Novel Method for Dynamic Improvement of Model Predictive Control based Microturbine Generation System

Pouyan Asgharian
Department of Electrical Engineering
University of Zanjan
Zanjan, Iran
pouyan.asgharian@znu.ac.ir

Reza Noroozian
Department of Electrical Engineering
University of Zanjan
Zanjan, Iran
noroozian@znu.ac.ir

***Abstract*—Microturbine (MT) is a highly reliable source that requires an efficient model as well as control for desirable operation. This paper introduces a novel method based on Model Predictive Control (MPC) in order to improve the dynamic performance of a stand-alone MT. The proposed approach is a proper alternative to the traditional dynamic model of microturbine in which Low-Value Gate (LVG) of the MT is altered by MPC. Simulation results confirm that this novel configuration has not had a devastating effect on the load side. Moreover, the MPC based MT represents enough fast dynamic response and in comparison to the conventional model, its fuel consumption along with speed drops are improved.**

Keywords—Microturbine, Model Predictive Control, Dynamic improvement, Fuel consumption, Speed drop

I. INTRODUCTION

Microturbine (MT) is one of the alternative sources with suitable efficiency and sufficient output to meet energy demand. The MT generates power within the range of 25kW to 1MW and its efficiency in non-CHP (Combined Heat and Power) configuration is about 20-30% that might be reached more than 75% by CHP system [1].

The microturbine generation (MTG) system has shown numerous own merits including high power to weight ratio, high reliability, low emissions level and ability of operation with various fuels like biogas. These useful features contribute to a vast range of applications such as premium power, peak shaving, remote power, co-generation, transportation system, resource recovery and stand by services [2, 3].

Recently, the MTG performance in stand-alone or grid-connected mode has been the main target of researchers and hence these issues are addressed appropriately [3-6]. Mentioned references are employed classical method (PI) and MPC [7] for three-phase inverter control or an energy storage system [8] to model a high reliable dynamic system. However, dynamic improvement of the MTG is not considered and the MT model optimization is absolutely an effective method for desirable dynamic response.

In [9] an artificial neural network-based model for stand-alone MT power plants is proposed. Also, in [10] a fuzzy logic-based governor and in [11] an adaptive neuro-fuzzy based governor has been used to get better dynamics of the MT. A fuzzy-PID algorithm [12] or a fuzzy-PID with tracking differentiator (TD) [13] are other proposed methods to regulate governor coefficients in diverse load conditions.

Model Predictive Control (MPC) is an advantageous controller for nonlinear systems. The MT predictive control using Hammerstein models is presented in [14] so as to enhance dynamics and speed oscillations. Observer-based MPC for an MT-CCHP system is also presented in [15].

In this paper, a novel and simple strategy based on MPC is proposed to modify the MT dynamic performance. This strategy is relying on speed samples as well as minimization of governor output. This proposed approach guarantees optimal consumption of fuel and lower speed drop at the moment of load variations. The rest of the paper is organized as follows: Section II is dedicated to formal dynamic modeling of the MT. The proposed method is illustrated in section III. Simulation results of a stand-alone MT and conclusion of the paper are presented in sections IV and V, respectively.

II. MICROTURBINE DYNAMIC MODELLING

The general configuration of single-shaft MT is shown in Fig. 1. Three control functions (speed control, temperature control and acceleration control) are entered to Low-Value Gate (LVG) for selection of least value. The LVG output is transferred to the fuel system which results in the lowest fuel consumption.

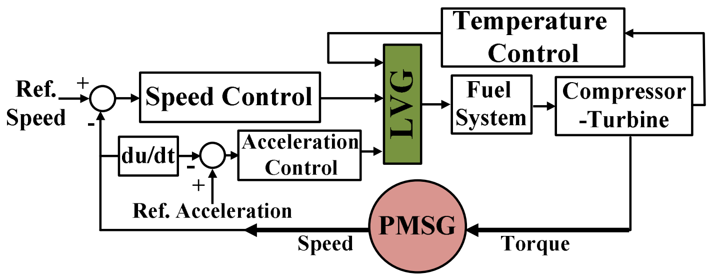


Fig. 1. Block diagram of a single-shaft MT

The single-shaft MT consists of a compressor, a combustor, a turbine, PMSG, and a recuperator in the format of different controller parts. Fig. 2 demonstrates the dynamic model of an MT that is, in fact, a detailed model of Fig. 1. Note that, all controllers are simulated in Per Unit (P. U.) except temperature control. Also, the recuperator is not considered due to long time constant along with little influence on the MT dynamic behavior.

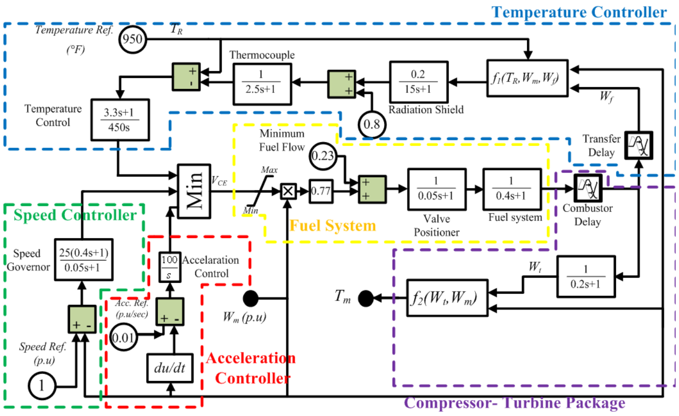


Fig. 2. The detailed dynamic model of the MT

Speed control operates based on an error between reference speed (ω_{ref}=1 per unit) and rotor speed. A lead-lag transfer function can be considered in order to model the speed governor [4].

$$gov = (25\times\frac{0.4s+1}{0.05s+1})\times(1-\omega) \quad (1)$$

Where ω is generator rotor speed (actual speed). Acceleration control may be applied to maintain the rate of rotor speed in predefined values, so this block can be ignored in steady-state [9].

Temperature control is used to limit turbine exhaust at a predetermined firing temperature. Temperature control consists of a thermocouple and radiation shield in which the output of thermocouple is compared with reference temperature (950 °F). When the thermocouple output exceeds the reference temperature, its negative difference leads to temperature reduction [3]. The exhaust temperature equation is as follows:

$$f_1 = 950 + 550(1-\omega) - 700(1-W_f) \quad (2)$$

Where W_f is the output of the fuel system after time delaying.

As mentioned above, the outputs of speed, acceleration and temperature control are entered into the LVG. The output signal of the LVG (V_{CE}) is passed through a limiter to enter the fuel system. It should be noted that the limiter maintains fuel demand and fire at a proper value. After that, the V_{CE} is scaled by 0.77 and is offset by 0.23 (fuel flow at the no-load condition) [3].

The fuel system consists of two series blocks include valve positioner and actuator. There are two delay blocks after the fuel system that they simulate delays of not only combustor but also flow transferring.

At the final stage, burnet fuel is entered into the turbine to produce mechanical power. Compressor and turbine are considered as a package because they are coupled together. The turbine dynamics is modeled by the following transfer function:

$$f_2 = 1.3(W_t - 0.23) + 0.5(1-\omega) \quad (3)$$

Where W_t is turbine dynamics output.

III. Improvement of Microturbine Dynamics

The MT operation can be enhanced by applying optimization methods like MPC to a dynamic model. The MPC operates based on the system model to predict the behavior of variables future in a predefined time horizon. The optimal solution achieves through minimizing a cost function [16]. Besides, the system model is a discrete-time state-space.

A. Proposed Method

In this novel strategy, the LVG is replaced by MPC, do similar to the traditional model, MPC block can receive temperature, speed and acceleration signals as three inputs. It should be noted that temperature and acceleration controllers may be ignored in steady-state operation and also calculation time will reduce too.

Parameters' value of speed governor in steady-state operation is equivalent to the conventional model. Speed governor control in Laplace form is expressed as follows:

$$gov = (\omega_{ref} - \omega)\left(\frac{W}{Ys+Z}\right) \quad (4)$$

Where W, Y, Z, and gov are variables and ω_{ref} is reference speed. An arbitrary variable Q can be considered as Q=ω_{ref}-ω and by rewriting of (4) in the time domain, we have:

$$gov\times Ys = QW - Z\times gov \rightarrow \frac{dgov}{dt} = \frac{QW - Zgov}{Y} \quad (5)$$

In order to predict the future of governor function, the discretization process for T_s sampling time should be considered. There are various approaches for discretization and Euler approximation is chosen in this paper. The derivative of the governor's function is replaced by a forward Euler approximation:

$$\frac{dgov}{dt} \approx \frac{gov(k+1) - gov(k)}{T_s} \quad (6)$$

By substitution of equation (6) in (5) and some modification, future forecast of governor function for k+1 samples is formulized:

$$gov(k+1) = \frac{QWT_s}{Y} + gov(k)\left[1-\frac{ZT_s}{Y}\right] \quad (7)$$

The last equation is the final mathematical function for prediction. In this method, speed values can consider for each arbitrary limitation (with i numbers) and hence governor function will be generated for each distinct group. By minimization of i numbers of gov function, optimal values of fuel as well as generator speed obtain. For instance, five percent of speed variations may consider. In the first step, there are some Qs in accordance with the percentage of speed limits. Secondly, with respect to (7) and Qs for T_s sampling time, some $gov(k+1)$ achieves (for k+1 samples). Finally, The least value between all $gov(k+1)$s is an optimal response that will be transferred to the fuel system. The flowchart of this novel method is illustrated in Fig. 3.

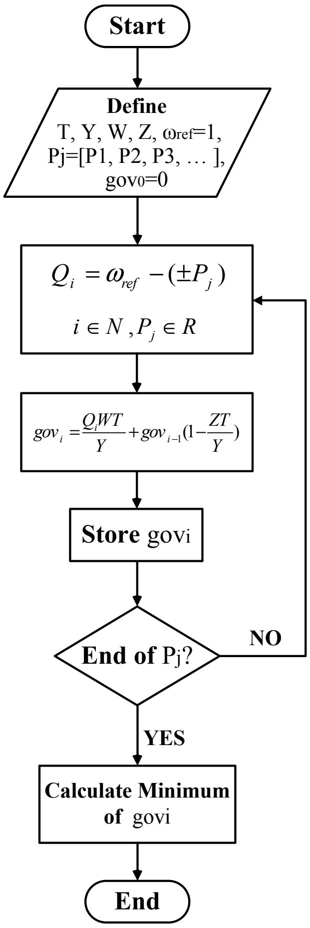


Fig. 3. Flowchart of MPC based MT

IV. Simulation Results

The MTG dynamic performance with MPC in stand-alone mode is simulated by MATLAB/Simulink. The interface converter is AC-DC-AC topology with a rectifier and also a three-phase inverter that the whole system is shown in Fig. 4. The value of each system parameters is presented in Table 1.

The simulation part aims to evaluate the proposed method on an MT based dispatchable source. Therefore, the main output parameters are shown to confirm dynamic improvement without any effect on the load side.

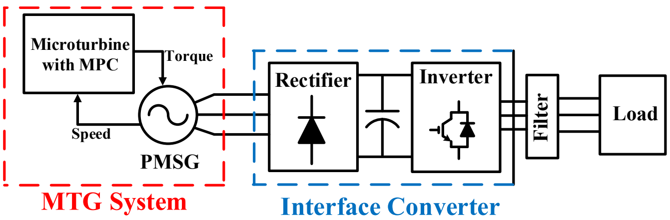


Fig. 4. The MTG system with interface converters

Each compartment of the MT has a small thermodynamic time constant (e.g. 1.5 ms), so the MPC sampling time can be considered equal to 500×10^{-6} s along with 155 speed samples (i. e. generating Q).

A load (*Load A*) has been connected to the MTG system until t=12s and at this moment, *Load B* is added to the system. The latter is disconnected at t=20s and the system supply only the primary load.

TABLE I. Studied System Parameters Value

Parameter	Value	Parameter	Value
MTG output power	30 kW	Load frequency	50 Hz
MTG output voltage	480 V	Inverter switching frequency	2 kHz
DC-link capacitor	3500 µF	*Load A*	5 kW
Filter inductance	3 mH	*Load B*	2.5 kW
Filter capacitor	300 µF	MPC sampling time	500 µs

There are two main parameters in the MT dynamics which include fuel demand signal and speed. These parameters determine the performance quality and cost of the MTG. The final purpose of this novel method is to improve fuel consumption and speed level without any detrimental influence on the whole system.

Fig. 5 shows speed variations for two different scenarios. In order to present a comprehensive analysis, the MT system operation with the conventional dynamic model (i. e. with LVG) and the MPC based dynamic model is compared. The blue line represents speed in the traditional model and the red line shows the MT dynamics with the proposed model.

When load increase, normally speed drop occurs. What stands out from this figure is that using MPC in the dynamic model can improve overall speed level and hence speed drop is enhanced.

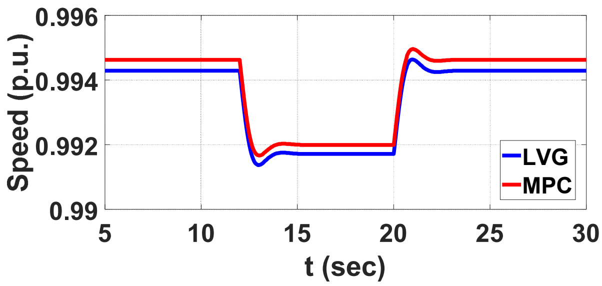


Fig. 5. Speed variations with and without MPC

Additional loads require higher output power and hence the rate of MT fuel consumption increase to meet the demands. The fuel demand signal is shown in Fig. 6. Similar to the previous figure, fuel consumption is considered in two diverse situations. It is clear from the figure that the fuel signal with MPC is lower as well as smoother especially in load rise than the conventional model. As a result, using the MPC leads to optimal fuel consumption and hence lower costs.

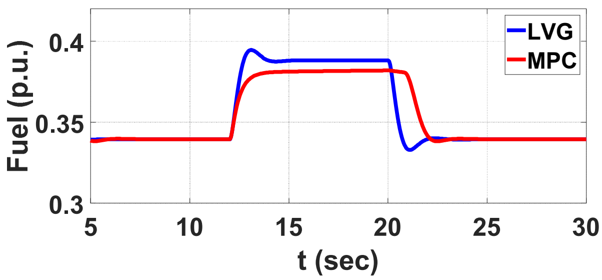
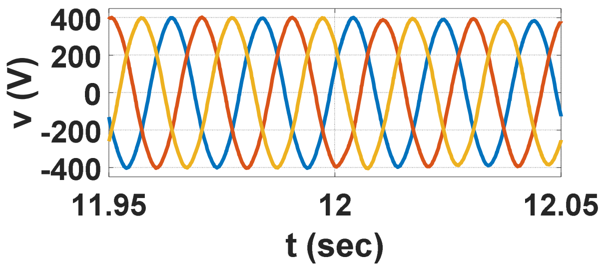
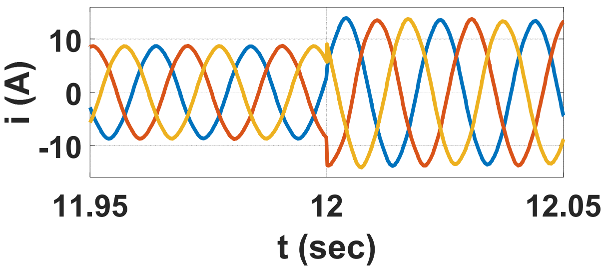


Fig. 6. Fuel demand variations with and without MPC

As further proof, three-phase load voltages and currents are shown in Fig. 7. The output voltage amplitude and frequency are 400 V and 50 Hz, respectively. When *Load B* is connected, three-phase currents increase and vice versa but voltages remain unchanged. It can be seen that load side voltages/currents are sinusoidal with low total harmonic distortion (THD) which means the MPC based MT makes no adverse impact on the load side.



(a)



(b)

Fig. 7. Load side outputs: (a) three-phase voltages, (b) three-phase currents

The voltage on the DC-link capacitor is shown in Fig. 8. When an additional load is applied results in a voltage drop from 700V to approximately 650V that is a normal condition. Also, there are not noticeable variations in DC-link voltage. Thus, it can be concluded that the dynamic improvement of the MT is not provided malfunction of other parts.

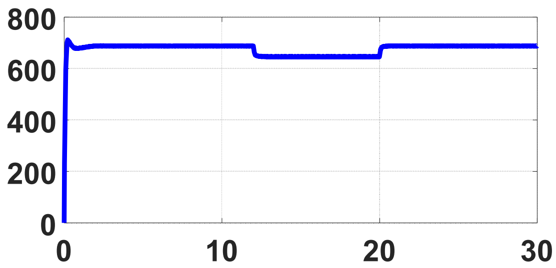


Fig. 8. DC-link voltage

V. Conclusion

In this paper, the MPC method is applied to the MT dynamic model in order to improve its performance. In the proposed approach, the MPC is used instead of LVG to predict and minimize the governor's output. Simulation results indicate that this novel strategy can reduce fuel consumption and increase speed overall level during load variations so, it contributes to lower costs and speed drop. In addition to the mentioned improvement, the load side and DC-link voltage are not affected by the proposed method. Therefore, the MPC based MT can be considered as an efficient substitute for the formal dynamic model.

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