Performance analysis of Variable Speed Diesel Generator

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Abstract:

Reliable power to remote hamlets remains a significant challenge, particularly in developing countries like India where grid extension is often economically not viable and technically impractical. Traditional constant-speed diesel generators (CSDGs), commonly employed in such applications, run at a constant speed irrespective of load changes, follow-on poor fuel efficiency, increased operating costs, and may cause potential engine damage due to prolonged low-load operation. This paper investigates a variable-speed diesel generator (VSDG) system in which a diesel engine is directly coupled to a doubly fed induction generator (DFIG). The proposed configuration enables the diesel engine to operate at variable speeds according to load changes while maintaining constant-frequency and constant voltage (CVCF) at the output. An indirect stator-flux-oriented vector control strategy is implemented for controlling the DFIG under isolated operating conditions. A mathematical model of the proposed VSDG system is formulated and simulated in the MATLAB/Simulink environment. The simulation results confirm the effectiveness of the proposed control strategy in maintaining the generator output voltage and frequency within the desired limits during variable-speed operation.

Keywords: Constant speed diesel generator; Variable speed diesel generator; Solar PV system; Hybrid energy; DFIG.

Introduction

Rising electricity demand in remote and isolated communities makes grid extension economically and technically challenging, particularly in developing countries like India. Hence, diesel generator (DG) sets comprising a constant-speed diesel engine coupled to a synchronous generator are widely used for reliable power supply [1]. Since the generated electricity must maintain a constant frequency, the diesel engine must be operated at synchronous speed regardless of the load demand. Such operating conditions can reduce fuel efficiency and increase operating costs. Moreover, prolonged operation of conventional constant-speed diesel generators at light or partial loads can degrade engine performance and durability,

as incomplete combustion may cause unburned fuel to enter the lubricating oil, leading to oil dilution and potentially severe engine damage [2].

One possible approach to reducing fuel consumption and operating costs in diesel generator systems is to operate the engine at variable speeds according to changing load condition. In a diesel engine, the rotational speed is primarily controlled by regulating the quantity of fuel injection. Since a diesel engine does not inherently limit its operating speed, a suitable speed-control mechanism is required. The governor serves this purpose by providing a feedback mechanism that regularly monitors the engine speed and regulates the fuel supply to compensate for speed variations, thereby maintaining the engine at the preset operating speed [3], [4].

Variable-speed operation of a diesel generator can mitigate several of the drawbacks associated with conventional constant-speed diesel generators, particularly during low- and partial-load conditions. This paper presents a performance analysis of a stand-alone variable-speed diesel generator system in which the diesel engine shaft is directly coupled to a doubly fed induction generator (DFIG). The proposed configuration enables the generator to deliver an output voltage of constant magnitude and frequency while allowing the diesel engine to operate at variable speeds according to the load demand. An indirect stator-flux-oriented vector control strategy is employed for controlling the DFIG during stand-alone operation. The performance of the proposed control strategy is evaluated through simulation, and the obtained results demonstrate its effectiveness and validate the proposed approach.

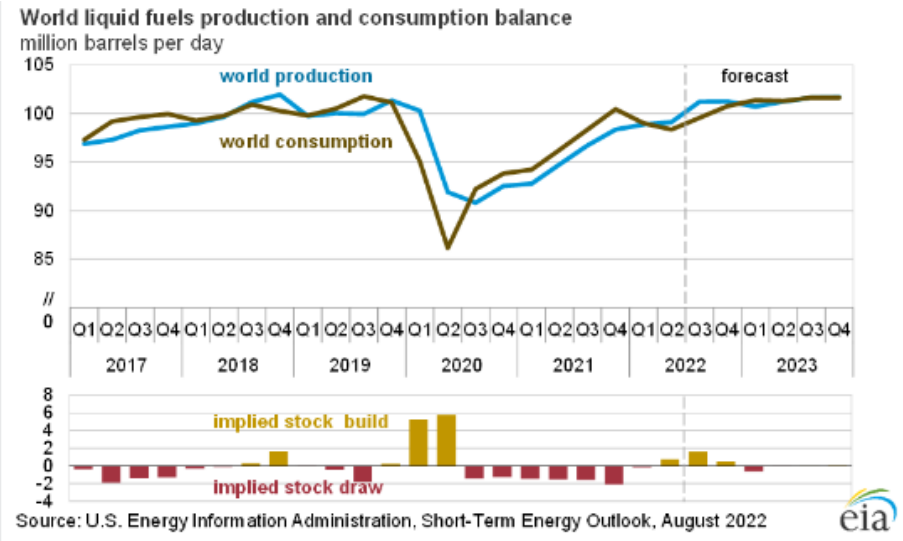


Figure 1. Expected worldwide growth in diesel demand

Conventional diesel generator systems operate at a constant synchronous speed, with the engine–governor regulating output frequency through fuel control and the synchronous generator–excitation system maintaining the required terminal voltage [5]–[8].

Variable speed diesel generator

Unlike conventional diesel generators that operate at a fixed engine speed and may exhibit poor fuel efficiency under low-load conditions, variable-speed diesel generators adjust the engine speed according to the power demand. In this operating concept, the engine rotational speed is decoupled from the frequency of the generated voltage, while power electronic converters regulate its magnitude, frequency, and phase. Thus, the required power can be supplied at a lower engine speed, potentially improving fuel efficiency under varying load conditions. This ability to adjust the engine speed according to the load demand is one of the major advantages of variable-speed diesel generators. Consequently, significant fuel savings can be achieved, particularly in isolated power systems where the rated capacity of the diesel generator is considerably higher than the average load demand.

Since the diesel engine speed is completely decoupled from the output voltage characteristics, this configuration permits a wide range of engine operating speeds (sub synchronous and super synchronous), which is primarily limited by the mechanical and operational capabilities of the diesel engine. Another configuration employs a doubly fed induction generator (DFIG), in which the slip frequency is controlled to compensate for variations in the rotor speed and maintain a constant synchronous frequency at the generator terminals. In this configuration, the permissible engine speed range is determined mainly by the capacity and operating limits of the back-to-back power converter. When a full-rated-power back-to-back converter is employed, the achievable speed range can be comparable to that of a fully decoupled configuration.

The feasibility of DFIG-based systems for variable-speed diesel engine operation has been demonstrated in [9], [10], while [11] investigates their application in grid-connected systems. This paper focuses on the modelling and simulation of a stand-alone variable-speed diesel generator using a DFIG. As shown in Fig. 2, the proposed system consists of a diesel engine coupled to a wound-rotor induction generator through a back-to-back power converter. The engine speed varies with load demand, whereas the DFIG maintains a constant output voltage magnitude and frequency irrespective of engine speed. An indirect stator-flux-oriented vector control strategy is employed for voltage and frequency regulation [12].

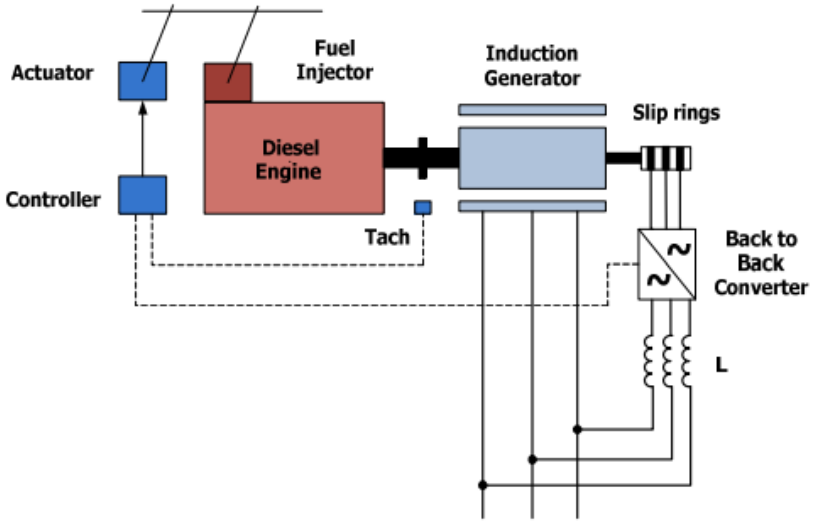


Figure 2. VSDG System Architecture

Modelling of Variable Speed Diesel Engine

In variable-speed operation, the diesel engine speed is regulated using an actuator, while the mechanical shaft torque is controlled by adjusting the fuel injection rate. The required engine speed and fuel quantity can be determined from a fuel consumption characteristics as a function of load power, which can be developed through experimental tests of the diesel engine–induction generator system under various operating conditions.

For modelling a variable-speed diesel generator, a generalized mathematical model of the diesel engine based on its torque–speed characteristics can be used. A simplified representation of the diesel engine model is shown in Fig. 3 [13]. The model parameters can be appropriately tuned and adjusted until the simulated characteristics is obtained.

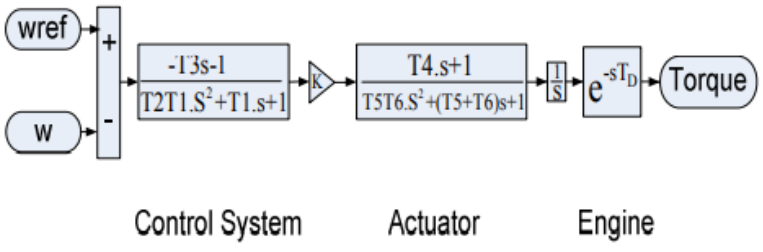


***Figure.3**: Simplified Diesel Engine model*

Figure 4 shows the optimal fuel-efficiency operating characteristics of the 30 kW diesel generator. Although the performance characteristics of a diesel engine may vary with changes in weather conditions, the obtained characteristic curve can be considered sufficiently demonstrative for modelling and

simulation purposes. The reference speed of the diesel generator is determined from the optimal fuel-efficiency curve according to the instantaneous load demand. The diesel engine is then operated at this reference speed to maintain near-optimal fuel efficiency and minimize fuel consumption.

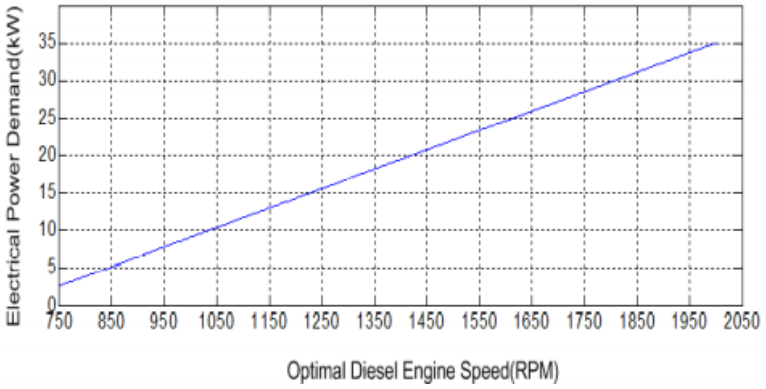


***Figure.4**: Optimal fuel efficiency characteristics*

A six-pole, 30 kW wound-rotor induction generator is selected based on the diesel engine's operating speed range. For a 50 Hz output, its synchronous speed is 1000 rpm. A back-to-back converter with a full power rating enables rotor-speed control from 0 to 2000 rpm, adequately covering the engine's operating range. For stand-alone operation, the DFIG is modelled using the d–q synchronous rotating reference frame based on Park's transformation, with governing equations similar to those used for grid-connected operation.

$$v_{ds} = R_s i_{ds} - \omega_s \lambda_{qs} + \frac{d\lambda_{ds}}{dt}$$
$$v_{qs} = R_s i_{qs} + \omega_s \lambda_{ds} + \frac{d\lambda_{qs}}{dt} \quad (1)$$

$$v_{dr} = R_r i_{dr} - (\omega_s - \omega_r)\lambda_{qr} + \frac{d\lambda_{dr}}{dt}$$
$$v_{qr} = R_r i_{qr} + (\omega_s - \omega_r)\lambda_{dr} + \frac{d\lambda_{qr}}{dt} \quad (2)$$

$$\lambda_{ds} = L_s i_{ds} + L_m i_{dr}$$
$$\lambda_{qs} = L_s i_{qs} + L_m i_{qr} \quad (3)$$

$$\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$
$$\lambda_{qr} = L_r i_{qr} + L_m i_{qs} \quad (4)$$

In the following equations, v, R, i, L, λ, and ω denote voltage, resistance, current, inductance, flux linkage, and electrical angular velocity, respectively. The subscripts $d$and $q$refer to the direct and quadrature axes, while $s$and $r$denote stator and rotor quantities. $L_m$represents mutual inductance, and i_{ms}denotes the excitation current. All electrical variables are time-dependent.

Under steady-state conditions, the stator flux derivative is zero. Neglecting stator resistance, the stator voltage is therefore determined primarily by the stator flux linkage, as given in (3). Unlike grid-connected DFIGs, where the stator flux is established by the grid, the flux in a stand-alone system is regulated through rotor-current control. Hence, an indirect stator-flux-oriented vector control strategy is employed. By aligning the q-axis with the stator-flux vector, $\lambda_{ds} = 0$and $\lambda_{qs} = L_m i_{ms}$. Substitution of these relations into (4) yields the following expression:

$$\left.\begin{aligned} i_{ds} &= -\frac{L_m}{L_s} i_{dr} \\ i_{qs} &= -\frac{L_m}{L_s}(i_{qr} - i_{ms}) \end{aligned}\right\} \quad (5)$$

Using Eq. (5) in Eq. (1), the following expression is obtained

$$i_{qr}^{*} = \frac{L_m}{\tau}\frac{di_{ms}}{dt} + i_{ms} - \frac{1}{\tau}u_{qs} \quad (6)$$

Where $\tau = \frac{R_s L_m}{L_s}$ Equation (6) indicates that the rotor q-axis current i_{qr}can be determined from the excitation current i_{ms}, while the effect of $u_{qs}$is neglected due to its relatively small magnitude. Similarly, Eq. (5) is used to determine the d-axis rotor current component i_{dr}.

$$i_{dr}^{*} = -\frac{L_s}{L_m} i_{qs} \quad (7)$$

Equation (7) also ensures that the d-axis remains aligned with the stator-flux vector. The corresponding stator-flux angle is obtained by integrating the reference synchronous angular speed $\omega_e$of the stator voltage, given by:

$$\theta_s = \int \omega_e dt \quad (8)$$

The d- and q-axis components of the rotor current can be regulated through appropriate control of the corresponding rotor voltages. Substituting Eq. (4) into Eq. (2) and applying Eq. (5) yields:

$$
\left.
\begin{aligned}
v_{dr} &= R_r i_{dr} + \sigma L_r \frac{di_r}{dt} - \omega_{slip} \sigma L_r i_{qr} \\
v_{qr} &= R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + \omega_{slip} \sigma L_r i_{dr} + \omega_{slip} \frac{L_m^2}{L_s} i_{ms}
\end{aligned}
\right\} \quad (9)
$$

Where $\omega_{slip} = \omega_s - \omega_r$ and $\sigma = 1 - \frac{L_m^2}{L_s L_r}$

Vector control Algorithm

The vector-control scheme for stand-alone DFIG operation is shown in Fig. 4. The rotor-side converter regulates the excitation flux and maintains the stator output voltage at the required magnitude and frequency, while the stator converter controls the DC-link voltage. Unlike grid-connected DFIGs, where the rotor converter provides independent active and reactive power control, a stand-alone DFIG does not offer such decoupled power regulation. Hence, the reactive power demanded by the load is supplied through the stator converter.

Since the excitation flux is established through the rotor-side converter, the DC link of the stand-alone DFIG system must be pre-charged before the generator is brought into operation. Furthermore, the DC-link system should be capable of responding to sudden variations in the reactive power demand of the load. Hence, the DC-link energy storage can be implemented using either a battery or a hybrid battery–capacitor storage system. The appropriate configuration can be selected by considering the trade-off between energy-storage capacity, dynamic performance, and overall system cost.

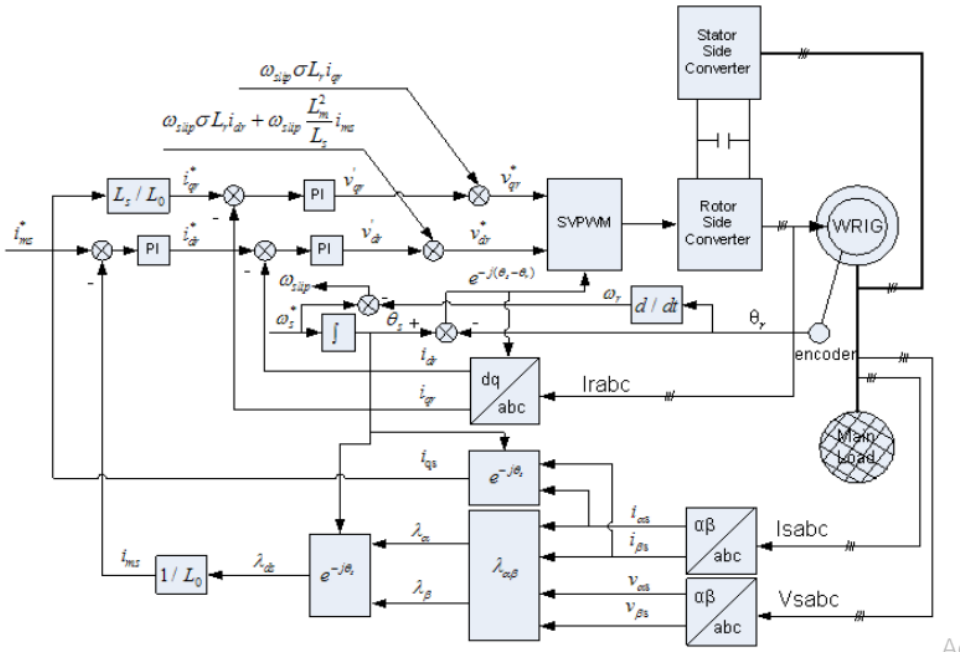


***Figure.4**: Vector control algorithm*

Simulation Results and Discussion

The MATLAB/Simulink model of the Variable-speed diesel generator employing a DFIG is shown in Fig. 5. The 30 kW DFIG is connected to a stand-alone grid and operates as a grid-forming source. The estimated load demand is fed to a look-up table that determines the optimal reference engine speed ω_{ref}. This reference is compared with the actual engine speed ω_r, and the resulting error is used to regulate the engine torque and mechanical power. The diesel engine drives the DFIG, which converts the mechanical input into electrical power for the load.

Although reactive power can be regulated through appropriate control of the stator-side converter, a purely resistive load is considered in the present simulation to simplify the analysis. Two load conditions are incorporated into the simulation. Two load conditions are considered for evaluating the generator performance. The first is a small, continuously connected load representing the minimum loading condition. The second is an additional higher load, switched through a three-phase circuit breaker, representing the maximum loading condition. The dynamic response of the proposed variable-speed diesel generation system under these conditions is presented in the following section.

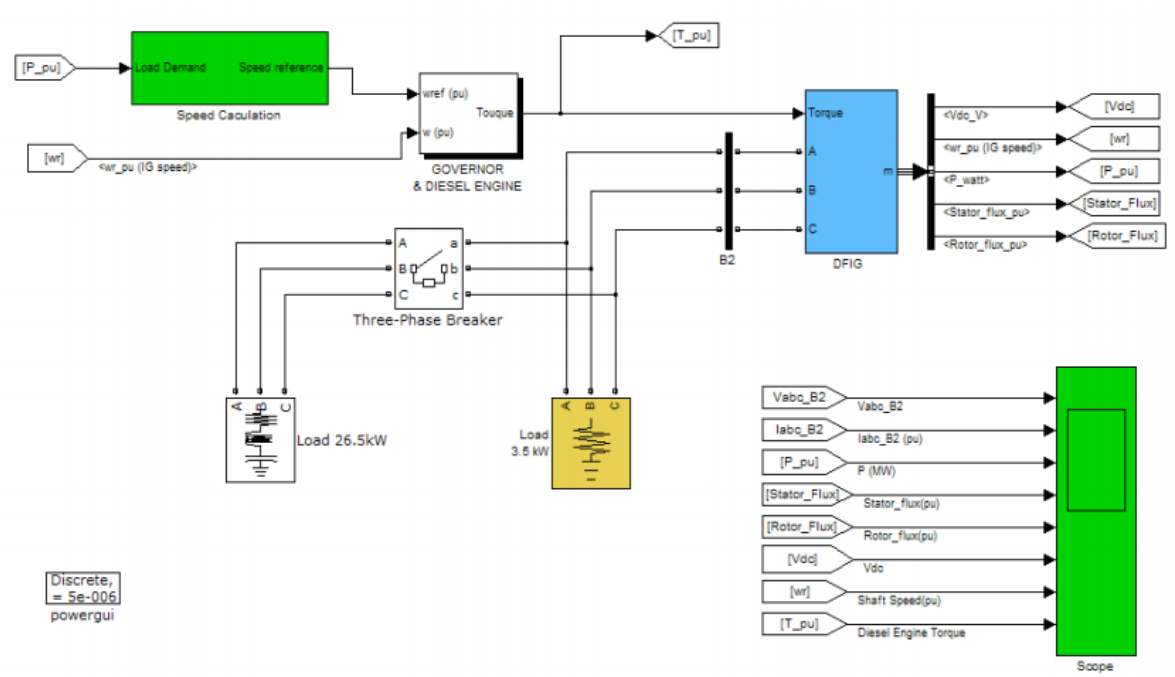


***Figure.5**: Proposed System Model in Simulink*

Figs. 6–11 present the transient response of the proposed system following a step variation in the main load. Initially, the variable-speed diesel generator supplies a 3.5 kW resistive load, which is approximately 10% of the 30-kW rated generator capacity. At t = 1.5 s, an additional 26.5 kW load is connected, resulting in a step change from roughly 10% loading to full-load operation. This represents one of the most elevated load variations considered for evaluating the transient performance of the variable-speed diesel generator.

Figure 6 illustrates the response of the stator flux to the sudden load variation. The stator flux remains close to its rated value under normal operating conditions. However, a temporary dip is observed at t = 1.5 s following the application of the additional load. This transient deviation is primarily attributed to the relatively slow mechanical response of the diesel engine, which cannot instantaneously respond to the sudden increase in power demand. The stator flux recovers to its rated value within approximately 0.1 s.

The dynamic responses of the DFIG stator voltage and current are presented in Figs. 7 and 8, respectively. Since the stator voltage is closely related to the stator flux, the sudden reduction in stator flux results in a corresponding transient dip in the stator voltage at t = 1.5 s. Following this disturbance, the stator current increases progressively as the generator responds to the increased load demand. Figure 9 illustrates the active-power output of the DFIG.

The response demonstrates that the generator requires a short transient interval to increase its power output and establish the power balance required by the newly applied load.

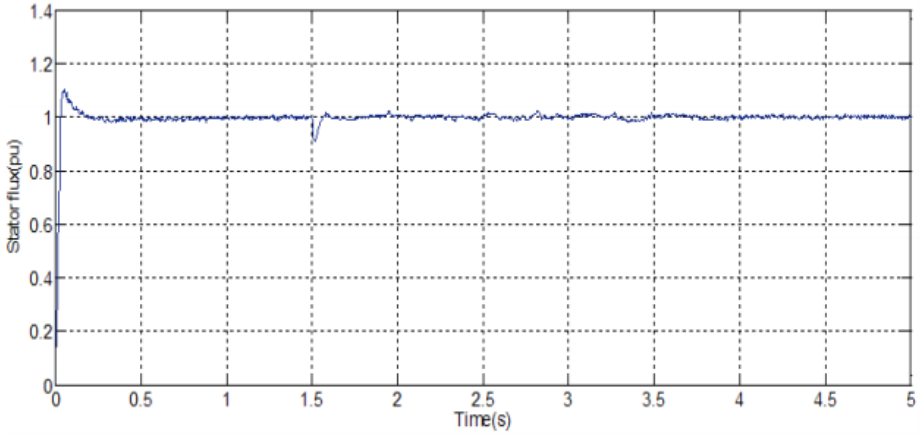


***Figure.6**: Response of Stator Flux to Load Variation*

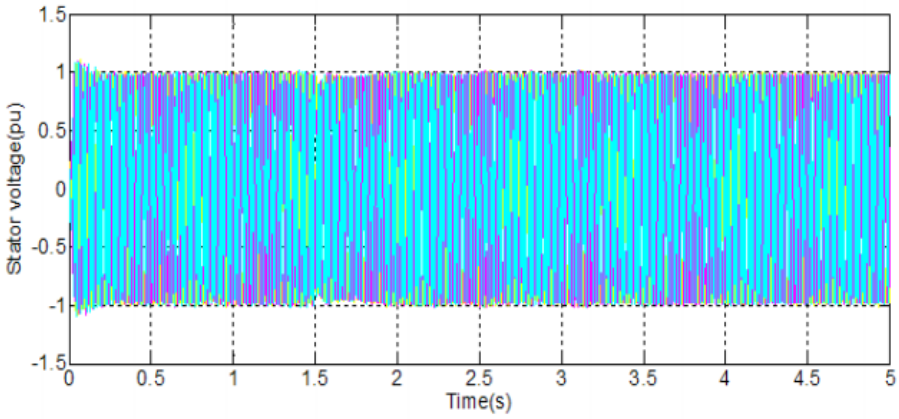


***Figure.7**: Response of Stator Voltage to Load Variation*

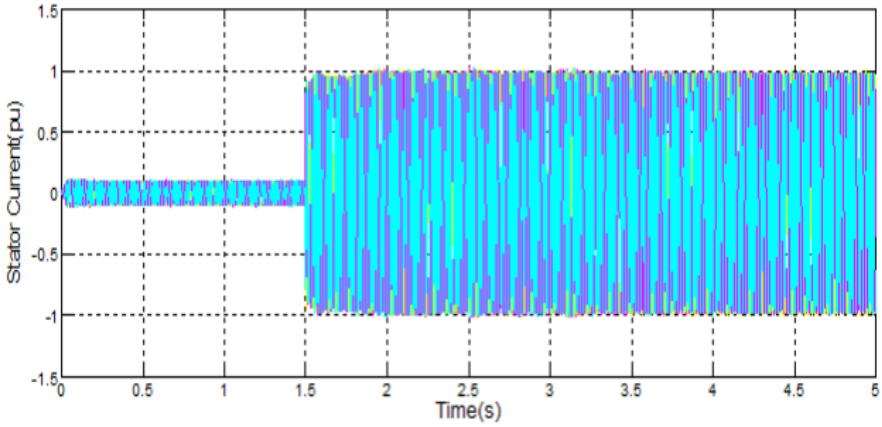


***Figure.8**: Response of Stator Current to Load Variation*

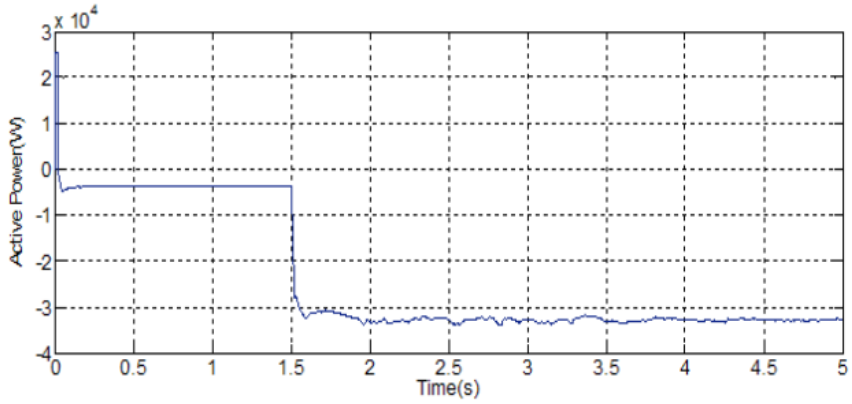


Figure.9: *Response of Active power to Load Variation*

When the load demand increases from 10% to the rated maximum value, the diesel engine is required to increase its rotational speed from 750 rpm to 2000 rpm in accordance with the optimal speed–load characteristic. Figure 10 illustrates the response of the system, demonstrating that the engine speed closely tracks the prescribed reference speed throughout the load transition.

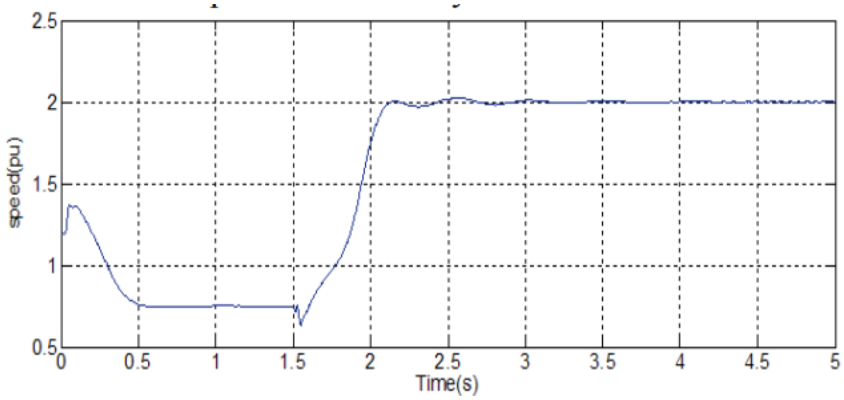


Figure.10*: Response of speed to Load Variation*

During the load transition, the rotor speed changes in the range of 750 to 2000 rpm, confirming DFIG operation in both sub-synchronous and super-synchronous regions. Figure 11 shows the DC-link voltage response. Since the rotor-side converter requires initial operation to establish the stator flux, the DC-link capacitor must be adequately charged before generator operation. The simulation results show a decrease in DC-link voltage from 1200 V to approximately 1155 V at startup.

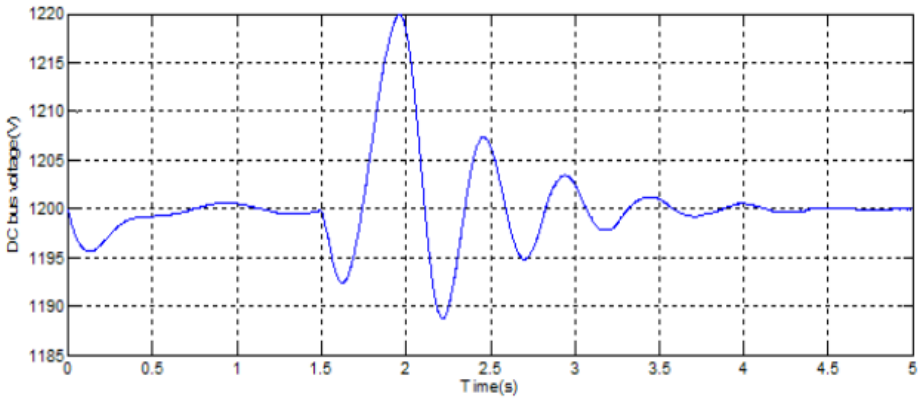


***Figure.11**: Response of DC bus voltage to Load Variation*

Conclusion

This paper presents the theoretical analysis, mathematical modelling, and simulation of a variable-speed diesel generator (VSDG) for stand-alone power generation. A DFIG-based VSDG system was modelled and investigated using the MATLAB/Simulink environment. A comparative analysis of conventional constant-speed diesel generators (CSDGs) and variable-speed diesel generators (VSDGs) was also carried out. The results indicate that variable-speed operation can provide improved fuel efficiency and reduced operating costs under continuously varying load conditions. The potential for fuel savings is particularly significant when the average load demand is considerably lower than the peak load, as the engine speed can be adjusted according to the instantaneous power requirement. Appropriate engine performance maps can therefore be employed to establish the optimum relationship between engine speed and load power. The simulation results confirm the feasibility of using a DFIG based variable-speed diesel engine operation in a stand-alone system. The indirect stator-flux-oriented vector control maintains stable electrical power during load variations, while effectively regulating the DC-link voltage independent of engine speed. Overall, the results validate the proposed DFIG-based variable-speed diesel generation system for stand-alone purposes.

References

1. Arriaga, Mariano & Canizares, Claudio & Kazerani, Mehrdad “Renewable Energy Alternatives for Remote Communities in Northern Ontario, Canada”. *Sustainable Energy, IEEE Transactions*, **8**, 661-670, 2013.
2. Miriam Madziga , Abdulla Rahil, Riyadh Mansoor “Comparison between Three Off-Grid Hybrid Systems (Solar Photovoltaic, Diesel Generator and Battery Storage System) for Electrification for Gwakwani Village, South Africa” *Int. Journal of Environments*,**7**, 1-21, 2018.

3. Qolipour, M.; Mostafaeipour, A, Tousi, M.O. “Techno-economic Feasibility of a Photovoltaic-Wind power plant construction for electric and hydrogen production: A Case Study”. *Renew. Sustain. Energy* Rev.**1**, 113–123, 2017.
4. Birudula Anil Kumar ; Raghu Selvaraj ; Thanga Raj Chelliah ; U. S. Ramesh “Improved Fuel-Use Efficiency in Diesel-Electric Tugboats With an Asynchronous Power Generating Unit”**.** *IEEE Transactions on Transportation Electrification*, 5, 565 – 578, 2018.
5. Tajuddin Waris, C.V.Nayar **“**Variable Speed Constant Frequency Diesel Power Conversion System Using Doubly Fed Induction Generator (DFIG)”. *IEEE Power Electronics Specialists Conference*, **8**, 2728- 2734, 2010.
6. Lim, P. and Nayar, C. “Modelling and Simulation of Photovoltaic-Variable Speed Diesel Generator Hybrid Power System for Off-Grid Rural Electrification”. *International Journal of Energy Science*. **2**, 5-14, 2012.
7. C. V. Nayar, S. J. Phillips, W. L. James, T. L. Pryor, and D. Remmer, “Novel wind/diesel/battery hybrid energy system”. *Solar Energy*, **51**, 65-78, 1993.
8. A. Lidozzi, L. Solero, and F. Crescimbini “Adaptive direct-tuning control for variable-speed diesel-electric generating units”. *IEEE Trans. Ind. Electron*, 59, 2126–2134, 2012.
9. T. Waris and C. V. Nayar “Variable speed constant frequency diesel power conversion system using doubly fed induction generator (DFIG)”. *Power Electronics Specialists Conference, PESC 2008, IEEE*, 2728- 2734, , 2008.
10. L. Joon-Hwan, L. Seung Hwan, and S. Seung-Ki, “Variable Speed Engine Generator with Super-Capacitor; Isolated Power Generation System and Fuel Efficiency”. *IEEE Industry Applications Society Annual Meeting,. IAS '08*, 1-5, 2008.
11. A. Engler, C. Hardt, P. Strauss, and M. Vandenbergh “Parallel Operation of Generators for Stand-alone Single-phase Hybrid Systems-First Implementation of a New Control Technology”. *European Photovoltaic Solar Energy Conference*, Munich, Germany, 2001.