INTEGRATED HIGH SPEED INTELLIGENT UTILITY TIE UNIT FOR
DISBURSED/RENEWABLE GENERATION FACILITIES

by

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ABSTRACT

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After experiencing the price hikes and rotating blackouts in California, the disbursed or distributed generation (DG) is considered as one of the most attractive alternatives for future utility industry. In addition to the conventional DG that uses fossil-fuel to generate power, the DG via renewable energy is of interest due to the environmental concern. Fuel cell and photovoltaic are the most promising technologies for the urban residential and small commercial users. For economic and reliability purposes, it is desirable for these facilities to be interconnected with the utility grid to perform peak shaving, demand reduction, and to serve as emergency and standby power supply. However, the mismatch between the utility tie protection and the equipment protection make it impossible for the fuel cell and/or photovoltaic to serve as

emergency and standby power supply when the utility supply is lost due to nearby external faults. To overcome this issue, this dissertation proposes the development of an integrated high-speed intelligent utility tie unit (IUT) to monitor, control, and protect the system for residential users to enable their disbursed/renewable generation facilities to serve as emergency and standby power supply. The proposed algorithm of the IUT is verified with computer simulation and experimental results.

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CHAPTER 1

INTRODUCTION

1.1 Background

The power industry is going through the process of deregulation that changes from the traditional vertically integrated monopoly system to competitive environment. In Texas, the process of deregulation is carried out by the Electric Reliability of Texas (ERCOT) to ensure the reliability and security of the electricity under the regulation of the Public Utility of Texas (PUCT). The Texas retail electric market has started since January 1, 2002. In California, after deregulated in 1998, the energy crisis in 2000 has created the price hikes and rotating blackouts in the state. That event reinforced the idea of distributed generation (DG) as an alternative of electricity supply to improve the system reliability. In addition to the conventional DG that uses fossil-fuel to generate power, the DG via renewable energy is of interest due to the environmental concern. The Texas Senate Bill 7 stated that additional 2000 MW of renewable energy is mandated to be installed in Texas system by 2009. Fuel cell and photovoltaic are the most promising technologies for the urban residential and small commercial users. For economic and reliability purposes, it is desirable for these facilities to be interconnected with the utility grid to perform peak shaving, demand reduction, and to serve as emergency and standby power supply.

1.2 Motivations and Objectives

As mentioned earlier, it is desirable for residential user to use the fuel cell as an emergency and standby power supply for economic and reliability purposes. But there is a coordination mismatch in the current regulation on the protection between the fuel cell and the utility supply when a nearby external fault occurs [1]. Let us consider a typical interconnection arrangement between the residential customer and the utility as shown in figure 1.1. Typically, the fuel cell is equipped with high speed disconnecting mechanism to protect the inverter transistor switches during fault condition and to limit the fault current contributed by the inverter to less than 2 times of the rated current for half cycle [2]. On the other hand, the operation speed of the utility tie breaker is 10 cycles or more. When an external fault happens, the fuel cell protection B1 will be activated immediately to separate the fuel cell from the system. The utility breaker B2 will then operate to isolate the fault. As a result, the user loses both power sources, and the fuel cell cannot be used as emergency and standby power supply. This dissertation proposes the development of an integrated high-speed intelligent utility tie unit (IUT) to monitor, control, and protect the system for residential users and enable their disbursed/renewable generation facilities to serve as emergency and standby power supply. The IUT will replace the traditional tie breaker and act as a smart coordinator between the fuel cell and the utility supply.

Figure 1.1 Interconnection between residential fuel cell and utility

1.3 Outline of Approaches

The operating principles of the IUT are explained as follows:

Response to the external fault: When an external fault occurs, the IUT will first detect any nearby external faults by analyzing the voltage and current signals. Then it will initiate a trip signal immediately to separate customer from the utility supply. This will consequently prevent the fuel cell from tripping. In the mean time, the circuit breaker at upper stream will be activated to isolate the external fault. The IUT will reconnect the customer back to the system after the fault is cleared and the service is restored.

Response to the internal fault: When an internal fault occurs, the protection mechanism of the fuel cell will operate to protect the fuel cell. The fuel cell can be reconnected after the fault is cleared. In this case, the IUT will perform the coordination tasks similar to the traditional tie breaker.

The IUT has both hardware and software components. There are four hardware components as shown in figure 1.2. The current and voltage signals are acquired by the voltage and current sensing devices and sent to the signal conditioning circuit to extract needed information. Then, the embedded control processor will detect and classify the fault and send the control signal to the tripping unit. Similarly, there are four software functions inside the embedded control processor; 1) digital filters, 2) fault detection, 3) fault classification, and 4) frequency estimation.

Figure 1.2 IUT hardware block diagram

1.4 Synopsis of Chapters

The material in this dissertation is organized as follows:

Chapter 1 introduces the background, motivations, objectives, and outline of approaches.

Chapter 2 discusses distributed generations and their interconnection to the utility grid focusing on residential fuel cells.

Chapter 3 presents computer simulation of a sample residential system. The steady state and short circuit condition are simulated using ATP-EMTP.

Chapter 4 describes the hardware components of the IUT which are current and voltage sensing devices, signal conditioning circuit, embedded control processor, and tripping unit.

Chapter 5 provides the software functions in the embedded control processor for fault detection and classification.

Chapter 6 shows the software testing results that implemented in Matlab.

Chapter 7 presents the experimental results when the hardware components and software functions are integrated and tested with internal and external fault.

Chapter 8 gives the conclusions, contributions, and further researches.

CHAPTER 2

GRID CONNECTION OF DISTRIBUTED GENERATION

2.1 Introduction

This chapter discusses distributed generations and their interconnection to the utility grid focusing on residential fuel cells.

2.2 Distributed Generations

Distributed generation is a small source of electric power generation or storage (typically ranging from less than a kW to tens of MW) that is not a part of a large central power source and is located close to the load [3]. The DG power can be generated from several energy equipment including internal combustion reciprocating engines, combustion or gas turbines, microturbines, wind turbines, photovoltaics, fuel cells, biomass, geothermal, energy storage systems such as batteries, or other technologies. The DG provides some benefits to the customer and the utility [4-6].

On customer side, the DG can reduce the energy bill if used during the peak hour of the day that the electric price is high. Also, it can improve the reliability and security when used as a back up power supply during the grid outage. Moreover, the DG can increase the energy efficiency; for example, a combined heat and power system.

On utility side, the DG can relieve the congestion in transmission and distribution so that the utility can utilize the existing facilities in a more efficient way. As a result, the utility can defer the capital investment on the transmission and distribution. In addition, the DG can be used as a hedge against the uncertain load growth or a hedge against the price spike of the electric price.

Recently, the DG via renewable energy draws a lot of attentions due to the environmental concern. Also, it is encouraged by the Texas Senate Bill 7 that additional 2000 MW of renewable energy are mandated to be installed in Texas system by 2009. Furthermore, the Energy Bill signed by President Bush includes an authorization of \$3.7 billion for hydrogen and fuel cell research and development. And the bill includes a fuel cell tax credit up to \$1,000 per kilowatt on the purchase of fuel cells used in residential or commercial applications. Therefore, the market potential of residential fuel cells is significant.

2.3 Fuel Cells

Fuel cells are electrochemical devices that convert chemical energy in fuels into electrical energy directly with high efficiency and low environmental impact [7]. They are classified by the type of electrolyte. The most common types are 1) polymer electrolyte fuel cell or proton exchange membrane fuel cell, 2) alkaline fuel cell, 3) phosphoric acid fuel cell, 4) molten carbonate fuel cell, and 5) solid oxide fuel cell. The proton exchange membrane (PEM) fuel cell is the most suitable for residential application because it has high power density and can operate at low temperature (60°C to 80°C). A unit cell of PEM fuel cell is shown in figure 2.1.

The hydrogen from fuel reaches to the anode and splits into electrons and protons. The electrons pass through the electric circuit. Meanwhile, the protons pass through the proton exchange membrane. The electrons and protons combine together at the cathode with the oxygen from the air giving the water and heat as product. Figure 2.2 shows the diagram of a residential fuel cell power plant [8]. Natural gas, propane, or methanol can be used as fuel with the steam to produce the hydrogen by fuel processor. The ambient air is the source of oxygen. The hydrogen and oxygen are sent to the cell stack to generate DC voltage. Then, the DC voltage is converted to AC voltage by the inverter. The batteries are used to store the energy and the capacitors may be needed for motor starting loads. This dissertation uses 7-kVA residential fuel cell model for the study.

Figure 2.1 Unit cell of PEM fuel cell

Figure 2.2 Diagram of a residential fuel cell power plant [8]

2.4 Fuel Cell Interconnection

In order to connect the fuel cell to the utility grid, it should comply with the interconnection regulations. The interconnection requirements of the Public Utility Commission of Texas [4] are selected for the study. During voltage or frequency disturbance, the fuel cell should be disconnected from the utility system to prevent it from energizing a de-energized circuit of the utility. For voltage disturbance, if the utility voltage is between 70% and 90% or 105% and 110%, the fuel cell should be disconnected within 0.166 seconds (10 cycles) after 30 seconds (1800 cycles) delay. If the utility voltage is less than 70% or greater than 110%, the fuel cell should be disconnected within 0.166 seconds after 0.166 seconds delay. For frequency disturbance, if the frequency is less than 59.3 Hz or greater than 60.5 Hz, the fuel cell should be disconnected within 0.25 seconds (15 cycles). After tripping due to the voltage or frequency disturbance, the fuel cell may be reconnected when the utility voltage or frequency return to normal range for 2 minutes or less depending on the agreement between the customer and the utility.

Table 2.1 Delay and trip time for voltage disturbance [4]

Percentage of 120 V	Trip time	
	Seconds	Cycles
< 70%	0.166 & 0.166	10 (Delay) & 10 (Trip)
70% - 90%	30.0 & 0.166	1800 (Delay) & 10 (Trip)
90% - 105%	Normal operating range	
105% - 110%	30.0 & 0.166	1800 (Delay) & 10 (Trip)
> 110%	0.166 & 0.166	10 (Delay) & 10 (Trip)

Table 2.2 Trip time for frequency disturbance [4]

Frequency (Hz)	Trip time	
	Seconds	Cycles
< 59.3	0.25	15 (Trip)
59.3 – 60.5	Normal operating range	
> 60.5	0.25	15 (Trip)

For power quality requirements, the individual harmonic current should not exceed 4% and the total demand distortion (TDD) should not exceed 5% of the maximum demand load current at fundamental frequency. The individual harmonic voltage should not exceed 3% and the total harmonic distortion (THD) should not exceed 5% of the voltage at fundamental frequency. And the flicker should not exceed 3% voltage dip according to IEEE Standard 519 [9].

In addition, the Texas regulation also specifies the control, protection, and safety equipment for the interconnection of DG to the utility grid. In case of single-

phase 7- kW residential fuel cell, this equipment includes an interconnection disconnect device, a generator disconnect device, an over-voltage trip, an under-voltage trip, an over/under frequency trip, and a synchronizing check (for the fuel cell with stand-alone capability).

CHAPTER 3

SYSTEM SIMULATION

3.1 Introduction

This chapter presents computer simulation of a sample residential system. The steady state and short circuit condition are simulated using ATP-EMTP. The results are used to verify the proposed algorithms.

3.2 System Description

A sample radial distribution system for residential user is shown in figure 3.1. The system is simulated by using the Alternative Transient Program (ATP) of the Electromagnetic Transient Program (EMTP) with sampling rate of 960 Hz. A 7-kVA DG (fuel cell) is selected to supply only critical loads and modeled as a constant current source. The DG rated current = $7\text{kVA}/120\text{V} = 58.33\text{ A}$. The full load is assumed to be 10 kVA with 0.95 lagging power factor. Therefore, the power supplying the load comes from both sources; the DG and the utility. The one line diagram of the system in ATP-EMTP is given in figure 3.2. The DG current flows from node 8 to 9, the tie unit current flows from node 15 to 9, and the load current flows from node 9 to 53. F1 is an internal fault; F2, F3, and F4 are external faults.

Figure 3.1 Sample radial distribution system for residential user

Figure 3.2 One line diagram of the system in ATP-EMTP

3.3 Calculation of System Parameters

The input parameters for the simulation program are calculated as follows:

V source: 13.2 kV, %R₁ = 5 %, %X₁ = 30 % for a typical utility system on a 100 MVA base.

$$Z_B = \frac{kV_B^2}{MVA_B} = \frac{(13.2kV)^2}{100MVA} = 1.7424 \Omega.$$

$$R_1(\Omega) = \frac{5}{100} * 1.7424\Omega = 0.08712 \Omega = R_{source}.$$

$$X_1(\Omega) = \frac{30}{100} * 1.7424\Omega = 0.52272 \Omega.$$

$$L = \frac{X_1}{2\pi f} = \frac{0.52272\Omega}{2\pi(60)} = 0.0013866 H = 1.3866 mH = L_{source}.$$

Transformer: 100 kVA, Delta Y-Grounded, 13.2 kV / 208 V, Z = 5 %, X/R = 6. The transformer model in the program requires both primary and secondary parameters.

Primary (delta)

$$Z_B = \frac{kV_B^2}{MVA_B} = \frac{(13.2kV)^2}{\left(\frac{100}{1000}\right)MVA} = 1742.4 \Omega.$$

$$Z = \sqrt{R^2 + X^2} = \sqrt{R^2 + (6R)^2} = \sqrt{R^2 + 36R^2} = \sqrt{37R^2} = \sqrt{37}R$$

$$\therefore R = \frac{Z}{\sqrt{37}}$$

$$Z(\Omega) = \frac{5}{100} * 1742.4\Omega = 87.12 \Omega.$$

$$R(\Omega) = \frac{Z}{\sqrt{37}} = \frac{87.12}{\sqrt{37}} = 14.32244 \Omega = R_{\text{primary}}.$$

$$X(\Omega) = 6R = 6 * (14.32244 \Omega) = 85.93464 \Omega.$$

$$L = \frac{X}{2\pi f} = \frac{85.93464 \Omega}{2\pi(60)} = 0.22795 \text{H} = 227.95 \text{mH} = L_{\text{primary}}.$$

Secondary (Y-grounded)

$$Z_B = \frac{kV_B^2}{MVA_B} = \frac{(0.208 \text{kV})^2}{\left(\frac{100}{1000}\right) \text{MVA}} = 0.43264 \Omega.$$

$$Z(\Omega) = \frac{5}{100} * 0.43264 \Omega = 0.02163 \Omega.$$

$$R(\Omega) = \frac{Z}{\sqrt{37}} = \frac{0.02163}{\sqrt{37}} = 0.00356 \Omega = R_{\text{secondary}}.$$

$$X(\Omega) = 6R = 6 * (0.00356 \Omega) = 0.02134 \Omega.$$

$$L = \frac{X}{2\pi f} = \frac{0.02134 \Omega}{2\pi(60)} = 5.66 * 10^{-5} \text{H} = 0.0566 \text{mH} = L_{\text{secondary}}.$$

Line from transformer to tie unit: 100 feet of AWG No.2 three-conductor copper cable in magnetic duct; $R = 0.202 \Omega / 1,000 \text{ ft}$, $X = 0.0448 \Omega / 1,000 \text{ ft}$.

$$R = \frac{0.202 \Omega}{1,000 \text{ ft}} * 100 \text{ ft} = 0.0202 \Omega = R_{\text{line}}.$$

$$X = \frac{0.0448 \Omega}{1,000 \text{ ft}} * 100 \text{ ft} = 0.00448 \Omega.$$

$$L = \frac{X}{2\pi f} = \frac{0.00448 \Omega}{2\pi(60)} = 1.18836 * 10^{-5} \text{H} = 0.01188 \text{mH} = L_{\text{line}}.$$

Load: 10 kVA, $\text{pf} = 0.95$.

$$P = S \cos \theta = 10 * 0.95 = 9.5 \text{ kW.}$$

$$Q = S \sin \theta = 10 * \sin(\cos^{-1} 0.95) = 3.123 \text{ kVAR.}$$

$$R = \frac{V^2}{P} = \frac{(120V)^2}{(9.5 * 1000W)} = 1.516 \Omega = R_{\text{load.}}$$

$$X = \frac{V^2}{Q} = \frac{(120V)^2}{(3.123 * 1000\text{VAR})} = 4.611 \Omega.$$

$$L = \frac{X}{2\pi f} = \frac{4.611 \Omega}{2\pi(60)} = 0.01223 \text{H} = 12.23 \text{mH} = L_{\text{load.}}$$

3.4 Simulation Results

The load voltage, load current, DG current, and tie unit current in normal condition are illustrated in figure 3.3. I_{load} , I_{DG} , and $I_{\text{tie unit}}$ lag $V_{\text{load}} = 17.3^\circ$. $I_{\text{load}} = 114 \text{ A}_{\text{peak}}$, $I_{\text{DG}} = 81 \text{ A}_{\text{peak}}$, $I_{\text{tie unit}} = 33 \text{ A}_{\text{peak}}$, and $V_{\text{load}} = 170 \text{ V}_{\text{peak}}$.

Figure 3.3 Voltage and current in normal condition

The internal fault at F1 and external faults at F2 to F4 are simulated; the voltages and the corresponding currents at tie unit in one of the inception angles are provided in figures 3.4 and 3.5. In figures 3.4(a) and 3.5(a), the voltage drops to zero while the current jumps up to $4956 A_{\text{peak}}$ at sample 106 when a solid ground fault happens at F1. For the external fault at F2, the voltage has fallen to $93 V_{\text{peak}}$ while the current has risen to $50 A_{\text{peak}}$ in the negative cycle. The results for the external fault at F3 are similar to those at F2. For the external fault at F4, the voltage has decreased to $2 V_{\text{peak}}$ while the current has increased to $105 A_{\text{peak}}$ in the negative cycle. One can observe that there is a decaying DC component when the fault took place at different inception angles [33] (with respect to the cosine of the load voltage) as seen from figures 3.6 to 3.8. The fault current is maximum when the inception angle is $\pi/2$ or $3\pi/2$. For internal fault, the maximum fault current is $5154 A_{\text{peak}}$ as shown in figures 3.6(c) and 3.6(g). In case of external fault, the maximum fault current is $112 A_{\text{peak}}$ as seen from figures 3.8(c) and 3.8(g). Hence, the tripping unit of IUT should tolerate at least $5154 A_{\text{peak}}$ or use fault current limiter so that the IUT can survive in the worst case scenario.

(a)

(b)

(c)

Figure 3.4 Voltage profile for fault at (a) F1, (b) F2 or F3, (c) F4

Figure 3.5 Current at tie unit for fault at (a) F1, (b) F2 or F3, (c) F4

Figure 3.6 Current at tie unit for fault at F1 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 3.7 Current at tie unit for fault at F2 or F3 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 3.8 Current at tie unit for fault at F4 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

CHAPTER 4

HARDWARE COMPONENTS

4.1 Introduction

This chapter presents the hardware components of the IUT. There are four hardware subsystems to be described: 1) current and voltage sensing devices, 2) signal conditioning circuit, 3) embedded control processor, and 4) tripping unit.

4.2 Current and Voltage Sensing Devices

High speed sensing is critical for this type of application because the response of the IUT for the nearby external faults should be faster than the built-in protection of the fuel cell. The target operation speed of the IUT for the nearby external faults is less than 8 ms. High speed Hall effect sensors are used for monitoring the system voltage and current. The response time of these sensors is 5-40 μ s.

4.2.1 Current Sensing Device [10-12]

The open loop Hall effect current transducer L03S050D15 from Tamura has been used to measure the current at tie unit with response time 5 μ s. The schematic of this device is shown in figure 4.1. The primary current I_p flowing in the conductor creates the magnetic flux concentrated in the magnetic core. When the magnetic flux passes through the Hall sensor mounted in the air gap of the magnetic core, the Hall voltage V_H can be produced proportionally to I_p as

$$V_H = KI_C B = KI_C \frac{\mu_0}{L_0} I_P \quad (4.1)$$

where K = sensitivity factor

I_C = control current

μ_0 = permeability of free space

L_0 = air gap width

I_P = primary current.

Figure 4.1 Open loop Hall effect current transducer

The Hall voltage is amplified to obtain output voltage V_{out} . The control current circuit and the amplifier are built inside the transducer. For L03S050D15 current

transducer with 5 turns of primary current carrying conductor, $V_{out} = 4\text{ V}$ when $I_p = 50/5\text{ A}$, in other words,

$$\frac{V_{out}}{I_p} = \frac{4}{50/5} = 0.4$$

$$V_{out} = 0.4I_p \quad (4.2)$$

L03S050D15 current transducer with 5 turns of primary current carrying conductor has been tested with 60-Hz sine wave primary current and the result is plotted in figure 4.2.

Figure 4.2 Response curve of L03S050D15 current transducer with 5 turns of primary current carrying conductor

4.2.2 Voltage Sensing Device [11-12]

The closed loop Hall effect voltage transducer LV 20-P from LEM, with response time 40 μ s, has been selected to measure the load voltage. The diagram of this device is depicted in figure 4.3. The primary current I_p drawing from the primary voltage V_p creates the magnetic flux concentrated in the magnetic core. The Hall sensor and associated electronic circuit are used to generate the secondary current I_s . The secondary current produces the opposite magnetic flux that can make the total flux equal to zero. The output voltage can be calculated from

$$V_{out} = R_M I_s = R_M \left(\frac{N_p}{N_s} I_p \right) = R_M \frac{N_p}{N_s} \left(\frac{V_p}{R_1} \right) = \frac{R_M N_p}{R_1 N_s} V_p \quad (4.3)$$

where R_1 = primary resistor

R_M = measuring resistor

N_p = number of primary turn

N_s = number of secondary turn

V_p = primary voltage

Figure 4.3 Closed loop Hall effect voltage transducer

If $V_P = 200 \text{ V}$ and $R_1 = 50 \text{ k}\Omega$ 10 W ,

$$I_P = \frac{V_P}{R_1} = \frac{200}{50,000} = 0.004 \text{ A}$$

$$P(R_1) = I_P^2 R_1 = (0.004)^2 (50,000) = 0.8 \text{ W}$$

For LV 20-P voltage transducer, $N_P / N_S = 25 / 10$, then

$$I_S = \frac{N_P}{N_S} I_P = \left(\frac{25}{10} \right) (0.004) = 0.01 \text{ A}$$

Choose $R_M = 100 \Omega$ 0.25 W

$$P(R_M) = I_S^2 R_M = (0.01)^2 (100) = 0.01 \text{ W}$$

$$V_{out} = I_S R_M = (0.01)(100) = 1 \text{ V}$$

Therefore,

$$V_{out} = \frac{R_M N_P}{R_1 N_S} V_P = \frac{100}{50,000} \left(\frac{25}{10} \right) V_P = \frac{V_P}{200}$$

$$V_{out} = \frac{V_P}{200} \quad (4.4)$$

LV 20-P voltage transducer has been tested with 60-Hz sine wave primary voltage and the result is shown in figure 4.4.

Figure 4.4 Response curve of LV 20-P voltage transducer

4.3 Signal Conditioning Circuit

The voltage and current signals are contaminated during fault conditions. It is necessary to use a signal conditioning circuit to extract desired information for fast and accurate decision making. An analog filter is employed to filter out disturbances and

measurement noise. A continuous-time active filter Max274 from MAXIM [13] is selected to implement the analog filter. A second-order Butterworth lowpass filter has been designed with cutoff frequency at 180 Hz. The frequency responses – magnitude, phase, and group delay – from filter design software are plotted in figure 4.5. At the fundamental frequency 60 Hz, the magnitude is 0 dB, the phase delay is -28 degrees and the group delay is 1.4 ms. The filter is implemented and tested with $2.08 V_{pp}$ sine wave input signal. The result is shown in figure 4.6.

Figure 4.5 Frequency response of a second-order Butterworth lowpass filter from filter design software

Figure 4.6 Frequency response of a second-order Butterworth lowpass filter from experimental result

4.4 Embedded Control Processor

The embedded control processor is the brain of the IUT. It analyzes the signals from the signal conditioning circuit and sends out necessary control signal for system protection. The TMS320C6713 DSP Starter Kit (DSK) module [14] is chosen to process the data. The DSK is based on the Texas Instruments (TI) floating-point TMS320C6713 digital signal processor operating at 225 MHz and the cycle time of the processor is 4.44 ns. It comes with on-board devices such as codec, DRAM, flash memory. The DSP on the DSK interfaces to on-board peripherals through a 32-bit interface. The DSK is designed to work with TI's Code Composer Studio development environment. The load voltage and tie unit current are acquired into two analog input channels of the codec, converted to digital by 16-bit A/D converters and then analyzed

by the DSP as given in figure 4.7. After the DSP has processed the input data, it will send the control signal through a digital output channel to the tripping unit.

Figure 4.7 Embedded control processor

4.5 Tripping Unit

4.5.1 Insulated Gate Bipolar Transistor [15-17]

A tripping unit is a protecting device of the IUT. It should have high current withstand capability, fast response time, and ease of control. An insulated gate bipolar transistor (IGBT) is selected as a tripping unit. IGBT is a MOSFET-BJT combination device. It has faster response time than thyristor and GTO, has lower on-state loss than power MOSFET, and has voltage control capability. Figure 4.8 shows the vertical cross section of the N-channel non-punch-through IGBT unit cell. The IGBT structure is similar to that of power MOSFET except the P^+ substrate. The IGBT is controlled by a gate-to-emitter voltage (V_{GE}).

injected into N^- drift region causing the flow of collector-to-emitter current. To turn off the IGBT, $V_{GE} = 0$ needs to be applied to remove the inversion layer in P body region, then the collector current falls and decays as the excess carriers recombine in N^- drift region [17].

4.5.2 Tripping Unit Description

MG400Q1US41 IGBT from Toshiba [18] has been selected as a tripping unit [19]. It can carry 400-A continuous current and can withstand 800-A current for 1 ms. Its switching time is $0.4 \mu s$ to turn on and $0.8 \mu s$ to turn off. The IGBT tripping unit as shown in figure 4.9 acts as an ac switch. During each half cycle, one IGBT and a free-wheeling diode of the opposite IGBT are conducted. For example in positive half cycle, the current flows through $IGBT_A$ and diode D_B to the load. This ac switch is controlled by V_{GE} of each IGBT.

Figure 4.9 AC switch using IGBT

In order to handle the short circuit current of the internal faults, two IGBT AC switches are connected in parallel with one of them in series with a reactor to limit the fault current [20] as depicted in figure 4.10. The IGBT switch 1 is normally on and the IGBT switch 2 is normally off. For an external fault, the embedded control processor sends a control signal to turn off IGBT switch 1 within half cycle; IGBT switch 2 remains off. When the external fault is cleared, IGBT switch 1 will be turned on again. For an internal fault, the IGBT switch 1 is turned off immediately by a short-circuit protection circuit and then the IGBT switch 2 is turned on for ten cycles to comply with the DG interconnection requirements and to improve the service continuity of the customers in the case of momentary faults. When the internal fault is cleared, IGBT switch 1 will be turned on and IGBT switch 2 will be turned off.

Two Hammond 195T5 reactors connected in series are applied in the tripping unit. Each reactor has $R = 0.64\Omega$, $L = 100\text{mH}$.

Figure 4.10 Tripping unit

The current flowing through each reactor is

$$I = \frac{V}{Z} = \frac{V}{2(R + j2\pi fL)} = \frac{120}{2(0.64 + j2\pi * 60 * 0.1)}$$

$$= 0.027 - j1.591 = 1.591 \angle -89.03^\circ \text{ A}_{\text{rms}}$$

The experimental result of connecting these two reactors with 120 V_{AC} source is illustrated in figure 4.11. The voltage and current are 115.2 V_{rms} and 1.2 A_{rms} respectively. The waveforms are recorded with 1600 samples/cycle. The phase difference ϕ between voltage and current can be calculated from the phase difference between zero crossing point A and B. Since point A and B are at sample 970 and 1354,

$$\phi = \frac{(1354 - 970)}{1600} * 360^\circ = 86.4^\circ$$

Resulting in $Z = \frac{V}{I} = \frac{115.2 \angle 86.4^\circ}{1.2 \angle 0^\circ} = 6.028 + j95.811$

Figure 4.11 Voltage and current when connecting two reactors with 120 V_{AC} source

4.5.3 IGBT Short Circuit Protection [21]

As mention earlier in case of internal fault, the IGBT switch 1 in figure 4.10 needs to be turned off immediately by the short-circuit protection circuit. The desaturation technique is used to detect the short circuit. This technique monitors V_{CE} of each IGBT. Given that $V_{CE} \approx 3 \text{ V}$ when MG400Q1US41 IGBT is turned on in normal condition and $V_{CE} > 8 \text{ V}$ in short-circuit condition, the short circuit can be detected by using a comparator in the circuit as shown in figure 4.12.

Figure 4.12 IGBT short-circuit protection circuit

When the IGBT is off, the diode D_A is reversed biased; the positive input of the comparator is 15 V. On the other hand, when the IGBT is on, the diode D_A is forward

biased, then the positive input of the comparator is about V_{CE} . If $V_{CE} > 8\text{ V}$ longer than $10\text{ }\mu\text{s}$ and the IGBT is on, the gate driver will perform soft shut down of the IGBT and send the Fault signal to the embedded control processor. The $10\text{-}\mu\text{s}$ delay is necessary to prevent a wrong detection because V_{CE} needs sometime to falls below 8 V (turn on time of IGBT) in normal condition.

Figure 4.13 IGBT switch 1 control circuit

Since IGBT switch 1 has two IGBTs, IGBT_A and IGBT_B, as shown earlier in figure 4.9, two protection circuits are utilized with control circuit as depicted in figure 4.13. If the fault is detected by the protection circuit of IGBT_A or IGBT_B, Switch 1 Fault will be activated to disable the two IGBTs via IGBT_A Control and IGBT_B Control. Because the applied sampling time of the DSP board is about 1 ms , the bypass route of Switch 1 Fault over the DSP board is necessary to assure that IGBT_A or IGBT_B will not be turned on in fault condition after built-in soft shut down in protection circuit is reset in 1.5 ms . The logical operation of switch 1 control circuit is given in table 4.1. In

normal condition, IGBT_A and IGBT_B are controlled by Switch 1 Control from DSP board. On the other hand, in fault condition, they are controlled by Switch 1 Fault.

Table 4.1 Logical operation of IGBT switch 1 control circuit

Condition	Switch 1 Fault	Switch 1 Control	IGBT _A Control and IGBT _B Control
Normal Condition	Low	High	High
	Low	Low	Low
Fault Condition	High	High	Low
	High	Low	Low

IGBT switch 1 short circuit protection is tested with 120 V_{AC} source and 100W resistive load. The results are shown in figures 4.14 and 4.15. The short circuit happens at time = 32.50 ms. After the short circuit is detected at time = 32.51 ms, the protection circuit performs soft shutdown of the faulting IGBT. Then, the Switch 1 Fault is activated at time = 32.52 ms to disable IGBT_A and IGBT_B so that these two IGBTs are not turned on in fault condition. As a result, IGBT switch 1 is protected.

Figure 4.14 Experimental result of IGBT switch 1 short circuit protection

Figure 4.15 Experimental result of IGBT switch 1 short circuit protection (zoom in figure 4.14)

CHAPTER 5

SOFTWARE FUNCTIONS

5.1 Introduction

The functions of the software in the embedded control processor are to detect and determine the fault type as soon as possible. There are four software functions to be discussed: 1) digital filters, 2) fault detection, 3) fault classification, and 4) frequency estimation.

5.2 Digital Filters

Digital filters are required to filter out the remaining disturbances after analog filtering in the signal conditioning circuit. Three filters have been designed with a sampling rate of 16 samples/cycle.

1) Nulling Filter [22] for DC, 3rd, 5th, and 7th harmonics rejection. The filter is designed by placing zeros on the unit circle at $e^{\pm j2\pi k/N}$ ($k = 0, 3, 5, 7$ and $N=16$) as illustrated in figure 5.1. The impulse response of the filter can be calculated by taking inverse z-transform of

$$H(z) = \prod_{i=1}^M (1 - a_i z^{-1}), \quad (5.1)$$

where a_i are the zeros and M is the number of zeros ($M=7$ in this case). The impulse response and frequency response of the nulling filter are given in figures 5.2 and 5.3.

Figure 5.1 Pole-zero plot of nulling filter

Figure 5.2 Impulse response of nulling filter

Figure 5.3 Frequency response of nulling filter

2) Sine Filter [23] for DC, 2nd to 7th harmonics rejection. The filter is designed by setting the magnitude and phase responses of the discrete Fourier transform (DFT), $H[k]$, and computing the impulse response, $h[n]$, from the DFT synthesis equation [24]

$$h[n] = \frac{1}{N} \sum_{k=1}^N H[k] e^{j2\pi(k-1)(n-1)/N}, \quad (5.2)$$

where $n = 1, 2, \dots, N$ and $N = 16$. This can be expressed in a matrix form as

$$\mathbf{h} = \frac{1}{N} \mathbf{E} \mathbf{H}. \quad (5.3)$$

Suppose that the required magnitude and phase at the fundamental frequency are 1 and -90° , the setting will be

$$H[k] = \begin{cases} -j, & k = 2, \\ j, & k = 16, \\ 0, & \text{otherwise.} \end{cases} \quad (5.4)$$

After solving the DFT synthesis equation, the resulting impulse response and frequency response are plotted in figures 5.4 and 5.5.

Figure 5.4 Impulse response of sine filter

Figure 5.5 Frequency response of sine filter

3) Cosine Filter [23] for DC, 2nd to 7th harmonics rejection. In this case, the phase at the fundamental frequency is shifted by 90° compared to the sine filter. The design is similar to that of the sine filter, but the phase at the fundamental frequency is 0. The setting is

$$H[k] = \begin{cases} 1, & k = 2 \text{ and } 16, \\ 0, & \text{otherwise.} \end{cases} \quad (5.5)$$

The resulting impulse response and frequency response are depicted in figures 5.6 and 5.7.

Figure 5.6 Impulse response of cosine filter

Figure 5.7 Frequency response of cosine filter

These three filters have been tested with Matlab generated input waveform as shown in figure 5.8(a). The input waveform is composed of 60-Hz sinusoidal signal with amplitude = 1, decaying DC component, 10% of 3rd harmonic, 9% of 5th harmonic, and 8% of 7th harmonic. The output waveforms after digital filtering are illustrated in figures 5.8(b) to 5.8(d). The results show that these three digital filters are able to eliminate the DC component, 3rd, 5th, and 7th harmonics from the input waveform as seen from the frequency responses in figures 5.9(b) to 5.9(d). The nulling filter is used for amplitude and phase estimations in preliminary testing. The sine filter and cosine filter are applied in frequency estimation method 1 in section 5.5.1.

Figure 5.8 Waveforms before and after digital filtering: (a) input waveform, (b) output waveform after using nulling filter, (c) output waveform after using sine filter, (d) output waveform after using cosine filter

Figure 5.9 Frequency responses before and after digital filtering: (a) frequency response of input signal, (b) frequency response of output signal after using nulling filter, (c) frequency response of output signal after using sine filter, (d) frequency response of output signal after using cosine filter

5.3 Fault Detection

When a fault happens in the system, the current will change abruptly. To detect this sudden change, the one-cycle-apart comparison has been used [29]. This method compares the present sample and the one-cycle-delay sample. For example, with 16 samples/cycle sampling rate, the present sample $s[n]$ will be compared with the one-cycle-delay sample $s[n-16]$ as shown in figure 5.10. If $|s[n] - s[n-16]|$ is greater than a threshold value ε , the fault is detected.

Figure 5.10 One cycle sliding window

Let the signal in normal condition be

$$s[n] = A \cos\left\{\phi + \frac{2\pi}{M} n\right\}, \quad (5.6)$$

where A is an amplitude, ϕ is a phase, $M = f_s / f_0$, f_s is a sampling frequency, f_0 is a fundamental frequency, and n is the sampling index. The selection of the threshold value can be considered from two cases of M ; 1) $M = 16$ and 2) $M \neq 16$.

1) **$M=16$** $f_s = 960$ Hz and $f_0 = 60$ Hz

In normal condition, the signal at time n is

$$s[n] = A \cos \left\{ \phi + \frac{2\pi}{16} n \right\}. \quad (5.7)$$

At time $n-16$,

$$\begin{aligned} s[n-16] &= A \cos \left\{ \phi + \frac{2\pi}{16} (n-16) \right\} \\ &= A \cos \left\{ \phi + \frac{2\pi}{16} n - 2\pi \right\} = A \cos \left\{ \phi + \frac{2\pi}{16} n \right\} = s[n]. \end{aligned} \quad (5.8)$$

Thus, in normal condition,

$$|s[n] - s[n-16]| = 0. \quad (5.9)$$

In fault condition, the signal is

$$s[n] = A_F \cos \left\{ \phi_F + \frac{2\pi}{16} n \right\}, \quad (5.10)$$

where A_F is a fault amplitude ($A_F > A$) and ϕ_F is a fault phase.

Therefore, in fault condition,

$$|s[n] - s[n-16]| > 0 \text{ unless } s[n] = s[n-16] = 0. \quad (5.11)$$

2) **$M \neq 16$** $f_s = 960$ Hz, $f_0 \neq 60$ Hz, f_0 is between 59.3 and 60.5 Hz (according

to normal operating range in table 2.2 of chapter 2)

In normal condition, the signal at time n is

$$s[n] = A \cos \left\{ \phi + \frac{2\pi}{M} n \right\}. \quad (5.12)$$

At time $n - 16$,

$$\begin{aligned} s[n-16] &= A \cos \left\{ \phi + \frac{2\pi}{M} (n-16) \right\} \\ &= A \cos \left\{ \phi + \frac{2\pi}{M} n - \frac{32\pi}{M} \right\}. \end{aligned} \quad (5.13)$$

It can be seen that in normal condition

$$|s[n] - s[n-16]| \neq 0. \quad (5.14)$$

If $M = 960/59.3$ ($f_s = 960$ Hz and $f_0 = 59.3$ Hz),

$$\max |s[n] - s[n-16]| \approx 0.074A. \quad (5.15)$$

If $M = 960/60.5$ ($f_s = 960$ Hz and $f_0 = 60.5$ Hz),

$$\max |s[n] - s[n-16]| \approx 0.053A. \quad (5.16)$$

In fault condition, the signal is

$$s[n] = A_F \cos \left\{ \phi_F + \frac{2\pi}{M} n \right\}. \quad (5.17)$$

Similar to those of $M = 16$ in fault condition,

$$|s[n] - s[n-16]| > 0 \text{ unless } s[n] = s[n-16] = 0. \quad (5.18)$$

The lowest threshold value should be greater than the maximum of $|s[n] - s[n-16]|$ in normal condition, $0.074A$. On the other hand, the highest threshold

value should be less than the maximum of $|s[n] - s[n-16]|$ in fault condition when $s[n-16] = 0$, A_F .

Hence, the threshold value should be set as

$$0.074A < \varepsilon < A_F. \quad (5.19)$$

5.4 Fault Classification

From the system simulation in figure 3.2 of chapter 3, the power flows from node 15 to 9 in normal condition. For internal fault, the power flows in the same direction as in normal condition with high fault current as seen in figure 3.6. However, in case of external fault, the power flows in the opposite direction and its magnitude is much less than that of the internal fault case as shown in figures 3.7 and 3.8 due to the DG's power limitation. Therefore, the fault type can be classified by taking the current amplitude and the power flow direction into consideration.

From the concept of complex power [25],

$$S = VI^* = P + jQ \quad (5.20)$$

If $V = |V|\angle\phi_v$ and $I = |I|\angle\phi_i$,

$$\begin{aligned} S = VI^* &= |V||I|\angle(\phi_v - \phi_i) \\ &= |V||I|\cos(\phi_v - \phi_i) + j|V||I|\sin(\phi_v - \phi_i) \\ &= P + jQ. \end{aligned}$$

The flow direction of real power, $P = |V||I|\cos(\phi_v - \phi_i)$, can be found from the phase difference between voltage and current. If the phase difference is less than 90° , P

flows in one direction. On the other hand, if the phase difference is greater than 90° , P flows in the opposite direction.

After the fault is detected, it can be classified by using the amplitude estimation of current signal $\hat{A}_i$, the phase estimation of voltage signal $\hat{\phi}_v$, and the phase estimation of current signal $\hat{\phi}_i$, where the reference is a cosine signal. The classification procedure is as follows. Let A_{high} and A_{low} are high and low threshold values,

1) If $\hat{A}_i \geq A_{high}$, it is an internal fault.

2) If $\hat{A}_i < A_{high}$,

2.1) if $\hat{A}_i \geq A_{low}$

2.1.1) if $|\hat{\phi}_v - \hat{\phi}_i| \geq 90^\circ$, it is an external fault,

2.2.2) if $|\hat{\phi}_v - \hat{\phi}_i| < 90^\circ$, it is a normal condition.

2.2) if $\hat{A}_i < A_{low}$, it is a normal condition.

Two algorithms have been studied for amplitude and phase estimation: 1) least square estimation and 2) recursive least square estimation.

5.4.1 Least Square Estimation [26]

A sinusoidal signal can be represented as

$$\begin{aligned} s[n] &= A \cos(\phi + \delta n) \\ &= A \cos \phi \cos \delta n - A \sin \phi \sin \delta n, \end{aligned} \quad (5.21)$$

where A is an amplitude, ϕ is a phase, $\delta = 2\pi f_0 / f_s$, f_0 is a fundamental frequency, f_s is a sampling frequency, and n is the sampling index.

At time $n-m$,

$$\begin{aligned} s[n-m] &= A \cos\{\phi + \delta(n-m)\} \\ &= A \cos \phi \cos \delta(n-m) - A \sin \phi \sin \delta(n-m). \end{aligned} \quad (5.22)$$

In matrix form,

$$\begin{aligned} \begin{bmatrix} s[n] \\ s[n-m] \end{bmatrix} &= \begin{bmatrix} \cos \delta n & -\sin \delta n \\ \cos \delta(n-m) & -\sin \delta(n-m) \end{bmatrix} \begin{bmatrix} A \cos \phi \\ A \sin \phi \end{bmatrix} \\ \begin{bmatrix} A \cos \phi \\ A \sin \phi \end{bmatrix} &= \begin{bmatrix} \cos \delta n & -\sin \delta n \\ \cos \delta(n-m) & -\sin \delta(n-m) \end{bmatrix}^{-1} \begin{bmatrix} s[n] \\ s[n-m] \end{bmatrix} \\ &= \frac{1}{\sin \delta m} \begin{bmatrix} -\sin \delta(n-m) & \sin \delta n \\ -\cos \delta(n-m) & \cos \delta n \end{bmatrix} \begin{bmatrix} s[n] \\ s[n-m] \end{bmatrix} \\ &= \frac{1}{\sin \delta m} \begin{bmatrix} -s[n] \sin \delta(n-m) + s[n-m] \sin \delta n \\ -s[n] \cos \delta(n-m) + s[n-m] \cos \delta n \end{bmatrix}. \end{aligned} \quad (5.23)$$

The amplitude and phase can be calculated as

$$\begin{aligned} A &= \sqrt{(A \cos \phi)^2 + (A \sin \phi)^2} \\ &= \frac{1}{\sin \delta m} \sqrt{s^2[n] + s^2[n-m] - 2s[n]s[n-m] \cos \delta m}, \end{aligned} \quad (5.24)$$

$$\begin{aligned} \phi &= \tan^{-1} \left(\frac{A \sin \phi}{A \cos \phi} \right) \\ &= \tan^{-1} \left\{ \frac{-s[n] \cos \delta(n-m) + s[n-m] \cos \delta n}{-s[n] \sin \delta(n-m) + s[n-m] \sin \delta n} \right\}. \end{aligned} \quad (5.25)$$

For $m = 1$ (one sample delay),

$$A = \frac{1}{\sin \delta} \sqrt{s^2[n] + s^2[n-1] - 2s[n]s[n-1]\cos \delta} \quad [27], \quad (5.26)$$

$$\phi = \tan^{-1} \left\{ \frac{-s[n]\cos \delta(n-1) + s[n-1]\cos \delta n}{-s[n]\sin \delta(n-1) + s[n-1]\sin \delta n} \right\}. \quad (5.27)$$

If $f_s / f_0 = M$ is the number of samples/cycle, in case of $m = M/4$ (quarter cycle delay),

$$\begin{aligned} A &= \frac{1}{\sin\left(\frac{2\pi}{M} \cdot \frac{M}{4}\right)} \sqrt{s^2[n] + s^2\left[n - \frac{M}{4}\right] - 2s[n]s\left[n - \frac{M}{4}\right]\cos\left(\frac{2\pi}{M} \cdot \frac{M}{4}\right)} \\ &= \sqrt{s^2[n] + s^2\left[n - \frac{M}{4}\right]} \quad [27], \end{aligned} \quad (5.28)$$

$$\phi = \tan^{-1} \left\{ \frac{-s[n]\cos \delta\left(n - \frac{M}{4}\right) + s\left[n - \frac{M}{4}\right]\cos \delta n}{-s[n]\sin \delta\left(n - \frac{M}{4}\right) + s\left[n - \frac{M}{4}\right]\sin \delta n} \right\}. \quad (5.29)$$

The phase difference between voltage and current can be computed by $\phi_v - \phi_i$.

One can also obtain the phase difference by another method as follows.

If the voltage and current signals are

$$v[n] = V \cos(\delta n + \phi_v),$$

$$i[n] = I \cos(\delta n + \phi_i).$$

At time $n - m$,

$$v[n - m] = V \cos\{\delta(n - m) + \phi_v\},$$

$$i[n - m] = I \cos\{\delta(n - m) + \phi_i\}.$$

The products of voltage and current are

$$\begin{aligned}
v[n]i[n] &= VI \cos(\delta n + \phi_v) \cos(\delta n + \phi_i) \\
&= \frac{VI}{2} \{ \cos 2\delta n \cos(\phi_v + \phi_i) - \sin 2\delta n \sin(\phi_v + \phi_i) \\
&\quad + \cos(\phi_v - \phi_i) \}, \tag{5.30}
\end{aligned}$$

$$\begin{aligned}
v[n]i[n-m] &= VI \cos(\delta n + \phi_v) \cos\{\delta(n-m) + \phi_i\} \\
&= \frac{VI}{2} \{ \cos \delta(2n-m) \cos(\phi_v + \phi_i) - \sin \delta(2n-m) \sin(\phi_v + \phi_i) \\
&\quad + \cos \delta m \cos(\phi_v - \phi_i) - \sin \delta m \sin(\phi_v - \phi_i) \}, \tag{5.31}
\end{aligned}$$

$$\begin{aligned}
v[n-m]i[n] &= VI \cos\{\delta(n-m) + \phi_v\} \cos(\delta n + \phi_i) \\
&= \frac{VI}{2} \{ \cos \delta(2n-m) \cos(\phi_v + \phi_i) - \sin \delta(2n-m) \sin(\phi_v + \phi_i) \\
&\quad + \cos \delta m \cos(\phi_v - \phi_i) + \sin \delta m \sin(\phi_v - \phi_i) \}, \tag{5.32}
\end{aligned}$$

$$\begin{aligned}
v[n-m]i[n-m] &= VI \cos\{\delta(n-m) + \phi_v\} \cos\{\delta(n-m) + \phi_i\} \\
&= \frac{VI}{2} \{ \cos 2\delta(n-m) \cos(\phi_v + \phi_i) - \sin 2\delta(n-m) \sin(\phi_v + \phi_i) \\
&\quad + \cos(\phi_v - \phi_i) \}, \tag{5.33}
\end{aligned}$$

In matrix form,

$$\begin{bmatrix} v[n]i[n] \\ v[n]i[n-m] \\ v[n-m]i[n] \\ v[n-m]i[n-m] \end{bmatrix} = \frac{VI}{2} \begin{bmatrix} \cos 2\delta n & -\sin 2\delta n & 1 & 0 \\ \cos \delta(2n-m) & -\sin \delta(2n-m) & \cos \delta m & -\sin \delta m \\ \cos \delta(2n-m) & -\sin \delta(2n-m) & \cos \delta m & \sin \delta m \\ \cos 2\delta(n-m) & -\sin 2\delta(n-m) & 1 & 0 \end{bmatrix} \begin{bmatrix} \cos(\phi_v + \phi_i) \\ \sin(\phi_v + \phi_i) \\ \cos(\phi_v - \phi_i) \\ \sin(\phi_v - \phi_i) \end{bmatrix} \tag{5.34}$$

$$\mathbf{s} = \mathbf{H}\boldsymbol{\alpha} \tag{5.35}$$

$$\boldsymbol{\alpha} = \mathbf{H}^{-1}\mathbf{s} \tag{5.36}$$

The phase difference is

$$\phi_v - \phi_i = \tan^{-1} \left\{ \frac{\sin(\phi_v - \phi_i)}{\cos(\phi_v - \phi_i)} \right\} = \tan^{-1} \left\{ \frac{\alpha_4[n]}{\alpha_3[n]} \right\}, \quad (5.37)$$

where $\alpha_i[n]$ is the i^{th} element of $\alpha[n]$. This method requires 4x4 matrix inversion of $\mathbf{H}$.

However, in case of quarter cycle delay, after substitute $\delta = 2\pi / M$ and $m = M / 4$, the matrix becomes

$$\begin{bmatrix} v[n]i[n] \\ v[n]i[n - \frac{M}{4}] \\ v[n - \frac{M}{4}]i[n] \\ v[n - \frac{M}{4}]i[n - \frac{M}{4}] \end{bmatrix} = \frac{VI}{2} \begin{bmatrix} \cos \frac{4\pi}{M} n & -\sin \frac{4\pi}{M} n & 1 & 0 \\ \cos \left(\frac{4\pi}{M} n - \frac{\pi}{2} \right) & -\sin \left(\frac{4\pi}{M} n - \frac{\pi}{2} \right) & 0 & -1 \\ \cos \left(\frac{4\pi}{M} n - \frac{\pi}{2} \right) & -\sin \left(\frac{4\pi}{M} n - \frac{\pi}{2} \right) & 0 & 1 \\ \cos \left(\frac{4\pi}{M} n - \pi \right) & -\sin \left(\frac{4\pi}{M} n - \pi \right) & 1 & 0 \end{bmatrix} \begin{bmatrix} \cos(\phi_v + \phi_i) \\ \sin(\phi_v + \phi_i) \\ \cos(\phi_v - \phi_i) \\ \sin(\phi_v - \phi_i) \end{bmatrix}. \quad (5.38)$$

It can be seen that

$$v[n]i[n] + v[n - \frac{M}{4}]i[n - \frac{M}{4}] = VI \cos(\phi_v - \phi_i)$$

$$v[n - \frac{M}{4}]i[n] - v[n]i[n - \frac{M}{4}] = VI \sin(\phi_v - \phi_i)$$

Therefore, the phase difference in case of quarter cycle delay is simply [28]

$$\phi_v - \phi_i = \tan^{-1} \left\{ \frac{VI \sin(\phi_v - \phi_i)}{VI \cos(\phi_v - \phi_i)} \right\} = \frac{v[n - \frac{M}{4}]i[n] - v[n]i[n - \frac{M}{4}]}{v[n]i[n] + v[n - \frac{M}{4}]i[n - \frac{M}{4}]}. \quad (5.39)$$

Because the real-life voltage and current in power system are not pure sinusoid, a decaying DC component and harmonics should be included in the signal model for better estimation [29]. For example if the decaying DC component is included, the signal at time $n - m$ will be

$$\begin{aligned}
s[n-m] &= A_0 e^{-(n-m)/\tau} + A \cos\{\phi + \delta(n-m)\} \\
&= A_0 e^{-(n-m)/\tau} + A \cos\phi \cos\delta(n-m) - A \sin\phi \sin\delta(n-m), \tag{5.40}
\end{aligned}$$

where A_0 and τ are the amplitude and time constant of the decaying DC component.

Using Taylor series expansion of the first two terms results in

$$s[n-m] = A_0 - A_0(n-m)/\tau + A \cos\phi \cos\delta(n-m) - A \sin\phi \sin\delta(n-m). \tag{5.41}$$

If $m = 0, 1, 2, \dots, k$, the signal in matrix form will be

$$\begin{bmatrix} s[n] \\ s[n-1] \\ \vdots \\ s[n-k] \end{bmatrix} = \begin{bmatrix} 1 & -n & \cos\delta n & -\sin\delta n \\ 1 & -(n-1) & \cos\delta(n-1) & -\sin\delta(n-1) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & -(n-k) & \cos\delta(n-k) & -\sin\delta(n-k) \end{bmatrix} \begin{bmatrix} A_0 \\ A_0/\tau \\ A \cos\phi \\ A \sin\phi \end{bmatrix} \tag{5.42}$$

$$\mathbf{s} = \mathbf{H}\mathbf{a} \tag{5.43}$$

$$\mathbf{a} = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{s} \tag{5.44}$$

Since there are 4 unknown variables; A_0, τ, A , and ϕ , at least 4 independent equations are needed to find the solution and requires 4x4 matrix inversion of $\mathbf{H}^T \mathbf{H}$. If more signal components are added in the signal model, the calculation complexity will increase. For example, if 3rd, and 5th harmonics are included, there will be 8 unknown variables and requires 8x8 matrix inversion to solve the problem.

5.4.2 Recursive Least Square Estimation [26],[29-30]

From the model of the sinusoidal signal,

$$\begin{aligned}
s[n] &= A \cos(\phi + \delta n) \\
&= A \cos\phi \cos\delta n - A \sin\phi \sin\delta n
\end{aligned}$$

It can be written as

$$s[n] = \mathbf{H}^T[n] \boldsymbol{\theta}[n], \quad (5.45)$$

where $\mathbf{H}[n]$ is an observation vector and $\boldsymbol{\theta}[n]$ is a parameter vector. In this case,

$$\mathbf{H}[n] = [\cos \delta n \quad -\sin \delta n]^T, \quad (5.46)$$

$$\boldsymbol{\theta}[n] = [A \cos \phi \quad A \sin \phi]^T. \quad (5.47)$$

By applying the weighted least square error criterion,

$$J(\boldsymbol{\theta}[n]) = \sum_{k=0}^n \lambda^{n-k} \left(s[k] - \mathbf{H}^T[k] \hat{\boldsymbol{\theta}}[k-1] \right)^2 \quad (5.48)$$

with a forgetting factor $0 < \lambda < 1$, the estimate of $\boldsymbol{\theta}[n]$ will be

$$\hat{\boldsymbol{\theta}}[n] = \hat{\boldsymbol{\theta}}[n-1] + \mathbf{K}[n] \left(s[n] - \mathbf{H}^T[n] \hat{\boldsymbol{\theta}}[n-1] \right), \quad (5.49)$$

where

$$\text{Gain factor } \mathbf{K}[n] = \frac{\mathbf{P}[n-1] \mathbf{H}[n]}{\lambda + \mathbf{H}^T[n] \mathbf{P}[n-1] \mathbf{H}[n]}, \quad (5.50)$$

$$\text{Covariance matrix } \mathbf{P}[n] = \lambda^{-1} \left(\mathbf{I} - \mathbf{K}[n] \mathbf{H}^T[n] \right) \mathbf{P}[n-1]. \quad (5.51)$$

The initial conditions are $\hat{\boldsymbol{\theta}}[-1] = \mathbf{0}$ and $\mathbf{P}[-1] = \alpha \mathbf{I}$, $\alpha > 0$. The estimates of amplitude and phase of the sinusoidal signal can be computed as

$$\hat{A}[n] = \sqrt{\hat{\boldsymbol{\theta}}_1^2[n] + \hat{\boldsymbol{\theta}}_2^2[n]}, \quad (5.52)$$

$$\hat{\phi}[n] = \tan^{-1} \left(\frac{\hat{\boldsymbol{\theta}}_2[n]}{\hat{\boldsymbol{\theta}}_1[n]} \right). \quad (5.53)$$

where $\hat{\boldsymbol{\theta}}_i[n]$ is the i^{th} element of $\hat{\boldsymbol{\theta}}[n]$. The phase difference between voltage and current can be found by using $\hat{\phi}_v[n] - \hat{\phi}_i[n]$.

Similar to the least square method, adding the decaying DC component and harmonics to the signal model of the recursive least square can improve the estimation. For example, if the decaying DC components, 3rd and 5th harmonics, are included, the signal model becomes

$$\begin{aligned}
s[n] &= A_0 e^{-n/\tau} + A \cos(\phi + \delta n) + A_3 \cos(\phi_3 + 3\delta n) + A_5 \cos(\phi_5 + 5\delta n) \\
&= A_0 - A_0 n / \tau + A \cos \phi \cos \delta n - A \sin \phi \sin \delta n + A_3 \cos \phi_3 \cos 3\delta n \\
&\quad - A_3 \sin \phi_3 \sin 3\delta n + A_5 \cos \phi_5 \cos 5\delta n - A_5 \sin \phi_5 \sin 5\delta n \\
&= \mathbf{H}^T[n] \boldsymbol{\theta}[n],
\end{aligned} \tag{5.54}$$

where

$$\mathbf{H}[n] = [1 \quad -n \quad \cos \delta n \quad -\sin \delta n \quad \cos 3\delta n \quad -\sin 3\delta n \quad \cos 5\delta n \quad -\sin 5\delta n]^T, \tag{5.55}$$

$$\boldsymbol{\theta}[n] = [A_0 \quad A_0 / \tau \quad A \cos \phi \quad A \sin \phi \quad A_3 \cos \phi_3 \quad A_3 \sin \phi_3 \quad A_5 \cos \phi_5 \quad A_5 \sin \phi_5]^T \tag{5.56}$$

The estimates of amplitude and phase of the fundamental frequency are

$$\hat{A}[n] = \sqrt{\hat{\boldsymbol{\theta}}_3^2[n] + \hat{\boldsymbol{\theta}}_4^2[n]}, \tag{5.57}$$

$$\hat{\phi}[n] = \tan^{-1} \left(\frac{\hat{\boldsymbol{\theta}}_4[n]}{\hat{\boldsymbol{\theta}}_3[n]} \right). \tag{5.58}$$

Unlike the least square method, the recursive least square method does not require matrix inversion even decaying DC components, 3rd and 5th harmonics, are included in the signal model. Therefore, only recursive least square estimation will be implemented in the embedded control processor.

5.5 Frequency Estimation

The estimates of amplitude and phase as mentioned earlier are based on the assumption that the fundamental frequency is constant at 60 Hz. For example, in (5.24) where $\delta = 2\pi f_0 / f_s$, f_0 is assumed to be 60 Hz. But the actual frequency in power system is not exactly 60 Hz. It can vary from 59.3 Hz to 60.5 Hz as shown in normal operating range in table 2.2 of chapter 2. The frequency mismatch between the assumed frequency and the actual frequency will cause ripple in amplitude estimation and drift in phase estimation. Therefore, the estimate of the fundamental frequency is needed in order to obtain the better estimates of amplitude and phase. Two methods are studied: method 1 and method 2.

5.5.1 Frequency Estimation Method 1[31]

This method uses the orthogonal property to estimate the frequency as shown in figure 5.11. The input signal $s[n]$ is passed through filters H_1 and H_2 to remove DC and harmonic components.

Figure 5.11 Frequency estimation method 1

The frequency responses of H_1 and H_2 have the same magnitude but the phase at fundamental frequency of H_2 is shifted by 90° compared to that of H_1 . Hence, the output $x[n]$ and $y[n]$ from H_1 and H_2 can form a vector $\mathbf{u}[n]$ as

$$\mathbf{u}[n] = [x[n] \quad y[n]]^T. \quad (5.59)$$

The fundamental frequency can be calculated by using two consecutive values of $\mathbf{u}[n]$ as depicted in figure 5.12.

Figure 5.12 Vector representation of $\mathbf{u}[n]$ and $\mathbf{u}[n-1]$

The angle between these two vectors is

$$\begin{aligned} \theta[n] - \theta[n-1] &= \tan^{-1} \left(\frac{\sin\{\theta[n] - \theta[n-1]\}}{\cos\{\theta[n] - \theta[n-1]\}} \right) \\ &= \tan^{-1} \left(\frac{\sin \theta[n] \cos \theta[n-1] - \cos \theta[n] \sin \theta[n-1]}{\cos \theta[n] \cos \theta[n-1] + \sin \theta[n] \sin \theta[n-1]} \right) \end{aligned}$$

$$= \tan^{-1} \left(\frac{x[n-1]y[n] - y[n-1]x[n]}{x[n-1]x[n] + y[n-1]y[n]} \right). \quad (5.60)$$

Since $\theta[n] - \theta[n-1] = 2\pi f_0 / f_s$, the estimate of fundamental frequency is

$$\hat{f}_0 = \frac{\theta[n] - \theta[n-1]}{2\pi / f_s} \quad (5.61)$$

5.5.2 Frequency Estimation Method 2[32]

If three consecutive samples of input signal are

$$s[n] = A \sin(\delta n + \phi) = A \sin(\alpha), \quad (5.62)$$

$$s[n-1] = A \sin\{\delta(n-1) + \phi\} = A \sin(\alpha - \delta), \quad (5.63)$$

$$s[n-2] = A \sin\{\delta(n-2) + \phi\} = A \sin(\alpha - 2\delta). \quad (5.64)$$

Let

$$p = \frac{s[n-1]}{s[n]} = \cos \delta - \frac{\cos \alpha}{\sin \alpha} \sin \delta. \quad (5.65)$$

It yields

$$\cot \alpha = \frac{\cos \delta - p}{\sin \delta}. \quad (5.66)$$

And let

$$q = \frac{s[n-2]}{s[n]} = \cos 2\delta - \frac{\cos \alpha}{\sin \alpha} \sin 2\delta. \quad (5.67)$$

Then

$$\cot \alpha = \frac{\cos 2\delta - q}{\sin 2\delta}. \quad (5.68)$$

From (5.66) and (5.68),

$$\frac{\cos \delta - p}{\sin \delta} = \frac{\cos 2\delta - q}{\sin 2\delta}.$$

After some manipulations, one can obtain

$$\delta = \cos^{-1} \left(\frac{s[n] + s[n-2]}{2s[n-1]} \right). \quad (5.69)$$

Since $\delta = 2\pi f_0 / f_s$, the estimate of fundamental frequency is

$$\hat{f}_0 = \frac{\delta}{2\pi / f_s}. \quad (5.70)$$

The disadvantage of this method is that when the value of $s[n-1]$ is close to zero, $\cos \delta$ will be greater than one. Therefore, only method 1 will be implemented in the embedded control processor.

CHAPTER 6

SOFTWARE TESTING

6.1 Introduction

To evaluate the accuracy of the algorithms, the software functions discussed in chapter 5 are implemented in Matlab. First, the fault detection technique has been tested. Second, the fault classification using amplitude and phase estimation are evaluated. Then, the frequency estimation is assessed. Finally, fault detection, fault classification, and frequency estimation are integrated and tested.

6.2 Fault Detection Test

The one-cycle-apart comparison algorithm in section 5.3 has been tested with tie unit currents generated from ATP-EMTP with fundamental frequency of 60 Hz, 59.3 Hz, and 60.5 Hz. The value 59.3 and 60.5 are selected according to the minimum and maximum of normal operating frequency in table 2.2 of chapter 2. There are three cases of input data for each fundamental frequency: 1) without noise, 2) with White Gaussian Noise (WGN), and 3) with harmonics. The descriptions of WGN and harmonics are as follows:

White Gaussian Noise (WGN): The WGN with zero mean and standard deviation = $0.0022A$ is added to make the Signal to Noise Ratio (SNR) = 50 dB. The SNR is defined as

$$SNR(dB) = 20 \log \left(\frac{A}{\sqrt{2}\sigma} \right),$$

where A is an amplitude of the fundamental sinusoidal signal and σ is a standard deviation of the WGN.

Harmonics: The current harmonics are composed of 4% of the third harmonic and 3% of the fifth harmonic. The total demand distortion (TDD) is

$$TDD = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I_L} = \frac{\sqrt{(0.04I_L)^2 + (0.03I_L)^2}}{I_L} = 0.05 = 5\%,$$

where I_h is the harmonic current and I_L is the maximum demand load current at the fundamental frequency. The 5% TDD is the limit in IEEE 519.

The threshold value ε is selected based on (5.19), $0.074A < \varepsilon < A_F$, where A is a current amplitude in normal condition and A_F is a current amplitude in fault condition. From figure 3.3 in chapter 3, the tie unit current = 33 A_{peak} or $A = 33$. The A_F from external fault F2 or F3 case in figure 3.7 is chosen since this case has the minimum A_F of 40. Therefore, $4 < \varepsilon < 40$, and the threshold = 4 and the threshold = 40 are selected to test the fault detection algorithm to find the minimum and maximum detection time.

The fault detection times for 60-Hz, 59.3-Hz, and 60.5-Hz tie unit current are shown in tables 6.1 to 6.3, respectively. For threshold = 4 A, the minimum detection

time is zero and the maximum detection time is 1 sample. For threshold = 40 A, the minimum detection time is also zero, but the maximum detection time is 2 samples.

Table 6.1 Fault detection time for 60-Hz tie unit current (sample)

Fault type	Inception angle	Threshold = 4 A			Threshold = 40 A		
		Without noise	With noise		Without noise	With noise	
			WGN	Harmonics		WGN	Harmonics
Internal fault F1	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	0	0	0
	$7\pi/4$	0	0	0	0	0	0
External fault F2 or F3	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	2	2	2
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	2	2	2
	$7\pi/4$	0	0	0	1	1	1
External fault F4	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	2	2	2
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	2	2	2
	$7\pi/4$	0	0	0	0	0	0

Table 6.2 Fault detection time for 59.3-Hz tie unit current (sample)

Fault type	Inception angle	Threshold = 4 A			Threshold = 40 A		
		Without noise	With noise		Without noise	With noise	
			WGN	Harmonics		WGN	Harmonics
Internal fault F1	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	0	0	0
	$7\pi/4$	0	0	0	1	1	1
External fault F2 or F3	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	1	1	1
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	0	0	0
	$7\pi/4$	0	0	0	2	2	2
External fault F4	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	0	0	0
	$7\pi/4$	0	0	0	1	1	1

Table 6.3 Fault detection time for 60.5-Hz tie unit current (sample)

Fault type	Inception angle	Threshold = 4 A			Threshold = 40 A		
		Without noise	With noise		Without noise	With noise	
			WGN	Harmonics		WGN	Harmonics
Internal fault F1	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	0	0	0	1	1	1
	$7\pi/4$	0	0	0	0	0	0
External fault F2 or F3	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	1	1	1
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	1	1	1	2	2	2
	$7\pi/4$	0	0	0	0	0	0
External fault F4	0	0	0	0	0	0	0
	$\pi/4$	0	0	0	0	0	0
	$\pi/2$	0	0	0	0	0	0
	$3\pi/4$	0	0	0	0	0	0
	π	0	0	0	0	0	0
	$5\pi/4$	0	0	0	0	0	0
	$3\pi/2$	1	1	1	1	1	1
	$7\pi/4$	0	0	0	0	0	0

6.3 Amplitude and Phase Estimation Test

The amplitude and phase estimations using three models of recursive least square (RLS) have been tested. The digital filters from section 5.2 are not used with RLS because they introduce delay ≥ 8 samples; 8-sample delay for nulling filter, 16-sample delay for sine filter and cosine filter. The input data are the tie unit currents generated from ATP-EMTP with fundamental frequency 60 Hz without noise. The three models of RLS are as follows:

Model 1: Use only fundamental sinusoidal component.

$$\mathbf{H}[n] = [\cos \delta n \quad -\sin \delta n]^T$$

$$\boldsymbol{\theta}[n] = [A \cos \phi \quad A \sin \phi]^T$$

$$\hat{A}[n] = \sqrt{\hat{\boldsymbol{\theta}}_1^2[n] + \hat{\boldsymbol{\theta}}_2^2[n]}$$

$$\hat{\phi}[n] = \tan^{-1} \left(\frac{\hat{\boldsymbol{\theta}}_2[n]}{\hat{\boldsymbol{\theta}}_1[n]} \right)$$

Model 2: Use fundamental sinusoidal component and decaying DC component.

$$\mathbf{H}[n] = [1 \quad -n \quad \cos \delta n \quad -\sin \delta n]^T$$

$$\boldsymbol{\theta}[n] = [A_0 \quad A_0 / \tau \quad A \cos \phi \quad A \sin \phi]^T$$

$$\hat{A}[n] = \sqrt{\hat{\boldsymbol{\theta}}_3^2[n] + \hat{\boldsymbol{\theta}}_4^2[n]}$$

$$\hat{\phi}[n] = \tan^{-1} \left(\frac{\hat{\boldsymbol{\theta}}_4[n]}{\hat{\boldsymbol{\theta}}_3[n]} \right)$$

Model 3: Use fundamental sinusoidal component, decaying DC component, 3rd harmonic component, and 5th harmonic component.

$$\mathbf{H}[n] = [1 \quad -n \quad \cos \delta n \quad -\sin \delta n \quad \cos 3\delta n \quad -\sin 3\delta n \quad \cos 5\delta n \quad -\sin 5\delta n]^T$$

$$\boldsymbol{\theta}[n] = [A_0 \quad A_0 / \tau \quad A \cos \phi \quad A \sin \phi \quad A_3 \cos \phi_3 \quad A_3 \sin \phi_3 \quad A_5 \cos \phi_5 \quad A_5 \sin \phi_5]^T$$

$$\hat{A}[n] = \sqrt{\hat{\boldsymbol{\theta}}_3^2[n] + \hat{\boldsymbol{\theta}}_4^2[n]}$$

$$\hat{\phi}[n] = \tan^{-1} \left(\frac{\hat{\boldsymbol{\theta}}_4[n]}{\hat{\boldsymbol{\theta}}_3[n]} \right)$$

The RLS procedure for amplitude and phase estimations of tie unit current is illustrated in figure 6.1 where $i[n]$ is a tie unit current sample. The three models use $\alpha = 3000$ and $\lambda = 0.99$. Note that if the fault is detected, the covariance matrix $\mathbf{P}$ will be reset to the initial condition [30].

The estimated current amplitudes are shown in figures 6.2 to 6.4 and the estimated current phases are shown in figures 6.5 to 6.7. The estimation using model 1 is the most oscillated as seen in figures 6.4(c), 6.4(d), 6.4(g), and 6.4(h) due to the decaying DC component in the fault current. The estimation using model 2 and model 3 are less fluctuated than those of model 1 since the decaying DC component is included in the signal model. However, the estimation using model 3 has longer delay than that of model 2 as seen in figures 6.6 and 6.7. Therefore, model 2 is selected for amplitude and phase estimations to be implemented in the embedded control processor.

Figure 6.1 RLS procedure for amplitude and phase estimations of tie unit current

Figure 6.2 RLS estimated current amplitude for fault at F1 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 6.3 RLS estimated current amplitude for fault at F2 or F3 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 6.4 RLS estimated current amplitude for fault at F4 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 6.5 RLS estimated current phase for fault at F1 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 6.6 RLS estimated current phase for fault at F2 or F3 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

Figure 6.7 RLS estimated current phase for fault at F4 when fault inception angle is (a) 0, (b) $\pi/4$, (c) $\pi/2$, (d) $3\pi/4$, (e) π , (f) $5\pi/4$, (g) $3\pi/2$, (h) $7\pi/4$

6.4 Frequency Estimation Test

Frequency estimation method 1 has been tested with ATP-EMTP generated input data as shown in figure 6.8. The sine filter and cosine filter from section 5.2 are used as filters H_1 and H_2 of method 1. In addition, a 32-sample averaging filter is applied at the output to smooth the estimated frequency.

Figure 6.8 Frequency estimation diagram

The input data are the load voltages in normal condition with fundamental frequency of 60 Hz, 59.3 Hz, and 60.5 Hz. There are three cases of input data for each fundamental frequency: 1) without noise, 2) with WGN, and 3) with harmonics. The characteristics of WGN and harmonics are identical to those of section 6.2. However, since the input data for frequency estimation are voltages, the total harmonic distortion (THD) is used instead of TDD. For the voltage harmonics comprising of 4% of the third harmonic and 3% of the fifth harmonic,

$$THD = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V_1} = \frac{\sqrt{(0.04V_1)^2 + (0.03V_1)^2}}{V_1} = 0.05 = 5\%,$$

where V_h is the harmonic voltage, and V_1 is the load voltage at the fundamental frequency. The 5% THD is the limit in IEEE 519. The frequency estimation results for 60-Hz, 59.3-Hz, and 60.5-Hz load voltages are shown in figures 6.9 to 6.11, respectively.

For 60-Hz input signal, the estimated frequency is 60.0019 Hz when the input signal has no noise as seen in figure 6.9(a). The estimation fluctuates between 59.98 Hz and 60.02 Hz if the input signal has WGN as depicted in figure 6.9(b). When the input signal has harmonics, the estimated frequency is the same as that of without noise case.

For 59.3-Hz input signal, the estimated frequency oscillates between 59.293 Hz and 59.310 Hz when the input signal has no noise as seen in figure 6.10(a). The estimation fluctuates between 59.28 Hz and 59.33 Hz if the input signal has WGN as depicted in figure 6.10(b). When the input signal has harmonics, the estimated frequency is similar to that of without noise case.

For 60.5-Hz input signal, the estimated frequency oscillates between 60.497 Hz and 60.507 Hz when the input signal has no noise as seen in figure 6.11(a). The estimation fluctuates between 60.48 Hz and 60.52 Hz if the input signal has WGN as depicted in figure 6.11(b). When the input signal has harmonics, the estimated frequency is similar to that of without noise case.

Therefore, the frequency estimation has the maximum error range of ± 0.03 Hz.

Figure 6.9 Frequency estimations for 60-Hz load voltages: (a) without noise, (b) with WGN, (c) with harmonics

Figure 6.10 Frequency estimations for 59.3-Hz load voltages: (a) without noise, (b) with WGN, (c) with harmonics

Figure 6.11 Frequency estimations for 60.5-Hz load voltages: (a) without noise, (b) with WGN, (c) with harmonics

6.5 Fault Detection and Classification with Frequency Estimation Test

The fault detection and classification have been tested with frequency estimation as follows:

1) Fault Detection: The one-cycle-apart comparison is used for fault detection of tie unit current with the detection threshold value = 4 A.

2) Fault Classification: After the fault has been detected, the current amplitude estimation, $\hat{A}_i$, and phase difference estimation between voltage and current, $\hat{\phi} = |\hat{\phi}_v - \hat{\phi}_i|$, are calculated using RLS model 2 from section 6.3 with $\alpha = 3000$ and $\lambda = 0.99$. Since the voltage during the fault condition is nearly zero in some cases, the prefault voltage is applied for voltage phase estimation.

3) Frequency Estimation: Method 1 is employed to calculate the estimated fundamental frequency, $\hat{f}_0$, using voltage signal. After the fault has been detected, the prefault estimated frequency is applied for amplitude and phase estimations.

The testing procedure is depicted in figure 6.12. The input data are the tie unit currents and load voltages generated from ATP-EMTP with fundamental frequency 60 Hz, 59.3 Hz, and 60.5 Hz. There are three cases of input data for each fundamental frequency: 1) without noise, 2) with WGN as described in section 6.2, and 3) with harmonics as described in section 6.2 for current signal and in section 6.4 for voltage signal.

Figure 6.12 Procedure for fault detection and classification with frequency estimation

The estimates of current amplitude and phase difference between voltage and current are given in tables 6.4 to 6.21. The highlighted area indicates the definite classification point of the estimation scheme. The fault classification procedure is demonstrated in figure 6.13 according to section 5.4.

Figure 6.13 Fault classification procedure

A_{high} should be set greater than two times of the full load current amplitude. A_{low} should be set greater than the maximum allowable exporting current amplitude of the fuel cell but less than the rated current amplitude of the fuel cell. From figure 3.3 in chapter 3, the full load current amplitude is 114, and the rated current amplitude of the fuel cell is 81. If the maximum allowable exporting current amplitude of the fuel cell is 35, by setting $A_{high} = 250$ and $A_{low} = 40$, the fault can be classified with 2-sample delay

for all cases. Thus, the maximum time required for fault detection and classification = maximum detection time + maximum classification time = $2 + 2 = 4$ samples or 4 ms. However, since the actual signals are highly contaminated during system faults, longer time delay may be needed for more reliable fault classification.

Table 6.4 Current amplitude estimation for 60-Hz input without noise (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3950	5807	5642	5387	5095	4855	4676	4606
	$\pi/4$	0	3068	6077	5777	5351	4914	4574	4362	4336
	$\pi/2$	0	107	4800	4398	3900	3498	3282	3295	3508
	$3\pi/4$	0	3872	3914	3952	4017	4075	4147	4211	4266
	π	0	3955	5805	5640	5387	5095	4854	4666	4583
	$5\pi/4$	0	3072	6074	5776	5351	4914	4568	4340	4289
	$3\pi/2$	0	108	4801	4401	3904	3498	3270	3258	3445
	$7\pi/4$	0	2922	3308	3238	3233	3306	3444	3620	3798
External fault F2 or F3	0	0	31	101	51	54	53	52	53	50
	$\pi/4$	0	44	89	57	56	58	55	56	52
	$\pi/2$	0	51	51	62	57	58	54	53	51
	$3\pi/4$	0	8	92	48	52	46	47	46	46
	π	0	31	101	51	54	53	52	53	51
	$5\pi/4$	0	44	89	57	56	58	55	56	52
	$3\pi/2$	0	51	51	62	57	58	54	53	51
	$7\pi/4$	0	27	73	53	54	49	48	46	46
External fault F4	0	0	7	112	80	86	81	82	82	82
	$\pi/4$	0	23	108	80	84	81	81	82	81
	$\pi/2$	0	70	85	80	80	80	80	81	81
	$3\pi/4$	0	61	97	81	84	81	83	82	82
	π	0	7	112	80	86	81	82	82	82
	$5\pi/4$	0	23	108	80	84	81	81	81	81
	$3\pi/2$	0	70	85	80	80	80	80	81	81
	$7\pi/4$	0	76	85	80	82	81	82	81	82

Table 6.5 Phase difference estimation for 60-Hz input without noise (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	6	109	60	62	63	64	63	62	60
	$\pi/4$	28	131	70	72	72	72	71	68	64
	$\pi/2$	73	176	86	86	83	78	72	66	62
	$3\pi/4$	39	63	54	52	51	50	49	49	50
	π	6	108	60	62	63	64	63	62	60
	$5\pi/4$	28	131	70	71	72	72	71	68	65
	$3\pi/2$	73	176	86	85	83	78	72	66	61
	$7\pi/4$	62	41	68	64	58	53	50	49	49
External fault F2 or F3	0	174	109	180	140	151	143	147	146	147
	$\pi/4$	152	131	170	140	152	145	149	149	149
	$\pi/2$	107	176	177	150	155	154	156	156	154
	$3\pi/4$	141	117	158	153	155	150	151	149	149
	π	174	108	180	140	151	143	147	146	147
	$5\pi/4$	152	131	170	140	152	145	149	149	149
	$3\pi/2$	107	176	177	150	155	154	156	156	154
	$7\pi/4$	118	139	152	156	156	156	156	154	152
External fault F4	0	174	72	159	161	160	162	161	162	161
	$\pi/4$	152	131	152	161	159	162	161	162	161
	$\pi/2$	107	176	151	162	160	162	162	162	162
	$3\pi/4$	141	117	168	162	163	162	162	163	162
	π	174	72	159	161	160	162	161	162	161
	$5\pi/4$	152	131	153	161	159	162	161	162	161
	$3\pi/2$	107	176	151	162	160	162	162	162	162
	$7\pi/4$	118	139	166	162	163	163	163	163	163

Table 6.6 Current amplitude estimation for 60-Hz input with WGN (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3950	5808	5642	5387	5095	4855	4675	4606
	$\pi/4$	0	3068	6075	5776	5350	4913	4573	4361	4335
	$\pi/2$	0	108	4800	4397	3899	3497	3282	3295	3507
	$3\pi/4$	0	3872	3914	3951	4017	4075	4146	4211	4265
	π	0	3955	5805	5639	5385	5094	4853	4665	4582
	$5\pi/4$	0	3072	6072	5774	5349	4912	4567	4339	4289
	$3\pi/2$	0	107	4801	4400	3904	3498	3270	3258	3445
	$7\pi/4$	0	2922	3309	3239	3233	3306	3445	3620	3799
External fault F2 or F3	0	0	31	101	51	54	53	52	53	50
	$\pi/4$	0	45	87	57	56	58	55	56	52
	$\pi/2$	0	50	51	62	56	58	54	53	51
	$3\pi/4$	0	8	91	47	52	46	47	46	46
	π	0	31	101	51	54	53	52	53	51
	$5\pi/4$	0	44	90	57	56	58	55	56	52
	$3\pi/2$	0	50	51	62	57	58	55	54	51
	$7\pi/4$	0	27	74	52	53	49	48	46	46
External fault F4	0	0	7	111	79	86	81	82	82	82
	$\pi/4$	0	24	107	80	84	81	81	82	81
	$\pi/2$	0	70	86	80	80	80	80	81	81
	$3\pi/4$	0	61	98	80	84	81	83	82	82
	π	0	7	112	80	86	81	82	82	82
	$5\pi/4$	0	23	108	80	84	81	81	81	81
	$3\pi/2$	0	70	85	80	80	80	80	81	81
	$7\pi/4$	0	76	84	80	82	81	82	81	82

Table 6.7 Phase difference estimation for 60-Hz input with WGN (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	6	109	60	62	63	64	63	62	60
	$\pi/4$	28	131	70	71	72	72	71	68	64
	$\pi/2$	73	176	86	85	83	78	72	66	62
	$3\pi/4$	39	63	54	52	51	50	50	49	50
	π	6	109	61	62	63	64	64	62	60
	$5\pi/4$	28	131	71	72	73	73	71	69	65
	$3\pi/2$	73	176	86	86	83	78	72	66	62
	$7\pi/4$	62	41	68	64	58	54	50	49	49
External fault F2 or F3	0	174	108	180	140	151	142	147	146	147
	$\pi/4$	152	131	171	140	151	145	149	149	148
	$\pi/2$	107	176	176	150	155	154	156	156	154
	$3\pi/4$	141	116	158	153	155	151	152	149	149
	π	174	109	180	141	152	143	147	146	147
	$5\pi/4$	152	131	170	140	152	145	149	149	149
	$3\pi/2$	107	176	173	150	155	154	156	156	154
	$7\pi/4$	118	139	152	157	156	156	156	154	153
External fault F4	0	175	72	159	162	160	162	161	162	162
	$\pi/4$	152	131	153	161	159	162	161	162	161
	$\pi/2$	107	176	150	162	160	162	162	162	162
	$3\pi/4$	141	117	169	162	163	162	162	163	162
	π	174	72	159	161	160	162	161	162	161
	$5\pi/4$	152	131	152	161	159	161	160	162	161
	$3\pi/2$	107	176	151	162	160	162	162	162	162
	$7\pi/4$	118	139	166	162	163	162	163	163	162

Table 6.8 Current amplitude estimation for 60-Hz input with harmonics (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3956	5812	5654	5395	5100	4860	4678	4608
	$\pi/4$	0	3073	6095	5784	5354	4917	4574	4362	4335
	$\pi/2$	0	107	4800	4402	3898	3494	3281	3294	3506
	$3\pi/4$	0	3867	3910	3943	4009	4072	4145	4211	4266
	π	0	3961	5810	5652	5395	5100	4858	4668	4584
	$5\pi/4$	0	3077	6092	5782	5354	4917	4569	4340	4289
	$3\pi/2$	0	107	4802	4405	3902	3494	3269	3257	3444
	$7\pi/4$	0	2925	3302	3236	3231	3303	3442	3619	3798
External fault F2 or F3	0	0	36	102	53	55	55	53	53	48
	$\pi/4$	0	49	76	59	56	58	54	53	51
	$\pi/2$	0	50	50	64	54	54	53	54	51
	$3\pi/4$	0	13	89	59	62	50	49	48	48
	π	0	36	102	53	55	55	53	53	48
	$5\pi/4$	0	49	76	58	56	58	54	53	51
	$3\pi/2$	0	50	50	64	54	54	53	54	51
	$7\pi/4$	0	24	54	42	55	53	50	48	47
External fault F4	0	0	2	110	71	80	78	80	80	79
	$\pi/4$	0	28	92	75	82	79	80	80	80
	$\pi/2$	0	69	84	78	79	79	80	82	82
	$3\pi/4$	0	66	97	94	95	86	85	83	83
	π	0	2	110	71	80	78	80	80	79
	$5\pi/4$	0	28	92	75	82	79	80	80	80
	$3\pi/2$	0	69	84	78	79	79	80	82	82
	$7\pi/4$	0	73	75	75	84	85	84	82	82

Table 6.9 Phase difference estimation for 60-Hz input with harmonics (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	6	109	61	62	63	64	64	63	60
	$\pi/4$	29	132	72	73	74	74	72	69	66
	$\pi/2$	73	175	86	85	82	78	72	65	61
	$3\pi/4$	40	63	53	52	50	49	49	49	49
	π	6	109	61	62	63	64	64	63	61
	$5\pi/4$	29	132	72	73	74	74	72	70	66
	$3\pi/2$	73	175	86	85	82	78	72	65	61
	$7\pi/4$	61	42	68	64	59	54	51	49	50
External fault F2 or F3	0	174	109	177	128	143	138	143	144	145
	$\pi/4$	151	132	178	135	150	143	150	150	150
	$\pi/2$	107	175	178	146	156	156	157	157	154
	$3\pi/4$	140	117	160	159	160	153	152	148	148
	π	174	109	177	128	143	138	143	144	145
	$5\pi/4$	151	132	179	135	150	143	150	150	150
	$3\pi/2$	107	175	178	146	156	156	157	157	155
	$7\pi/4$	119	138	157	162	159	159	158	155	153
External fault F4	0	174	71	161	166	163	164	163	162	160
	$\pi/4$	151	132	156	163	159	162	159	159	159
	$\pi/2$	107	175	151	165	159	159	161	162	162
	$3\pi/4$	140	117	166	164	165	163	164	164	164
	π	174	71	161	166	163	164	163	162	160
	$5\pi/4$	151	132	156	163	159	162	159	159	159
	$3\pi/2$	107	175	151	165	159	159	161	162	162
	$7\pi/4$	119	138	154	153	162	162	162	162	162

Table 6.10 Current amplitude estimation for 59.3-Hz input without noise (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	4281	5024	4998	4933	4827	4740	4661	4617
	$\pi/4$	0	4019	5866	5710	5455	5161	4918	4731	4652
	$\pi/2$	0	1827	5799	5422	4895	4395	4036	3866	3926
	$3\pi/4$	0	2840	3324	3238	3213	3276	3414	3598	3788
	π	0	4279	4926	4909	4861	4773	4702	4634	4594
	$5\pi/4$	0	4076	5805	5662	5427	5150	4919	4733	4642
	$3\pi/2$	0	1970	5857	5487	4967	4467	4095	3893	3911
	$7\pi/4$	0	1265	3948	3636	3289	3078	3039	3166	3408
External fault F2 or F3	0	0	12	104	47	53	48	49	49	48
	$\pi/4$	0	31	103	51	54	53	52	53	51
	$\pi/2$	0	51	70	62	58	60	56	56	53
	$3\pi/4$	0	28	71	54	54	49	48	47	47
	π	0	10	103	47	53	48	49	49	48
	$5\pi/4$	0	29	103	50	54	53	52	53	50
	$3\pi/2$	0	51	72	61	57	60	56	56	53
	$7\pi/4$	0	44	51	60	56	55	52	50	49
External fault F4	0	0	38	108	81	86	82	83	82	82
	$\pi/4$	0	8	113	80	86	81	83	82	82
	$\pi/2$	0	49	98	80	82	80	80	81	80
	$3\pi/4$	0	77	84	80	82	81	82	81	82
	π	0	40	107	81	86	81	83	82	82
	$5\pi/4$	0	11	113	80	86	81	83	82	82
	$3\pi/2$	0	47	99	80	82	80	80	81	80
	$7\pi/4$	0	78	80	80	80	80	80	81	81

Table 6.11 Phase difference estimation for 59.3-Hz input without noise (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	17	86	53	53	54	55	55	55	54
	$\pi/4$	5	108	60	61	62	63	63	62	60
	$\pi/2$	50	152	80	80	80	79	76	71	66
	$3\pi/4$	64	39	69	65	59	54	51	49	49
	π	19	83	53	53	53	54	54	54	54
	$5\pi/4$	3	106	59	60	61	62	62	61	59
	$3\pi/2$	47	150	79	79	79	78	75	71	66
	$7\pi/4$	88	14	85	82	77	70	63	57	55
External fault F2 or F3	0	163	86	168	145	152	144	147	145	146
	$\pi/4$	175	108	179	139	151	142	146	145	146
	$\pi/2$	130	152	166	143	153	149	152	152	151
	$3\pi/4$	116	141	151	156	156	156	155	153	152
	π	161	83	167	146	152	144	147	145	146
	$5\pi/4$	177	106	178	140	151	142	146	145	146
	$3\pi/2$	133	150	166	143	152	148	152	152	151
	$7\pi/4$	92	166	162	154	156	156	157	156	154
External fault F4	0	163	94	165	161	162	162	162	162	162
	$\pi/4$	175	72	159	161	160	162	161	162	161
	$\pi/2$	130	152	149	161	159	162	161	162	162
	$3\pi/4$	116	141	166	162	163	163	163	163	163
	π	161	97	166	161	162	162	162	162	162
	$5\pi/4$	177	74	160	161	160	162	161	162	161
	$3\pi/2$	133	150	149	161	159	162	161	162	162
	$7\pi/4$	92	166	157	162	162	162	162	162	162

Table 6.12 Current amplitude estimation for 59.3-Hz input with WGN (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	4281	5023	4997	4933	4827	4740	4660	4617
	$\pi/4$	0	4019	5866	5710	5456	5161	4918	4731	4652
	$\pi/2$	0	1827	5800	5421	4894	4395	4036	3866	3926
	$3\pi/4$	0	2839	3324	3238	3212	3276	3414	3597	3787
	π	0	4278	4925	4908	4860	4772	4702	4633	4594
	$5\pi/4$	0	4075	5805	5662	5427	5150	4919	4733	4642
	$3\pi/2$	0	1969	5855	5486	4967	4466	4095	3893	3911
	$7\pi/4$	0	1265	3949	3636	3289	3078	3039	3166	3408
External fault F2 or F3	0	0	12	105	47	53	48	49	49	48
	$\pi/4$	0	31	103	51	54	53	52	53	50
	$\pi/2$	0	52	69	62	57	60	56	56	53
	$3\pi/4$	0	28	70	53	54	49	48	47	47
	π	0	11	101	46	52	48	49	49	48
	$5\pi/4$	0	29	102	50	54	53	52	53	50
	$3\pi/2$	0	51	73	62	58	60	56	56	53
	$7\pi/4$	0	44	51	60	56	55	52	50	49
External fault F4	0	0	38	108	80	87	81	83	82	82
	$\pi/4$	0	8	112	80	86	81	83	82	82
	$\pi/2$	0	49	99	80	82	80	80	81	80
	$3\pi/4$	0	76	82	80	81	81	81	81	82
	π	0	40	106	81	86	81	83	82	82
	$5\pi/4$	0	12	114	80	86	81	83	82	82
	$3\pi/2$	0	47	99	79	82	80	80	81	80
	$7\pi/4$	0	79	80	80	80	80	80	81	81

Table 6.13 Phase difference estimation for 59.3-Hz input with WGN (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	17	86	53	54	54	55	55	55	54
	$\pi/4$	5	108	60	61	62	63	63	62	60
	$\pi/2$	50	152	80	80	80	79	76	71	66
	$3\pi/4$	64	39	69	65	59	54	51	49	49
	π	19	84	53	53	54	54	54	54	54
	$5\pi/4$	3	106	59	60	62	62	62	61	60
	$3\pi/2$	47	150	79	79	79	78	75	71	66
	$7\pi/4$	88	14	85	82	77	70	63	57	55
External fault F2 or F3	0	163	86	168	145	152	144	147	145	146
	$\pi/4$	175	108	180	139	151	142	146	145	146
	$\pi/2$	130	152	167	143	153	149	152	152	151
	$3\pi/4$	116	141	152	156	156	156	155	153	152
	π	161	83	166	145	152	144	147	145	146
	$5\pi/4$	177	106	178	139	151	142	146	145	146
	$3\pi/2$	133	150	165	142	152	148	152	152	151
	$7\pi/4$	92	166	163	154	156	156	157	156	154
External fault F4	0	163	94	165	161	162	162	162	162	162
	$\pi/4$	175	72	159	161	160	162	161	162	161
	$\pi/2$	130	152	149	161	159	162	161	162	162
	$3\pi/4$	116	141	164	161	163	162	163	163	162
	π	161	97	165	161	162	162	162	162	162
	$5\pi/4$	177	75	160	161	160	162	161	162	162
	$3\pi/2$	133	150	150	162	159	162	161	162	162
	$7\pi/4$	92	165	158	162	162	162	162	162	162

Table 6.14 Current amplitude estimation for 59.3-Hz input with harmonics (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	4287	5030	5009	4941	4832	4745	4663	4618
	$\pi/4$	0	4023	5883	5716	5458	5164	4918	4729	4651
	$\pi/2$	0	1826	5799	5425	4892	4390	4034	3865	3925
	$3\pi/4$	0	2835	3318	3237	3210	3275	3414	3598	3789
	π	0	4284	4931	4920	4869	4778	4706	4636	4595
	$5\pi/4$	0	4080	5822	5669	5430	5153	4919	4732	4641
	$3\pi/2$	0	1969	5857	5491	4964	4461	4093	3892	3910
	$7\pi/4$	0	1268	3931	3625	3288	3079	3038	3166	3409
External fault F2 or F3	0	0	18	103	43	50	48	48	48	45
	$\pi/4$	0	35	87	50	53	53	51	51	49
	$\pi/2$	0	51	69	62	55	57	56	58	54
	$3\pi/4$	0	33	70	67	65	54	50	48	48
	π	0	16	102	42	49	47	48	48	45
	$5\pi/4$	0	33	87	49	53	52	51	51	49
	$3\pi/2$	0	50	71	62	55	57	56	58	54
	$7\pi/4$	0	40	41	51	58	60	54	52	50
External fault F4	0	0	32	105	69	79	77	79	80	80
	$\pi/4$	0	4	94	74	83	78	81	81	82
	$\pi/2$	0	49	98	77	82	81	81	83	82
	$3\pi/4$	0	81	87	91	91	85	83	82	82
	π	0	35	104	69	78	77	79	80	80
	$5\pi/4$	0	7	94	74	83	78	82	82	82
	$3\pi/2$	0	46	99	77	82	81	81	83	82
	$7\pi/4$	0	75	82	80	82	84	82	82	81

Table 6.15 Phase difference estimation for 59.3-Hz input with harmonics (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	17	86	54	54	55	55	55	55	54
	$\pi/4$	6	109	61	63	64	65	64	63	61
	$\pi/2$	49	152	79	80	80	78	75	70	65
	$3\pi/4$	65	38	68	64	58	53	50	48	48
	π	19	84	53	53	54	55	55	55	54
	$5\pi/4$	4	107	61	62	63	64	64	63	61
	$3\pi/2$	47	149	78	79	79	78	75	70	66
	$7\pi/4$	87	15	85	83	77	70	63	58	55
External fault F2 or F3	0	163	86	165	130	144	138	142	143	146
	$\pi/4$	174	109	174	133	149	140	147	148	148
	$\pi/2$	131	152	166	139	154	152	153	152	151
	$3\pi/4$	115	142	155	156	156	156	154	151	149
	π	161	84	164	131	144	138	143	143	146
	$5\pi/4$	176	107	173	133	149	140	147	148	148
	$3\pi/2$	133	149	166	139	154	152	153	152	151
	$7\pi/4$	93	165	177	163	158	157	158	157	154
External fault F4	0	163	94	167	163	163	163	163	162	160
	$\pi/4$	174	71	159	161	159	161	159	159	159
	$\pi/2$	131	152	149	164	157	159	160	163	162
	$3\pi/4$	115	142	164	168	168	165	165	165	165
	π	161	96	168	162	163	163	163	162	160
	$5\pi/4$	176	73	160	161	159	161	159	159	159
	$3\pi/2$	133	149	149	164	157	159	160	163	162
	$7\pi/4$	93	165	143	153	161	164	163	163	163

Table 6.16 Current amplitude estimation for 60.5-Hz input without noise (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3332	6015	5745	5365	4966	4651	4449	4412
	$\pi/4$	0	2089	5813	5435	4932	4450	4103	3939	3998
	$\pi/2$	0	2599	3294	3169	3107	3153	3290	3488	3695
	$3\pi/4$	0	4175	4699	4692	4669	4610	4565	4521	4497
	π	0	3268	6019	5741	5352	4945	4621	4402	4348
	$5\pi/4$	0	1996	5776	5394	4887	4403	4048	3867	3905
	$3\pi/2$	0	1231	3908	3582	3239	3036	3008	3150	3401
	$7\pi/4$	0	3727	3732	3766	3839	3914	4007	4095	4172
External fault F2 or F3	0	0	41	93	55	55	57	54	55	52
	$\pi/4$	0	50	74	60	57	59	56	56	53
	$\pi/2$	0	31	67	54	54	50	49	47	47
	$3\pi/4$	0	7	101	46	52	47	48	48	47
	π	0	42	92	55	56	57	55	55	52
	$5\pi/4$	0	50	72	60	57	59	56	56	53
	$3\pi/2$	0	30	65	54	53	50	48	47	46
	$7\pi/4$	0	12	89	48	52	46	47	46	46
External fault F4	0	0	15	110	80	85	81	82	82	81
	$\pi/4$	0	44	100	80	82	80	80	81	81
	$\pi/2$	0	78	82	80	81	81	81	81	82
	$3\pi/4$	0	43	106	81	86	81	83	82	82
	π	0	17	109	80	85	81	82	82	81
	$5\pi/4$	0	46	100	80	82	80	80	81	81
	$3\pi/2$	0	77	82	80	81	81	81	81	82
	$7\pi/4$	0	64	95	81	84	81	83	82	82

Table 6.17 Phase difference estimation for 60.5-Hz input without noise (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	22	125	68	69	70	70	69	67	63
	$\pi/4$	45	148	78	78	79	77	75	70	66
	$\pi/2$	67	36	73	68	62	56	52	50	50
	$3\pi/4$	22	81	53	53	53	54	54	54	53
	π	23	126	68	69	70	71	70	67	64
	$5\pi/4$	46	149	78	79	79	78	75	71	66
	$3\pi/2$	89	14	85	82	77	70	63	57	55
	$7\pi/4$	43	60	56	54	51	50	49	49	49
External fault F2 or F3	0	158	125	172	140	152	144	149	148	148
	$\pi/4$	135	148	166	143	153	149	152	152	151
	$\pi/2$	113	144	153	157	157	157	156	155	153
	$3\pi/4$	158	81	166	148	153	146	149	146	148
	π	157	126	172	140	152	145	149	148	149
	$5\pi/4$	134	149	166	144	153	149	152	152	151
	$3\pi/2$	114	143	153	157	157	157	156	155	153
	$7\pi/4$	137	120	156	154	155	152	153	150	150
External fault F4	0	158	125	154	161	159	162	161	162	161
	$\pi/4$	135	148	149	161	159	162	161	162	162
	$\pi/2$	113	144	165	162	163	163	163	163	163
	$3\pi/4$	158	99	166	161	162	162	162	162	162
	π	157	126	154	161	159	162	161	162	161
	$5\pi/4$	134	149	149	161	159	162	161	162	162
	$3\pi/2$	114	143	164	162	163	163	163	163	163
	$7\pi/4$	137	120	168	162	163	162	162	163	162

Table 6.18 Current amplitude estimation for 60.5-Hz input with WGN (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3332	6015	5744	5365	4965	4651	4448	4412
	$\pi/4$	0	2089	5816	5435	4932	4451	4103	3939	3998
	$\pi/2$	0	2599	3294	3169	3107	3153	3290	3488	3695
	$3\pi/4$	0	4175	4698	4693	4670	4610	4566	4521	4498
	π	0	3267	6018	5741	5352	4945	4620	4402	4348
	$5\pi/4$	0	1996	5774	5393	4887	4402	4048	3867	3905
	$3\pi/2$	0	1232	3907	3582	3240	3036	3008	3150	3401
	$7\pi/4$	0	3727	3732	3766	3838	3914	4007	4095	4172
External fault F2 or F3	0	0	41	92	55	55	57	54	55	52
	$\pi/4$	0	50	73	60	57	59	56	56	53
	$\pi/2$	0	31	66	53	54	50	49	47	47
	$3\pi/4$	0	8	101	46	52	47	48	48	47
	π	0	41	92	55	56	57	54	55	52
	$5\pi/4$	0	50	73	60	57	59	56	56	52
	$3\pi/2$	0	30	64	54	53	50	48	47	46
	$7\pi/4$	0	12	88	49	53	46	47	46	46
External fault F4	0	0	15	111	80	85	81	82	82	81
	$\pi/4$	0	44	101	80	82	81	81	81	81
	$\pi/2$	0	78	83	80	81	81	81	81	82
	$3\pi/4$	0	43	104	81	86	81	83	82	82
	π	0	17	108	80	85	81	82	82	81
	$5\pi/4$	0	46	99	79	82	80	80	81	80
	$3\pi/2$	0	77	82	80	81	81	81	81	82
	$7\pi/4$	0	65	95	80	84	81	82	82	82

Table 6.19 Phase difference estimation for 60.5-Hz input with WGN (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	22	125	68	69	70	70	69	66	63
	$\pi/4$	45	148	78	79	79	78	75	70	66
	$\pi/2$	67	36	73	68	62	56	52	50	50
	$3\pi/4$	22	81	53	53	53	53	54	54	53
	π	23	126	68	69	70	70	70	67	64
	$5\pi/4$	46	149	79	79	79	78	75	71	66
	$3\pi/2$	89	14	85	82	76	69	62	57	55
	$7\pi/4$	43	60	56	54	51	50	49	49	49
External fault F2 or F3	0	158	125	173	139	152	144	149	148	148
	$\pi/4$	135	147	167	143	153	149	152	152	151
	$\pi/2$	113	144	153	157	157	157	157	155	153
	$3\pi/4$	158	81	166	147	153	146	149	146	148
	π	157	126	171	141	152	144	149	148	149
	$5\pi/4$	134	149	165	144	153	149	152	152	151
	$3\pi/2$	114	143	153	157	157	157	156	155	153
	$7\pi/4$	137	120	156	154	156	152	152	150	150
External fault F4	0	158	125	154	161	159	162	161	162	161
	$\pi/4$	135	147	149	161	159	162	161	162	162
	$\pi/2$	113	144	165	162	163	163	163	163	163
	$3\pi/4$	158	99	166	162	162	162	162	162	162
	π	157	126	154	161	159	162	161	162	161
	$5\pi/4$	134	149	150	162	159	162	161	162	162
	$3\pi/2$	114	143	165	162	163	162	163	163	163
	$7\pi/4$	137	120	168	162	163	162	162	163	162

Table 6.20 Current amplitude estimation for 60.5-Hz input with harmonics (A)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	0	3337	6019	5756	5373	4971	4656	4451	4414
	$\pi/4$	0	2094	5832	5441	4935	4453	4104	3939	3998
	$\pi/2$	0	2599	3298	3168	3107	3152	3288	3486	3695
	$3\pi/4$	0	4171	4696	4681	4659	4606	4564	4520	4497
	π	0	3273	6023	5753	5360	4950	4625	4405	4350
	$5\pi/4$	0	2000	5794	5401	4890	4406	4049	3867	3905
	$3\pi/2$	0	1232	3908	3586	3239	3035	3007	3148	3400
	$7\pi/4$	0	3731	3737	3770	3837	3910	4005	4094	4171
External fault F2 or F3	0	0	47	94	60	58	59	56	55	50
	$\pi/4$	0	55	65	63	58	61	55	53	51
	$\pi/2$	0	31	72	48	46	48	50	48	47
	$3\pi/4$	0	3	97	55	60	50	50	50	49
	π	0	47	93	61	59	60	57	56	50
	$5\pi/4$	0	55	64	64	58	61	55	53	51
	$3\pi/2$	0	29	70	47	45	48	50	47	47
	$7\pi/4$	0	8	70	37	53	50	48	47	47
External fault F4	0	0	21	109	73	81	79	80	80	78
	$\pi/4$	0	49	87	76	81	79	79	79	80
	$\pi/2$	0	77	84	76	76	80	84	82	82
	$3\pi/4$	0	48	104	94	97	86	85	83	83
	π	0	23	109	73	81	79	80	80	78
	$5\pi/4$	0	50	87	77	80	79	79	79	80
	$3\pi/2$	0	76	84	76	76	80	83	82	82
	$7\pi/4$	0	61	80	72	86	86	85	83	83

Table 6.21 Phase difference estimation for 60.5-Hz input with harmonics (degree)

Fault type	Inception angle	Delay after fault detected (sample)								
		0	1	2	3	4	5	6	7	8
Internal fault F1	0	23	126	68	69	71	71	70	67	64
	$\pi/4$	46	149	79	80	80	79	76	71	67
	$\pi/2$	66	37	74	69	63	57	53	51	52
	$3\pi/4$	22	80	52	52	53	53	53	53	53
	π	24	127	69	70	71	71	70	68	65
	$5\pi/4$	47	150	79	80	80	79	76	72	67
	$3\pi/2$	89	14	85	82	76	69	62	57	55
	$7\pi/4$	42	61	56	54	52	51	50	50	50
External fault F2 or F3	0	157	126	175	130	145	141	145	146	146
	$\pi/4$	134	149	179	139	151	147	152	152	152
	$\pi/2$	114	143	151	159	160	160	160	157	155
	$3\pi/4$	158	81	168	159	161	150	150	147	147
	π	156	127	175	131	145	141	146	146	147
	$5\pi/4$	133	150	179	139	151	147	152	153	152
	$3\pi/2$	116	142	152	159	159	159	160	158	155
	$7\pi/4$	138	119	157	154	159	157	156	152	151
External fault F4	0	157	126	156	168	163	164	163	163	161
	$\pi/4$	134	149	156	165	159	163	160	160	160
	$\pi/2$	114	143	168	157	157	160	161	161	161
	$3\pi/4$	158	100	163	161	162	162	162	163	163
	π	156	127	156	168	163	165	163	163	161
	$5\pi/4$	133	150	156	165	159	163	160	160	160
	$3\pi/2$	116	142	167	157	157	160	161	161	161
	$7\pi/4$	138	119	160	155	161	161	161	162	162

CHAPTER 7

SYSTEM INTEGRATION AND TESTING

7.1 Introduction

The hardware components and software functions of the IUT are integrated and tested in this chapter. First, the system integration is discussed. Then, the IUT is evaluated with internal and external fault testing.

Figure 7.1 System diagram

7.2 System Integration

The system diagram is shown in figure 7.1 and the IUT operation procedure is depicted in figure 7.2. The load voltage and tie unit current are measured and sent to the embedded control processor. After signal analysis, the embedded control processor will send the control signal to IGBT switch 1 and IGBT switch 2.

The operation of the IUT starts with turning on IGBT switch 1. Then, the load voltage $v[n]$ and tie unit current $i[n]$ are obtained with sampling frequency 960 Hz. After that, the frequency estimation is calculated. The fault detection using one-cycle-apart comparison, $|i[n] - i[n-16]|$, is checked every sampling time except the first 16 samples of $i[n]$.

When the fault is detected, $|i[n] - i[n-16]| > \varepsilon$, the fault can be classified as internal fault by IGBT switch 1 short circuit detection as described in chapter 4 section 4.5.3. The IGBT switch 1 is turned off, and the IGBT switch 2 is turned on for 10 cycles. Then, the estimated current amplitude, $\hat{A}_i[n]$ is calculated and compared with the current amplitude when IGBT switch 2 is on during internal fault, A_i (*fault with reactor*) = 1.2 A_{rms} as shown in figure 4.11 of chapter 4. If $\hat{A}_i[n] < A_i$ (*fault with reactor*), it is a momentary internal fault, IGBT switch 1 will be turned on and IGBT switch 2 will be turned off. On the other hand, if $\hat{A}_i[n] \geq A_i$ (*fault with reactor*), it is a permanent internal fault, IGBT switch 1 and IGBT switch 2 will be turned off.

For external fault classification, after the fault is detected, and IGBT switch 1 short circuit is not detected, the process is delayed for 3 samples (the 3-sample delay is

selected based on the 2-sample classification time from software testing results in section 6.5 plus 1-sample delay for better classification). Then, $\hat{\phi}_v(prefault)$, $\hat{A}_i[n]$, and $\hat{\phi}_i[n]$ are calculated. If $\hat{A}_i[n] \geq A_{low}$ and $|\hat{\phi}_v(prefault) - \hat{\phi}_i[n]| \geq 90^\circ$, it is an external fault, IGBT switch 1 and IGBT switch 2 will be turned off. On the contrary, if $\hat{A}_i[n] < A_{low}$ or $|\hat{\phi}_v(prefault) - \hat{\phi}_i[n]| < 90^\circ$, it is a normal condition.

Figure 7.2 IUT operation procedure

7.3 Internal Fault Test

The test circuit diagram for internal fault is illustrated in figure 7.3 and the test setup is shown in figure 7.4. The load is a 100W light bulb. A magnetic contactor is used to create a permanent internal fault.

Figure 7.3 Test circuit diagram for internal fault

The load voltage, tie unit current, Switch 1 Control, and Switch 2 Control during internal fault condition are plotted in figures 7.5 and 7.6. The fault happens momentarily at time = 77.94 ms and becomes permanent fault after time = 93.75 ms due to the characteristic of the magnetic contactor. The transient fault current is negative in

positive voltage period because of the nonlinear characteristic of the current transducer during the transient period. The fault is detected at the first strike (time = 77.94 ms), then Switch 1 Control becomes low and Switch 2 Control becomes high for 10 cycles. In other words, IGBT switch 1 is off and IGBT switch 2 is on for 10 cycles following the internal fault detection. Since the permanent internal fault has $\hat{A}_i[n] = A_i$ (*fault with reactor*) = 1.2 A_{rms} during the 10 cycles delay, IGBT switch 1 and IGBT switch 2 are turned off after the delay period according to the response to permanent internal fault in figure 7.2. IGBT switch 2 is turned off at the zero crossing of the tie unit current to prevent the induced voltage from the reactors.

Figure 7.4 Test setup for internal fault

Figure 7.5 Load voltage, tie unit current, Switch 1 Control, and Switch 2 Control during internal fault condition

Figure 7.6 Load voltage, tie unit current, Switch 1 Control, and Switch 2 Control during internal fault condition (zoom in figure 7.5)

7.4 External Fault Test

The test circuit diagram for external fault is illustrated in figure 7.7. The load is a 100W light bulb. A solid-state relay is used to create an external fault. The load voltage, tie unit current, and Switch 1 Control during external fault condition are plotted in figures 7.8

Figure 7.7 Test circuit diagram for external fault

Figure 7.8 Load voltage, tie unit current, and Switch 1 Control during external fault condition

In normal condition, the tie unit current is zero. When the fault happens at time = 30.65 ms, the tie unit current has increased to 3.3 A. After the fault is detected (with threshold 0.5 A) and classified, switch 1 is turned off at time = 35.77 ms and the tie unit current becomes zero. The response time in this case = 35.77 – 30.65 = 5.12 ms which is less than half cycle as desired. The response time is composed of t_D (the time between the fault point and the next sampling point), detection time, and classification time as shown in figure 7.9. Since $0 < t_D < 1$ ms, $0 < \text{detection time} < 2$ ms, and classification time is fixed at 3 ms, the maximum response time = 1 + 2 + 3 = 6 ms. In other words, the IUT can response to the external fault within 6 ms.

Figure 7.9 Fault detection and classification timeline

CHAPTER 8

CONCLUSIONS

8.1 Conclusions

This dissertation proposes the development of an integrated high-speed intelligent utility tie unit (IUT) to monitor, control, and protect the system for residential users to enable their disbursed/renewable generation facilities to serve as emergency and standby power supply. The distributed generations and their interconnection to the utility grid focusing on residential fuel cells are discussed. High speed operation is critical for the IUT because the response of the IUT for the nearby external faults should be faster than the built-in protection of the fuel cell. The target operation speed of the IUT for the nearby external faults is less than 8 ms.

The sample system is simulated by using ATP-EMTP. The Hall effect sensors are used to monitor the system voltage and current. The DSP and IGBT are selected as an embedded control processor and a tripping unit, respectively. The fault detection using one-cycle-apart comparison and the fault classification using recursive least square estimation are implemented in Matlab along with frequency estimation. The computer simulation shows that the proposed algorithms can detect and classify the fault within 4 ms. The hardware components and software functions of the IUT are integrated and tested with internal and external fault. The experimental result indicates

that the IUT can response to external fault within 6 ms which is less than 8 ms as desired. However, since the actual signals are highly contaminated during system faults, the tradeoff between speed and accuracy may be needed for fault classification.

8.2 Contributions

This dissertation makes the following contributions to the field of power system engineering:

1) The one-cycle-apart comparison has been derived to detect the fault. The amplitude and phase estimation using least square estimation and recursive least square estimation have been analyzed and compared to classify the fault type. In addition, two methods of frequency estimation have been studied. These techniques can be applied for fault detection and classification in power system.

2) The IUT has been developed using fault detection and classification algorithms implemented in the digital signal processor along with the IGBT tripping unit to enable the distributed generations as emergency and standby power supply.

8.3 Further Researches

The IUT performance can be improved by the following suggestions:

1) Use higher rated current IGBT for better withstand capability of the tripping unit in case of internal fault.

2) Apply higher rated current reactor to enhance the classification of momentary internal fault.

3) Develop a synchronizing check function to test the IUT with the actual fuel cell.

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