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Dynamic Modeling of a Microturbine Generation System for Islanding Operation based on Model Predictive Control

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***Abstract*—Recently, distributed generation is an interesting subject because of its potential merits. Between various types of DGs, Microturbine Generation (MTG) systems are as most reliable source. Microturbines are required to interface converters in islanding or grid-connected operation modes. Converters control is a great challenge and predictive control is an appropriate solution to achieve desired outputs. In this paper, a detailed modeling of MTGs and interfaced converters is presented which are controlled by Model Predictive Control (MPC) method. MPC scheme for current control in inverter is purpose of this paper as a new method to control of MTGs. Simulation results show that dynamic performance of the MTG is acceptable and output current is sinusoidal without any filter.**

***Keywords*—distributed generation; microturbine; MPC; dynamic model; current control**

I. Introduction

Recent researches are focused on power generation near the load to reduce costs and losses which is called Distributed Generation (DG). Based on IEEE Standard 1547, distributed generators are electric generation facilities connected to an Electric Power System (EPS) through a point of common coupling. There are several types of DGs like wind turbine, photovoltaic, microturbine (MT) and etc. MTs are known as most reliable sources which have appropriate efficiency and power ranges.

MTs are a simple gas turbine which are operate based on Brayton cycle. Output power of the MT is in range of 25 kW to 1 MW and its efficiency is about 20-30% which is reach up to 80% by CHP.

Generally, MT advantages are compact size, reliability, low initial cost, inexpensively maintenance, control simplicity, low emissions level, fewer moving parts and ability to operates with various fuels like natural gas, diesel, propane, kerosene and biogas. MT applications include peak shaving, premium power, remote power and in transportation system [7].

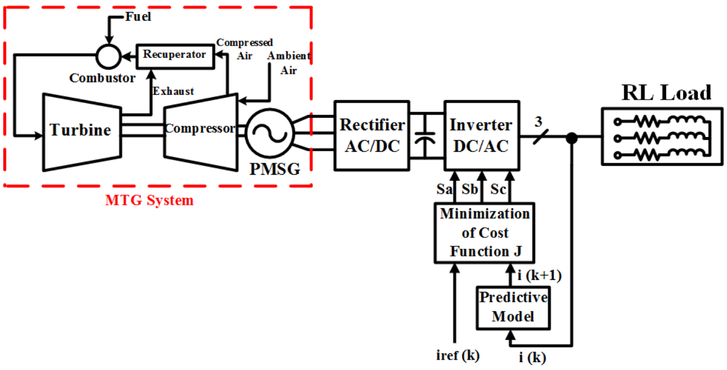

Fig. 1. Microturbine generation system with MPC

Main parts of the MT are compressor, combustion chamber, turbine, recuperator and a PMSG. At first, ambient air is enters to compressor and then, compressed air is mixed with fuel in a combustion chamber or combustor. Heated air with high pressure level is passed through a turbine and cause to turn it. Finally, PMSG is run and produce electrical power by turbine mechanical torque. To achieve higher efficiency, a recuperator is used. Recuperator is like a heat exchanger which is used to heat up compressed air. Heat of turbine exhausted gas is passed through recuperator and cause to increase of compressed air temperature leading to decreasing of fuel consumption.

Two general types of the MT are single-shaft design and split-shaft design. In single-shaft model, all mentioned components are mounted on a single shaft. Rotational speed of the turbine is very high because of compact size lead to produce high frequency power in range of 1.2-4 kHz. High frequency power is required to a converter to achieve desired power with appropriate frequency. AC-DC-AC structure or AC-AC structure are general method to convert high frequency power to desire. In split-shaft model, there are two separate parts which are coupled together by a gearbox.

In AC-DC-AC configuration, high frequency voltage is converted to DC voltage and then is converted to 50 Hz or 60Hz voltage. Fig. 1 shows a single-shaft MT with interfaced converters which are controlled by MPC in isolated mode. Detailed modeling of each part is illustrated in the following sections.

Dynamic modeling of a heavy gas turbine is presented by Rowen in [1]. A mathematical model of PMSG and MT based on Rowen model in isolated mode is proposed in [2]. [3] and [4] is about basic principle of the MT as a distributed generation. Dynamic modeling of a MTG and detailed control strategies in grid-connected and islanding modes is presented in [5]-[7].

There are various method to control of the inverter which V-f strategy is a common method in islanding. Predictive control based on model or MPC control strategy is a new and optimal solution for desired performance of the inverter. Using of MPC to control of a three-phase inverter is proposed in [8]-[13] but using of MPC in dynamic modeling of MTG systems has been not reported in the technical literature.

In this paper, a single-shaft model with AC-DC-AC structure is presented. Current control is used to control of three-phase inverter with RL load. Switching of the inverter is adjusted by MPC and this configuration is not required to any output filter. The rest of this paper is organized as follows. In section Ⅱ, dynamic modeling of each parts include MT, PMSG, inverter and current control strategy based on MPC is proposed and in section Ⅲ, simulation results in isolated mode is proposed. Finally, Conclusions are stated in Section Ⅳ.

II. Model Description

A. Microturbine Modeling

Dynamic model of the microturbine includes temperature control, fuel system, speed governor, acceleration control and turbine dynamic blocks. Fig. 2 shows microturbine dynamic model which is divided to separate sections. Outputs of temperature control, speed control and acceleration control are as inputs of Low Value Select (LVS) which is selected minimum value of its inputs. Minimum value of the LVS is used for fuel system to adjust valve position. Turbine and compressor dynamic are related to produce mechanical power for PMSG. Modeling of each mentioned section is illustrated in following and parameter values are given in appendix.

1) Speed and Acceleration control

Speed control operation is based on error between reference speed and PMSG rotor speed and the speed error is enters to LVS. A lead-lag or PID controller is used to model of speed governor [1]. Moreover, X and Y are the governor lead and lag time, respectively and Z is a constant value to represent the governor mode in droop or isochronous.

Acceleration control is used to limit increase of rate of rotor speed [2]. When the rotor speed is near the rated speed, this block is eliminated but in this paper, it is used for modeling.

2) Temperature control

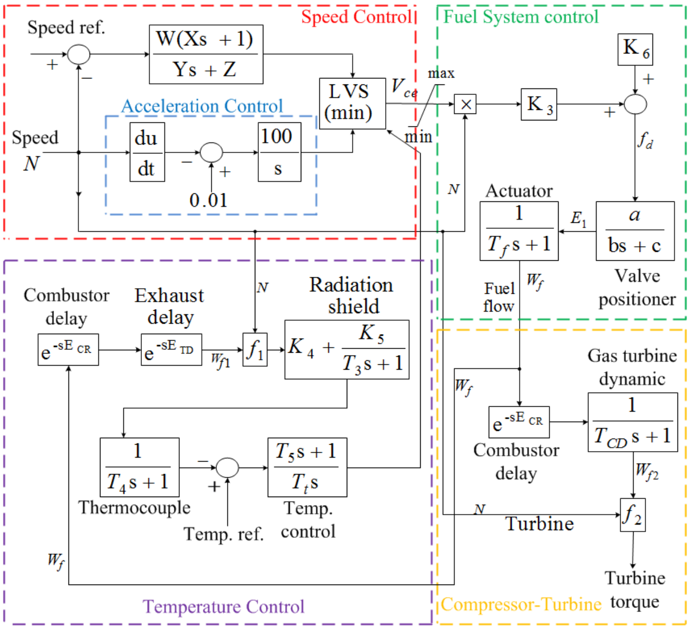

Fig. 2. Dynamic model of microturbine

The inputs of temperature control are fuel flow, speed deviation and reference temperature. Temperature control is used to control of combustion temperature with respect to fuel demand and reference temperature. The exhaust temperature characteristic is as following function:

$$f_1 = T_R - a_{f1}.(1 - W_{f1}) + b_{f1}.\Delta N \tag{1}$$

Where, f_1 is temperature control function, W_{f1} is related to fuel flow after combustion process, ΔN is rotor speed deviation, a_{f1} and b_{f1} are constant values and T_R is temperature reference. Temperature measurement is carried out by thermocouple and is compared with temperature reference. Normally reference is higher than thermocouple output but when it is lower, a negative value is produce to decrease temperature. According to Fig. 2, K_4 and K_5 are constant in radiation shield transfer function, T_3 and T_4 are the time constant of the radiation shield and thermocouple transfer function, respectively and T_5 with T_t are the time constant of the temperature control transfer function. The output of this section is enters to LVS like speed and acceleration control signals.

3) Fuel system control

Fuel system is consist of two series block which are valve positioner and actuator. The output of the LVS (V_{ce}) is scaled by K_3 and is offset by K_6 that is represent of fuel flow at no load condition. The valve position block is as follow:

$$E_l = \frac{a}{bs + c} f_d \tag{2}$$

Where, b and a are valve positioner gain and time constant, respectively. C is a constant value and f_d is scaled V_{ce}. The actuator transfer function is as following:

$$W_f = \frac{1}{T_f s + 1} E_l \tag{3}$$

Where, T_f is actuator time constant, E_l is output of the valve positioner and W_f is the fuel demand signal in per unit.

4) Compressor-Turbine

This section is important because of mechanical power production. Turbine and compressor are considered in one package because they are mounted on a same shaft. Fuel flow and speed deviations are input signals to produce mechanical torque. The turbine dynamic is modeled by following transfer function:

$$W_{f2} = \frac{1}{T_{CD}s + 1} W_f \tag{4}$$

Where, T_{CD} is time constant and W_f fuel flow signal after delay time. Mechanical torque function is:

$$f_2 = a_{f2} + b_{f2} W_{f2} + c_{f2}.\Delta N \tag{5}$$

Where, a_{f2}, b_{f2}, c_{f2} are constant values.

B. Permanent Magnet Synchronous Machine (PMSM) Modeling

It is required to a generator to produce electrical power. PMSM is superior because field winding in synchronous generator is replaced by a permanent magnet leads to lower losses and lower costs. All equations are converted from abc frame to dq0 reference frame to have simple modeling. In this model assumes that stator flux is sinusoidal which is caused to sinusoidal electromotive forces and PMSM is a two pole machine. Equations in rotor reference frame are as following:

- ***Electrical equations***

$$v_d = r_s i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \tag{6}$$

$$v_q = r_s i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \lambda_f \omega_r \tag{7}$$

$$T_e = 3/2 \left[\lambda_f i_q + \left(L_d - L_q \right) i_q i_d \right] \tag{8}$$

Where L_d and L_q are d and q axis inductances, r_s is stator winding resistance, i_q and *id* are q and d axis currents, respectively, v_q and v_d are q and d axis voltages, respectively, ω_r is mechanical angular velocity, λ is flux linkage and T_e is electromagnetic torque.

- ***Mechanical equations***

$$\frac{d\theta_r}{dt} = \omega_r \tag{9}$$

$$\frac{d\omega_r}{dt} = 1/J \left(T_e - T_m - F\omega_r \right) \tag{10}$$

Where J is rotor and load inertia, F is rotor and load combined viscous friction, T_m is mechanical torque and θ_r is rotor angular position. Parameter values are presented in appendix.

Equivalent circuit of the PMSM in dq0 reference frame is shown in Fig. 3. Note that, mentioned equations are based on permanent magnet motor. Reverse current direction with negative electric torque are features of permanent magnet generator.

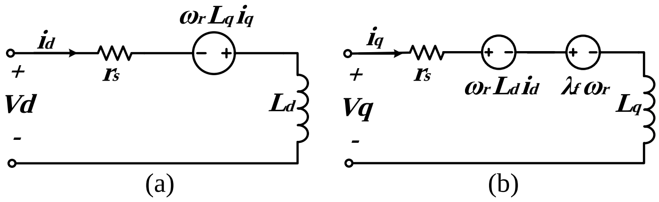

Fig. 3. PMSM equivalent circuit model: a) d-axis, b) q-axis

C. Rectifier Modeling

Rectifier is used to convert AC voltage to DC. PMSG output voltage is high frequency and along with rectifier it is convert to constant voltage. Controllable rectifier or uncontrollable rectifier are types of it. In this paper an uncontrolled rectifier or diode rectifier is used and forward voltage of diodes is 0.7 V. detailed modeling of three-phase diode rectifier is presented in [14] and [15].

D. Inverter Modeling

In this paper, a three-phase inverter with current control is assumed. Switching pattern is determined based on load current feedback and MPC scheme. A three-phase inverter is shown in Fig. 4. In each leg, a switch must be on to avoid short circuit of DC-link voltage. Switching states is represented like following:

$$S_i = \begin{cases} 1 \; if \; S_1, S_2, S_3 \;\; on \\ 0 \;\; if \; S_4, S_5, S_6 \;\; on \end{cases} \quad , \quad i=a,\, b,\, c \tag{11}$$

These switching states define output voltage of the inverter:

$$v_{aN} = S_a \times V_{dc} \tag{12}$$

$$v_{bN} = S_b \times V_{dc} \tag{13}$$

$$v_{cN} = S_c \times V_{dc} \tag{14}$$

The output voltage vector is:

$$V = \frac{2}{3} \left(v_{aN} + a v_{bN} + a^2 v_{cN} \right) \tag{15}$$

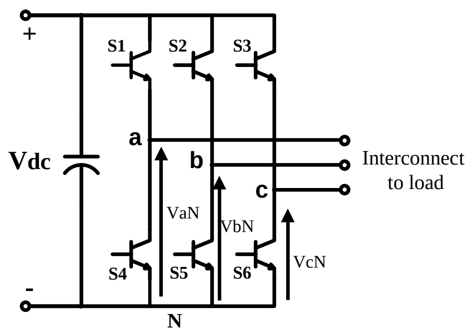

Fig. 4. Three-phase inverter

Where, $a = 1\angle 120^{\circ}$ and v_{aN}, v_{bN}, v_{cN} are phase to neutral voltages. V is dependent on switching states. So, eight possible switching vector are presented in Table I.

With respect to (12)-(14) and to have simple configuration, inverter is modeled by multiplying of the DC voltage and S_a, S_b, S_c which are generated by MPC program. In this model, it is assumed that V_{dc} is ideal and switching states are based on Table I. best switching pattern is occur in each cycle by MPC.

TABLE I.
SWITCHING STATES AND VOLTAGE VECTORS

S_a	S_b	S_c	Voltage Vector (V)
0	0	0	$V_0 = 0$
1	0	0	$V_1 = \frac{2}{3} V_{dc}$
1	1	0	$V_2 = \frac{1}{3} V_{dc} + j \frac{\sqrt{3}}{3} V_{dc}$
0	1	0	$V_3 = -\frac{1}{3} V_{dc} + j \frac{\sqrt{3}}{3} V_{dc}$
0	1	1	$V_4 = -\frac{2}{3} V_{dc}$
0	0	1	$V_5 = -\frac{1}{3} V_{dc} - j \frac{\sqrt{3}}{3} V_{dc}$
1	0	1	$V_6 = \frac{1}{3} V_{dc} - j \frac{\sqrt{3}}{3} V_{dc}$
1	1	1	$V_7 = 0$

E. Load Modeling

A stand-alone resistive-inductive load along with back-emf is considered. Fig. 5 shows the load which is connected to inverter. It is assumed that load is star connection, e_i is used for back-emf, R is resistive and L is inductance of the load. The back electromotive force (emf) is the voltage drop in an AC circuit caused by magnetic induction and pushes against the current which induces it and is assumed to be sinusoidal with constant frequency and amplitude.

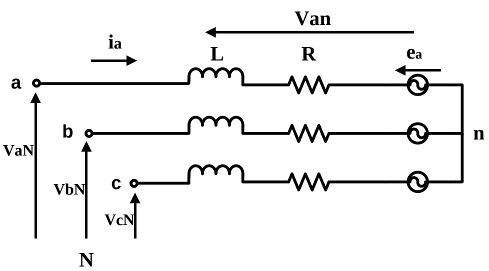

Fig. 5. Stand-alone resistive-inductive load

With a Kirchhoff's voltage low (KVL) in Fig. 5 yields:

$$v_{aN} = L\frac{di_a}{dt} + Ri_a + e_a + v_{nN} \quad (16)$$

$$v_{bN} = L\frac{di_b}{dt} + Ri_b + e_b + v_{nN} \quad (17)$$

$$v_{cN} = L\frac{di_c}{dt} + Ri_c + e_c + v_{nN} \quad (18)$$

Moreover, following equations is valid:

$$v_{an} = v_{aN} - v_{nN} \quad (19)$$

$$v_{bn} = v_{bN} - v_{nN} \quad (20)$$

$$v_{cn} = v_{cN} - v_{nN} \quad (21)$$

Since the load is balance, then $i_a+i_b+i_c=0$ as well as the back-emf is a balanced voltage and then $e_a+e_b+e_c=0$.

With (16)-(18) and considering balanced current and back-emf, we have:

$$v_{nN} = \frac{1}{3}(v_{aN} + v_{bN} + v_{cN}) \quad (22)$$

By substituting (16)-(18) into (19)-(21), three-phase voltage is expressed

$$v_{an} = L\frac{di_a}{dt} + Ri_a + e_a \quad (23)$$

$$v_{bn} = L\frac{di_b}{dt} + Ri_b + e_b \quad (24)$$

$$v_{cn} = L\frac{di_c}{dt} + Ri_c + e_c \quad (25)$$

By applying Laplace transform to (23)-(25), the transform function is obtained which currents are as outputs, voltages are as inputs and load is considered as $1/(Ls+R)$ and e_i are sinusoidal wave with constant frequency and amplitude.

F. Model Predictive Control (MPC)

Predictive control is a control solution which is use system model for predicting of future behavior. In predictive control methods, prediction is use for controlled variables to obtain an optimal solution [8].

MPC is as subset of predictive control. MPC is uses to predict the future of the variables in a specified horizon to achieve an optimal solution by minimizing of a cost function. MPC operates in a N_p predictive horizon with N_c control horizon to obtain appropriate solution. The cost function g is represent desired behavior of the system.

In this paper, the model which is used for prediction is a discrete-time model. The objective of the current control is to minimize the error between measurement current and reference current. So, cost function is difference between currents in sample time k+1.

$$g = |i_{ref}(k+1)| - |i_m(k+1)| \quad (26)$$

Where, i_{ref} is reference current and i_m is measurement current. It is desirable that measurement current follow the reference current lead to minimize of the cost function.

It is assumed that reference current doesn't widely change in one sampling time, so $i_{ref}(k+1)=i_{ref}(k)$ is a correct equation in high sampling frequency.

Reference currents are three-phase 50 Hz balanced currents and measurement currents are load currents. In MPC program, all currents are transform into αβ frame. Outputs of MPC is S_a, S_b, S_c which are enter to the inverter. Comprehensive illustration is shown Fig. 1.

III. Simulation Results

In this paper, dynamic modeling of the microturbine generation system unit with MPC control is investigated. The MTG system which is shown in Fig. 1 is modeled and simulated by MATLAB/Simulink software. The simulation parameters are given in appendix and all time functions are in second. Fig. 6 shows simulated dynamic model of the system in MATLAB. Note that there is any filter in output of the inverter and with a simple passive filter, output waveforms are better.

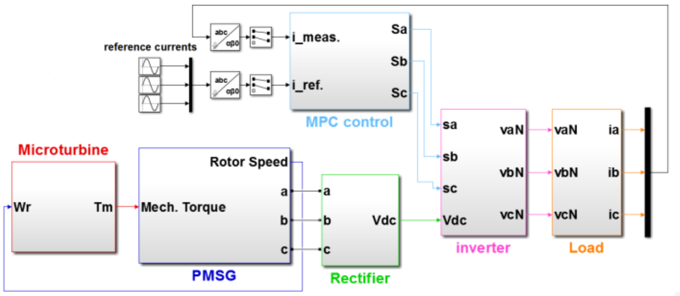

Fig. 6. Simulated dynamic model

Rotor speed of the PMSG in per unit (p.u) is shown in Fig. 7. After a few second of variation, speed is reached to 1 p.u and variations amplitude is small.

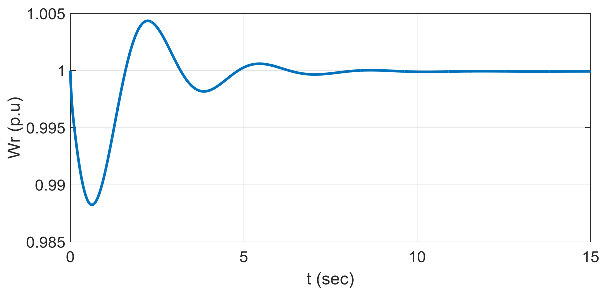

Fig. 7. Rotor speed of the MTG

Fuel of the MT is shown in Fig. 8. Fuel demand changes few second same as rotor speed. Amplitude of fuel variation is acceptable and in fixed position is about 0.24 p.u.

Fig. 9 is shown output voltage of the PMSG. Voltage is sinusoidal and high frequency. The frequency of voltage is 1500 Hz which is mentioned in appendix as PMSG frequency.

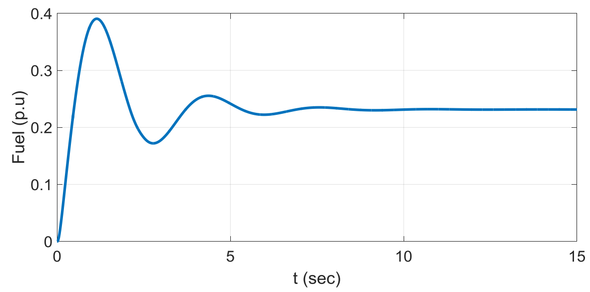

Fig. 8. Fuel demand of the MTG

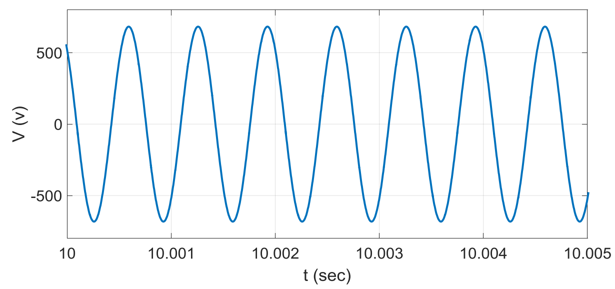

Fig. 9. Output Voltage of the PMSG

Fig. 10 shows the DC-link voltage. Voltage is reach to steady state after 5 second. The value of voltage in steady state is about 785 V. voltage at DC side is function of PMSG voltage and PMSG operation.

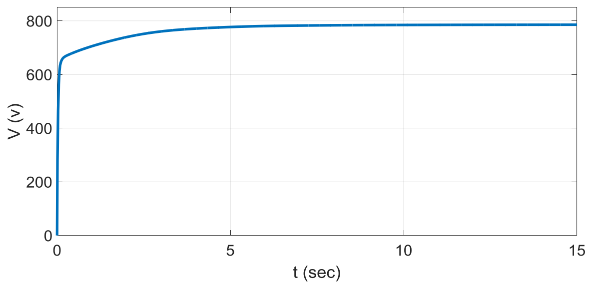

Fig. 10. Voltage at DC side

The switching signals of the MPC is shown in Fig. 11. Switching frequency is 40 kHz which is used to control of the inverter.

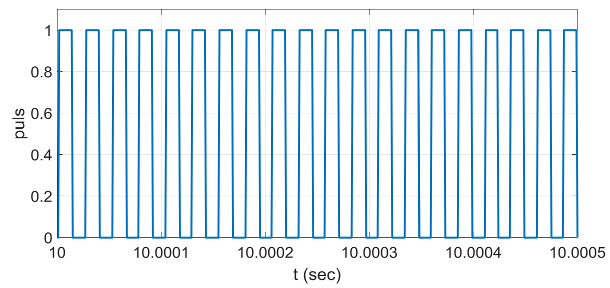

Fig. 11. Switching signals of the MPC

The output voltage of the inverter is shown in Fig. 12. DC-link voltage is multiplying with switching signals lead to produce inverter voltage. Based on mentioned parameters, this figure is belong to v_{aN}.

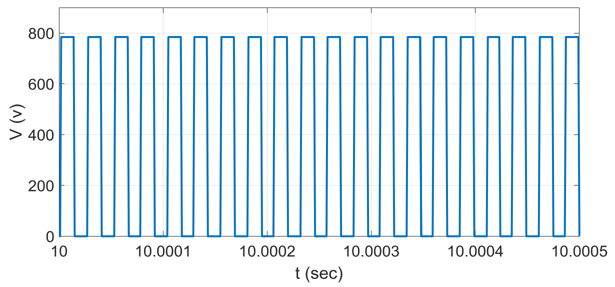

Fig. 12. Output voltage of the inverter

Fig. 13 shows load voltage without back-emf. This figure is voltage on *RL* load and is equal to v_{an}-e_a. The frequency of voltage is 50 Hz. The waveform is close to sinusoidal waveform but there is a few ripples and additional pulses. It is required to a filter for better voltage waveform.

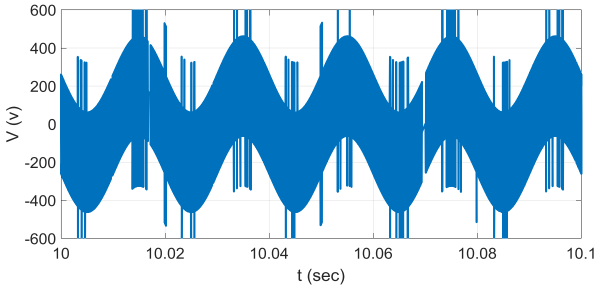

Fig. 13. Load voltage without back-emf

The output current is shown in Fig. 14. The current is sinusoidal with low harmonic and ripples. The MPC scheme for current control performance is desirable. Current control cause to have sinusoidal current lead to sinusoidal voltage. Load current is as feedback current too. It is use to produce optimal switching by MPC.

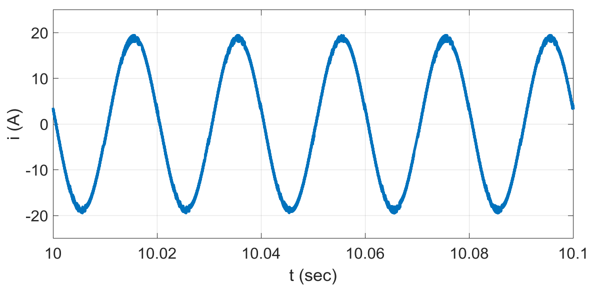

Fig. 14. Load current

Total Harmonic Distortion (THD) is a criterion to evaluate a waveform. Sinusoidal waveforms have very low THD and vice versa. Fig. 15 shows THD of load current. The THD value is under IEEE standard and is about 2%. Low THD lead to lower losses in power system or loads.

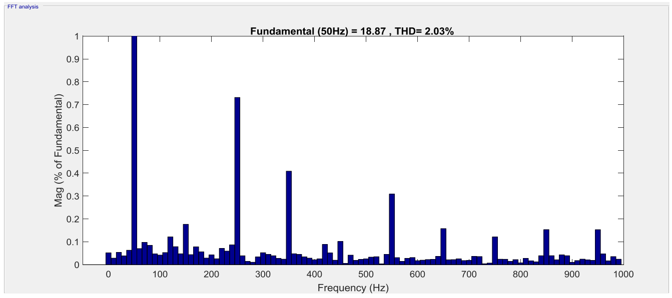

Fig. 15. THD of output current

IV. Conclusion

In this paper, dynamic modeling of a microturbine generation system is presented along with dynamic model of interface converters and load. MTG is operated in stand-alone mode which is supplying a resistive-inductive load. Desired control of the inverter is a challenge but MPC is used as optimal solution. Predictive of future variables help to produce optimal switching for inverters. Main objective is current control of the inverter with MPC and for this purpose detailed modeling of the MTG based on MPC with current control cost function is introduced. Simulation results show that MPC performance is acceptable and output current is sinusoidal with standard THD. MTG control with MPC is a new and desired method.

Appendix

1) *Parameters of the microturbine*

- Speed control:

$W=25$, $X=0.4$, $Y=0.05$, $Z=1$.

- Fuel system control:

$K_3=0.77$, $K_6=0.23$, $a=1$, $b=0.05$, $c=1$, $T_f=0.4$.

- Temperature control:

$K_4=0.8$, $K_5=0.2$, $T_3=15$, $T_4=2.5$, $T_R=950$ °F, $T_5=3.3$, $T_t=450$, $E_{CR}=0.01$, $E_{TD}=0.04$, $a_{f1}=700$, $b_{f1}=550$.

- Compressor-turbine combination:

$T_{CD}=0.2$, $a_{f2}=-0.3$, $b_{f2}=1.3$, $c_{f2}=0.5$.

2) *PMSG parameters*

Rated power=30 kW, rated voltage=500 V, rated frequency=1500 Hz;

$R_s=0.253\ \Omega$, $L_q=L_d=0.6875$ mH, $P=2$, $J=0.011$ kgm^2, $F=0$, $\lambda=0.0534$ wb.

3) *Load parameter*

$R_L=10\ \Omega$, $L_L=5$ mH, $e=100$ V.

MPC sampling rime: 25e-6 s

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