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IoT-Based Adaptive Online Air Filter Diagnosis and Emission Control Mechanism for Internal Combustion Generators Lacking Advanced Systems

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Abstract: This paper represents the design of a real-time monitoring system of air filter functioning in large-scale diesel generators, specifically the old generators that lack inbuilt emission control such as the Exhaust Gas Recirculation (EGR). The system was efficient in tracking important parameters such as airflow rate, temperature, pressure and humidity, providing accurate information on the condition of air filters. The findings showed that engine performance and emissions are greatly affected by the conditions of air filters. Installing a clogged air filter led to a reduction in airflow and an increase in engine stress which led to a greater consumption of fuel whilst operating in the absence of a filter allowed the maximum airflow but increased the chances of pollutants reaching the engine. EGR system was very effective in reducing NO2 by reducing the combustion temperature with the CO and CO2 emissions kept within acceptable ranges. Using the EGR system along with incorporation of real-time monitoring was used to guarantee maximum engine performance and reduced hazardous emissions. The combination of microcontrollers and sensors allowed to collect data and control it accurately, which guaranteed the efficiency of engine operation. Remote monitoring was made possible through the digital interface and cloud storage, thus making informed decision-making and preventive maintenance a possibility. The real-time data and alerts provided by this system optimized the maintenance schedules, minimizing potential occurrences of unexpected breakdowns and premature replacements, which enhanced the operating efficiency of the system and provided cost-Saving.

Keywords: *Real-Time Monitoring; Air Filter Performance; Diesel Generators; Emission Control; Exhaust Gas Recirculation (EGR).*

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I. INTRODUCTION

Nowadays, demand for generators has increased largely due to electricity shortages, power cuts, and growth of the fields which necessitated a constant and reliable power supply. Generators come in many varieties that operate on diesel, gasoline, or kerosene as the energy source. Among these, diesel generators are more widely used due to their characteristics such as large capacity, parallel work, independent work, the lack of parallel work with regional power grid, not being affected by power grid outages, and high reliability [1]. As the key components of diesel generator sets, diesel engines can generate a lot of respirable particulate matter, and generate toxic gases, including carbon monoxide (CO), nitrogen oxides (NOx), hydrocarbons (HC), in the normal working process of this equipment. These pollutants have a negative effect on human respiratory health and cause respiratory diseases such as asthma, bronchitis, and lung cancers [2].

The engine's air intake system is a system that brings ambient air into the engine with the correct amounts, purity, and pressure. That guarantees the best fuel combustion within the engine and the maximum engine performance, lifetime, fuel efficiency, and emission [3]. The main purpose of the air filtration system is to eliminate the pollutants that are contained in the air intake and then pass into the engine to be combusted. It has a direct influence on the reliability, durability, and performance of the engine, as well as the fuel economy, power output, level of emission, and overall efficiency [4]. This indicates air filters are a critical component of diesel generators, but their efficiency is rarely

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monitored. Once the air filtering system is replaced, there is no proper way to know the efficiency of the air filtering system. Filter replacement is typically based on operating time or usage duration rather than actual condition. Lack of real time monitoring causes some uncertainty that in most cases results in premature replacement or delayed maintenance that results in higher cost of operation and higher emissions. Another source of air pollution is diesel generators that produce harmful substances including nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM). These emissions are leading to environmental degradation and significant health risks [5]. The air filter is essential in the reduction of these emissions because it prevents the infiltration of contaminants into the engine. The state and performance of air filters are not constantly monitored. Due to this, maintenance decisions tend to be inefficient. This leads to unnecessary maintenance expenses, low engine performance and increasing smoke emissions [6].

The applicability of the Exhaust Gas Recirculation (EGR) mechanism in the reduction of NOx emissions is well established because it involves the recirculation of a part of the exhaust gases into the combustion chamber. As the recirculated exhaust displaces part of the oxygen in the intake, combustion temperatures have been lowered, and the resulting NOx formation accordingly [7]. Analysis shows that up to 30% NOx reduction in diesel generator EGR systems is achievable [5].

In a cost-effective and real-time monitoring system for parameters filtration efficiency, differential pressure, temperature, and relative humidity developed by [8] for Heating, Ventilation, and Air Conditioning (HVAC) systems. This system makes it possible to implement more accurate and timely decisions about maintenance and thereby avoid premature replacements and maintain optimum filter performance on time. In addition, [6] demonstrates another use of the airflow resistance concept to detect clogging by the measurement of the pressure drop across the filter. Their approach is a relatively reliable way to detect the incremental buildup of particulates, while the filter is still usable, giving operators time to act before it is totally clogged.

Accordingly, the proposed research paper will suggest a real-time air filter performance control system of large-scale diesel generators along with an emission control mechanism. The proposed system aims at increasing the equipment protection through preserving the clean performance of the equipment and ensuring the lifespan of diesel generators. It also helps in optimized maintenance as it allows timely intervention, energy use and operation cost reduction, and minimized engine parts wear. Moreover, the system decreases the waste of filters changes by monitoring them based on their performance besides contributing to lowered emissions and more environmental sustainability.

In diesel generators, combining real-time air filter monitoring with an EGR-based emission control strategy is a combination that can provide substantial benefits to diesel generator's operational efficiency, extend equipment lifespan, maintenance cost savings, environmental compliance, etc. This integrated system has the potential to provide complete optimization of diesel generator performance, minimizing emissions while enhancing generational power supply by monitoring real-time key parameters like pressure differential, airflow rate, and particle concentration as well as emissions.

II. METHODOLOGY

In this project, used normal atmospheric air as the intake of the engine and adopted the exhaust gas recirculation (EGR) technique and air filter condition monitoring system. The experiments are conducted in 6 cylinder, 4-stroke, water-cooled, direct inject diesel engine coupled to an electrical generator. Air filter parameters such as pressure drop, air flow rate, temperature, and humidity are determined. Those emissions such as Nitrogen Dioxide (No2), Carbon Monoxide (CO), and Carbon Dioxide (CO2) are measured circulation of engine exhaust with the EGR technique resulting in lowered NO2 and CO.

➢ *Air Filter Manifold Modification*

This experiment was carried out on a Cummins diesel generator. In the experiment, it is needed to obtain pressure drop, air flow rate, temperature, and humidity inside the air filter. Sensors are used for measuring these parameters of the filter. A steel pipe was taken which is suitable with the engine inlet original manifold hose. BME 680 sensor and air flow sensor were fixed inside the steel pipe. This steel pipe is connected to the air filter and engine inlet manifold when taking the measurements. By using hose clips, the steel pipe is fixed properly.

➢ *EGR System Modification*

An internal combustion engine coupled with an exhaust gas recirculation (EGR) system lowers NOX emissions while significantly preserving fuel efficiency and longevity. In this experiment, Exhaust gas of the engine recirculates to the inlet manifold of the engine. Also, it is necessary to make some modifications to the engine since the original engine had no EGR system. The exhaust outlet (silencer) of the engine was connected to the air intake manifold to enable exhaust gas recirculation. It is shown as in figure 1.

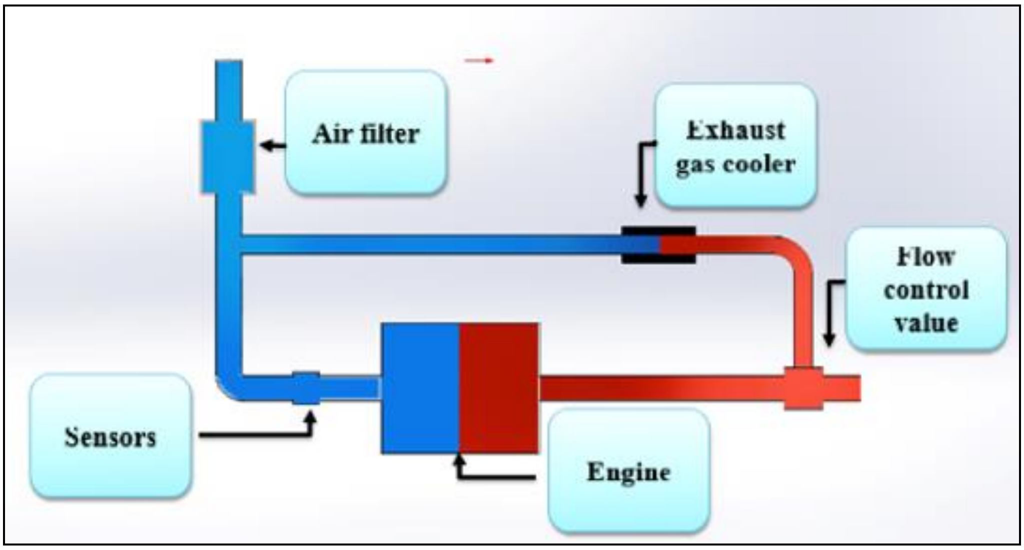

Fig 1 EGR System Modification

➢ *EGR Valve and EGR Cooler*

EGR valve is used to control the amount of exhaust gas entering to the EGR system. It is operated by using a servo motor. Operating the valve partially blocks the gas release to the environment and increases the gas entering to the EGR system. The EGR cooler is used as an exhaust cooler because high peak combustion temperature can lead to increase in NOx emission. When Exhaust gas is cooled it leads to reduce NOx emission levels (It lowers the peak combustion temperature).

➢ *Exhaust Gas Analysis*

In this experiment exhaust gas emissions were analyzed. MQ-7, MQ-135, and CJMCU- 6814 sensors were used to measure CO, CO2, and NO2 respectively. These three sensors are mounted at the Silencer outlet.

➢ *Data Collecting Procedure*

After the complete implementation of the system, the required data was obtained. The experimental setup is illustrated in Figure 2. Key air filter parameters, including pressure drop, temperature, airflow rate, and humidity, were measured under several operating conditions, namely with a clogged air filter, without an air filter, and with a clean air filter. Variations in these parameters were observed for each condition. These variations were used within the system to determine the condition of the air filter.

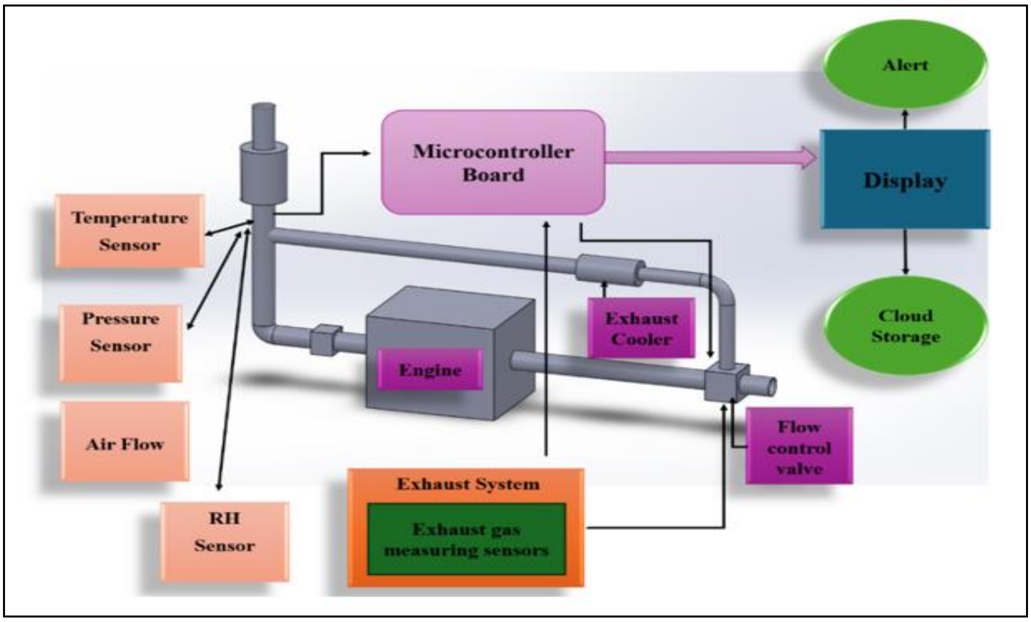

Fig 2 Schematic Diagram of the Experimental Setup

The emissions of exhaust gases were observed and noted under each condition of the filters. Depending on the filter condition identified, the quantity of exhaust gas recirculated to the EGR system is controlled by using the EGR valve. Every sensor output will be handled by a microcontroller (Mega WiFi R3 ATmega2560 ESP8266, 32 Mb memory, is compatible with Arduino Mega and NodeMCU ESP8266). These controlled actuators such as the

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EGR valve and the cooler pump are then controlled using processed data and the state of the air filter is also evaluated. Moreover, all the measured parameters are stored in the cloud, and the users may see real-time data about air filters work and exhaust emissions on the digital interface. This allows them to decide on the maintenance of the air filters anywhere and at any time.

- *Software Intergration*

The system software was created by using a mixture of programming languages, development tools, and frameworks to assist in effective data collection, processing, and visualization processes. Server-side operations and API development were done in PHP, and real-time updates and interactive user interfaces were done in JavaScript. To create a responsive and structured web application, HTML, CSS and Bootstrap were used. The development environment was the Visual Studio Code, and the Arduino IDE was employed in the programming of the microcontroller and setting up of the ESP8266 module. XAMPP was used to offer Apache server and MySQL database to store and host data.

The system incorporates a secure login interface, live dashboard and data monitoring of sensor data and an option of data logging that gives access to the past records. The application of a RESTful API was used to accept the transmitted data in the form of JSON to the Arduino through the ESP8266 Wi-Fi module. The sensor data are processed and stored at timestamps and dynamically shown on the dashboard. The system also incorporates errors in handling mechanisms to maintain data integrity. Extensive testing and optimization were conducted to ensure accurate data transmission, efficient memory usage, and reliable system performance. The interface of the system dashboard illustrates in figure 3 and figure 4 illustrates the data log.

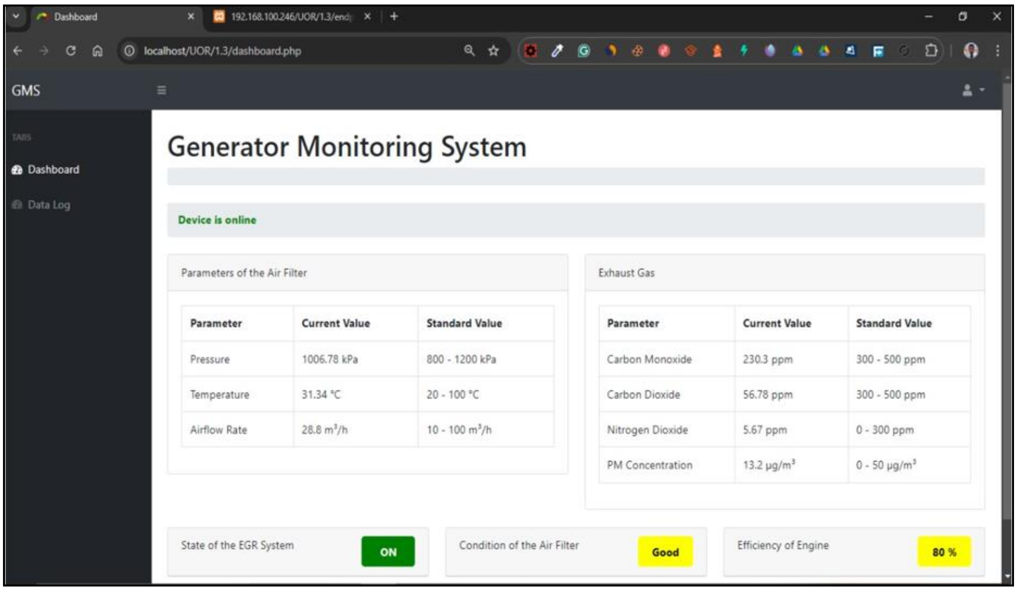

Fig 3 Interface of the System (Dashboard)

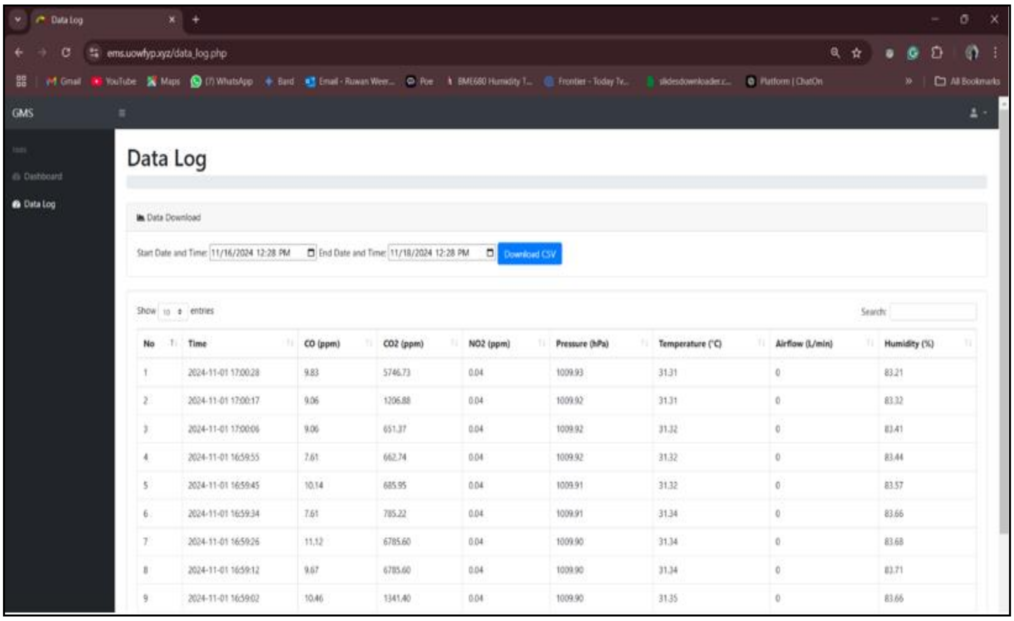

Fig 4 Interface of the System (Data Log)

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III. RESULTS AND DISCUSSION

- *Results*

The findings prove the efficacy of the real-time air filter monitoring system to assess the state of air filters and assist in controlling emissions in large-scale operations of diesel generators. There were also considerable differences in airflow when different filters were used. When using a clean air filter, the flow rate was 28.00-32.27 L/min whereas when using a blocked filter, the flow rate was 8.47-14.90 L/min, which showed the limited airflow that can constrain the engine performance and increased the mechanical stress. Conversely, no air filter caused a faster flow rate of between 59.36 and 65.78 L/min that, despite increasing, airflow, permits unfiltered particles to get into the engine and might cause more wear and emissions.

The thermal behavior was relatively constant with a temperature ranging between 31.21 and 31.57 oC on using a clean filter and 36.29 to 36.62 oC on using blocked filter, showing that thermal behavior was not heavily affected by the condition of the filter. The pressure measurements revealed some differing values of 1006.21-1007.42 hPa of a clean filter, 975.63-979.65 hPa of a blocked filter, and 1010.09-1010.98 hPa without a filter. The low pressure in the blocked state is correlated with a limited airflow and could influence engine efficiency and fuel consumption. The humidity of the air also differed and was 74.30%-74.87% and 61.78%-62.86% with clean and blocked filters respectively, which means that fluctuations in air properties may affect the combustion process.

The adoption of the Exhaust Gas Recirculation (EGR) system helped to achieve the target of good emission control as the combustion temperature was low and thus produced less nitrogen dioxide (NO2). There were no excessive carbon monoxide (CO) and carbon dioxide (CO2) emissions, which defines the stable functioning of the engine. Besides, the system was effective in real-time acquisition of data by using in-built sensors and a microcontroller and all the data was stored in cloud-based storage. This facilitated constant monitoring and ensured the timely decision-making to ensure the optimum performance of the generators and minimization of the environmental impact.

- *Discussion*

The article describes the design of a real-time air filter monitoring system of large-scale diesel generators with emphasis on older generators that lack an external EGR system or real-time monitoring. The system is able to monitor the critical factors of airflow rate, temperature, pressure, and humidity, and provide accurate information on the state of the air filters. Findings indicate that blocked filters decrease airflow, augment engine pressure, and elevate the use of fuel, whereas free airflow in the absence of appropriate filtration poses a danger of engine pollution. The system is compatible with an internal combustion engine and is particularly helpful with older generators which lack modern monitoring and regulations of the emissions. The system helps to increase engine efficiency, minimize unexpected breakdowns, and lower operational expenses through the ability to collect and continuously monitor data, perform preventive maintenance, and support cost effective operations.

These results indicate that the air filter condition significantly affects both the engine performance and emission levels. When the air filter becomes blocked, it causes a high-pressure drop and a reduced airflow rate, forcing the engine to work harder to draw in air. This situation decreases total efficiency, consumes more fuel, and imposes more loads on engine parts. Despite the comparatively small variations in temperature and humidity, some fluctuation was noted because of the limited airflow. Without the air filter, the air enters the engine freely, without resistance, and the rate of airflow into the engine is increased. Nevertheless, such a condition permits contaminants to enter into the engine, which could result in long-term mechanical damage. Even though the level of emission was found to be lower in this instance, the non-use of filtration affects the durability and reliability of the engines in the long run.

An effective air filter that is well operating offers a balance between sufficient circulation and effective elimination of contaminants. In this state, constant pressure drop, airflow rate, temperature, and humidity measurements were detected, which signified the ideal engine operation, increased fuel efficiency, and stable performance.

The EGR system offered the best reduction in NO2 emissions, especially in conditions where air filter was functioning correctly. Recycling exhaust gas reduces the temperature of combustion hence reducing the production of NOx and CO. The maximum emission of carbon monoxide arose when the air filter was blocked because of the incomplete combustion caused by the limited air flow. In contrast, operation without an air filter showed lower emissions. However, this condition increases the risk of long-term engine wear due to the entry of contaminants. Carbon dioxide emissions were highest in the absence of an air filter, as increased air intake promotes more complete combustion. With a properly functioning air filter, CO_2 levels remained balanced, supporting efficient combustion and optimal engine performance.

Integration of the real time monitoring system with the EGR based emission control mechanism was successful where balanced emissions and optimal engine performance could be maintained. Using sensors to check air filter conditions, and adjusting the EGR valve, kept the engine always running efficiently. By enabling users to remotely monitor engine conditions and help inform decisions about air filter maintenance and emission control, the digital interface and cloud storage made for a facilitated interface. The enhanced proactive maintenance provided by this real time data access reduces the risk of unexpected failures and helps to comply with emission regulations.

These findings from this project show that real time monitoring is necessary to keep large scale diesel generators efficient and performant. Absolute variations in flow rate, pressure, and emissions are observed that underscore the need to monitor the continuous air filters and take timely corrective

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measures. The EGR system shows significant reductions in NO2 , CO and CO2 emissions levels.

IV. CONCLUSION

This paper will demonstrate the importance of real-time monitoring in the process of enhancing the performance, efficiency, and reliability of large scales diesel generators. The system invented was able to measure the key parameters that include the rate of airflow, pressure, temperature, and humidity and delivered precise and timely data regarding air filter status. The findings prove that an air filter not allowed to pass through limits the air supply, and the engine load and burns more fuel, whereas operating without an air filter, although letting in as much air as possible, causes the risk of contaminant entry and lasting engine damage.

Additional features that were added to the system, which was the Exhaust Gas Recirculation system, were used to better the performance of the system by cutting down on the emission of NO2, by lowering the temperature of the combustion thus enabling the system to retain the carbon monoxide and the carbon dioxide emission within tolerable levels. Such a solution will guarantee effective engine work and less harm to the environment.

Introducing a system of real-time control over performance can result in improved equipment security as keeping air filters in the right state. It helps to implement optimized maintenance schedules based on real-world filter performance and not by a schedule, minimized emissions and environmental impact to facilitate regulatory adherence and more effective operations through less frequent unnecessary replacement and timely maintenance measures. Moreover, it will lead to lower operation costs and high reliability of the system in general.

As conclusion the suggested system is a holistic and viable way of streamlining the operation of the diesel generators, prolonging the lifespan of the equipment, and ensuring the performance of the equipment is eco-friendly.

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