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Dynamic Analysis of the West Tripoli Gas Turbine Power Plant Using MATLAB Simulation

"التحليل الديناميكي لمحطة توليد الكهرباء الغازية غرب طرابلس باستخدام محاكاة MATLAB"

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Abstract

This research paper presents an analytical study of the performance of the West Tripoli Gas Power Plant, focusing on the dynamic behavior of the gas turbine. A simulation model was developed using MATLAB/Simulink to analyze the plant's response under various operating conditions, including fault scenarios. Additionally, the study incorporates the analysis of nonlinear equations governing the synchronous machine, which play a crucial role in understanding its dynamic interactions within the power system. The obtained results provide insights into the impact of faults on plant performance, contributing to the development of improved operational and maintenance strategies to enhance efficiency and stability under different operational scenarios.

الملخص:

تقدم هذه الورقة البحثية دراسة تحليلية لأداء محطة التوليد الغازية في غرب طرابلس، مع التركيز على السلوك الديناميكي للتوربين الغازي. تم تطوير نموذج محاكاة باستخدام (MATLAB/SIMULINK) لتحليل استجابة المحطة تحت ظروف تشغيل مختلفة، بما في ذلك سيناريوهات الأعطال. بالإضافة إلى ذلك، تتناول الدراسة تحليل المعادلات غير الخطية التي تحكم سلوك الآلة المتزامنة، والتي تلعب دورًا محوريًا في فهم تفاعلاتها الديناميكية داخل نظام الطاقة. توفر النتائج المستخرجة رؤى حول تأثير الأعطال على أداء المحطة، مما يساهم في تطوير استراتيجيات تشغيل وصيانة محسنة لتعزيز الكفاءة والاستقرار في ظل سيناريوهات التشغيل المختلفة.

Introduction

Gas turbine power plants play a pivotal role in modern energy generation, providing a significant portion of electricity across the globe. These plants utilize the principles of thermodynamics to convert fuel into mechanical energy, which is subsequently transformed into electrical energy. With the increasing demand for sustainable and efficient energy solutions, understanding the dynamics of gas turbine operations has never been more critical.[1]

Simulation has emerged as a powerful tool in the field of engineering, allowing for the analysis and optimization of complex systems without the need for extensive physical experimentation. Particularly in the context of gas turbines, simulation can provide insights into performance under various operational conditions, identify potential issues before they arise, and enhance overall efficiency. MATLAB, an idely used programming environment in engineering, offers robust capabilities for modeling and simulating gas turbine systems. [2-3]

This paper will explore how MATLAB simulations can enhance our understanding of gas turbine power plant dynamics, examining the fundamental principles of gas turbine operation, the specific techniques employed in MATLAB, and real-world applications that demonstrate the effectiveness of simulation in optimizing power plant performance. By delving into these aspects, the essay aims to underscore the importance of simulation as a vital tool in the ongoing advancement of gas turbine technology.

The South Tripoli Gas Turbine Power Plant:

Libya possesses numerous power generation plants, including steam and gas stations, all operating within a unified electrical grid to supply electricity to all regions of Libya: the west, east, and south. Among these plants are the South Tripoli Gas Turbine Power Plants, which consist of eight units. These are divided into three small units with an actual capacity of 50 MW each, and five large units with an actual capacity of 96 MW, reaching up to 100 MW at peak capacity.

In 1992, the General Electricity Company of Libya (GECOL) signed a contract with ABB, a Swiss-Swedish multinational corporation, to construct five gas turbine units, of the South Tripoli Gas Turbine Power Plant as illustrated in Figure (1). Construction of these units commenced in 1994 under the supervision of ABB. The total installed capacity was designed to be 500 MW, with each unit capable of producing a maximum power of 100 MW. However, the actual power output is 94 MW per unit when operating on diesel fuel, yielding a total of 470 MW (94 × 5 = 470 MW). When using natural gas as fuel, the actual power output increases to 96 MW per unit, resulting in a total of 480 MW. The type of gas turbines installed is GT13D3, and the units are named GT-11, GT-12, GT-13, GT-14, and GT-15. [4-5].

Figure (1) The South Tripoli Gas Turbine Power Plant

Units' electrical system

Each generation unit at the South Tripoli Power Plant is equipped with a three-phase synchronous generator with a capacity of 121 MVA and a generation voltage of 10.5 kV. This voltage is stepped up to the grid voltage of 220 kV using the main transformer (GEN STEP-UP TRANSFORMER), enabling synchronization and connection of the unit to the grid.

Each of the five units is also equipped with an auxiliary transformer (UNIT AUXILIARY TRANSFORMER) with a capacity of 5.1 MVA, a primary voltage of 10.5 kV, and two secondary circuits: one at 2 kV and the other at 400 V. Additionally, the plant has station service transformers (STATION SERVICE TRANSFORMERS) located at the first and fifth units, each with a capacity of 3 MVA and a voltage of 10.5 kV/6.6 kV.

The station service transformers at units one and five feed the 6.6 kV (Station Board) line located in the main control room. This line is also powered by a 30 kV line through a step-down transformer and by a diesel generator (Black Start Diesel). Therefore, the 6.6 kV (Station Board) line is supplied by four sources:

1. The station service transformer of unit one.
2. The station service transformer of unit five.
3. The 30 kV substation.
4. The Black Start Diesel generator.

The (Station Board) 6.6 kV line is responsible for powering station loads such as lighting, cooling systems, firefighting pumps, and other auxiliary loads. It is important to note that the diesel generator is used only in emergencies, while the main supply for these loads is through the station service transformers of units one or five. The presence of a 30 kV/6.6 kV transformer is critical for powering station loads during the initial startup phase before the units are operational.

At the output of the 6.6 kV (Station Board) line, there are three step-down transformers, two of which are rated at 6.6 kV/2 kV and are known as Black Start Transformers. These transformers provide power to the Static Frequency Converter (SFC) for units one, two, four, and five. The SFC is responsible for supplying the required voltage in case the unit auxiliary transformer fails to supply the respective units. [4-5]

Mathematical Modeling and Simulation of a Gas Turbine Power Plant

A gas turbine power plant consists of several key components: compressor, combustion chamber, turbine, and generator. The mathematical modelling of such a system is based on thermodynamic and fluid dynamics equations, including energy balance, mass flow, and efficiency considerations.

1. Compressor Model

The compressor increases the pressure of incoming air before entering the combustion chamber. The governing equations include:

Energy balance equation.[6]:

$$h_{c,out} - h_{c,in} = \frac{W_c}{\dot{m}_a} \quad \text{..} \ (1)$$

where:

1. $h_{c,in}$ and $h_{c,out}$ are the inlet and outlet enthalpies (kJ/kg).
2. W_c is the compressor work (kW).
3. $\dot{m}_a$ is the mass flow rate of air (kg/s).

- Polytropic compression equation [6]:

$$P_{c,out} = P_{c,in} \left(\frac{T_{c,out}}{T_{c,in}}\right)^{\frac{\gamma}{\gamma-1}} \text{..} \ (2)$$

where:

1. $P_{c,in}$ and $P_{c,out}$ are the inlet and outlet pressures (Pa).
2. $T_{c,in}$ and $T_{c,out}$ are the inlet and outlet temperatures (K).
3. γ is the specific heat ratio of air.

2. Combustion Chamber Model

The combustion chamber burns fuel to increase the temperature of compressed air.

- Energy balance equation [6]:

$$\dot{m}_a h_{c,out} + \dot{m}_f h_f = \left(\dot{m}_a + \dot{m}_f\right) h_{b,out} \quad \text{.. (3)}$$

where:

1. $\dot{m}_f$ is the mass flow rate of fuel (kg/s).
2. h_f is the fuel enthalpy (kJ/kg).
3. $h_{b,out}$ is the exit enthalpy after combustion (kJ/kg).

- Heat addition equation: [7]

$$Q_{comb} = \dot{m}_f \times LHV \quad \text{.. (4)}$$

where:

1. LHV is the lower heating value of the fuel (kJ/kg).

3. Turbine Model

The turbine extracts energy from high-temperature gases to drive both the compressor and the generator.

- Energy balance equation [8]:

$$W_t = \dot{m}_g\left(h_{t,in} - h_{t,out}\right) \quad \text{.. (5)}$$

where:

2. W_t is the turbine work (kW).
3. $\dot{m}_g$ is the mass flow rate of gas (kg/s).
4. $h_{t,in}$ and $h_{t,out}$ are the inlet and outlet enthalpies of the turbine (kJ/kg).

- Polytropic expansion equation [7]:

$$P_{t,out} = P_{t,in}\left(\frac{T_{t,out}}{T_{t,in}}\right)^{\frac{\gamma-1}{\gamma}} \quad \text{... (6)}$$

where:

5. $P_{t,in}$ and $P_{t,out}$ are the inlet and outlet pressures (Pa).

6. $T_{t,in}$ and $T_{t,out}$ are the inlet and outlet temperatures (K).

4. Generator Model

The generator converts mechanical power from the turbine into electrical power.

- Power output equation [8]:

$$P_{elec} = \eta_g W_{mech} \quad \text{.......} (7)$$

where:

7. P_{elec} is the electrical power output (kW).
8. η_g is the generator efficiency.

- Overall efficiency of the power plant [6]:

$$\eta_{overall} = \frac{P_{elec}}{m_f \times LHV} \quad \text{.......} (8)$$

Excitation System Transfer Function

The given equation (9) represents the transfer function of the excitation system:[9]

$$\frac{V_{fd}}{e_f} = \frac{1}{K_e + sT_e} \quad \text{.......} (9)$$

Symbol Definitions:

- V_{fd} : Field winding voltage
- e_f : Excitation system input
- K_e : Gain constant of the excitation system
- s : Laplace operator
- T_e : Time constant of the excitation system

This equation models the dynamic response of the excitation system in the frequency domain. The upper and lower limits of the excitation system output (Ef_{max} and Ef_{min}) are determined based on the terminal voltage and the reference voltage V_{ref}.

Synchronous Machine Simulation:

The synchronous machine operates either as a generator or a motor depending on the operating condition. The model is used to determine the machine's electrical behaviour based on voltage equations (9-14) in the dq reference frame. The equivalent magnetic field of the synchronous machine figure (2) is represented using a model that reflects the effect of magnetic saturation based on magnetization curves.

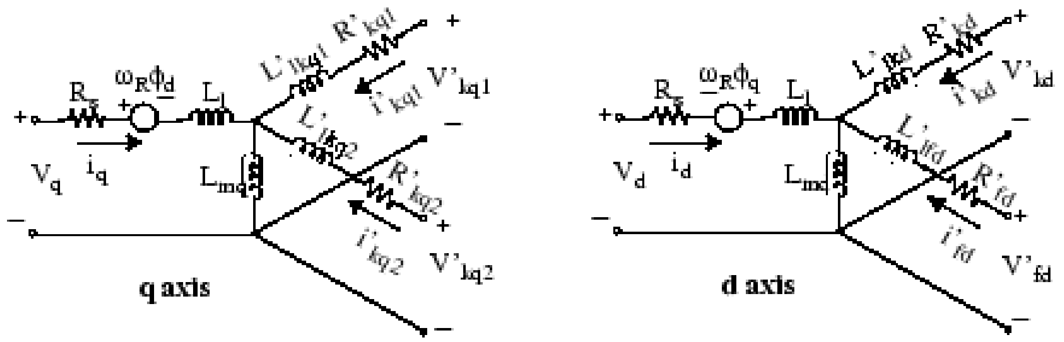


Figure (2) illustrates the equivalent circuit of the synchronous machine.

From this equivalent circuit, the following equations can be derived, the equations (10 – 15) of the Synchronous Machine in the dq Reference Frame [10]

Voltage Equations:

$$V_d = R_s i_d + \frac{d}{dt}\varphi_d - \omega_R \varphi_q \qquad V_q = R_s i_q + \frac{d}{dt}\varphi_q + \omega_R \varphi_d \quad \ldots\ldots\ldots\ldots\ldots\ldots (10)$$

Flux Linkage Equations:

$$\varphi_d = L_d i_d + L_{md}\left(i'_{fd} + i'_{kd}\right) \qquad \varphi_q = L_q i_q + L_{mq} i'_{kq} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (11)$$

Field Winding Voltage and Flux Equations:

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d}{dt}\varphi'_{fd} \qquad \varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd}) \quad \ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots (12)$$

Damper Winding Voltage and Flux Equations (d-axis):

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d}{dt}\varphi'_{kd} \qquad \varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}\left(i_d + i'_{fd}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (13)$$

Damper Winding Voltage and Flux Equations (q-axis):

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d}{dt}\varphi'_{kq1} \qquad \varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (14)$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d}{dt}\varphi'_{kq2} \qquad \varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (15)$$

Symbol Definitions:

- V_d, V_q : Direct and quadrature axis stator voltages
- i_d, i_q : Direct and quadrature axis stator currents
- φ_d, φ_q : Direct and quadrature axis stator flux linkages
- R_s : Stator resistance
- ω_R : Rotor angular velocity
- L_d, L_q : Direct and quadrature axis self-inductances
- L_{md}, L_{mq} : Mutual inductances in the d- and q-axes
- V'_{fd} : Field winding voltage
- i'_{fd} : Field winding current
- R'_{fd} : Field winding resistance
- L'_{fd} : Field winding self-inductance
- $V'_{kd}, V'_{kq1}, V'_{kq2}$: Damper winding voltages
- $i'_{kd}, i'_{kq1}, i'_{kq2}$: Damper winding currents
- $R'_{kd}, R'_{kq1}, R'_{kq2}$: Damper winding resistances
- $L'_{kd}, L'_{kq1}, L'_{kq2}$: Damper winding self-inductances

This structured format ensures clarity for inclusion in a research paper. Let me know if you need any modifications!

This model assumes the currents flowing into the stator windings. The measured stator currents, which are fed back by the synchronous machine block (I_a, I_b, Ic, I_d, I_q), represent the currents flowing out of the machine.

Gas Turbine Simulation:

the gas turbine is represented by a block Figure (3) containing the required inputs and outputs to simulate its real operation. Linear equations are used to model the turbine as it functions in reality. The turbine model is based on linear Gover equations, along with a PID controller to regulate the system's dynamic performance.[11]

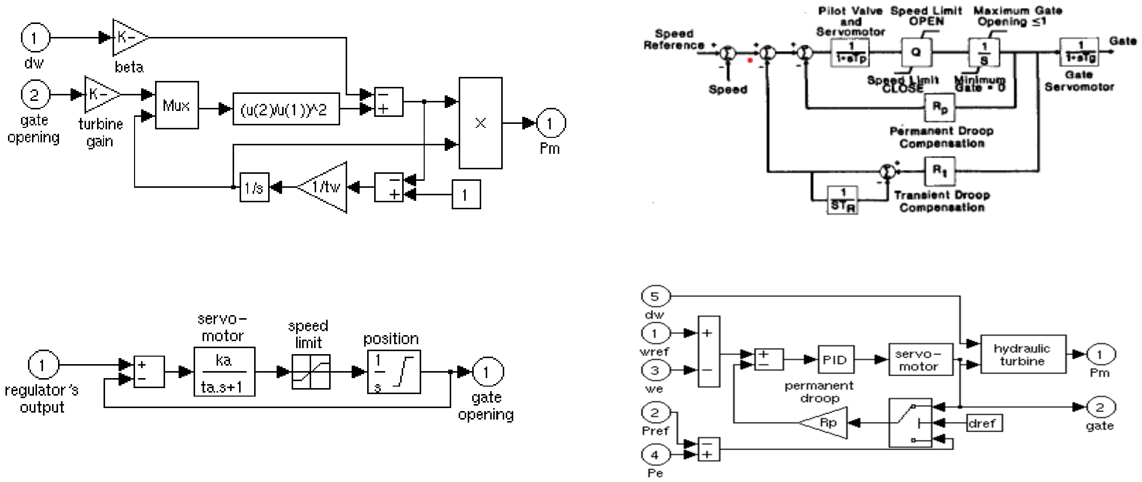


Figure (3): MATLAB-Based design of a Hydraulic Turbine Model Implementing Nonlinear Equations and a Gate Servo Motor Using a Second-Order System of Equations.

Gas Power Plant Simulation Steps

The machine uses a Simulink model to simulate the gas power plant, as shown in Figure (4). The model includes the hydraulic turbine and its associated control unit (Hydraulic Turbine and Governor - HTG). The figure also illustrates the excitation system Powergui and the method used for machine modelling.

The turbine operates at a three-phase voltage of 200 volt-amperes (VA) and is connected to a primary generator running at 13.8 kV with a speed of 112.5 revolutions per second. The voltage is transmitted through a transformer to an electrical grid at 230 kV, with the load measurement taken at t = 0.2 seconds. [12]

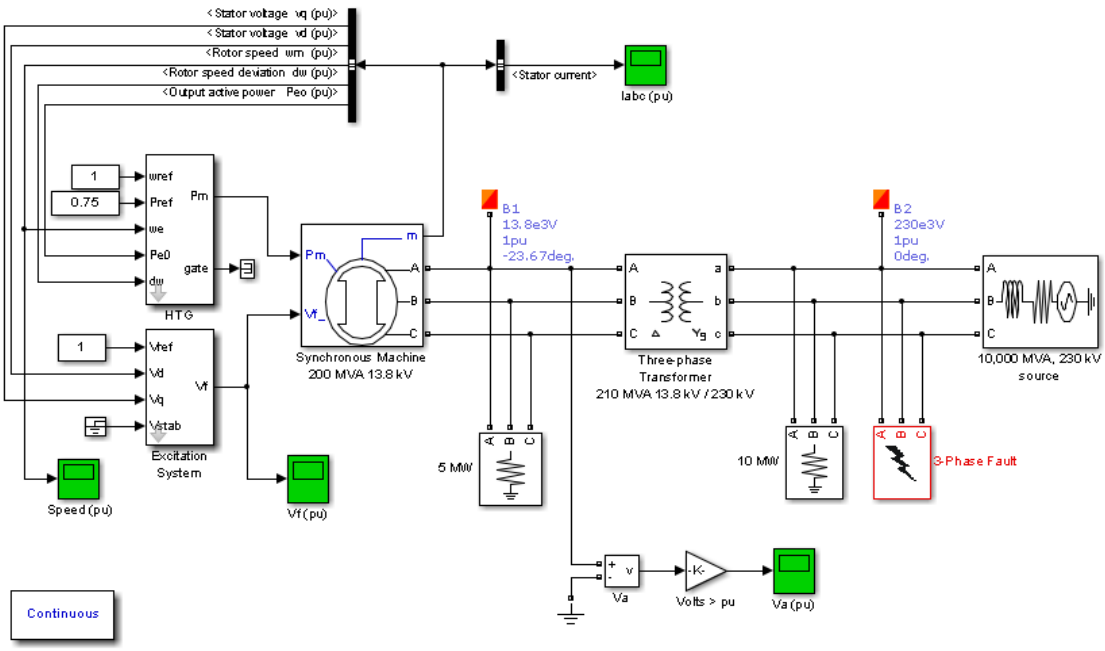


Figure (4) Simulation of the Gas Power Plant Using MATLAB Simulink

Starting the Plant in a Stable State:

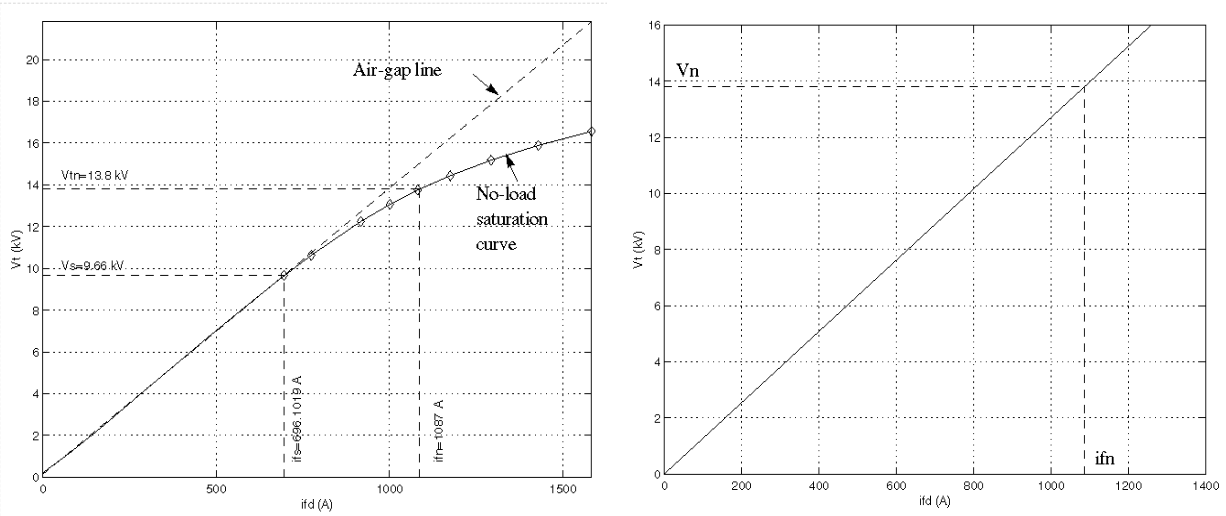
To ensure stable operation of the plant, the synchronous machine must be operated according to the required load. First, the voltage is initialized using a PV unit, and the Powergui tool is opened to adjust the terminal voltage. The voltage is set to match the required load using values extracted from the power plant data sheet, which includes:

- Terminal voltage rmsV = 13800 V
- Active power P = 150 MW
- Reactive power Q = 3.4 MVAR
- Field voltage Vf = 1.291 pu

Magnetic Saturation Curve

Figure (5) graphically illustrates the quality of the curve fitting, where the tangent represents the actual data points entered into the dialog box.

Without saturation, the typical curve may appear as shown in Figure (5). Since the current and voltage are related, i_{fn} is 1087 A, and V_n is 13800 V L-L (VRMS), which corresponds to 11268 V ph-ph



(V_{RMS}). Saturation is modeled by fitting a polynomial to the curve corresponding to the matrix of input data points, as illustrated in Figure (5). The more data points entered, the better the fit to the original curve. [12]

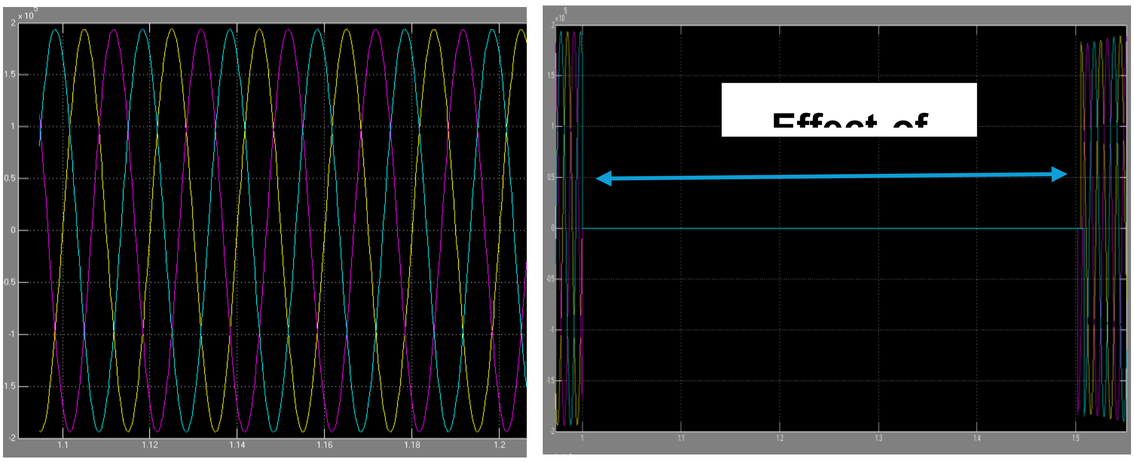
Figure (5) Magnetic Saturation Curve

Results and dissection

Result 1 power plant Three-Phase Current under normal and fault conditions

Scientific Discussion of the Three-Phase Current Simulation Results, figure (6) shows they provided simulation results the three-phase current of a gas power plant by away (a) represent the result the phase current without fault and result (b) three phase current with fault

The simulation results illustrate the three-phase stator current behaviour of a gas power plant under normal and fault conditions. In the steady-state scenario, the currents exhibit a balanced sinusoidal waveform, indicating stable generator operation. However, at **t = 1s**, a fault occurs, causing a sudden current spike, likely due to a short circuit or line-to-ground fault. This is followed by a sharp current suppression, possibly due to protective relay activation, and a gradual recovery phase as the system attempts to stabilize. These findings emphasize the need for advanced fault detection and mitigation strategies to ensure system reliability.



a b

figure (6) shows provided simulation results the three-phase current of a gas power plant by away (a) represent the result the phase current without fault and result (b) three phase current with fault

Result 2 power plant synchronous generator phase to phase current under normal and fault conditions

The results in Figure (7) illustrates analyses study of stator current behaviour of a synchronous generator in a power plant under steady-state and fault conditions using MATLAB simulation. In normal operation, the three-phase currents are balanced and sinusoidal, while under fault conditions, significant harmonic distortion, increased current magnitude, and transient instability occur. The fault waveform exhibits a beating effect and high-frequency oscillations, indicating possible short circuits or control failures. A substantial rise in RMS current suggests severe electrical disturbances requiring advanced protection schemes. Future research can focus on spectral analysis and machine learning for improved fault detection and classification.

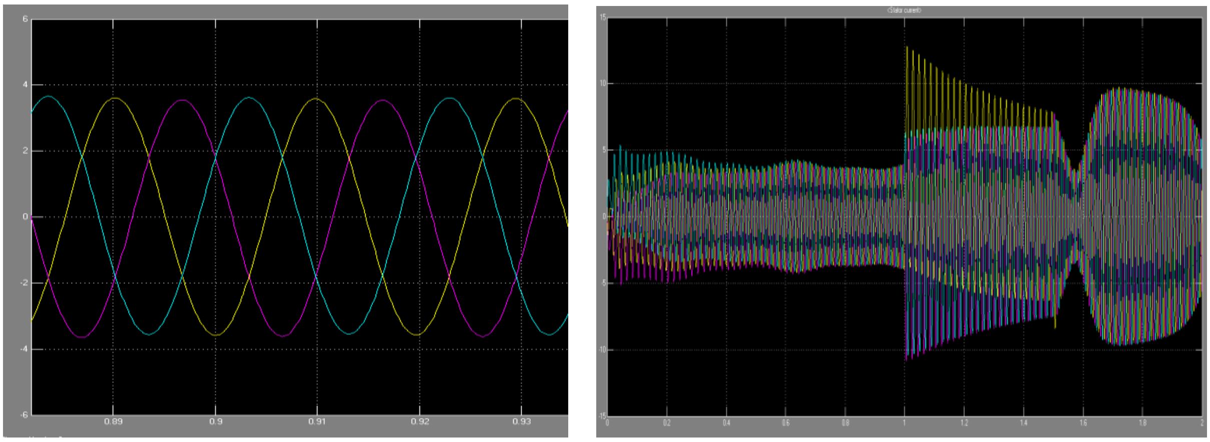
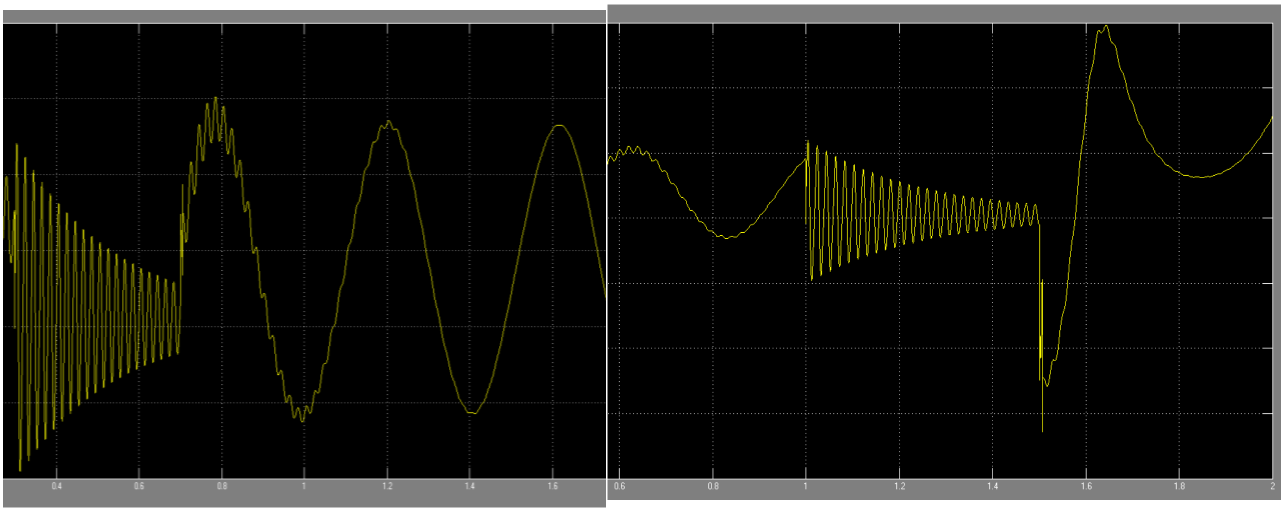


Figure (7) power plant synchronous generator current under normal and fault conditions

Result 3 the power output of a gas power plant under both steady-state and fault conditions:

The figure (8) illustrates the simulation results the power output behaviour of a gas power plant under steady-state and fault conditions. In the steady-state, the power waveform remains stable without oscillations, confirming normal operation. Upon fault occurrence, a sudden power drop is observed, followed by oscillations indicating system instability. The recovery phase suggests the activation of protective mechanisms to restore stability. This analysis provides insights into the plant’s dynamic response and fault mitigation strategies.

Figure (8) the power output of a gas power plant under both steady-state and fault conditions



Conclusion:

This research paper conducted an analytical study on the performance of the gas power plant in West Tripoli, focusing on the dynamic behaviour of the gas turbine and the impact of various faults on system stability and performance. By developing a simulation model using **MATLAB/Simulink**, the plant's response under different operating conditions was analysed, providing valuable insights into operational dynamics and fault interactions.

The results highlight the significance of studying the nonlinear equations governing the synchronous machine's behaviour to better understand dynamic interactions within the power system, ultimately aiding in the enhancement of operational and maintenance strategies. Furthermore, the study underscores the necessity of implementing advanced protection strategies to ensure grid stability and improve efficiency. Based on these findings, future research could explore advanced performance optimization techniques and innovative solutions to further enhance the reliability of electrical systems under various operational challenges.

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