increases from 5 kW to 10 kW, we assume that the output voltage of the fuel cell is changed from 250 V to 130 V. On the other hand, when the load decreases from 10 kW to 5 kW, the output voltage of the fuel cell is changed from 130 V to 250 V. In addition, we assume that the parameters of the reformer and stack are: $R_r = 0.05$ Ω and $C_r = 42.8$ mF, $R_s = 0.02$ Ω and $C_s = 4.2$ mF to show a general dynamic response of the fuel cell [69].
Figure 8.27: Simulation results under a linear load

(a) 130 V and 10 kW

(b) 300 V and 0.5 kW
Figure 8.28: Simulation results under a nonlinear load

Figure 8.27 shows simulation waveforms under the heavy and light load: (a) heavy load (130 V and 10 kW) and (b) light load (300 V and 0.5 kW). Figure 8.28 shows simulation results under the nonlinear load (130 V and 7 Ω). Figures 8.29 and 8.30 show the results under load step changes at 70 msec: load increase and decrease, respectively. Also, Figure 8.31 shows PWM waveforms of six power transistors at heavy load to regulate the average DC-link voltage ($V_{C2}$) as well as the inverter output voltage, and the shoot-through that both upper and lower power switches in a leg are simultaneously turned on is definitely shown. Figure 8.32 shows the real load current ($i_{LA}$) and estimated load current ($i_{\text{LA}}^*$) under the heavy load (130V/10kVA): upper (linear load) and lower (nonlinear load).

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Figure 8.29: Simulation results when the load increases at 70 msec

Figure 8.30: Simulation results when the load decreases at 70 msec
Figure 8.31: Six PWM gating signals

Figure 8.32: Estimated load current under a heavy load
In Figures 8.27 and 8.30, each figure indicates: (a) Power request, (b) Output voltage of the fuel cell ($V_{in}$) and capacitor ($V_{C2}$), (c) Load line-to-line voltages ($V_{LAB}$, $V_{LBC}$, $V_{LCA}$), (d) Inverter output phase currents ($i_{iA}$, $i_{iB}$, $i_{iC}$), and (e) Load phase currents ($i_{iA}$, $i_{iB}$, $i_{iC}$). As shown in Figures 8.29 to 8.30 (b), (d), a good voltage regulation of capacitor voltage ($V_{C2}$) is presented in spite of a slow change of the fuel cell output voltage under load changes.
CHAPTER 9

CONCLUSION

This dissertation studies the circuit models and control strategies for two topologies of the fuel cell powered distributed generation systems. In Topology 1, each DGS unit positions the battery in parallel to the fuel cell for a standalone AC power plant and a grid-interconnection. In Topology 2, a Z-source converter, which uses L and C components and shoot-through zero vectors without a DC to DC power converter to boost the DC-link bus voltage, is adopted for a standalone AC power generation.

In the first topology, two applications are presented: a standalone power system (a single DGS unit and two DGS units) and a grid-interconnection. First, dynamic model of the fuel cell with a voltage-current polarization curve of the stack is given based on electrochemical process. Second, controllers of two full-bridge DC to DC converters are designed: a unidirectional full-bridge DC to DC boost converter for the fuel cell and a bidirectional full-bridge DC to DC boost/buck converter for the battery. The dynamic model of the fuel cell and two DC to DC power converters are used for this topology in common. Third, for a three-phase DC to AC inverter without or with a Δ/Y transformer, a discrete-time state space circuit model is given and two discrete-time feedback
controllers are designed: voltage controller in the outer loop and current controller in the inner loop. Furthermore, for a parallel operation of two DGS units in a standalone AC power system, a new droop control method is proposed that can properly control the load-sharing such as the real, reactive, and harmonic powers. The proposed scheme is implemented by harmonic sharing control loop as well as combined droop method and average power control method, and power information exchange between each DGS unit is needed to ensure good load sharing. In particular, the theory of the average power control method can significantly reduce the sensitivity about voltage and current measurement errors, and the harmonic control loop is also added to guarantee harmonic power sharing under nonlinear loads. With reference to the simulation results (Figures 8.14 through 8.21), it is shown that the proposed control method is very effective for each DGS unit to properly share the loads such as the real, reactive, harmonic powers in a standalone AC power system. Last, for power flow control of the DGS connected in parallel to the grid, real and reactive power controllers are proposed. Particularly, a synchronization issue between an islanding mode and a paralleling mode to the grid is investigated, and two case studies are performed. Simulation test-beds using Matlab/Simulink are constructed for each configuration of the fuel cell based DGS with a three-phase AC 120 V/60 Hz/50 kVA and the proposed circuit models and control strategies are verified by various results.

In the second topology, this dissertation presents system modeling, modified space vector PWM (MSVPWM) implementation and design of a closed-loop controller of the Z-source converter that employs L and C components and shoot-through zero vectors for the standalone AC power generation. The Z-source converter does not need
power transistors, voltage/current sensors and a DSP controller as part of a DC to DC boost converter. As a result, it may have some advantages such as enhanced reliability, increased efficiency and lower cost at the expense of the added complexity in control. Also, a new control algorithm is presented which can guarantee a fast and no-overshoot current response, a zero steady state voltage error under unknown load, and low Total Harmonic Distortion (THD). The fuel cell system is modeled by an electrical R-C circuit in order to include slow dynamics of the fuel cells and a voltage-current characteristic of a cell is also considered. A discrete-time state space model is derived to implement digital control and a space vector pulse-width modulation (SVPWM) technique is modified to realize the shoot-through zero vectors that boost the DC-link voltage. In addition, three discrete-time feedback controllers are designed: a discrete-time optimal voltage controller, a discrete-time sliding mode current controller, and a discrete-time PI DC-link voltage controller. Furthermore, an asymptotic observer is used to reduce the number of sensors and enhance the reliability of the system. Various simulation results using Matlab/Simulink are presented under both light/heavy loads and linear/nonlinear loads for a three-phase AC 120V/60 Hz/10 kVA, and the analyzed circuit model and proposed control strategy are effectively demonstrated.

Consequently, this research can be a reference to those who want to demonstrate the fuel cell based DGS discussed in the previous chapters for industrial applications such as stationary and distributed power generation systems that require a three-phase AC voltage output. In the future, experimental results about all configurations will be presented using a prototype test-bed with a real fuel cell to verify the proposed circuit models and control algorithms.
BIBLIOGRAPHY


