Modelling and Simulation of Microturbine in Islanded and Grid-connected Mode as Distributed Energy Resource

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***Abstract*- This paper presents modeling and simulation of microturbine (MT) to analyze its load following performance as distributed energy resource (DER) with general as well as critical priority loads. The system comprises of a synchronous generator and a MT coupled to it. Simulations are carried out in islanded and grid-connected mode of the system to observe its behavior when supplying customer's variable loads. It also incorporates modeling and simulation of microturbine with a speed control system of the MT-synchronous generator to keep the speed constant with load variation. The load following characteristics is observed and validated for this MT-synchronous generator model in Matlab-Simulink environment with power system block sets. This is applicable with combined heat power (CHP) generators both with general fuel as well as bio-fuels. The use of bio-fuels is very much promising for generating green power preventing green house gas emissions for fighting against global warming. But it may take some time to be in the market place for its commercial use.**

***Index Terms*- Microturbine, synchronous generator, recuperator, distributed energy resources, speed control**

I. Introduction

DERs have received significant attention as a means to improve the performance of the electrical power system, provide low cost energy, and increase overall energy efficiency. DERs are energy sources that are located near the load. By locating sources near the load, transmission and distribution costs are decreased and delivery problems mitigated. DER application can relieve transmission and distribution assets, reduce constraints, and improve power quality and reliability [1]. DERs are constituted by a variety of small, modular distributed generation (DG) technologies that can be combined with energy management and storage systems. **DER** devices enable renewable energies utilization and more efficient utilization of waste heat in combined heat and power (CHP) applications and lowering emissions. [2]. Recent technology improvements in various types of DERs, including microturbines, fuel cells, mini-hydro, battery storage, and so on, have created the opportunity for large-scale integration of DERs into distribution systems. Such on-site supply may be the most practical approach to address increasing power demand and power quality requirements, given the current electric utility restructuring as well as public environmental policy [3].

MTs are small and simple-cycle gas turbines. The outputs of the microturbines range typically from around 25 to 300 KW. They are part of a general evolution of in gas turbine technology. Techniques incorporated into the larger machines, to improve the performance, can be typically found in MTs as well. These include recuperation, low NOx emission technologies and the use of advanced materials, such as ceramic for the hot section parts [4][5]. Unlike traditional backup generators, MTs are designed to operate for extended periods of time and require little maintenance. They can supply a customer's base-load requirements or can be used for standby, peak shaving and cogeneration applications. In additions, the current generation MTs has the following specifications [6][7]:

- Relatively small in size, compared to other distributed resources.
- High efficiency, fuel-to-electricity conversion can reach 25%-30%. However, if the waste recovery is used, combined heat and electric power could achieve energy efficiency levels greater than 80%.
- Environmental superiority, NOx emissions lower than 7 parts per million for natural gas machines in practical operating ranges.
- Durable, designed for 11,000 hours of operation between major overhauls and a service life of at least 45,000 hours.
- Economical, system costs lower than $500 per KW, costs of electricity that are competitive with alternative including grid-connected power for market applications.
- Fuel flexibility, capable of using alternative/optional fuels including natural gas, diesel, ethanol, landfill gas and other bio-mass derived liquids and gases.

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There are essentially two types of MTs. One is high speed single shaft unit with a compressor and turbine mounted on the same shaft as an electrical synchronous machine. In this case, the turbine mainly ranges from 50,000 r.p.m. to 120,000 r.p.m. The other type of MT is split-shaft designed which uses a power turbine rotating at 3,000 r.p.m. and a conventional generator connected via a gear box [4][5].

Ref. [8] reported the development of a single stage axial flow MT for power generation. Nichols, D.K. et al. discussed the MT technology, its facilities and relevant test results [9]. Guda, S.R. demonstrated the development of a MT model and its operation with a permanent magnet synchronous generator [10]. Suter, M. reported an active filter for MT [11]. Adaptive control of fuel cell and MT is well described in [12]. Gaonkar, D.N. et al. demonstrated the development of a MT model from the dynamics of each part which is suitable for studying various operational aspects of the same [13]. Ho, J.C. et al. presented the performance of a MT system for cogeneration application [14]. Literature [15] proposed a control system for dispersed generators based on PI control and which was verified control simulations. A control system was developed for generated power control using generator data using double-loop configuration, controlling, respectively, the generated power and electric energy. Next, the proposed load-following control was verified.

There are several issues related to the operation and integration of a microturbine to a distribution system and in particular its load following characteristics is of great importance. In this paper, the operating performance of a microturbine and its load following characteristics are validated and presented as it has been simulated in islanded and grid-connected mode via a distribution system.

II. Microturbine Model

The designs of microturbines are composed of the following parts [4][5]:

(a) *Turbine*: There are two kinds of turbines, high speed single shaft turbines and split shaft turbines. All are small gas turbines.

(b) *Alternator*: In the single shaft design, an alternator is directly coupled to the single shaft turbine. The rotor is either a two or four pole permanent design, and the stator is a conventional copper wound design. In the split shaft design, a conventional induction or synchronous machine is mounted on the power turbine via gearbox.

(c) *Power electronics*: In the single shaft design, the alternator generates a very high frequency three phase signal ranging from 1500 to 4000 Hz. The high frequency voltage is first rectified and then inverted to a normal 50 or 60 Hz voltage. In the split shaft design, the power inverters are not required.

(d) *Recuperator*: The recuperator is a heat exchanger which transfers heat from the exhaust gas to the discharge air before it enters the combustor. This reduces the amount of fuel required to raise the discharge air temperature to that required by the turbine.

(e) *Control and communication*: Control and communication systems include full control of the turbine, power inverter and start-up electronics as well as instrumentation, signal conditioning, data logging, diagnostics, and user control communications.

In this work, we are mainly interested on slow dynamic performance of the system, not the fast transients that may happen, the microturbine model considered is based on the following assumptions:

(a) The recuperator is not included in this model as it is mainly used to raise the efficiency of the system.

(b) The temperature control and acceleration control have no impact on the normal operating conditions; therefore, they can be omitted in the turbine model.

(c) The micro turbine does not use any governor, so, the model is not included in the model [4][5].

For load following analysis purposes a simplified block diagram for the microturbine can be represented as shown in Fig.1.

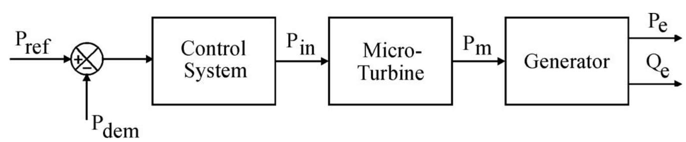

Fig. 1 Microturbine model

The real power control is described as conventional PI-control function as illustrated in Fig. 2.

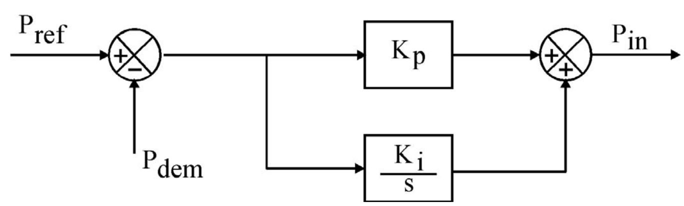

Fig. 2 Control system model

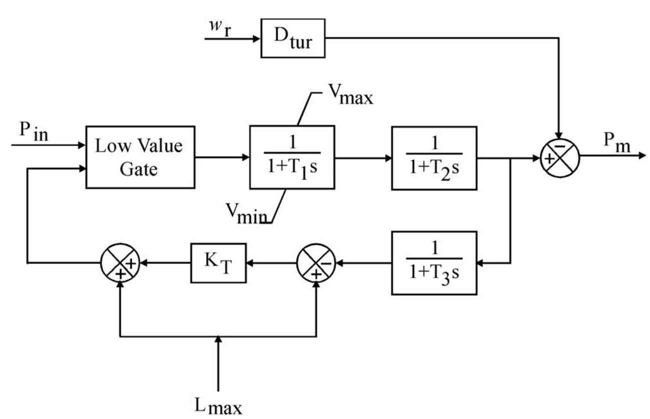

Fig. 3 Turbine model

The real power control variable P_{in} is then applied to the input of the microturbine. In control system of the microturbine, P_{dem} is the demanded power, P_{ref} is the reference power, P_{in} is the power control variable to be applied to the input of the microturbine, K_p is the proportional gain and K_i is the integral gain of the proportional-integral controller. For turbine model GAST model is used which is most commonly used dynamic models of gas turbines [4][5]. This model is simple and follows typical guidelines as shown in Fig. 3.

III. Model Description

The synchronous machine used in the simulations is based on Matlab Simulink synchronous machine block set. The parameters related to the machine are given in Table2. The distribution network is of 11 KV rating and modeled by a simple R-L equivalent source of short circuit level 500 KVA with a load of 5 KW. It has a wye-delta connected transformer with voltage ratio of 11 KV/440 V. other related parameters of the distribution system are shown in Table3. For simulations of MT-generator system in islanded and grid-connected mode which have been carried out in Matlab-Simulink environment, the system configuration has been considered as shown in Fig.4. The MT can supply its own loads without being connected with the distribution system. The Distribution system is also capable of supplying its own loads separately. The MT-generator system can be connected/disconnected to distribution system by closing/opening a circuit breaker (CB).

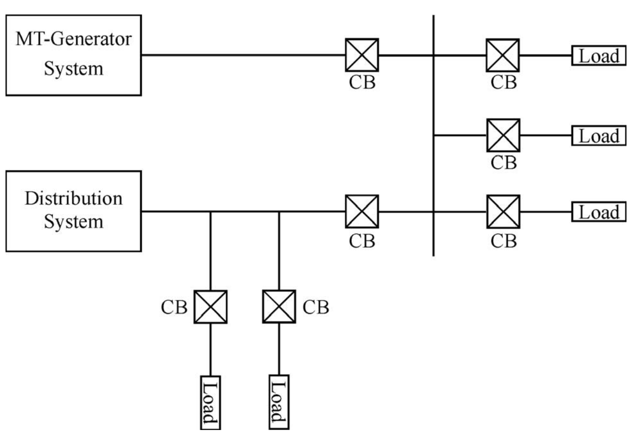

Fig. 4 System configuration block diagram

IV. Model Parameters

The parameters used for simulations of MT-generator system and distribution system are based on [5] and adopted as illustrated in Table 1, Table 2 and Table 3 respectively.

TABLE 1
MICROTURBINE PARAMETERS

Parameter	Value
Rated power, P_{rate}	150 KW
Real power reference, P_{ref}	1.0
Proportional gain, K_p	0.1
Integral gain, K_i	1.0
Damping of turbine, D_{tur}	0.03
Fuel system lag time constant 1, T_1	10.0 s
Fuel system lag time constant 2, T_2	0.1 s
Load limit time constant, T_3	3.0 s
Load limit, L_{max}	1.2
Maximum value position, V_{max}	1.2
Minimum value position, V_{min}	-0.1
Temperature control loop gain, K_T	1.0

TABLE 2
SYNCHRONOUS GENERATOR PARAMETERS

Parameter	Value
Rated power, P_{rate}	150 KW
Rated voltage, V_{rate}	440 V
Frequency, f	60 Hz
No. of poles , P	2
Damping factor, K_D	60 p.u.
Inertia constant, H	0.822 s
Internal resistance, R	0.02 p.u.
Internal reactance, X	0.3 p.u.

TABLE 3
DISTRIBUTION SYSTEM PARAMETERS

Parameter	Value
3-ph source base voltage	11 KV
3-ph source S.C. level	500 KVA
3-ph source X/R ratio	6
Dist. trans. nominal power	200 KVA
Frequency	60 Hz
Dist. trans. primary voltage	11 KV
Dist. Trans. secondary voltage	440 V

V. Simulations and Results

The simulations of MT have been performed in Matlab-Simulink environment and those are presented as follows:

A. Islanded mode:

(*i*) In this simulation, the MT is initially running with a load of 30 KW applied to the generator bus up to t=150 seconds. After that, another load of 90 KW has been applied at t=150 seconds. The power demand to the system is illustrated in Fig.5.

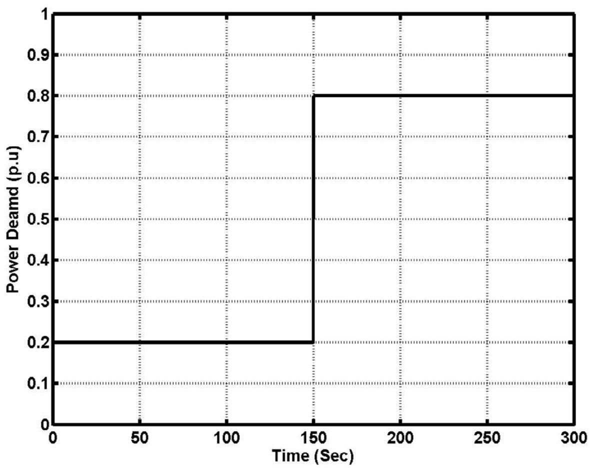

Fig. 5 Power demand to the MT

Fig.6 illustrates the mechanical output power of the MT to the input of the generator. It has been observed that mechanical output power of the MT takes a time of 80-100 seconds to reach the input power demand. The electrical power output of the generator is shown in Fig.7 and it has been found that it follows the power demand as desired. The speed of the MT-generator is represented by the Fig.8. The speed of MT-generator increases with increase in power demand takes a time of about 80-100 seconds to reach steady-state.

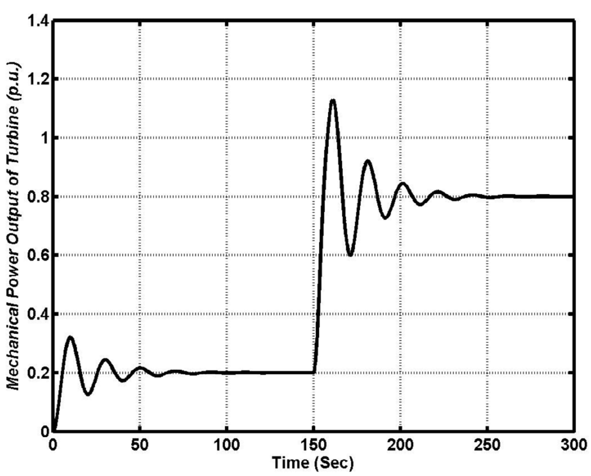

Fig. 6 Mechanical power output of MT

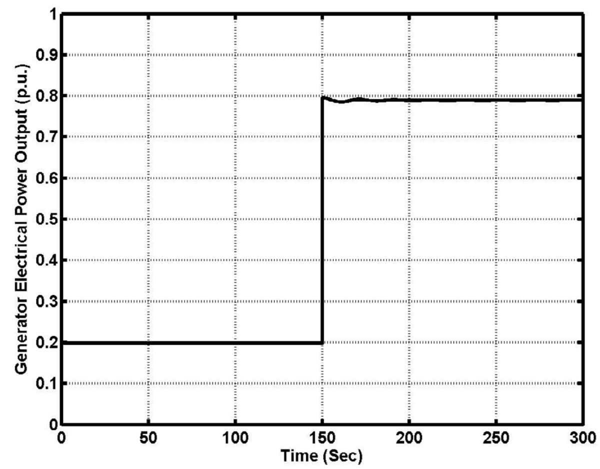

Fig. 7 Generator electrical power output

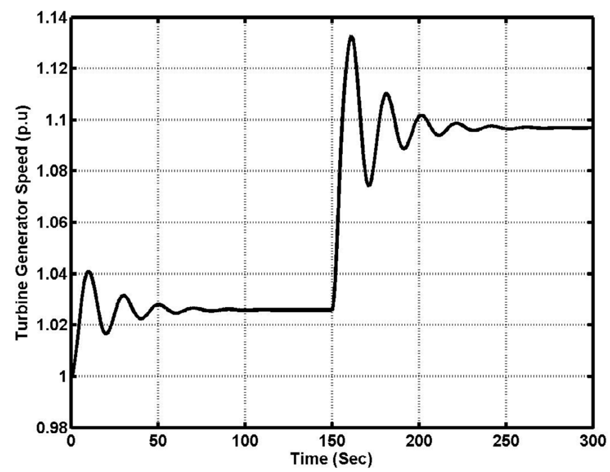

Fig. 8 MT-generator speed

(*ii*) In the next simulation, a speed control has been incorporated with the MT-generator system to maintain the speed constant at 1 p.u. The MT-generator system is running initially at no load. At time t=50 seconds a load of 0.2 p.u. is applied and at t=200 seconds another load of 0.6 p.u. is applied. The mechanical power output of the MT is shown in Fig.9 which displays that the MT follows the input power demand but with some time lag.

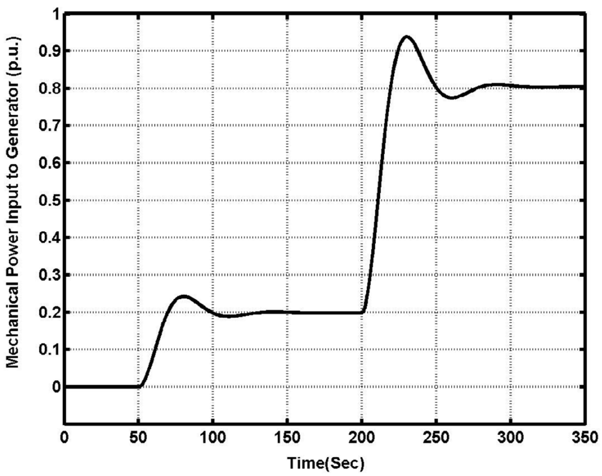

Fig. 9 MT output to generator

The electrical power measured at the generator output is illustrated in Fig.10 to show that the electrical load is initially zero, 0.2 p.u. from t=50 seconds to t=200 seconds and 0.8 p.u. from t=200 seconds to t=350 seconds.

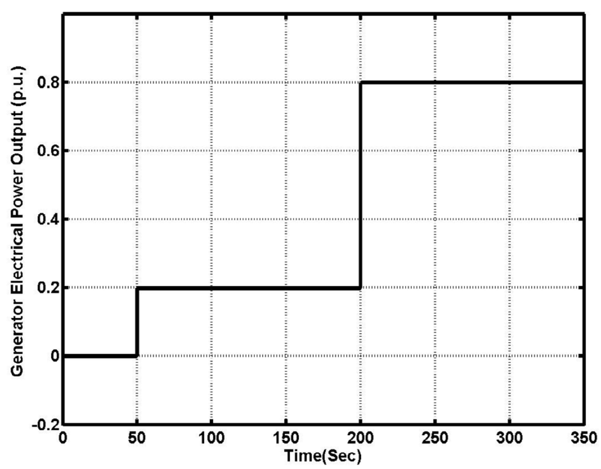

Fig. 10 Generator output

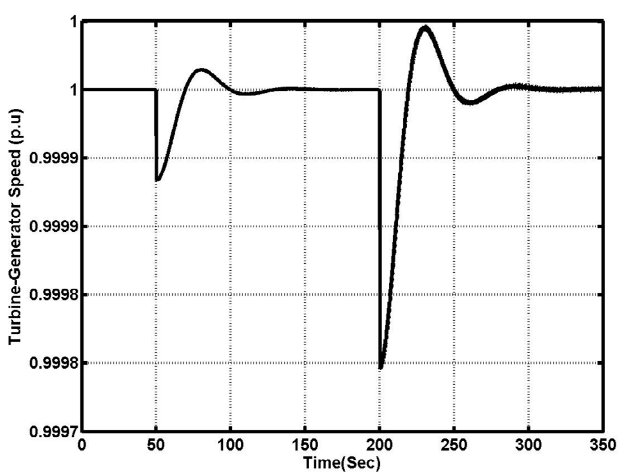

Fig. 11 MT-generator speed

The MT-generator speed is represented in Fig.11 which shows that the speed drops at the instant the load demand increases but it reaches 1 p.u. and maintained at that level as desired at steady-state.

B. Grid-connected mode:

In this simulation, the MT-generator system has been connected/disconnected to a distribution system. The MT-generator system and distribution both are running initially at no load and at time t=5 seconds, 0.2 p.u. load is applied to MT-generator system and a load of 160 KW is connected to the distribution system. The MT-generator and the distribution system are running with their own load separately. At time t=125 seconds another load of 0.6 p.u. is applied to MT-generator system. At time t=250 seconds, the MT-generator system is interconnected with the distribution system and at time t=375 seconds the MT-generator is disconnected from the distribution system. The total simulation time is 500 seconds. The mechanical power output of the MT and the electrical power output of the generator are represented in Fig.12 and Fig.13 respectively.

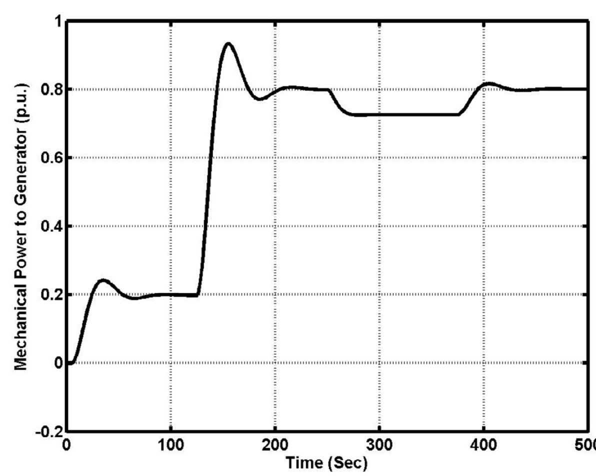

Fig. 12 MT mechanical power output

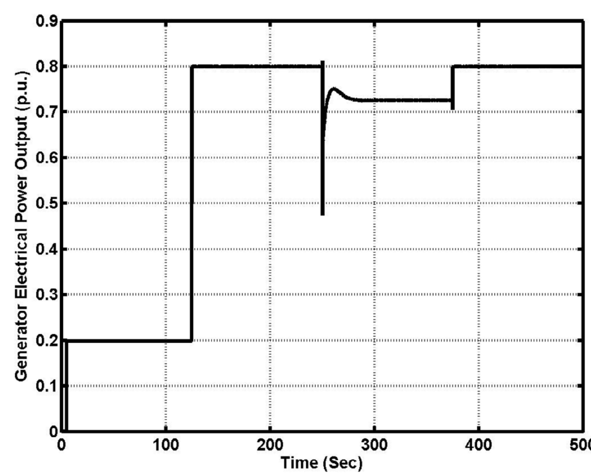

Fig. 13 Generator electrical power output

The responses of the MT and generator to the input power demand are similar to those observed in the previous simulations. Fig.14 represents the generator voltage. It shows that the voltage drops from 1 p.u. as the load on the generator is applied and increases above 1 p.u. as load is with drawn but it again reaches to 1 p.u. after a very short time.

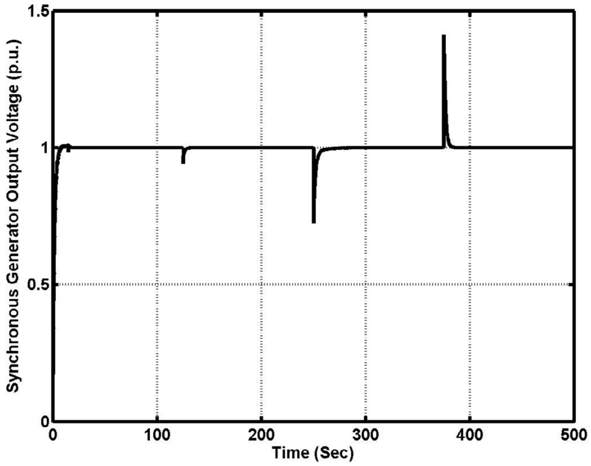

Fig. 14 Generator voltage

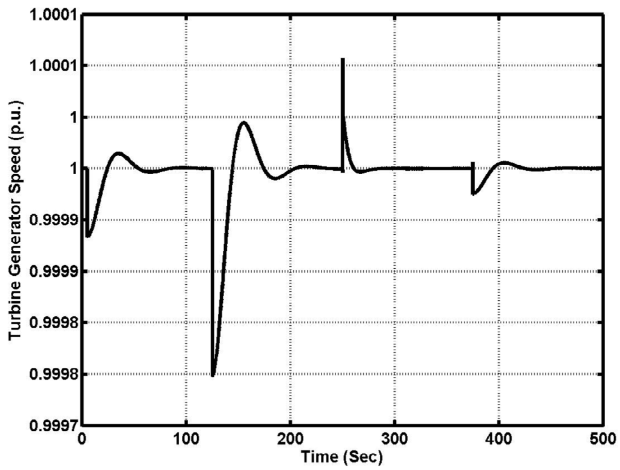

Fig. 15 MT-generator speed

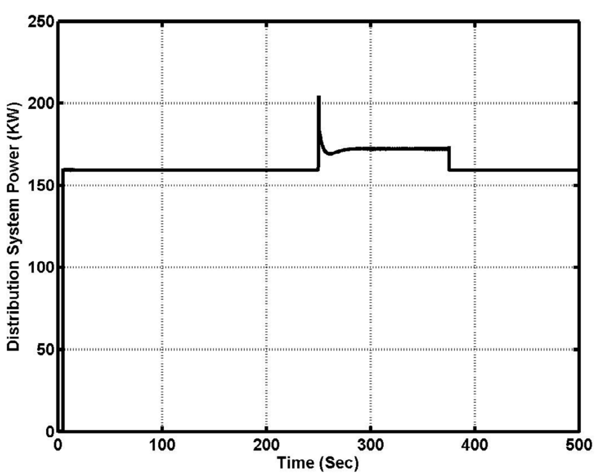

Fig. 16 Distribution system power

The variation of MT-generator speed is illustrated in Fig.15 which is also similar to that obtained with speed control in islanded mode. Fig.16 shows the variation of distribution system power which demonstrates that it is at zero up to 5 seconds; after that it maintains 160 KW up to 250 seconds. As it has been connected to the MT-generator system at t=250 seconds, it shares a load of about 12 KW from the other system which is also evident from the electrical power output of the generator. The shared load is again transferred to MT-generator system as it is disconnected at t=375 seconds.

VI. Conclusion

Modelling and simulation of microturbine are performed for its operation both in islanded mode and grid-connected mode. Its load following performance as distributed energy resource with priority loads has been thoroughly tested and validated. Simulation has also been performed with a speed control system incorporated to the MT-synchronous generator to keep the speed constant for varying load. The load following characteristics observed from the simulation studies carried out in Matlab-Simulink environment are analyzed and presented in this paper. It has been observed that the MT can be used both in islanded and grid-connected mode as a distributed energy resource to supply customer load demands as and when required. Since microturbines are mainly used for CHP systems with very high energy efficiency, its use is highly appealing with regard to distributed generators using both with general fuels and bio-fuels. Once the world wide uproar of anti-islanding and islanding protections are sorted out to implement successful implementation of microgrids, this model will be highly applicable for its online implementation in microgrid.

VII. References

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