

Energy Management and Control Strategy of DC Source and Microturbine Generation System by Using PQ Controller and Droop Control in Islanded Mode

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Abstract: The requirements of power quality, public environment policy and expansion power demand are providing better opportunity to the microturbine (MTG) to be best microsources for improving the system stability, reliability and power quality. This paper presents modelling and control strategy of MTG system by using PQ controller and Droop control in islanded mode. The model developed in this work includes the individual components of prime mover like, compressor, heat exchanger, burner and turbine. The model of MTG system consists of microturbine, permanent magnet synchronous machine and power electronics interfacing circuit for generation and conversation from AC/DC/AC respectively and design of PQ controller including droop control with current and voltage loop and power loop. The simulations are carried out in islanded mode of the system to observe its behavior when supplying customer under variable load. It also incorporates modeling and simulation of microturbine with speed control, temperature control, and heat control, frequency control, voltage control and designing of filters in order to eradicate harmonics and suppress all kind of disturbance exist in network during transmission and distribution. The load following characteristics is observed and validated for this MTG-synchronous generator model in Matlab-Simulink environment with power system block.

Keywords: Distributed Generation (DG), Microturbine Generation System, DC source, PQ Controller and Droop Control

1. Introduction

In nowadays microturbines are marketable and commercialized as a distributed generation (DG) technology like other microsources such as photovoltaic arrays, fuel cells, wind turbines and direct current source (DC), microturbine and photovoltaic arrays are generally best microsource suited to compensate and improve power system stability, reliability and play a key role in heat production and the same time supply power to the utility grid [5]. Therefore microturbine is suitable for small applications and are designed to produce electricity for onsite energy needs and for end users in close proximity to the generation site. Many microturbine, their output are varies between 30 kilowatt (kW) up to 250 megawatts (MW) [6-7]. DG allows the rural electrification, industry to reduce the traditional cost of

service with a specific controller such as PQ controller and droop control in order to be integrated in electrical network with static transfer switch (STS). Distributed energy resources are composed by varieties of small modular distributed generation (DG) technologies that can be combined with energy management system like battery charging and discharging algorithm and storage systems. Distributed energy resources allows renewable energies utilization and more efficient utilization of waste heat in combined heat and power (CHP) applications and lowering emissions in order to sustainable an environment [3-4]. Normally MTG has the following specifications:

1. Relatively small in size compared with other distributed energy resources.

2. It has higher efficiency, fuel to electricity conversion which can vary 25% to 30%. In whatever way, if the waste recovery is used, combined heat and electric power could achieve energy efficiency levels greater than 80%.
 3. Environmental superiority, NO_x emissions lower than 7 parts per million for natural gas machines in practical operating ranges.
 4. Durable, designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
 5. Economical, system costs lower than \$500 per KW, costs of electricity that are competitive with alternative including grid-connected power for market applications [3].
 6. Fuel flexibility, capable of using alternative/optional fuels including natural gas, diesel, ethanol, landfill gas and other bio-mass derived liquids and gases.
- Generally there are two types of microturbines which are namely recuperated and unrecuperated microturbine and those type are completely different according to the table below

Table 1. Comparison between types of Microturbine [12].

Unrecuperated	Recuperated
Compressed air is mixed with fuel and burned under constant pressure conditions. Efficiency 15%.	A sheet metal heat exchanger (recuperator) recovers temperature of the air stream supplied to the combustor. Efficiency 20~30%.

How a microturbine works?

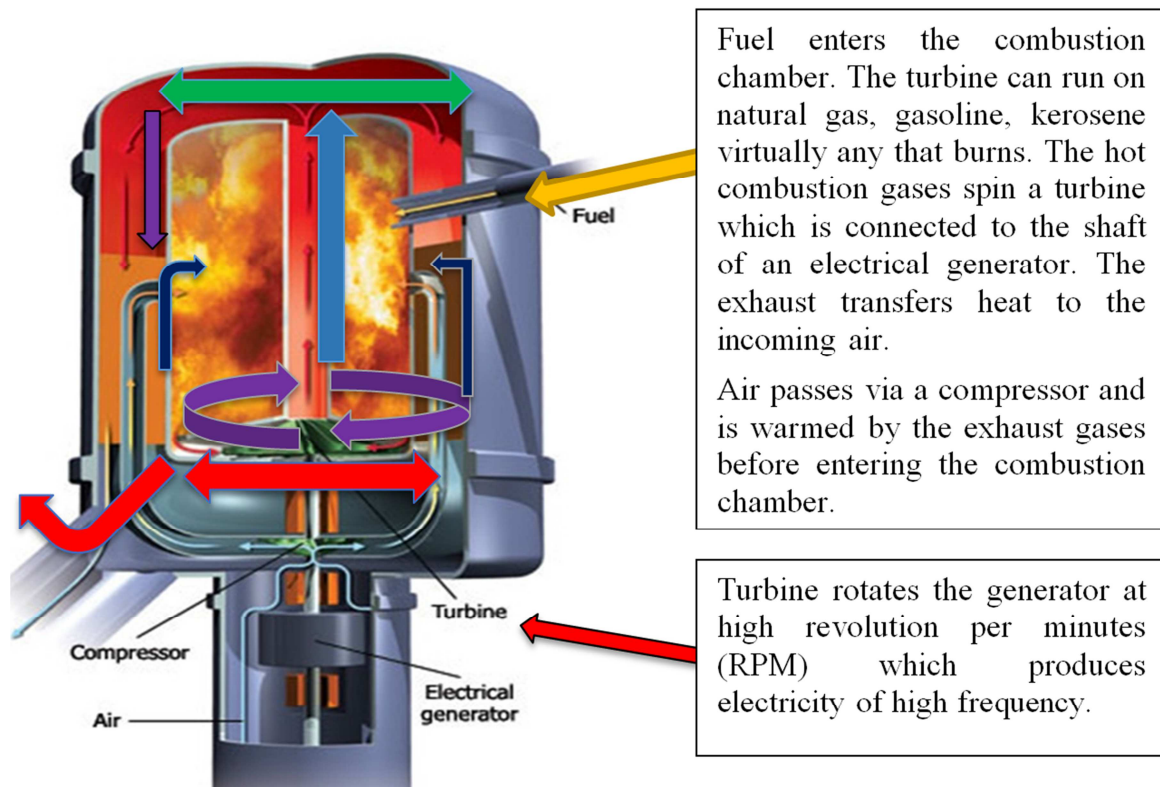


Figure 1. Working principle of microturbine [13].

2. Microturbine Generation System and Control Strategies

Figure 2 is composed by two microsources namely DC source controlled by PQ controller in order to control frequency and voltage meanwhile second microsource which is microturbine is controlled by droop control in order to provide frequency and voltage to the PQ controller because PQ controller can't work alone. Normally there are more than four type of PQ controller but i decided to use the following type of PQ controller and it is drawn in figure 4 [8].

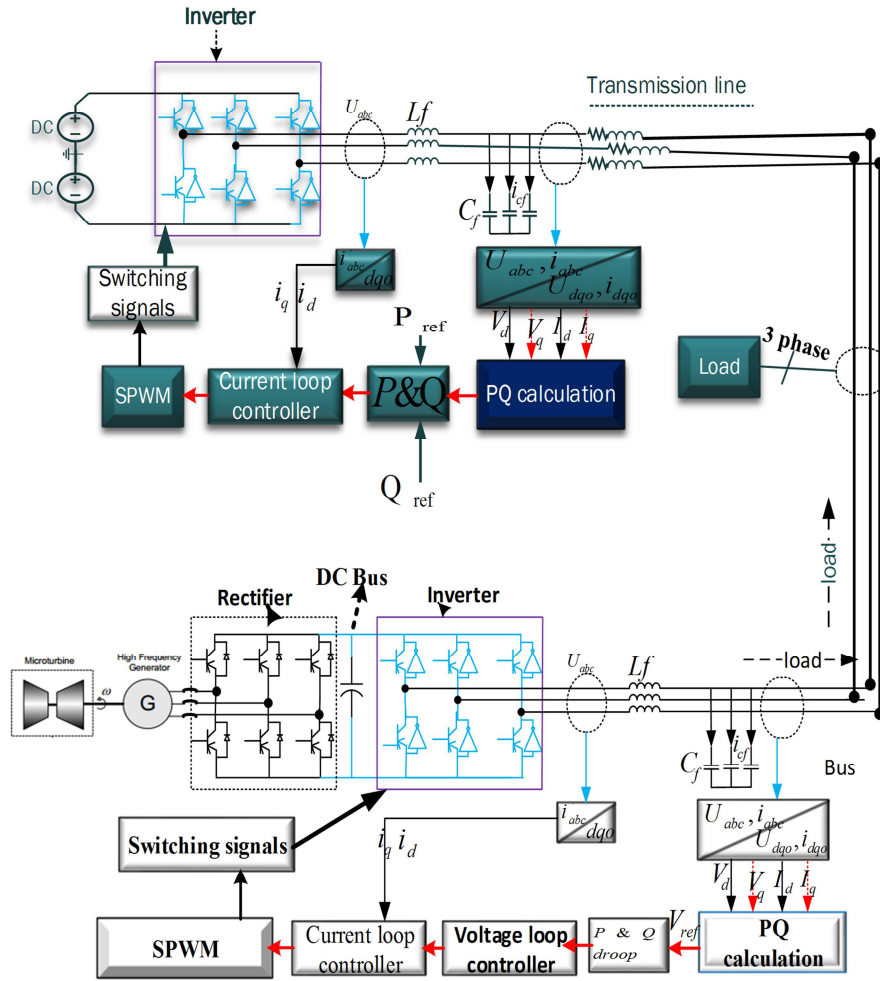


Figure 2. Schematic diagram of microturbine generation system and its control strategies.

Even though voltage and frequency are depending on variation of loads so that in order to maintain frequency and voltage in range we should have some limitation based on the droop control and schematized in figure 3 [8].



Figure 3. Schematic diagram of droop control.

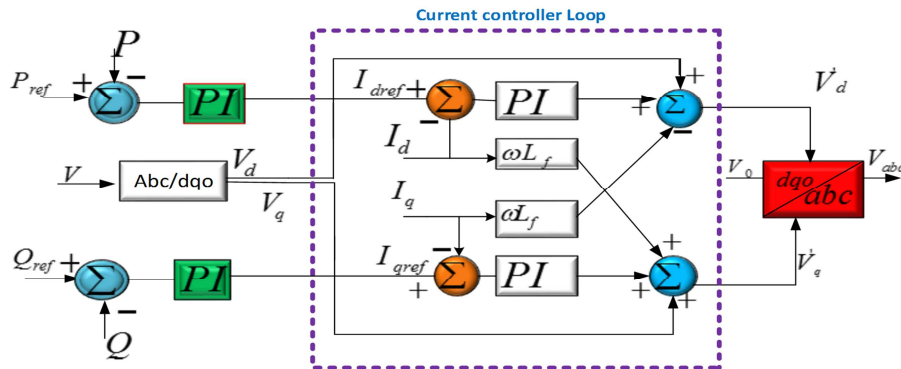


Figure 4. Schematic diagram of PQ controller.

Figure 4 presents the PQ controller which is frequently used for maintaining the magnitude and frequency of voltage when the load continue to fluctuates as illustrated in figure 4. The PQ controller strategy provides current reference signal by decoupling the active and reactive power with the regulation of PI controller. A current error signal formed by the reference current and the inverter current will provide PWM signals to the inverter by the effects of PI controller. An ideal SPWM model is utilized to satisfy the inverter's requirement, and a three-phase phase locked loop (PLL) is adopted in following the voltage angles of the grid, which supports frequency for the control system.

3. Dynamic Model of Microturbine Generation System

3.1. Modelling and Control Strategy of Microturbine

Figure 2 represents overall model of microgrid with two microsources but for microturbine is a model of single shaft microturbine which is composed by a speed control which is approximately 96000 rpm, acceleration control, temperature control, fuel flow control and compressor control [9-10].

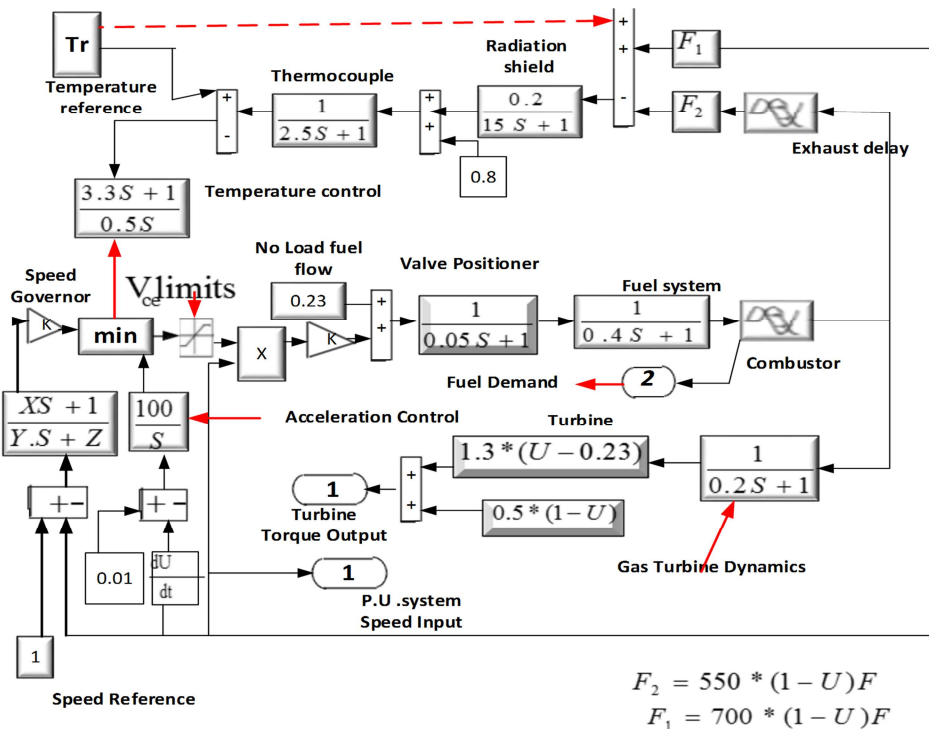


Figure 5. Schematic diagram of an internal control of microturbine [11].

3.1.1. Speed and Acceleration Control Strategy

The differential control mode is normally called droop control meanwhile it has been considered as the primary means of speed control for microturbine under load variation with different conditions. A droop governor is proportional to the speed controller where the input is a speed error formed by a reference speed and the microturbine generator system rotor speed while the output is proportional to the speed error. In this paper, a lead lag transfer function has been used to represent the speed controller, as shown in Figure 6.

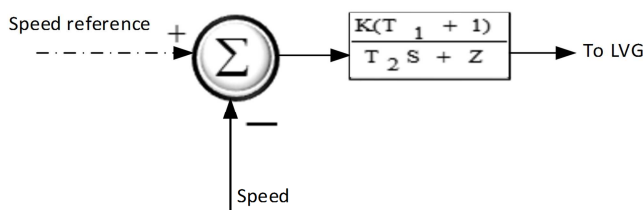


Figure 6. Diagram of the speed controller for the micro-turbine [16].

3.1.2. Fuel Control System

The main parts of fuel system are fuel valve and actuator. The fuel come out from the fuel system results from the inertia of the fuel system actuator and of the valve positioner and its equations are expressed below. The valve positioner transfer function is [14]:

$$E_1 = \frac{K_v}{T_n S + C} F_d \quad (1)$$

In addition, the fuel system actuator transfer function can be expressed as [14]:

$$W_f = \frac{K_f}{T_f S + C} E_1 \quad (2)$$

In the equations (1) and (2), K_V and K_f are the valve positioner (fuel system actuator) gain, T_v, T_f are called the valve positioner and fuel system actuator time constants,

whereas c is a constant, moreover F_d and E_1 are the input and outputs of the valve positioner eventually W_f is the fuel required signal in p. u. The output of the LVG, V_{ce} , represents the least quantity of fuel needed for that particular operating point and is an input to the fuel system. Another input to the fuel system which is the per-unit turbine speed N . The per-unit value for V_{ce} is directly correspond to the per-unit value

of the mechanical power on turbine at steady-state. The fuel flow control as a function of V_{ce} is shown in Figure 7. The value of V_{ce} is from the gain K_3 ($K_3 = 1 - K_6$), although that output is delayed and offset by minimum value of fuel flow K_6 that is required to ensure the continuous combustion process. In addition, K_6 is the minimum amount of fuel required at no load available and at rated speed [15]:

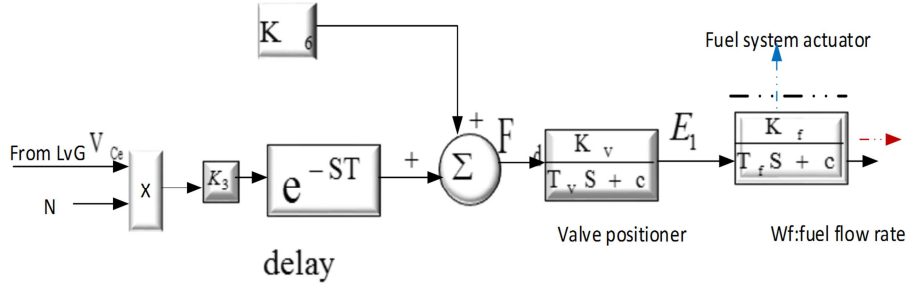


Figure 7. Control block diagram of the fuel system.

The figure 7 the fuel system parameters are specified accordingly this:

$$K_v = 1, T_v = 0.05, C = 1, K_3 = 0.33, K_6 = 0.23, K_f = 1, T_f = 0.04$$

3.1.3. Compressor Turbine System

The compressor-turbine is a linear and non-dynamic device. It is also the vital part of the microturbine. The annotation block diagram of compressor-turbine system is shown in figure 8 whereby the torque and the exhaust temperature characteristics has shown in the figure 8 in addition for single shaft gas turbine are essentially linear with respect to fuel flow and turbine speed. These characteristics are given and described by the following equations [17], [18].

$$T = K_{HHV}(W_{f2} - 0.23) + 0.5(1 - N)[Nm] \quad (3)$$

And the exhaust system function is given by this equation [17], [18]:

$$T_x = T_R - 700(1 - W_{f1}) + 550(1 - N)^{\circ}F \quad (4)$$

$T_{CR} = 0.01$, $T_{TD} = 0.04$, $T_{CD} = 0.2$, $K_{HHV} = 0.2$. K_{HHV} is the coefficient that depend upon the enthalpy or higher heating value of the gas in the combustion chamber and T_R is the reference temperature. In the torque equation, the K_{HHV} and the constant 0.23 cater for the typical power/fuel characteristic, which varies linearly and gradually from zero power at 23% fuel flow rate to the rated output at 100% fuel flow rate. This system, input is fuel W_f demand signal in per unit and outputs are the per unit turbine torque and exhaust temperature ($^{\circ}F$).

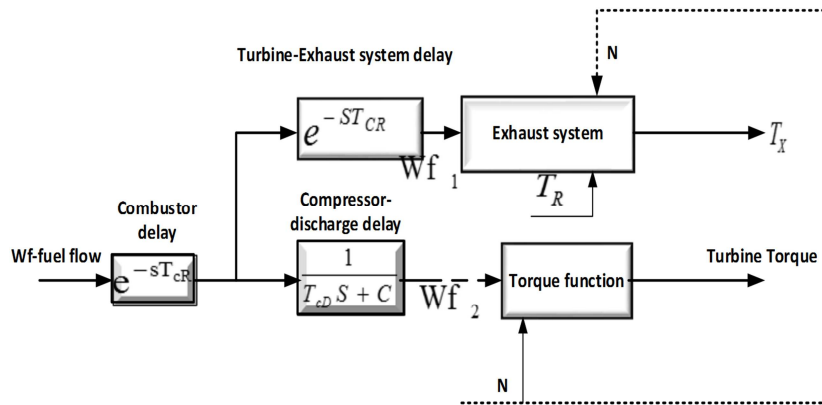


Figure 8. Diagram of compressor turbine package of microturbine [16], [14].

3.1.4. Temperature Control System

The main role of temperature control is to restrict turbine output power at a predetermined firing temperature, independent of variation in environmental temperature or fuel characteristics. The exhaust temperature which is calculated by means of a series of thermocouple which

incorporated inside and is compared with a reference value, and the error between them is considered as temperature control signal. The temperature controller works by limiting the fuel input to limit the exhaust temperature of a microturbine in order to play a protective role on the turbine parts, as shown in Figure 9 [1].

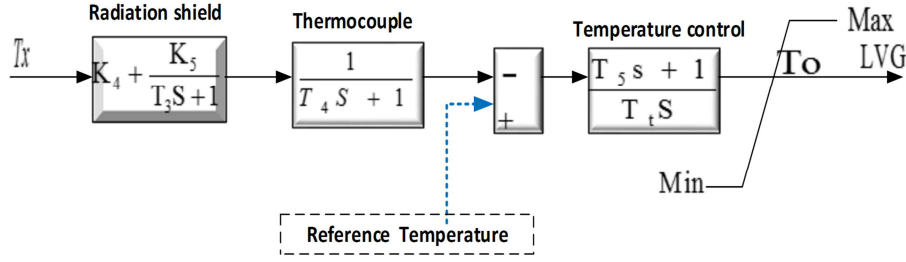


Figure 9. Temperature control block.

$$K_4 = 0.8, K_5 = 0.2, T_3 = 15, T_4 = 2.5, T_5 = 3.3, T_t = 450^\circ\text{F}, T_R = 950^\circ\text{F}.$$

3.1.5. Permanent Magnet Synchronous Machine

As aforementioned, the single shaft microturbine produces electrical power through a high speed permanent magnet synchronous generator directly driven by the compressor turbine shaft. In this paper the mathematical model of the PMSG is provided in MATLAB/SIMULINK software package and some assumptions have made where $L_{dm} = L_{qm}$ and interior magnet machine are negligible and dqo axis equation can be written as follows [16], [18], [5], and [19]:

$$V_{ds} = R_s i_{ds} - \omega_e \Psi_{qs} + \frac{d\Psi_{ds}}{dt} \quad (5)$$

$$V_{qs} = R_s i_{qs} + \omega_e \Psi'_{ds} + \omega_e \Psi_f + \frac{d\Psi_s}{dt} \quad (6)$$

The electromagnetic torque produced in the machine air gap is based on conversion of three phase to two phase where we take this ration of 3/2 and the torque is given by:

$$T_e = \frac{3}{2} * \frac{P}{2} (\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \quad (7)$$

And the mechanical torque is written as follows [18], [5], and [19]:

$$T_m = J \frac{d\omega}{dt} + T_e + R_\Omega \omega \quad (8)$$

The signs of torques have different meaning according the sign the reason why if the generated torque T_e and shaft torque T_{shaft} are positive exclusively for motor operation and negative for generator operation only [2]. Therefore, the equivalent circuits of permanent magnet synchronous machine is based on the equations (5), (6) and (7) so it can be represented by as follows [2]:

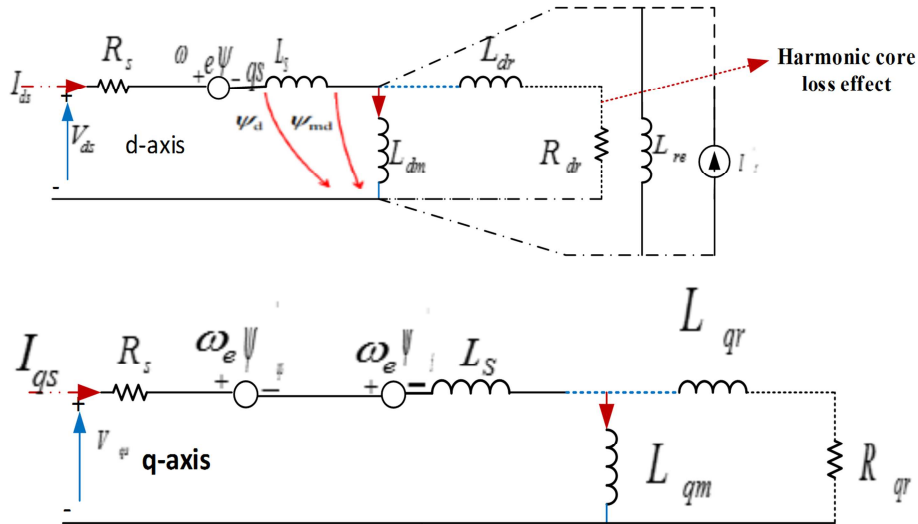


Figure 10. Equivalent circuits of permanent magnet synchronous machine.

3.2 Diagram of Voltage and Current Loop Controller

In order to supply power quality, voltage and current should be controlled dynamically with highest precision. Technically there are many control strategies which are ubiquitous and are named current and voltage loop controller, therefore, They have different advantages which are listed are here:

1. Fast transient response.
2. Automatic dynamic limitation.
3. Best achievement of current sharing between parallel inverters etc. However, the equations of voltage and current loops are written as follows [15]:

$$\begin{cases} e_d = (k_p + \frac{K_i}{s})(i_d^* - i_d) - \omega L i_q + V_d \\ e_q = (K_p + \frac{K_i}{s})(i_q^* - i_q) - \omega L i_d + V_q \end{cases} \quad (9)$$

$$\begin{cases} i_d = (K_p + \frac{K_i}{s})(V_d^* - V_d) - \omega C V_q + i_{Ld} \\ i_q = (K_p + \frac{K_i}{s})(V_q^* - V_q) + \omega C V_d + i_{Lq} \end{cases} \quad (10)$$

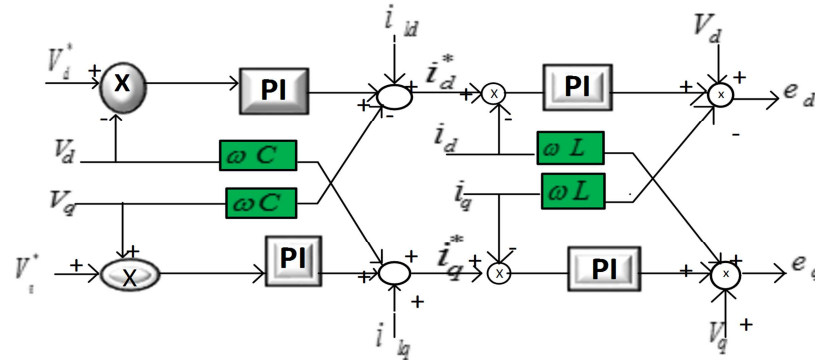


Figure 11. Diagram of voltage and current loop controller.

Table 2. Parameters.

Active power (P)	80kW	$PI_1, (K_I, K_P)$	56,138
Reactive Power (Q)	80kVar	$PI_2, (K_I, K_P)$	89,344
Nominal frequency (fn)	50 * ±0.4%	$PI_3, (K_I, K_P)$	65,0
Nominal voltage (Vn)	500 * ±5%	$PI_4, (K_I, K_P)$	107,0
Droop coefficient (Kp)	0.0003125	$PI_5, (K_I, K_P)$	0.003e-9, 0.9e-30
Droop coefficient (Kq)	2.5e-6	$PI_6, (K_I, K_P)$	0.003e-10, 1.5e-32
Filters value (L_f, R_f, C_f)	1.352mH, 0.2Ω, 75e-4F	$PI_7, PI_8, (K_I, K_P)$	44,600, 2.1, 600

3.2.1. Simulation Results

Therefore, figure 12 presents three phase voltage obtained after using filter where a filter suppressed harmonics and another parasites and V_{abc} is symmetric because of filtration principle so that it has been used during designing of voltage and current loop for adjusting proportional integral as well but the principle of designing filters has been used.

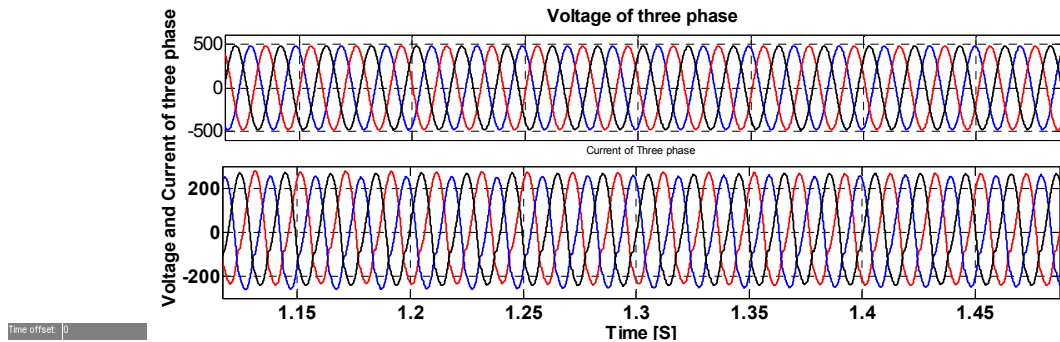


Figure 12. Three phase voltage and three phase current.

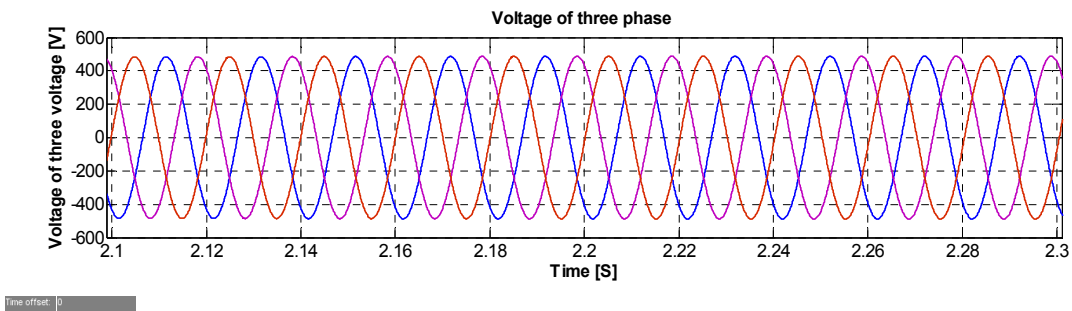


Figure 13. Three phase voltage.

Figure 13 represents voltage of three phase obtained after using filtration mechanism where a filter eliminated all harmonics and another kind of parasite. Filter has been used for making three phase voltage to be so symmetric.

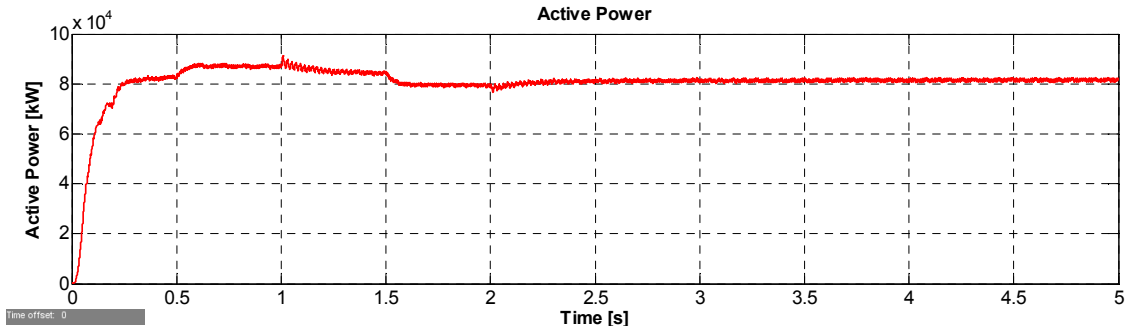


Figure 14. Reactive power produced by microturbine.

This active power produced by microturbine at 0.5s there is a load connected on network meanwhile at 1.5 s that load has been disconnected and active power decreased until it reached an initial value.

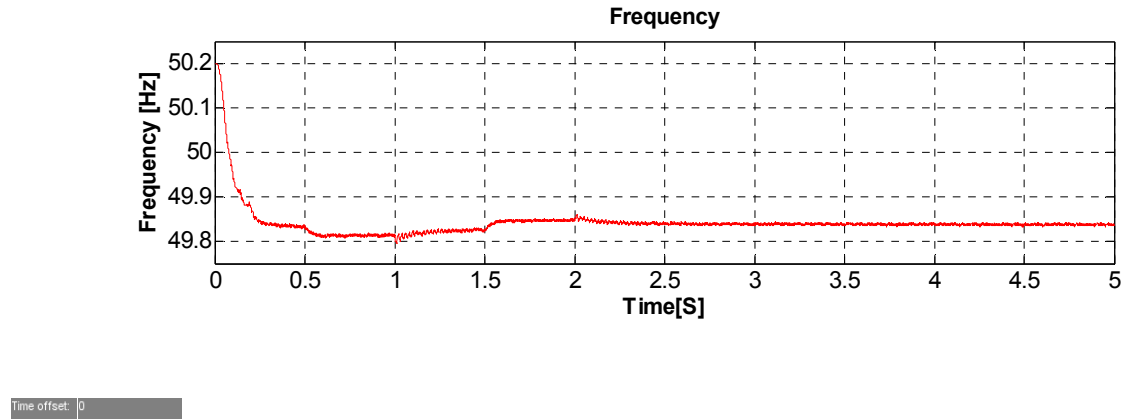


Figure 15. Frequency of network in hertz.

Schematically frequency depends on variation of active power where the changes of active power automatically affect frequency. In order to achieve the effectiveness and competitiveness of PQ controller in islanded mode the connection and disconnection of loads on network should be handled carefully for avoiding some network problems such as blackout and brownout.

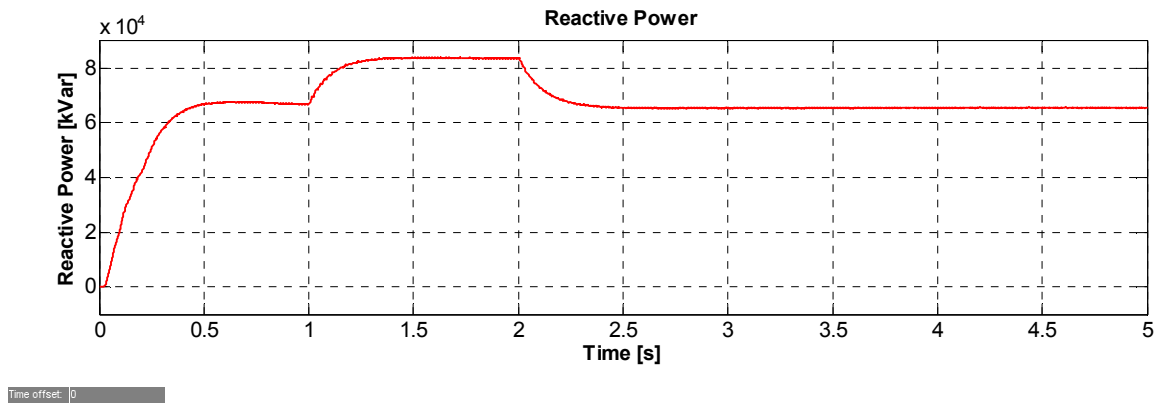


Figure 16. Reactive power from microturbine.

The reactive power increased at 1s because of a load connected whereas at 2s that load has been disconnected and reactive power decreased but in main network inducted load is connected since the starting of simulation. Therefore the variation of reactive power has been provoked some impact on voltage due to the principal of PQ controller that is the reason why figure 3 presents the constraints of voltage and frequency. So that voltage and frequency are restricted at $V_n^* \pm 5\%$ and $f_n^* \pm 0.4\%$ where they have been implementation due to the results.

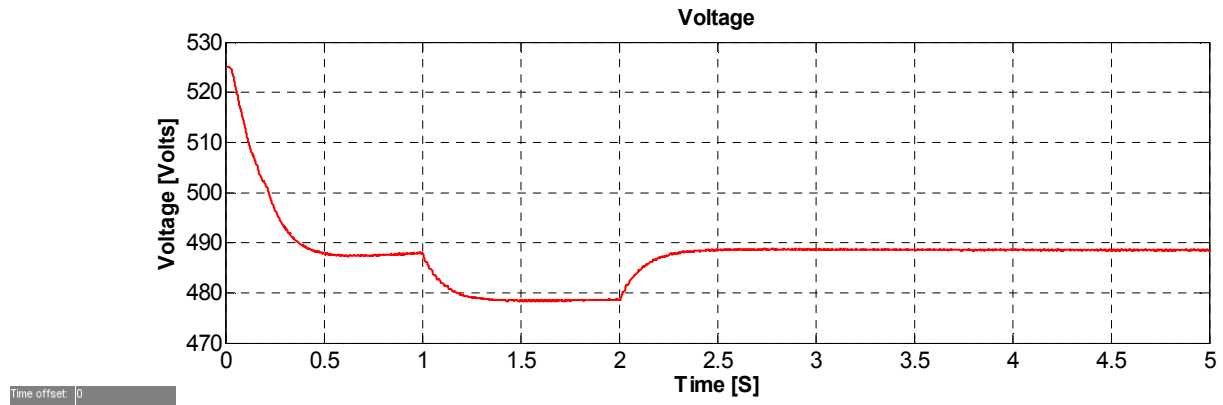


Figure 17. The Frequency of microturbine under variation load.

This voltage is depending on load here the voltage dropped too much until under the standard. Initially they were a load connected and at 1 second and disconnected at 2 seconds which it has made the voltage increases completely due to the principal of droop controller and PQ controller. As we know in islanded mode frequency and voltage are controlled by PQ controller.

3.2.2. Conclusion

In this paper, a power control strategy has been proposed for voltage source converter-based on power conversions principle. The current loop control strategies have been used and verified as the inner loop of the PQ control structure and compared together to achieve better control of the output power of the voltage source converter (VSC). The superiority of the proposed power control strategy based on adjustment of PI-controllers has been assessed in different situations of supplying the load and disconnection method. The competitiveness and effectiveness of controller-based on power control strategy in tracking the power reference values with almost zero steady-state error during the step changes at the load has been represented. Therefore, It has also been shown that the proposed power control strategy provides fast dynamics and less transient effect in the reactive and active output power than the conventional approach and has the capability of most decoupled control of the reactive and active power. The performance of the proposed control strategy in rejecting imported disturbances that happen due to uncertainties of the load parameters has also been investigated and checked with consistency. It has been showed that the PQ controller response is much better at the time instant of the load variation and having superiority operation meanwhile the reactive and active power has come back to their initial values after the disconnection of the loads and the load enters the new condition.

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