SABBATICAL REPORT

Submitted to
The Office of Provost

cc: The Improvement of Learning Committee

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Objective

The voltage source inverters are the key enabling devices of the modern grid-interfaced power processing systems, which include the grid-tied distributed generation systems (sourced by diesel engine, solar PV array, wind, or bio-mass), the flexible AC transmission systems, and the active power quality improvement devices (UPS, Active Power Filters, Voltage Sag compensator, VAR Compensator etc.). Many new techniques have been developed in recent years to solve the interfacing problems with the power grid, but new challenges emerge due to the updated regulation standards and the new microgrid/smart grid concept. The objectives of the sabbatical leave are:

- Gain knowledge of the control techniques of the modern grid-connected voltage source converter through literature study.
- Gain knowledge of the micro-grid and modern distributed generation system through literature study.
- Develop a set of textbook materials featuring the modern voltage source inverter controls which may lead to a final publication as well as be used as the main text for a new course proposed to the EE department enriching the power curriculum.
Procedures and Outcomes

A. Literature Study

I have read over 300 papers published in the professional journals and conference proceedings. I have also read several related books. These literatures cover a wide range of the topics involving the voltage source converters. I was able to expand and/or enhance my understanding on the following key knowledge:

- Switching patterns of the space vector PWM control
- Grid synthesizing control
- Various phase locked-loop control technique for grid-tied voltage converters
- Inverter voltage controls in $dq$ reference-frames
- Current based inverter power control
- Voltage based inverter power control
- Governor control and automatic voltage regulation of the turbine-generator
- Droop based power control for the voltage source converter
- Concepts of the micro-grid and distributed power generation
- Parallel operation of the inverter-interfaced DG systems
- Islanded operation of the distributed generation systems
- Instantaneous real and reactive power theorem
- Active power filter controls
- Uninterrupted power supply for the micro-grid and the main grid.
- VAR compensation
- Power quality issue of the grid-interfaced voltage source inverter

B. Outreach

To expand my eyesight in the related field, I paid a visit to American Super Conductor Cooperation. The engineers there gave me several presentations related to the company’s products in the renewable energy field, where the voltage source inverters are involved and play important rules in terms of power integration with the grid, reactive power support and power system fault tolerance. I also had a chance to tour the production facility, where several VAR compensation units were being assembled.
I also paid a visit to the new renewable energy research center at UW-Milwaukee, where some inverter-interfaced renewable distributed generation systems were being studied.

C. Text Material Development

I have developed a draft version of the textbook. The tentative title and the contents of the draft version are summarized below:

Title:
Controls and Applications of the Modern Voltage Source Inverter (Draft)

Contents:

Chapter 1. Three-Phase Voltage Source Inverter Fundamental

1. Basic concept
2. Operational Principle of the Three-Phase Voltage Source Inverter
3. Total Harmonics Distortion
4. Space Vectors of Three-Phase AC System

Chapter 2. Basic Inverter Control Methods

1. Six-Step Inverter Control
2. Inverter Direct Voltage Control Using PWM Techniques
   2.1. The Direct SPWM Technique
      2.1.1. The Uni-Polar SPWM Strategy
      2.1.2. The Bi-Polar SPWM Strategy
      2.1.3. Modulation Frequency Requirement for Direct SPWM
   2.2. Carrier Based SPWM Voltage Control for Three-Phase VSI
      2.2.1. Basic Operation
      2.2.2. Formulate the Targeted AC Output
      2.2.3. Amplitude Modulation Index Limits of Regular SPWM
      2.2.4. 3rd Order Harmonics Injection
      2.2.5. Harmonics and Output Filter for SPWM inverters
   2.3. Space Vector Modulation (SVM) Control
2.3.1 Basic Operation
2.3.2 Modulation Limits of the SVM Control
2.3.3 Switching Pattern of SVM

3. Current Based Inverter PWM Controls
   3.1 Hysteresis Current Control of Inverters
   3.2 PI Gain Based Current PWM Control for Inverters.

Chapter 3. The Reference-Frame Theorem for Three-Phase AC Systems

1. Stationary abc to Stationary qd Reference-Frame Transformation
2. Stationary qd to Rotating qd Reference-Frame Transformation
3. Stationary abc – Rotating qd0 Reference-Frame Transformation
4. Arbitrary Reference-Frame Transformation (Rotating abc – Rotating qd0)
5. Balanced Three-Phase Quantities in Various qd0 Reference-Frame
   5.1. In the General Rotating qd0 Reference-Frame
   5.2. In the Stationary qd0 Reference-Frame
   5.3. In the Synchronous qd0 Reference-Frame
6. Instantaneous Power Equation in the Rotating qd0 Reference-Frame
   6.1. Instantaneous Power
   6.2. Real and Reactive Power

7. The dynamic qd Model Development of the Three-Phase AC Network
   7.1 Needs for the Dynamic Models
   7.2 Complication of the Inductor and Capacitor v-i Relationships in the qd Reference-Frame.
   7.3 The qd0 Model Development of the Three-Phase Network – A Case Study

Chapter 4. Grid Voltage Tracking for Inverter Controls - Magnitude Estimation and Phase-Locked Loop

1. Background
2. Single-Phase AC Voltage Estimation through Direct Inverse Tangent Calculation
3. Single-Phase Based PLL (Phase-Locked Loop)
   3.1. Basic PLL structure Improving Inverse Tangent Phase Angle Estimation
   3.2. Orthogonal Angle-Tracking Observer (ATO) Based PLL
3.3. Single-Phase Based Synchronous Reference-Frame PLL (SRF PLL)
3.4 Single-Phase PLL with Double Frequency Errors

4. Single-Phase AC Voltage $90^\circ$ Phase Shifter
   4.1. Direct sine construction using the estimated phase angle and magnitude
   4.2. $90^\circ$ phase shifter using the 1st order all-pass, unity gain filter
   4.3. SOGI (Second Order Generalized Integrator) based $90^\circ$ phase shifter
   4.4. Other Single-phase AC based phase shifting methods

5. Three-Phase AC Synthesizing Strategies Extended from Single-Phase Methods
6. Three-Phase Synchronous Reference-Frame Based Phase-Locked Loop (SRF PLL)
7. Zero-Crossing Detection Based Phase-Locked Loop

Chapter 5. Voltage Source Inverter Power Control

1. Background
2. Floating Operation Mode of the Inverter-Interfaced DGs
3. Closed-Loop Power Control Strategies for Inverters Connected to Infinite Bus
   3.1. Power Control through Current Feedback Regulation
      3.1.1 Using Hysteresis Current Control
      3.1.2 Using PI based Current Control
   3.2. Power Control through Direct Voltage Regulation
   3.3. Power Controls in the Islanded Operation Mode
      3.3.1 Intentionally Islanded Micro-grid
      3.3.2. Islanded Micro-grid with Single DG
      3.3.3. Islanded Micro-grid with multiple DGs

Chapter 6. Droop-Based Power Regulation for DGs

1. Basic Operational Features and Droop Concept of the Traditional Turbine Generators
   1.1. Proportional Relationship between $f_e$ and $\omega_m$
   1.2. Generator Model and Power Equations
      1.2.1 Generator Model
      1.2.2. Field Excitation and $Q-V$ characteristics
   1.3. Frequency (or Speed) Governor Controls for Active Power Regulation
1.3.1 Basic concept
1.3.2 Modes of governor control
1.3.3 Mode choices under different operational conditions
1.3.4 Choice of the droop parameter

1.4. Rotor Field Excitation and Reactive Power Regulation
1.4.1 AVR and $Q-V$ characteristic Selection
1.4.2 Voltage Droop and $Q-V$ Droop Gain

2. Droop Power Controls for Inverter-Interfaced DGs
2.1 Differences between the Inverter-Interfaced DGs and the Synchronous Generator DGs Implementing the Droop Power Controls
2.2 Typical Droop-Power Control Strategy for DGs with Highly Inductive Interfacing Impedance
2.3 Phase-Angle V.S. Real Power Droop Variation
2.4 Droop Control Modification Considering High Resistivity Interfacing Impedance
2.5 Limitations of the Droop Power Control

I plan to use the above material as the main textbook reference for a proposed EE special topic course (see section D for details) first. After it get matured and tested, I will consider either self-publish it to keep the cost down, or working with a publisher later on.

D. Proposed New EE Course

I have proposed to the chair of the Electrical Engineering Department and the EE curriculum committee chair to offer a new senior level special topic course, The Controls and Applications of the Grid-Interfaced Voltage Source Converters. I expect to use the text material I have developed as the main book reference for this course. Due to the enrollment and scheduling
issues, the final decision regarding the semester to run the course has yet to be made from the EE department. I will keep working with the EE department in the coming semesters to finalize the course structure and schedule. I am excited that I will have a chance to share the knowledge with the students at UWP in the near future. Below is a brief description of the proposed new course:

Course Code: EE4980 Current Topics in EE
Course Title: The Controls and Applications of the Grid-Tied Voltage Source Inverter.
Credit Hours: 3 credits.
Prerequisites: EE3020, EE3320 and EE3410. (EE3770 is strongly recommended though not mandatory.)
Course Coverage: voltage source inverter topology, basic inverter controls, space vector controls, reference-frame theorem for advanced inverter controls, concept of distributed generation and micro-grid, inverter power controls, droop-based controls, and selected grid-tied inverter applications (active power filter, VAR compensation, voltage sag compensator, HVDC transmission, wind or solar generation systems, etc.)