

Modeling and Simulation of a Power Conditioning System for the Hybrid Fuel-Cell/Turbine Power Plant

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Abstract—Power conditioning system is an interface between distributed generation and utility grid. This paper presents the model of a power conditioning system (PCS) for the hybrid direct fuel-cell/turbine (DFC/T) power plant. It regulates voltage, current and power transmitted from the hybrid DFC/T power plant to utility grid. The proposed system consists of DC/DC converters, a grid-connected SPWM DC/AC inverter, and an LCL filter. To regulate and stabilize the DC link voltage, DC/DC converter with PI controller is adopted. With the dual-loop PI based grid-connected SPWM inverter, both active and reactive power transmitted to utility grid from the hybrid DFC/T power plant can be controlled. The LCL filter can greatly reduce the current harmonic distortion (THD). Theoretical analysis, modeling methodologies and control schemes are presented. The whole model was developed in Matlab/Simulink environment with all the parameters given. Simulation results demonstrate that the proposed PCS can follow a dynamic load with the error less than 1% and reduce the THD to 1.65%.

Index Terms—Power conditioning system, DC link voltage, power flow control, LCL filter, PI controller, fuel cell plant, grid interface.

I. INTRODUCTION

Distributed energy sources, such as fuel cells, wind turbines and photovoltaic, can not only provide clean energy without environmental pollution but also achieve higher energy efficiency than traditional fossil fuel. Furthermore, distributed energy sources can reduce transmission loss and distribution cost. Among all distributed generations, fuel cell has become the most promising power plant due to its high efficiency and, furthermore, not being limited to weather conditions.

However, when fuel cell power plant is connected to distribution network, problems in power flow control and power quality need to be resolved. Power conditioning system (PCS) is developed to solve these problems and regulates voltage, current and power transmitted into the utility grid [1].

Previously, some research has been done about power

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conditioning problems. General structure and basic principles of PCS for fuel cell power plant have been investigated in [1]. In converter design, Bjazic, Ban and Volaric created a mathematical model of the Boost type DC/DC converter for fuel cell applications [2]. Wang, Liu, Chen and Wang built a model of DC/DC converter by using state space equations based on Matlab/Simulink [3]. Dai, Marwali, Woo and Keyhani concentrated on a power flow control scheme for distributed generation by using three phase inverter in [4]. Wang, Nehrir and Gao developed an interface between proton exchange membrane fuel cell (PEMFC) and the power grid, but they did not concentrate on power quality issues when PEMFC was connected to distribution network [5]. Liserre, Blaabjerg and Hansen proposed a detailed LCL filter design procedure for three-phase rectifiers to improve power quality in [6]. Guo, Wu and Gu analyzed the stability conditions of LCL filter for grid-connected inverters [7]. Liu, Song and Erzen designed an LCL and control scheme for three phase inverters [8].

This paper presents an integrated power conditioning system model for the hybrid direct fuel-cell/turbine (DFC/T) power plant. The proposed PCS is composed of DC/DC converters, a large capacitor, a three-phase DC/AC inverter and an LCL filter. It connects the hybrid DFC/T power plant with utility grid. Via conditioning voltage and current, power flow can be successfully controlled under dynamic load and power quality can be improved through the LCL filter.

II. INTRODUCTION TO POWER CONDITIONING SYSTEM

A. Overview of Hybrid Fuel-Cell/Turbine Power Plant

Fuel-cell power plants convert the chemical energy stored in fuel into electric energy directly. There are many kinds of fuel cell power plants. The Morton Carbonate Fuel Cell (MCFC) has high efficiency and high power density and thus considered to be the most promising fuel-cell power plant for large-scale power generation [9].

The fuel-cell power plant mathematical model used in this paper was first developed by Lukas, Lee and Ghezal-Ayagh [10]. Yang, Lee, Junker and Ghezal-Ayagh optimized the DFC/T model and proposed the intelligent control system including fuzzy fault diagnosis and accommodation system. By integrating micro-turbine into fuel-cell power plant, the overall plant efficiency is expected to achieve 75% [11].

B. The Proposed Power Conditioning System

As Fig. 1 shows, the proposed PCS is the interface between the hybrid DFC/T power plant and utility grid. It regulates three-phase voltage and three-phase current. It also controls active and reactive power flow and improves power quality. The power generated by DFC/T power plant is regulated and controlled by PCS, which is mainly composed of Buck-Boost DC/DC converters, a large capacitor and a full bridge three-phase sinusoidal pulse-width modulation (SPWM) based DC/AC inverter and an LCL filter. The DC/DC converter regulates the unstable DC voltage generated by DFC/T power plant. To further regulate the DC link voltage and reduce ripples of the DC link voltage, a large capacitor is placed between converter and inverter. Three-phase DC/AC inverter chops DC link voltage into AC. Under the control of dual-loop SPWM based controller, active and reactive load following can be achieved. Before transmitting the energy to utility grid, LCL filter can greatly reduce current harmonic distortion to a very low level.

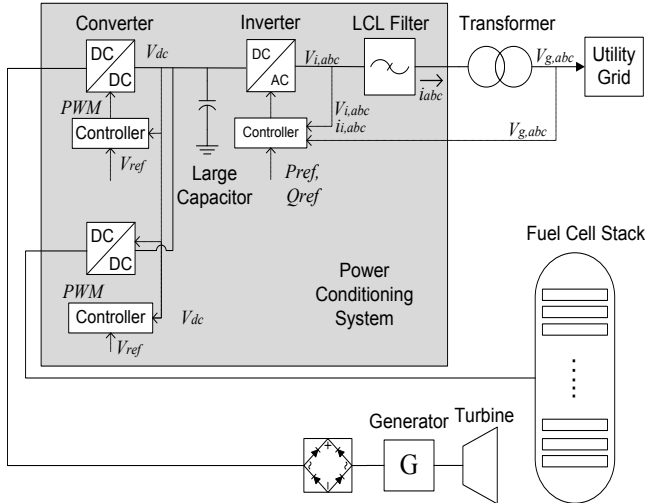


Fig. 1. Overall structure of DFC/T, PCS and utility grid.

III. DC/DC CONVERTER AND ITS CONTROLLER

A. Modeling of DC/DC Converter

In order to transmit the power to utility grid, the two output voltages, fuel-cell stack voltage and micro-turbine voltage should be converted to 480V and then connected in parallel with the three-phase SPWM inverter. As can be seen from Fig. 2, the output voltages of fuel-cell stack and micro-turbine are not stable and even vary in a wide range; from 100V to 600V. Since the DC link voltage is supposed to be 480V, a Buck-Boost converter is adopted here. A feedback proportional-integral (PI) controller is adopted to make the converter stable under small signal disturbance and regulate the duty ratio.

Fig. 3 shows the topology of the buck-boost circuit, where V_{fc} is the output voltage of fuel-cell stack or micro-turbine, V_{dc} is DC link voltage, L is the inductance with its

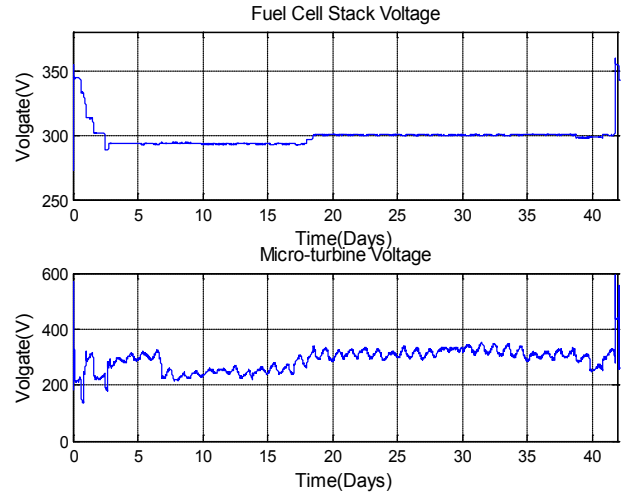


Fig. 2. Output voltage of hybrid DFC/T power plant.

equivalent series resistance (ESR) R_L , C is the capacitance with its ESR R_c , and R_{eq} is the equivalent load. The switch, controlled by a PWM signal, controls the whole circuit to be buck type or boost type. According to the different positions of the switch, there are two modes of this circuit. For each mode, mathematical model can be created according to the circuit topology. Then by combining the two sets of equations together, we get:

$$\begin{bmatrix} \dot{i}_L \\ \dot{v}_c \end{bmatrix} = \begin{bmatrix} -R_L - (1-S) \frac{R_{eq} R_c}{R_{eq} + R_c} & -\frac{R_{eq}(1-S)}{L(R_{eq} + R_c)} \\ \frac{R_{eq}(1-S)}{C(R_{eq} + R_c)} & -\frac{1}{C(R_{eq} + R_c)} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} + \begin{bmatrix} S \\ 0 \end{bmatrix} \frac{1}{L} v_{fc}$$

$$v_{dc} = \begin{bmatrix} \frac{R_{eq} R_c (1-S)}{R_{eq} + R_c} & \frac{R_{eq}}{R_{eq} + R_c} \end{bmatrix} \begin{bmatrix} i_L \\ v_c \end{bmatrix} \quad (1)$$

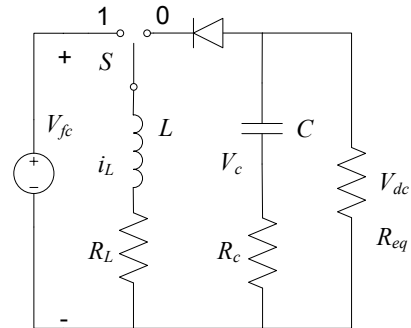


Fig. 3. Topology of the Buck-Boost converter.

When modeling, the switching mode S can be either 0 or 1, which is due to the switching chopper. When $S=0$, the switch is at position 0, and the inductor is discharging and the capacitor is charging. When $S=1$, the switch is at position 1, the inductor is charging and the capacitor is discharging. Thus, this model is not an average model but a detailed dynamic model. In order to model converter, we must find the equivalent resistance R_{eq} . Since the output voltage is regulated to be 480V and active power of hybrid

DFC/T power plant is 300kW, the equivalent resistor is calculated as $R_{eq}=0.9614 \Omega$.

B. Converter Controller Design

Fig. 4 is the converter system block diagram. A PI type controller is implemented here. The transfer function of the PWM generator is just a gain. All ESRs having been neglected, the following equations give the small signal transfer function of the Buck-Boost converter [12]:

$$G_{dc}(s) = \frac{V_{dc}}{d} = \frac{R_{eq}(1-D)^2 - DLs}{(1-D)^2} \cdot \frac{V_{fc}}{LCR_{eq}s^2 + sL + R_{eq}(1-D)^2} \quad (2)$$

$$V_{dc} = \frac{D}{1-D} V_{fc} \quad (3)$$

Here, D is the duty ratio, which controls the converter, defined by $D=T_1/T_s=T_1/(T_0+T_1)$, where T_0 is the time period when $S=0$ and T_1 is the time period when $S=1$, and $T_s=T_0+T_1$ is the duty cycle. Thus, the value of the duty ratio is a decimal between 0 and 1. For analysis and design purpose, all parameters in (2) must be fixed values. Thus, the average values are used here. The average method can be used to analyze the stability of Buck-Boost converter system even if there exists a switching device in the circuit [12]. The DC link voltage is 480V and the average value of V_{fc} is 300V. Then according to (3), the average value of duty ratio D is 0.6154. Then transfer functions of each block in Fig. 4 can be found to design the PI parameters. After that, we can find the whole converter system transfer function. The bode plot of the open-loop transfer function is shown in Fig. 5. The phase margin of the open-loop transfer function is 97.2 degree, which indicates that the proposed converter control system is stable.

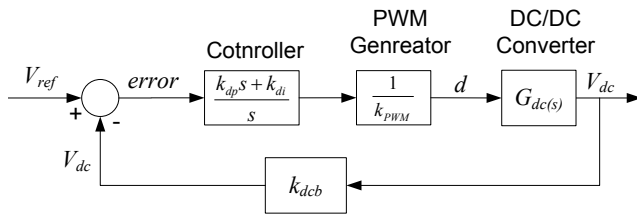


Fig. 4. Block diagram of the DC/DC converter control system.

IV. DC/AC INVERTER DESIGN

A. Theoretical Analysis of Power Flow

Consider a network, as shown in Fig. 6, with two power sources. Theoretically, active and reactive power delivered from inverter side to grid side are given by [13]:

$$P = \frac{V_i V_g}{Z} \cos(\theta_z - \theta_i) - \frac{V_g^2}{Z} \cos(\theta_z) \quad (4)$$

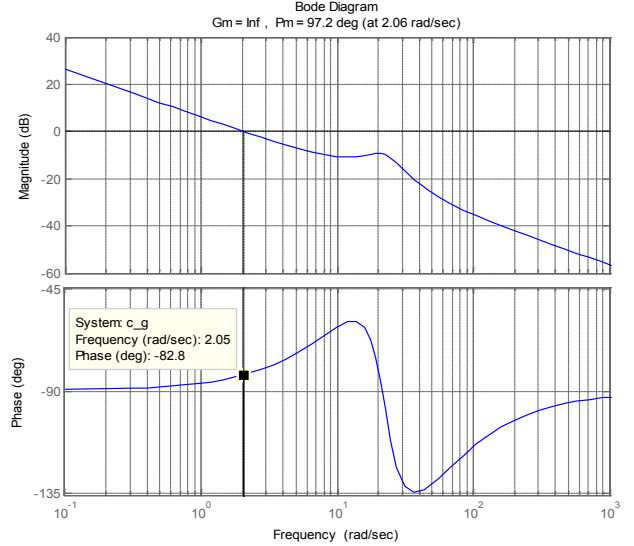


Fig. 5. Bode diagram of the DC/DC converter control loop.

$$Q = \frac{V_i V_g}{Z} \sin(\theta_z - \theta_i) - \frac{V_g^2}{Z} \sin(\theta_z) \quad (5)$$

In (4), (5) and Fig. 6, V_g is the voltage magnitude at the grid side with 0 degree phase angle, V_i is the voltage magnitude and θ_i is the voltage phase angle at the inverter side, and Z is the impedance between inverter and utility grid, which includes the impedance of LCL filter, transmission line and transformer. From these equations, we can see the simple relationship between power and voltages. Active power mainly depends on voltage phase angle and reactive power mainly depends on the voltage magnitude [13]. Thus, to deliver a set of specific P and Q to utility grid, we can simply regulate the voltage magnitude and angle at the inverter side. Since voltage magnitude and phase angle at the grid side can be sensed and the impedance between the inverter and grid can be known, thus, according to (4) and (5), the corresponding voltage magnitude and angle at the inverter side can be calculated as the reference, as given by:

$$V_i = \sqrt{\frac{Z^2}{V_g^2} (P^2 + Q^2) + V_g^2 + 2PZ \cos(\theta_z) + 2QZ \sin(\theta_z)} \quad (6)$$

$$\theta_i = \theta_z - \arccos\left(\frac{PZ}{V_g V_i} + \frac{V_g}{V_i} \cos(\theta_z)\right) \quad (7)$$

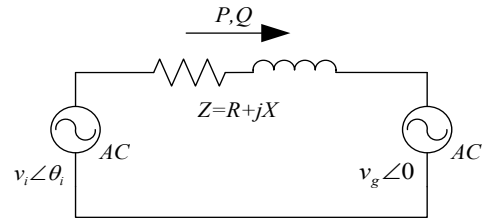


Fig. 6. Power flow between two power sources.

B. Three-Phase DC/AC Inverter and SPWM Controller

Fig. 7 shows the design of the inverter system, where a three-phase full-bridge inverter is implemented. An LCL filter is connected between inverter and grid for the purpose of reducing current harmonics. After going through LCL filter, current would be transferred to utility grid via transformer and transmission line.

The overall control scheme for three-phase PWM inverter is shown in the shaded area in Fig. 7. When specific P and Q references are given, and then according to (6) and (7), the reference voltage magnitude and phase angle at the inverter side can be calculated. Since the calculated voltage reference is in the three-phase abc -frame, it should be transformed into the voltage reference in the $dq0$ -frame. The voltage reference in the $dq0$ -frame is compared with the actual voltage in the $dq0$ -frame. The error is the input to the PI controller, whose output is sent to the inner loop. The inner current loop works in a similar way with the outer voltage loop. But compared with the outer loop, the inner loop runs much faster. After the controlled signals are generated, they are inverse transformed to the three-phase abc -frame to control the SPWM generator.

C. Control Scheme

Fig. 8 and Fig. 9 are the block diagrams of the current loop and voltage loop, respectively. For the inner current loop, the detailed transfer functions are give in each block

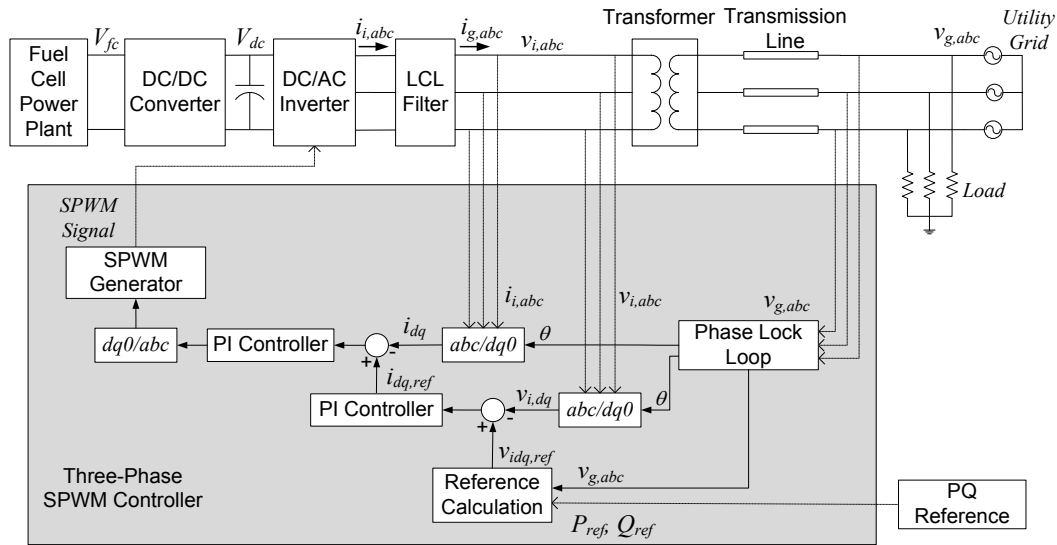


Fig. 7. Three-phase SPWM Control System.

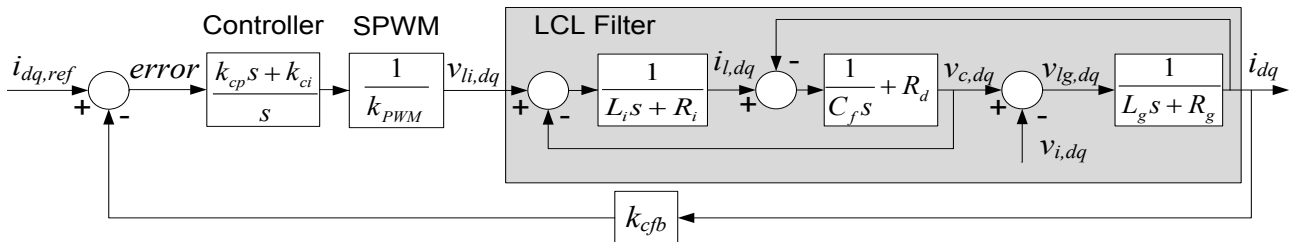


Fig. 8. Block diagram of the inner current loop.

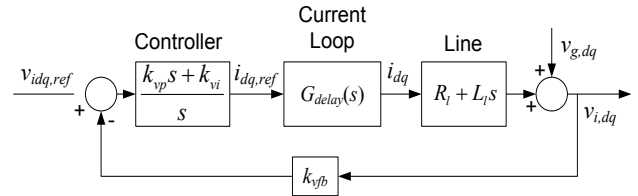


Fig. 9. Block diagram of the outer voltage loop.

and the transfer function of LCL filter is give in Section V. When modeling the outer loop, the inner loop is a problem. The inner current loop transfer function can be modeled as a gain with a time delay. The reason for this is that the inner loop runs much faster than the outer loop, which means the inner loop has been stable when outer loop is still changing. Therefore, the inner loop can be modeled as a gain with a time delay [12]. Since the grid frequency is about 60Hz, the transformer can be modeled by using the fixed equivalent impedance. As we can see from Fig. 10, the phase margin of the inner loop is 42.7 degree and the phase margin of outer loop is 90.6 degree. Thus, both loops are stable under small signal disturbance.

V. LCL FILTER DESIGN

A. Topology and Transfer Function of LCL Filter

To transmit energy to utility grid, current harmonics must be reduced since harmonics are harmful to power systems.

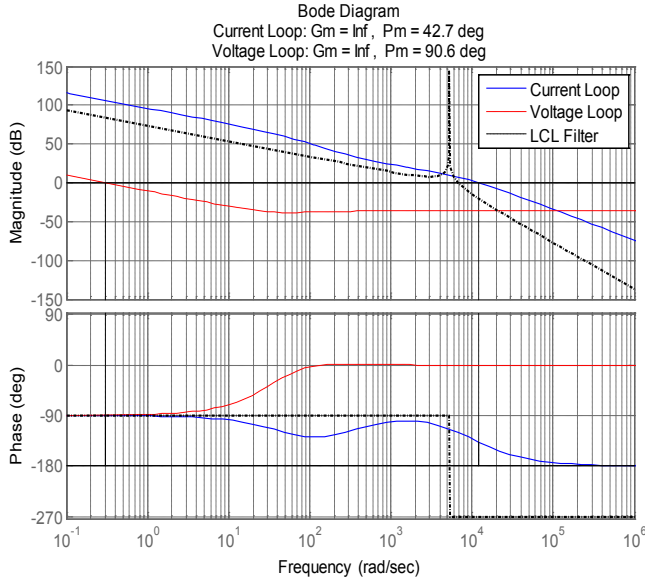


Fig. 10. Bode plot of the voltage loop, the inner current loop and LCL filter.

Typically, L filter is enough in reducing low frequency harmonics to a satisfactory level. But since high frequency switching devices in the three-phase inverter would generate lots of high frequency harmonics, an LCL filter with a damping resistor is adopted here in order to reduce both low and high frequency harmonics.

The block diagram of the LCL filter is shown in Fig. 8 and we can find the transfer function of LCL filter as

$$G_{LCL}(s) = \frac{i_g(s)}{U_{il}(s)} = \frac{\frac{1}{C_s} + R_d}{(L_i s + R_i) \cdot (L_g s + R_g) + (\frac{1}{C_s} + R_d) \cdot (L_i s + L_g s + R_i + R_g)} \quad (8)$$

B. LCL Filter Parameter Design

The overall inductance, $L_i + L_g$, is supposed to be as large as possible in order to have lower THD. But too large inductance would slower the system response. Thus, there is a tradeoff between low THD and system response. The capacitor C_f , which mainly reduces the high frequency harmonics, should not be too large in case it absorbs too much reactive power. The series resistor R_d , which increases the system damping, is essential in order to prevent the system from resonance oscillation [7]. Also, when designing LCL parameters, resonance frequency should be in a specific range. The detailed parameter design steps can be found in [6]. All resistors have been neglected and (9) gives the equations for resonance frequency:

$$f_{res} = \frac{1}{2\pi} \sqrt{\frac{L_i + L_g}{L_i L_g C_f}} \quad (9)$$

Fig. 10 shows the bode plot of the LCL filter. The resonance frequency is about 834Hz, which meets the requirement of the LCL filter. Since the switching frequency is 10kHz, and the high frequency harmonics generated by switching can be greatly reduced through LCL filter.

VI. SIMULATION RESULTS

A. DC Link Voltage

In modeling the converter system, Fig. 4 and Equ. (2) give the transfer function of each block. The parameters used are: $L=3.4\text{mH}$, $R_L=12.3\text{m}\Omega$, $C=86\text{mF}$, $R_C=5.1\text{m}\Omega$, $k_{dp}=0.0001$, $k_{di}=0.001$, and $k_{PWM}=1$. The results of DC/DC converter model, which is the DC link voltage, are shown in Fig. 11. Since it is too slow and not necessary for us to run for 42 days of simulation data, we have only simulated 60 seconds here. In this first 60 seconds, the output voltage of hybrid DFC/T power plant varied significantly. As we can see in Fig.11, DC/DC converter and super capacitor have regulated the voltage into a stable 480V, which has already been in steady state for a long time. Therefore, 60 seconds of simulation data is sufficient to prove its stability. The overshoot is also reduced.

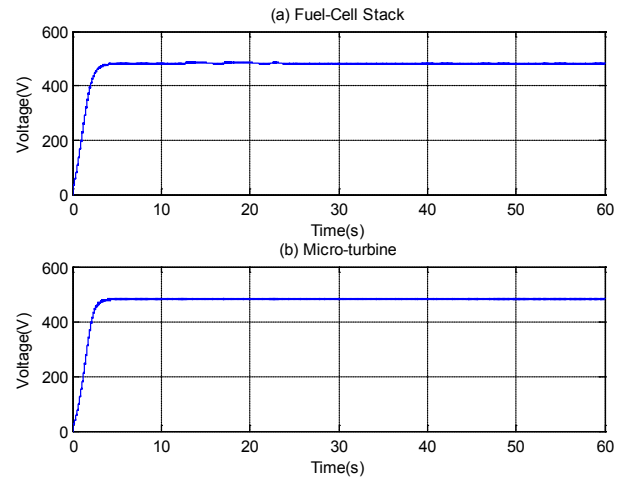


Fig. 11. DC link voltage of the converter.

B. Power Flow Control

The transfer functions in the inverter control system can be found in Fig. 8, Fig. 9 and Equ. (8). In the simulation, the parameters are: $k_{cp}=3$, $k_{ci}=700$, $k_{PWM}=1$, $k_{vp}=3$, $k_{vi}=150$, $R_f=2\text{m}\Omega$, and $L_f=0.05\text{mH}$. The LCL parameters can be found in the following. Fig. 12 shows The PQ regulating performance. When the power references are set as $P=250\text{kW}$ and $Q=60\text{kVAR}$, the result shows that active and reactive power can be precisely controlled under static load.

Fig. 13 describes the load following under a dynamic load. The solid line is the active power output and the dashed line is the active power reference. The proposed three phase PWM controller can follow dynamic load with small error and time delay.

C. Current Harmonics

The parameters of LCL filter are: $L_f=0.13\text{mH}$, $R_f=6\text{m}\Omega$, $C_f=800\text{uF}$, $R_d=0.6\Omega$, $L_g=0.07\text{mH}$, and $R_g=5\text{m}\Omega$. In Fig. 14, the figure on top is the current waveform that transmitted into utility grid and the figure on bottom is total harmonics

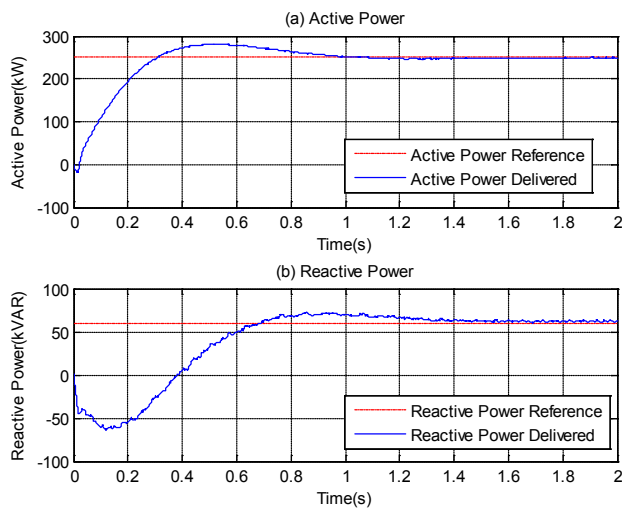


Fig. 12. Power flow control under static load.

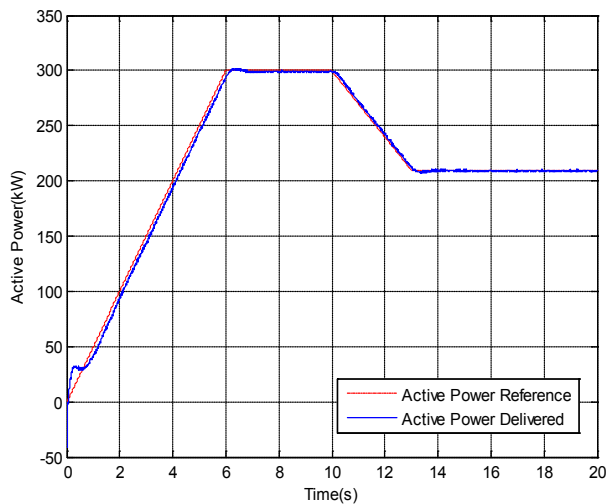


Fig. 13. Power flow control under dynamic load.

distortion, 1.65%, which is below 5% and meets the IEEE standard for transmission [14].

VII. CONCLUSION

This paper presents the model and simulation of a power conditioning system (PCS) for the hybrid DFC/T power plant. Three main tasks of the proposed PCS are DC link voltage regulation, power quality improvement and power flow control. Correspondingly, PCS is composed of a DC/DC converter, a DC/AC inverter and an LCL filter. The modeling process is presented for each part. The PI control schemes are adopted and system's stability issues are analyzed in the converter and inverter control. System parameters and simulation results are given. The PCS is modeled and simulated in Matlab/Simulink. Simulation results show that the three main problems are solved very well.

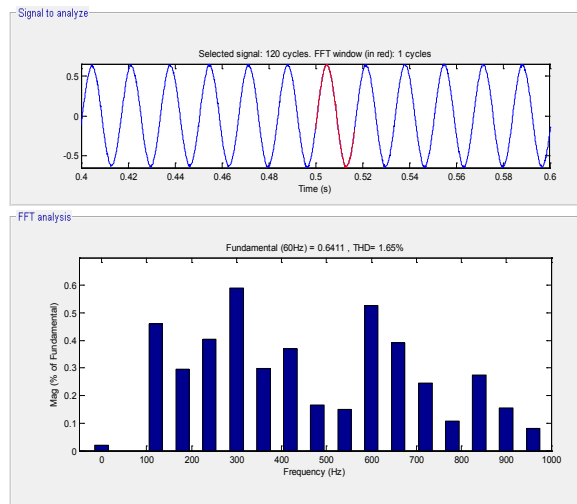


Fig. 14. Current and the THD.

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