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Full Length Research Paper

Viability Analysis of Ubungo II Gas Power Plant Efficiency Improvement Using Co-generation System

Elias E. Nyanda[1,2], Aviti T. Mushi[2*] and Jackson J. Justo[2]

[1]Ubungo II Gas Power Plant, Tanzania Electric Supply Company, Dar es Salaam
[2]Department of Electrical Engineering, College of Engineering and Technology, University of Dar es Salaam
ORCID: https://orcid.org/0000-0002-2958-2919
https://orcid.org/0000-0003-0638-0713
[*]Corresponding Author: aviti.thadei@udsm.ac.tz or aviti.bahati@gmail.com

ABSTRACT

The power utility, Tanzania Electric Supply Company Limited (TANESCO) is faced with challenges of supplying adequate power to the ever-increasing demand. To this end, this paper explores the installed Ubungo Gas Power Plant (UGP II) located in Dar es Salaam to find means of utilizing it in co-generation method. The study embarked on detailed modelling of the system and run simulations which indicated that the co-generation can result to power generation efficiency increase between 10.42 to 50.92%. It is recommended to change the UGP II to exploit this co-generation method. Further, the study could be improved by including more parameters of the gas and steam plant and verify them experimentally.

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INTRODUCTION

Utility power systems have increased deployment of co-generation plants for fulfilling electricity demand, in the ever-increasing electric power consumers. Cogeneration power plant system is capable of producing heat and electricity simultaneously in a single plant, such as gas fired power plant (Enel X, 2022). This achieves better energy yield powered by just one primary energy source, thereby guaranteeing a better energy yield that is much more possible to achieve using two separate production sources and processes. This process is achieved with the help of turbine control system. Simple gas turbine control system is composed of the turbine, axial compressor and combustion chamber. The axial compressor compresses air which goes through the combustor and blazes with fuel gas yielding to high pressure exhaust gas at high temperature. This exhaust gas expands through the turbine and steam generator, and after use in co-generation applications, it is forced back to the atmosphere (Aljundi, 2009). This type of cogeneration is deployed by Tanzania Electric Supply Company Limited (TANESCO), a Tanzanian utility company responsible for all generation (TANESCO, 2022a), transmission (TANESCO, 2022b) and distribution (TANESCO, 2022c) of electricity within Tanzania.
TANESCO generates power mainly from hydro and thermal power plants, and some other sources. Thermal power plants contribute 60.27% total installed capacity while hydro plants contribute 33.91%,

biomass 0.62% and diesel contribute 5.20%. Hydro power plants are interconnected with national grid system with capacity totaling to 561.843 MW. During the year 2018 the total units fed to the national grid and those on isolated thermal power plants amounted to 5,759 GWh. The TANESCO using its own generators produced 3,110 GWh while the imports from independent power producers (IPPs) were 2,649 GWh. It is not a secret that these generation capacity does not meet all the power requirements of Tanzania, therefore as of recent years, TANESCO has managed to engage generation mix program combining thermal and hydro power. In the thermal arena, TANESCO exploits natural gas and diesel generation in her own power plants. Some other IPPs chip in with diesel, thus powering the nation. However, the installed capacity of power supplied by TANESCO and these IPPs is not enough to cater for the existing demand, therefore, this paper undertakes to investigate the viability of using co-generation as a possible solution to increase energy output of TANESCO thermal power plants.

One of TANESCO's thermal power plant is Ubungo Gas Power Plant II (UGPII) located in Dar es Salaam, which deploys a simple cycle power generation facility. This UGPII comprises of three industrial gas turbine driven generators each rated 43 MW. The model of these gas turbines is SGT800 manufactured by Siemens industrial turbo machinery of Sweden (Siemens, 2022). Installed capacity of the power plant is 129 MW minimum plus maximum tolerance of up to +5%. The power plant was commissioned on 01st July 2012 and uses natural gas from Mtwara region specifically Madimba area supplied by TPDC (TANESCO, 2022d). This power plant is built for base load operation and forms part of the TANESCO base generation pool. It has a black start facility unit. It is synchronized to the national grid through 132 kV power transformers.

Operation of UGPII is facing a problem of low plant efficiency and wastage of large amount of natural gas at the hot water boiler due to un-availability of co-generation system. The power plant is also facing a challenge of low power generation due to un-availability of the fogging system at the air intake filter system. Therefore, this paper undertakes to address these problems by proposing the co-generation and fogging system for the UGPII.

METHODS AND MATERIALS

System description

Co-generation system incorporates two thermodynamic cycles which are Rankine and Brayton cycles. The co-generation system is responsible for converting and pressurizing water into superheated steam utilizing the sensible heat of the turbine exhaust gas (Canière et al., 2006). The co-generation system has the following components: economizers, evaporators, superheaters and steam drum superheaters. Evaporator boils steam. Water temperature is increased to an approximate temperature near the saturation temperature by economizer (Casolino et al., 2015). In the gas flow pathway within the co-generation system, these modules are arranged in a sequence order. The heat transfer co-generation system modules are not in parallel with one another with respect to simple cycle combustion turbine exhaust gas flow. Co-generation system circuit components are interspersed within the setting to improve or optimize the co-generation system thermal conversion performance (Saad & Cheng, 1997). Configuration of three-pressure level co-generation system is given in Figure 1 (Das, 2006). It incorporates low, medium and high drums. Heat exchangers are divided into smaller banks to enhance exploitation of available energy in the gas turbine exhausts.

General physical structure of a gas turbine unit

The primary input parameters to the simple cycle gas turbine system are natural fuel gas and air flow (see Figure 2). Electrical energy generated, pressure ratio across the compressor and exhaust temperature are fundamental output variables of the simple cycle gas turbine system. In order to attain the required output power, fuel and air flows are revamped. Maintaining high exhaust temperature means considering into account the maximum permissible turbine inlet temperature (de Sa & al Zubaidy, 2011).

Gas turbine control system

Two main closed control loops are speed-load and exhaust temperature control (Figure 3). During operation of the gas turbine, these control loops are always in operation (Basrawi et al., 2011).

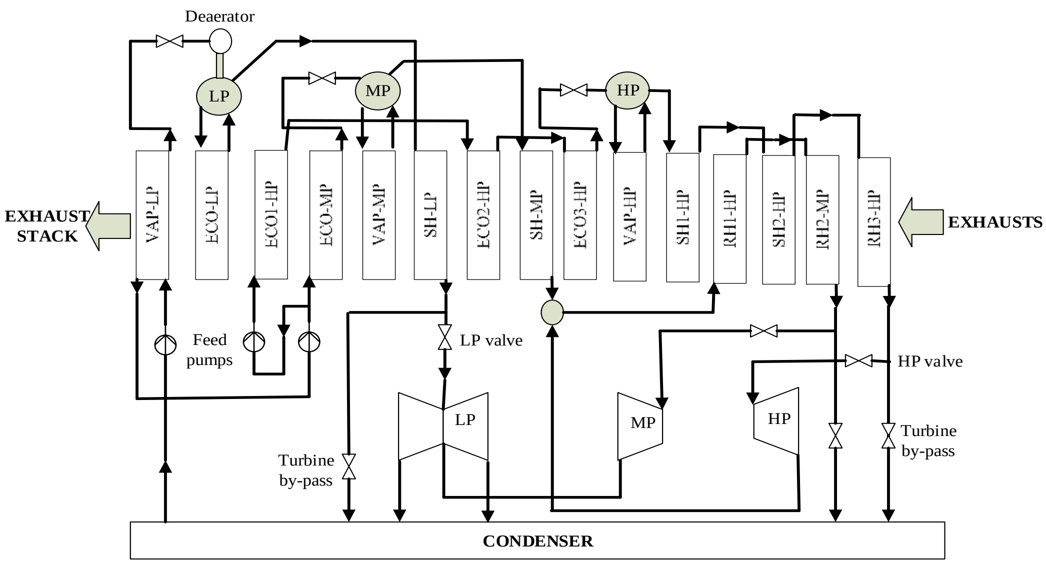

Figure 1: Scheme of co-generation system (Das, 2006)

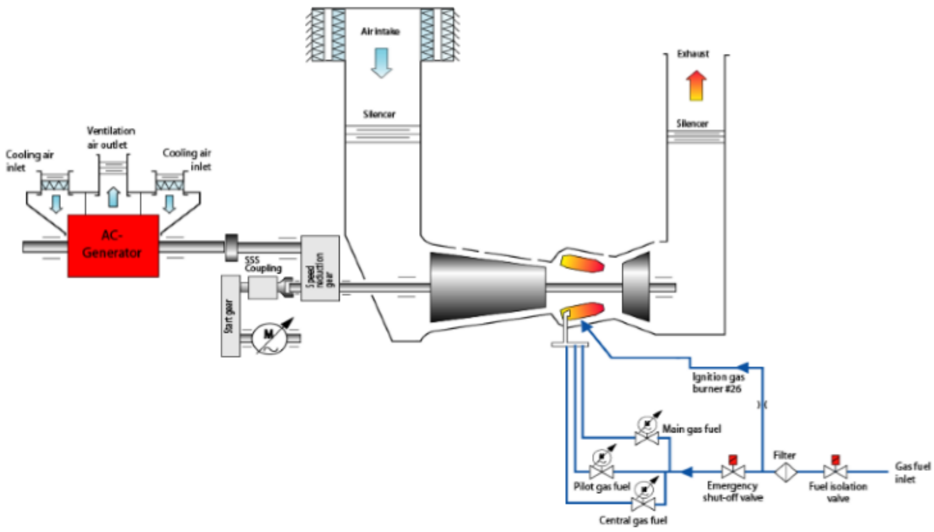

Figure 2: Simple cycle gas turbine system (de Sa & al Zubaidy, 2011)

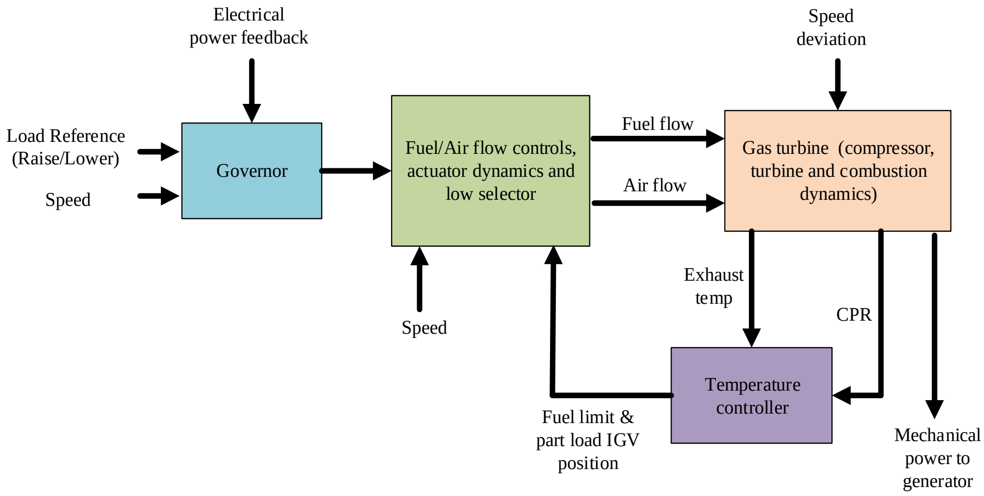

Figure 3: Simple cycle gas turbine control system (Basrawi et al., 2011)

Temperature controller

Temperature controller limits fuel flow to the gas turbine thus limiting the temperature of the exhaust gas at 1200°C. The air flow decreases with the speed of the turbine shaft which results to maintaining the shaft speed at the required setpoint (Ganapathy, 1994).

Air flow control

In co-generation system, flue temperature is maintained at permissible limits. This is attainable by closing inlet guide vanes (IGV) under specific control. When IGV control is active and the demand of flue gas flow rises, the IGV opens proportionally in order to avoid violation of temperature limit (Horlock, 2003).

Flue flow control

The turbine operates at maximum temperature when IGVs are fully open. The flue gas flow is limited in order to avoid offending the internal maximum allowable range of the machine. This process is attained by natural gas flow controller of the temperature control system (Ibrahim & Rahman, 2012).

Natural gas control

This system comprises of control valves, combustor chamber and volume of the expansion path. Once combustion reaction occurs, there is time delay to transmit gas from combustion chamber through turbine system. Simple time constant can be used to model continuous displacement of airflow through the compressor (Kaushik, 2004).

Co-generation system

The main purpose of the co-generation system is to convert pressurized water into superheated steam utilizing the sensible heat of the turbine exhaust gas (Kazarinov et al., 2017). This system is depicted by Figure 4. The following are some of advantages of application for the co-generation system:

a) Recovering the exhaust waste heat from gas turbine, that would have otherwise been expelled.
b) Helps to improve overall plant efficiency.
c) Reduces nitrogen (NOx) emissions since it is equipped with selective catalytic reduction (SCR) system thus providing environmental benefits.

Combined cycle power plant load control loop

The power output of the combined cycle plant responds accordingly with the reference when load control loop functions. Power blocks are assigned to every block in combined cycle gas turbine (CCGT). Steam turbine is part of the follower regardless of the amount of steam produced (Mehta & Mehta, 2008).

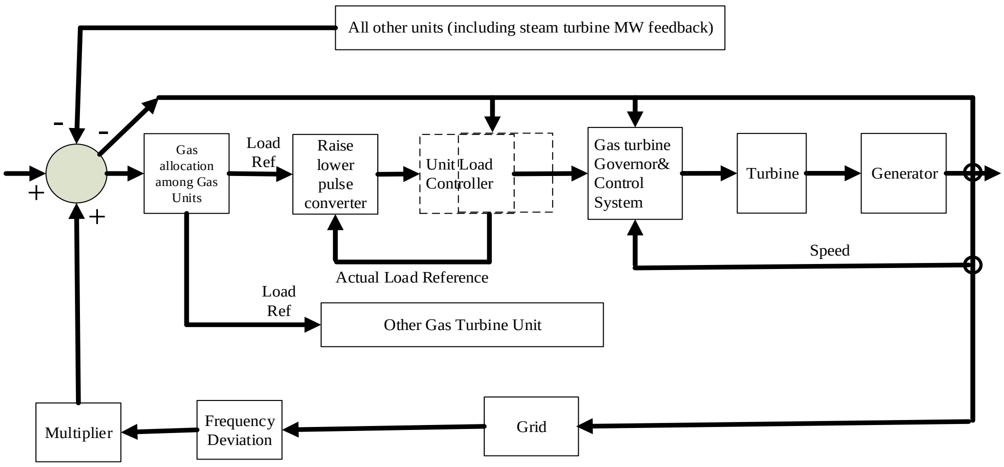

Figure 4: Co-generation fundamental load control loop (Mehta & Mehta, 2008)

The PID controller

The PID is a generic feedback control system which functions on the basis of difference between values of a measured process variable and a desired set point (Reddya et al., 2011). The PID algorithm is described in the Equation (1).

$$u(t) = K\left[e(t) + \frac{1}{T_t}\int_0^t e(\tau)d(\tau) + T_d\frac{de(t)}{dt} \right] \quad (1)$$

$$u(t) = r(t) - y(t)$$

where r is the reference variable, u is the control signal, e is the control error, K is the proportional controller gain, T_t is the integral controller time constant, t and τ are continuous time variables, and T_d is the derivative controller time constant. See Figure 5 for how this system is interconnected to control the process such as temperature of a gas turbine.

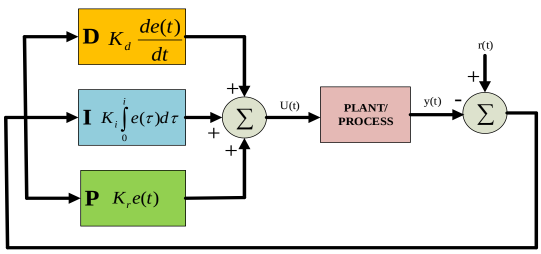

Figure 5: Block diagram of PID controller (Reddya et al., 2011)

Simple cycle gas turbine system description

The gas turbine drives the generator which transforms the mechanical shaft power to electrical power. The gas turbine shaft is connected to the generator via a speed reduction gear which reduces the 6600 rpm of the turbine shaft down to a generator speed of 1500 rpm. The gas turbine is started by an electrical starter motor.

Main components of the conventional gas turbine system

The gas turbine is composed of three main sections which are axial compressor, combustion chamber and turbine (Figure 6). The compressor compresses the intake air. The hot gases are expanded through the turbine, which drives the compressor and the generator. The gases are exhausted through the exhaust diffuser.

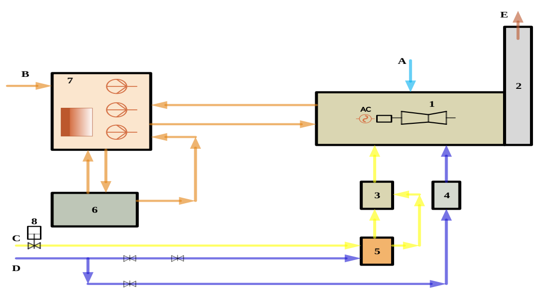

Figure 6: Simple Cycle Gas Turbine System Block Diagram (Sabouhi et al., 2016)

In Figure 6, the numbers/letters are

explained as follows: 1 – gas turbine, 2 – exhaust gas stack, 3 – fuel gas pressure control unit, 4 – instrument air unit, 5 – flue gas filtering unit, 6 – lubricating oil cooler, 7 – lubricating oil tank and pumps, 8 – emergency shut-down valve, A – intake air via filters, B – lubricating oil from common oil tank, C – flue gas from common flue gas system, and D – instrument air from compressor unit.

General system description of CCGT

Sensible heat from the CCGT exhaust gas stream is released by the co-generation system (Figure 7). The heat transfer surfaces within the co-generation system change the heat into usable steam. Power augmentation of the combustion turbine produces useful steam in three separate pressure levels of the combustion turbine (Sivanagaraju, 2010). This paper suggests that implementation of this co-generation system will result to improved gas plant efficiency.

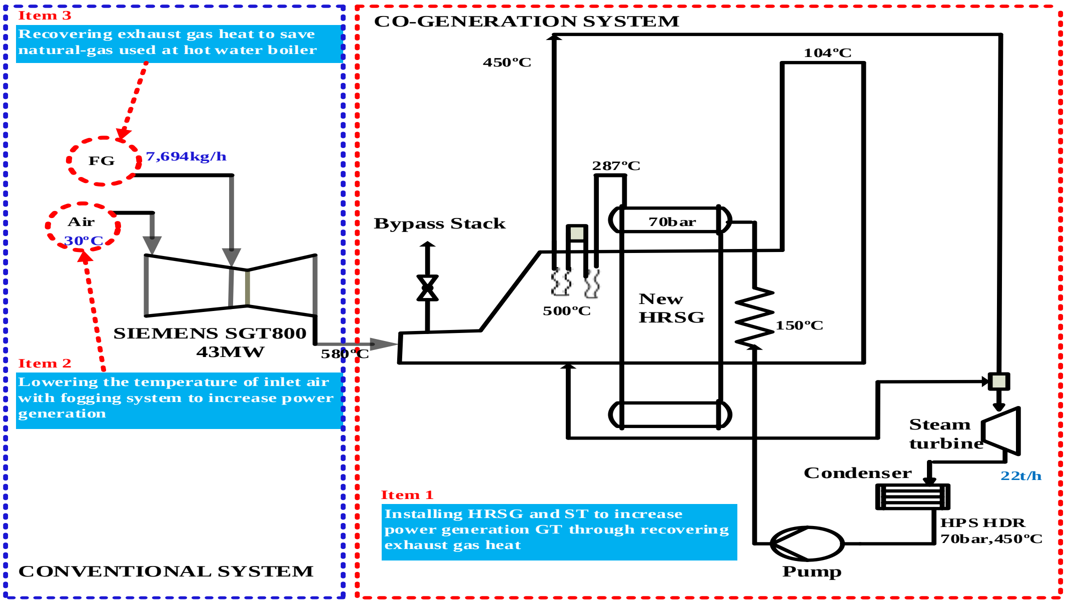

Figure 7: Combined cycle gas turbine system block diagram (Sivanagaraju, 2010)

Determination of system efficiency of simple CCGT

The CCGT efficiency can be calculated by Equation (2),

$$\eta = \frac{(T_3 - T_4) - (T_2 - T_1)}{T_3 - T_2} \qquad (2)$$

where η is the CCGT plant efficiency, T_1 is the inlet ambient air temperature of the compressor, T_2 is the outlet temperature of the compressor, T_3 is the inlet temperature of the combustion chamber, T_4 is the outlet temperature of the combustion chamber.

Heat balance equations of steam and gas in co-generation system

Energy balance of steam and gas in combined co-generation system cycle should be sufficient to generate the pressure and steam as shown in the Equations (3) – (5).

$$m_s(h_1 - h_4) = m_{eg} c_{peg}(T_d - T_a) \qquad (3)$$

$$m_s(h_5 - h_4) = m_{eg} c_{peg}(T_x - T_a) \qquad (4)$$

The m_s is the steam mass flow rate, h_1 is the compressor inlet specific stagnation enthalpy, h_4 is the combustion chamber outlet specific stagnation enthalpy, m_{eg} is the exhaust gas mass flow rate, and c_{peg} is the specific heat of exhaust gas at constant pressure. The T_d, T_a, and T_x are exhaust gas temperature of gas turbine outlet, exhaust gas cooling temperature, and exhaust gas temperature respectively. In these equations, heat rejected Q_{eg} by exhaust gas is given by Equation (5), also Figure 8.

$$Q_{eg} = m_{eg} c_{eg} (T_d - T_a) \tag{5}$$

System configuration and requirements of gas turbine energy balance

The energy balance needs all energy flowing in and out of the control volume to be accounted for, shown by Figure 8.

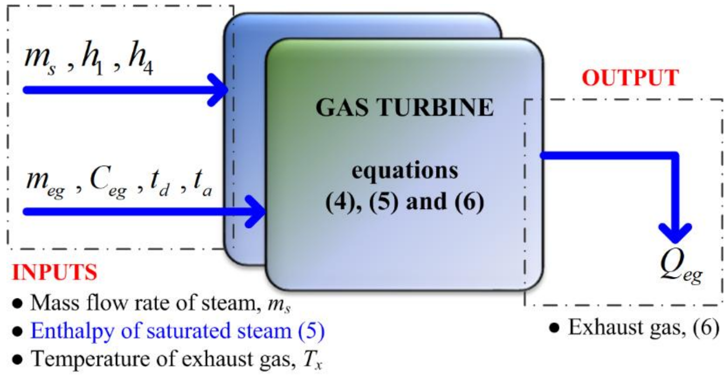

Figure 8: System Configuration of gas turbine energy balance (Undril & Garmendia, 2009)

Mathematical modelling of combined cycle system components

Capacity of the various components of the co-generation system are designed and calculated as described in the following explanations.

Economizer heat capacity Q is obtained from Equation (7),

$$Q = mc\Delta t \tag{7}$$

and depicted by Figure 9. Where mass flow rate of the fluid is m, specific heat of water is c, and temperature difference is Δt.

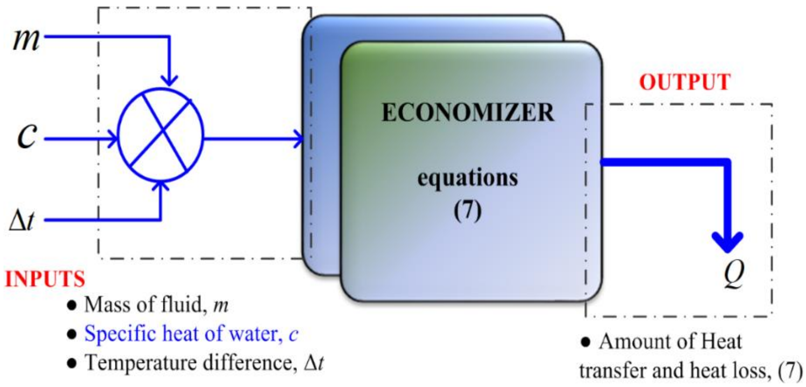

Figure 9: System configuration of economizer (Wadhwa, 2017)

Air pre-heater design calculations are based on the ASME design code. Therefore, the boiler efficiency with air pre-heater, η_{ba} can be calculated according to Equation (9).

$$\eta_{ba} = \frac{m_s (H_s - H_W)}{M_F C_V} \times 100\% \qquad (9)$$

The steam enthalpy is H_s, water enthalpy is H_w, rate of fuel used is M_F, and gross calorific value of fuel is C_V.

Boiler efficiency, and boiler efficiency with economizer are both computed using Equations (9) – (10).

$$H_w = H_f + xH_{fg} \qquad (10)$$

Further calculations of efficiencies of evaporator (see Figure 10), superheater, HRSG capacity, output power of steam turbine, and co-generation system efficiencies are easily obtained from literature, e.g., (Gülen, 2019; Reddya et al., 2011; Wadhwa, 2017), thus readers are advised to seek them for further clarifications.

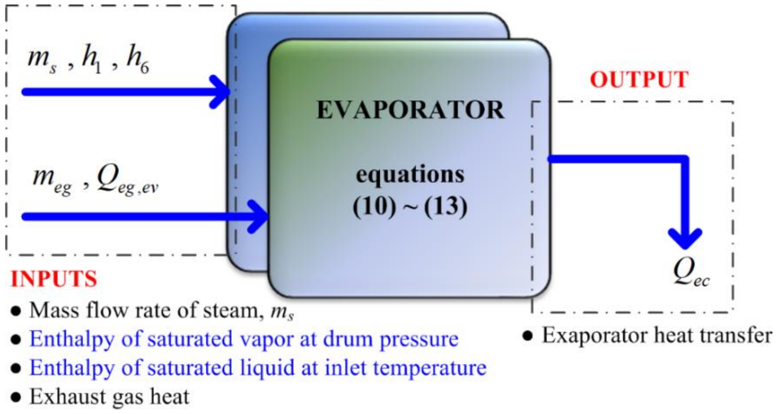

Figure 10: System Configuration of Evaporator (Wadhwa, 2017)

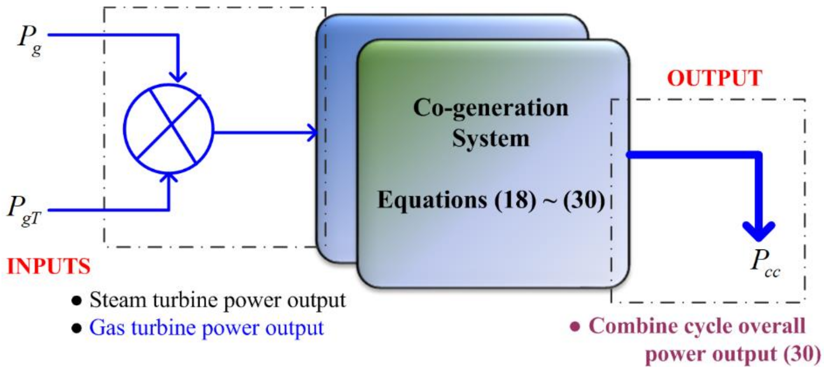

Figure 11: System configuration of co-generation system (Yilmaz, 2006)

SIMULATIONS

This chapter describes the results and findings of all calculations made in fulfillment of the problem under study.

Simulation setup of simple cycle gas turbine system

Running the derived model in MATLAB software for computing plant efficiency for conventional system by using the input parameters such as compressor inlet ambient air temperature, compressor outlet temperature, inlet temperature of the combustion chamber and outlet temperature of the combustion chamber. Results show that, plant efficiency for the conventional system is 30% and output power of the gas turbine is 43 MW as shown in Figure 12.

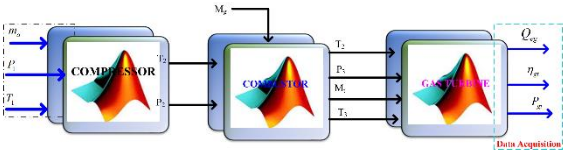

Figure 12: Simulation setup for simple cycle gas turbine system

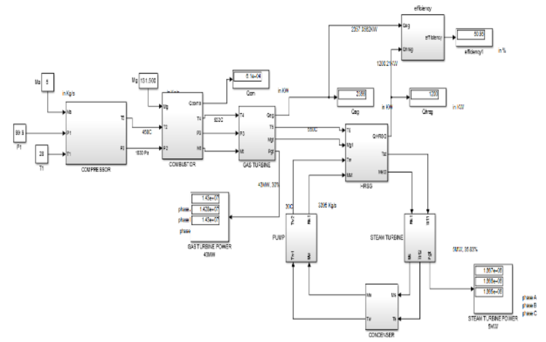

Fig 13: MATLAB Simulation setup for combined cycle system

Simulation setup of simple cycle gas turbine system

Running the derived model in MATLAB software for computing plant efficiency for the proposed system by using two main input parameters such as co-generation system capacity and heat rejected by exhaust gas. Results show that, the plant efficiency for the proposed system is 50.92% and output power of co-generation system is 48 MW as shown in Figure 13.

Comparison between simple cycle and combined cycle system

In CCGT, IGV of a gas turbine can be put closed longer during loading and unloading in order to restrict air flow through the turbine hence increasing turbine exhaust temperature for the same fuel flow rate.

RESULTS

Case 1: Plant efficiency with and without co-generation system

Figure 14 gives a variation of plant efficiency with and without co-generation system. It is observed that, plant efficiency with co-generation system is higher than plant efficiency without co-generation system. The percentage increase of plant efficiency with and without co-generation system is 20.92%.

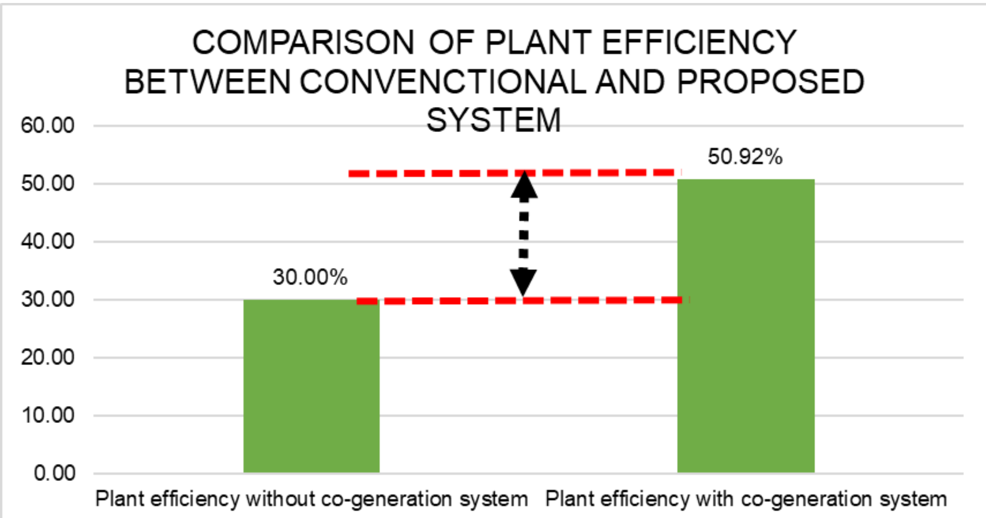

Figure 14: Plant efficiency with and without co-generation system

Case 2: Output power with and without co-generation system

Figure 15 gives a variation of output power without co-generation system and with co-generation system. It is observed that, output power with co-generation system is higher than without co-generation system. The percentage increase of the output power with and without co-generation system is 10.42%.

Case 3: Rate of inlet temperature with gas turbine heat supplied

Figure 16 shows the variation of inlet temperatures with heat supplied in gas turbine. Temperature increase is more in Brayton cycle compared to Rankine cycle. As heat supplied in gas turbine the inlet temperature increases as steam turbine inlet temperature increases. At a particular point of heat supplied it was found that the inlet temperature of gas turbine is greater than inlet temperature of steam turbine.

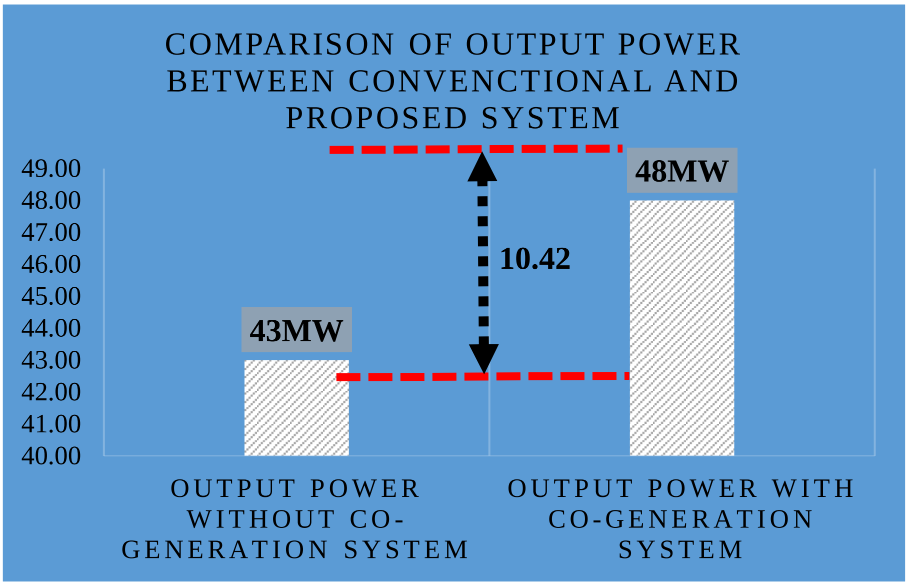

Figure 15: Output power with and without co-generation system

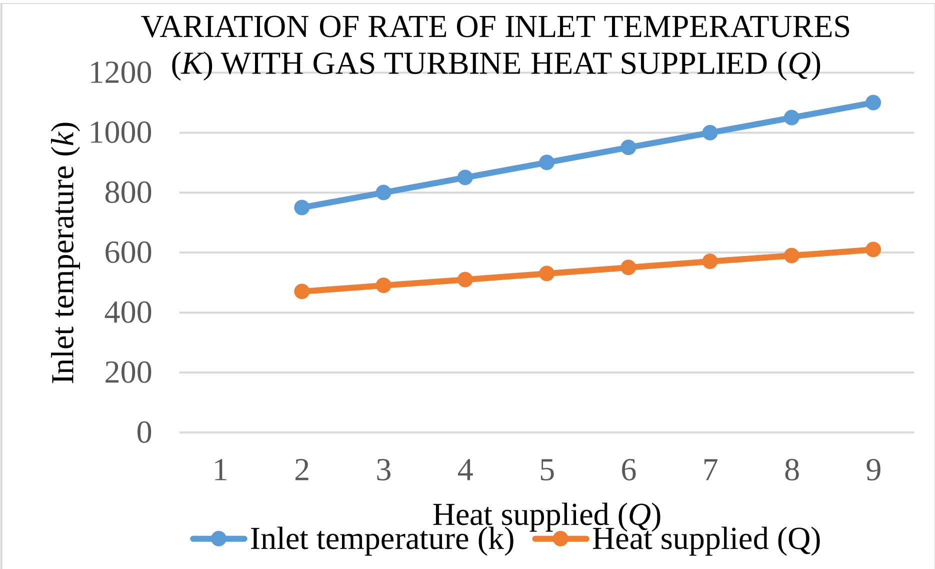

Figure 16: Rate of inlet temperature with gas turbine heat supplied

Case 3: Rate of inlet temperature with gas turbine heat supplied

Fig 16 shows the variation of inlet temperatures with heat supplied in gas turbine. Temperature increase is more in Brayton cycle compared to Rankine cycle. As heat supplied in gas turbine the inlet temperature of it increases and as well as steam turbine inlet temperature increases. At a particular point of heat supplied it was found that the inlet temperature of gas turbine is more than inlet temperature of steam turbine.

SIGNIFICANCE OF THIS PAPER

In summary, the study of improvement at UGPII improves performance of national grid since the power generation will increase and there will be reliable power supply to customers. If this study will be successful and implemented, both customers and utility will be benefit as follows:

a) Reliability and continuity of power supply to customers will be ensured.
b) Stability and smooth operations of the system will be ensured.
c) Saving of natural gas in which TANESCO is incurring high cost (5.2564 USD/mmBTU) to purchase natural gas from Tanzania Petroleum Development Corporation (TPDC).
d) Reduction in the company's expenditure since the power generation will be high.

CONCLUSION AND RECOMMENDATIONS

Co-generation is considered as one of the very important and favourable energy efficient approach for producing electrical power and useful thermal energy from a single fuel natural gas source. This research presents the improved plant efficiency of an open cycle 43 MW industrial gas turbine at UGPII using co-generation system. It necessitates modernizing a steam bottoming power plant to the simple cycle power plant by using a co-generation system. The focus is to improve plant efficiency and natural gas saving as well as minimizing the total exhaust gas emission to the environments. Different data collection was taken from human machine interface, log books, manufacturer's manual and monitoring screen. Different variables of the steam turbine system were fixed by using the application of Simulink software. The results show that, the combined cycle power plant system had a total power output of 48 MW, made up of 43 MW from the simple cycle gas turbine power plant and 5 MW (increase of 10.42%) from the steam turbine. The condenser cooling water parameters contain a mass flow of 1,180.42 kg/s, inlet and outlet temperatures of 29.8˚C and 35.8˚C respectively. The system efficiency of the co-generation system is 50.92% against the previous 30% of the simple cycle system. To this end, the following are some of the recommendations:

a) To increase the overall efficiency of UGPII from the current efficiency of 30% to 50.92%, by installation of two heat recovery system generators and one steam turbine at current two gas turbines exhaust gas systems (GT1 and GT2).
b) Installation of the fogging system in the gas turbine air intake system is recommended since it will decrease the inlet air temperature and increase the power generation.
c) To save the large amount of natural gas which is being wasted at the hot water boiler, the installation of co-generation system is recommended.

d) To reduce in total emission of the flue gas to the environments, installation of steam turbines is recommended.

Future plans for this study involve detailed analysis of all the co-generation systems and using them as inputs to the simulation and an experimental implementation.

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