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Improving fuel consumption efficiency of synchronous diesel generator operated at adjustable speed using adaptive inertia weight particle swarm optimization algorithm

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Abstract

Diesel generator is a reliable source of electricity, but it requires quite high operational costs, especially for fuel. This paper describes a technique for reducing fuel consumption in Diesel Engine Synchronous Generator systems. The system is originally a Constant Speed Diesel Synchronous Generator (CSD-SG), but during certain conditions, the speed is reduced to minimize fuel consumption by adjusting the Specific Fuel Consumption (SFC) map. SFC is defined as the amount of fuel consumed by a diesel engine generator for each unit of power output. It shows various numbers depending on the speed and operating power. In this paper, we use the Adaptive Inertia Weight Particle Swarm Optimization (AIWPSO) algorithm to select of the proper SFC curve at a certain speed and operating power. AIWPSO employs an adaptive inertial weight adjustment method, which enables this algorithm to achieve faster convergence than conventional Particle Swarm Optimisation (PSO) algorithms. The system is embedded with AC/DC/AC power electronics converter to regulate the frequency. Data set of 1000 kVA Cummins diesel engine generator from the oil and gas company in Central Java, Indonesia was taken for simulations. The results show that the AIWPSO algorithm calculates the fuel consumption as 1,678 liters per day on a typical condition, whereas in the previous method, the linear line needs 1,693 liters per day. Therefore, using AIWPSO method can save up to 450 liters of fuel per month. The simulation results show that the proposed method can improve fuel efficiency compared to the previous model.

1. Introduction

A Diesel Engine Generator (DEG) is commonly used as a backup or stand-alone power generator in hospitals, data centers, laboratories, factories, and others. There are many advantages of using DEG, such as its simplicity of construction and installation, reliability, and capacity range of 2 kW to 2 MW (1). This has been implemented in the electrical systems of oil refineries in Indonesia, where DEGs are used to drive equipment such as pumps and control systems (2).

According to (3), the Constant Speed Diesel Synchronous Generator (CSD-SG) is currently the most popular DEG system. The CSD-SG system is suitable for use at loads close to the maximum (4), but in real-world conditions, generators typically operate at low loads, resulting in a considerable decrease in efficiency (5). Moreover, at low loads, the engine does not function effectively and does not completely burn the fuel, resulting in the production of diesel soot (6). This will reduce system durability and raise maintenance costs. The use of load banks in industrial systems (especially in the United States) is an effort to reduce these unfavorable effects (7). Load banks are automatic resistors that load generators by converting electrical energy into heat. The load bank makes fuel consumption costs much higher. In addition, CSD-SG also has disadvantages such as high operational costs, especially costs related to fuel (8).

Several attempts have been made to reduce low-load DEG system fuel consumption. Such as deactivation of cylinders by (9) and (10), but for power systems greater than 100 kW, it is difficult to implement because it still requires a sufficient amount of power, so all cylinders must be utilized. Dual fuels that utilize diesel and gas have been shown to reduce fuel consumption (11), however, the resultant hydrocarbon and carbon dioxide emissions are higher than conventional diesel (12).

Utilizing variable-speed technology is another way to save fuel. According to the variable rotation speed system of the DFIG-type generator (13), if the diesel generator operates in variable speed mode, fuel efficiency can be increased. In a permanent magnet diesel generator, an incremental algorithm can optimize the fuel consumption of a diesel engine-based variable speed generator system (14). However, other aspects such as voltage or frequency control are not discussed. In another study, (15) determined that variable speed operation provides significant advantages at lower load levels. Below 30-40% of full load, the specific fuel consumption (SFC) of the system can significantly exceed its rated full load. Less fuel is required to generate the same quantity of power with a lower SFC value, indicating greater fuel efficiency. A high SFC value indicates increased fuel usage and decreased efficiency. A lower SFC value indicates better fuel efficiency, which means that less fuel is needed to produce a given amount of power. A high SFC value indicates higher fuel consumption and lower efficiency.

In this paper, the system of using variable speed to minimize DEG fuel usage is referred to as the Adjustable Speed Diesel Synchronize Generator (ASD-SG). The ASD-SG architecture that has been studied involves creating a control circuit for using ASD-SG with a 3-step converter. This has been done by (16) and (17) using a boost rectifier and inverter circuit that will cause losses in each converter. Furthermore, (18) evaluated adjustable speed diesel generators on ships that use unregulated rectifiers for generator output, resulting in a less reliable system. Other researchers (19) investigated ASD-SG for DC distribution when voltage fluctuations are affected by engine speed changes. (15), on the other hand, only talk about diesel and generator characteristics and lack discussion about the converter. In the SFC model, which has not yet received a speed recommendation from the manufacturer (20), it has not yet implemented a computational model. However, diesel engine speed control is still based on a method that employs an imaginary reference line connecting two points.

By utilizing algorithm (21), the optimal value can be attained. Some are utilized in performance enhancement research. The genetic algorithm (GA) is one of the most effective algorithms for solving performance enhancement problems, according to (22). This study shows that GA is very effective for increasing diesel engine performance and reducing emissions. This study also reveals that the GA algorithm requires a large number of iterations. Moreover, according to a number of studies, the GA algorithm has disadvantages such as premature convergence and low processing efficiency (23) (24). This drawback of the technique is overcome by a newer algorithm, Particle Swarm Optimization (PSO). Multiple investigations have demonstrated that this PSO algorithm yields superior outcomes. For example, research by (25) confirms this matter. Based on his findings, Ding concludes that PSO is superior to GA for estimating biomass kinetic parameters. However, according to the findings of several other studies, PSO standards frequently demonstrate early convergence.

In previous studies of the ASD-SG system, the engine speed control did not make use of comprehensive calculations. Previous research (20) only used an imaginary linear line approach to control operating speed by selecting two points (maximum and minimum) on the Specific Fuels Consumption (SFC) curve. SFC is a curve that indicates the relationship between diesel engine rotational speed, power, and fuel consumption under varying load conditions. In this investigation, the Adaptive Inertia Weight Particle Swarm Optimization (AIWPSO) algorithm was utilized to determine a diesel engine rotation value that is greater to the PSO standard.

The Adaptive Inertia Weight Particle Swarm Optimization algorithm is a modification of the standard PSO that emphasizes adaptive inertial weights. This algorithm achieves faster convergence than standard Particle Swarm Optimization (PSO) algorithms due to the adaptive inertial weight (26). AIWPSO also consumes less memory and runs faster than other metaheuristic systems (27). In this study an AC/DC/AC power converter is used which acts as an interface between the ASD-SG system and the load. The AC/DC converter system uses the Vienna rectifier to change the output voltage of the AC generator to a stable DC voltage. Furthermore, three-phase DC/AC converters using inverters will be responsible for maintaining the flexibility and control needed to manage the supply of three-phase electrical energy to demand.

2. Research Method

This research enhances system performance in reducing DEG fuel consumption by employing ASD-SG, which employs a power electronics converter based on the latest studies. The data comes from a 1000 kVA Cummins diesel generator at oil and gas company in Blora, Central Java, Indonesia (7°8' N, 111°36' E). Utilizing the AIWPSO algorithm, the computation is performed in order to obtain the best speed-power reference value. The results of the computations will be compared to the previous model, which continues to establish diesel engine speed using an approach based on an imaginary line connecting two points.

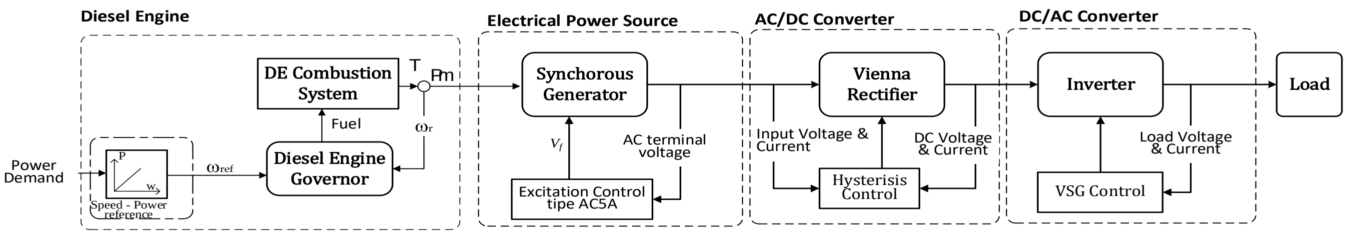

Figure 1. The ASD-SG Investigated Architecture of the Adjustable Speed Diesel Synchronous Generator

The ASD-SG system shown in Figure 1 consists of a diesel engine system, a generator system and an AC/DC/AC power electronics converter system. The power electronics system consists of a Vienna rectifier and an inverter. The engine power demand is determined by multiplying the voltage and the current that is obtained from the load side. The engine speed is controlled according to the load by changing the fuel flow to the engine.

2.1 Control strategy

Control systems used in this system consist of diesel engine control systems, generator control systems, and power electronics converter control systems. The governor is in charge of controlling the rotation of the diesel engine (28,29). The exciter controls the generator and is in responsible for maintaining the generator output voltage (30). The excitation system controls field current from the synchronous generator. It is the responsibility of the Vienna rectifier system to maintain a constant dc output value (31). The application of the Vienna rectifier system can be used for a capacity of 1 kW (32) to 5 MW (33) and as a current rectifier at high voltage and high power, as well as a boost rectifier (34). In the simulation of the Vienna rectifier system, the control system is intended to use an input nominal AC voltage of 400 V and a nominal DC bus output voltage of 700 V. The inverter control method uses a virtual synchronous generator (VSG). Researchers have been interested in this VSG control system because of its ability to adjust frequency and voltage in both networked and stand-alone (35) (36) (37). The input voltage for the inverter is 700 Vdc, and the output voltage is 400 V, with a constant frequency of 50 Hz.

2.2 Strategy for reducing fuel consumption

As described previously, engine rotational speed and torque influence fuel consumption. In the previous study (20), the curve for the engine speed control system was chosen using a linear line equation by taking two points (maximum and minimum) from the fuel flow rate curve in the absence of a manufacturer's recommendation. Therefore, with reference to the previous weaknesses, this paper offers a curve selection model from SFC data using the AIWPSO algorithm to be able to minimize fuel use while still being able to serve the load properly. In this research, Figure *2* depicts the rotational speed control model that reduces fuel consumption by following load demand.

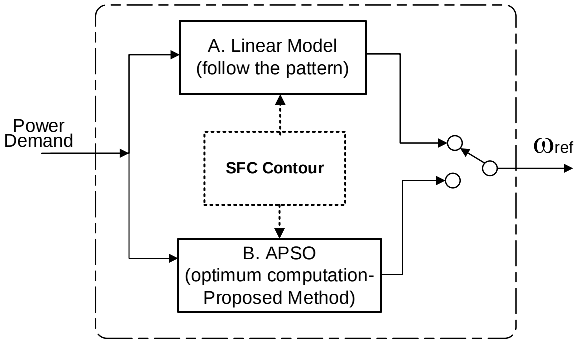

Figure 2 Speed - Power Control Reference model to minimize fuel use in this study

2.3 Load Model

The simulation adopts a resistive load model with values between 210 and 320 kW obtained from operating data. The load model utilized in this simulation is depicted in Figure *3*. Furthermore, several proposed models are simulated with MatLab/Simulink using the load model to observe the results.

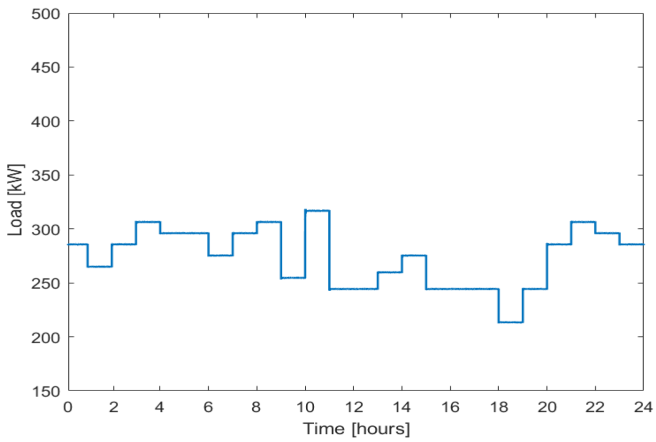

Figure 3 The Daily Load Model is Adopted for the Simulation

2.4 Fuel consumption curve

Considering the specific engine fuel consumption curve, this simulation aims to minimize the fuel consumption of the ASD-SG system. However, since the authors were unable to obtain detailed engine data published from the manufacturer for the ASD-SG system, a fuel contour map was simulated in Matlab using the contour.m function and data from the CSD-SG system (38).

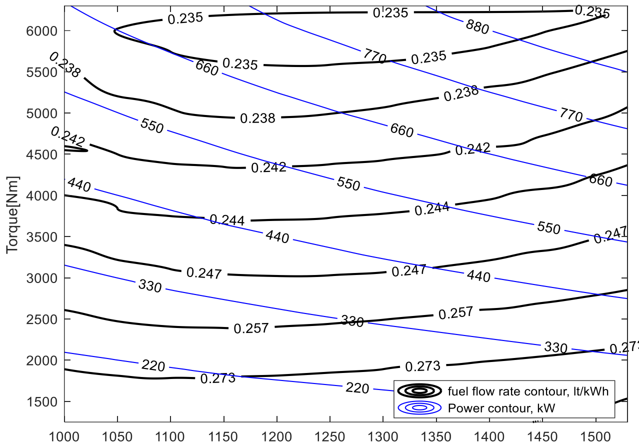

Figure 4 Map of Power and Fuel Flow Rate Contours in Relation to Diesel Engine Torque and Speed

Figure 4 depicts the power contour characteristics associated with fuel consumption, torque, and engine speed for a 1000 kVA diesel engine. From Figure 4, it can be observed that even if the power generated is the same, the fuel consumption at different speeds will vary. The lower the fuel flow rate, the more efficient the engine, as it can generate more power while consuming less fuel. For instance, while the engine is running at 440 kW, variable speed technology can reduce fuel consumption from 0.257 ltr/kWh at 1500 rpm and 2815 Nm of torque to 0.244 ltr/kWh at 1130 rpm and 3735 Nm of torque.

On the contour map, the relationship between the fuel flow rate and the engine's Specific Fuel Consumption (SFC) can be expressed as Equation 1 while the relationship between torque, speed and power is written in Equation 2 (39).

$$SFC = \frac{v_{fuel} \times \rho \times 1000}{3600} \tag{1}$$

$$\begin{aligned} P_e^i &= \omega_e^i \tau_e^i \\ &= \frac{2\pi n_e^i}{60} \times \tau_e^i \end{aligned} \tag{2}$$

where SFC is Specific Fuel Consumption (g/kWh), v_{fuel} is the fuel flow rate (ltr/kWh), ρ is the density of fuel (kg/m^3), P_e^i indicates the operating point of the engine power (kW), ω_e^i is the operating point of the engine rotation speed (rad/s), n_e^i is the operating point of the generator rotation speed (rpm), and τ_e^i is the operating point of the engine torque (Nm).

The following Equation 3 can be utilized to determine the amount of fuel that is consumed by the engine while it is operating:

$$T_{fuels} = v_{fuels} \times P_e^i \times t \tag{3}$$

where T_{fuels} is the total amount of fuel consumed (liters) and t is the engine operating time (hours).

Furthermore, the variation in fuel flow rate will influence the rotational speed of the diesel engine. The generator output frequency will be affected by the change in rotational speed, as shown in Equation 4.

$$f = \frac{p.n_e^i}{120} \quad (4)$$

where f is the frequency (Hz), p is the number of generator poles.

2.5 Adaptive Inertia Weight Particle Swarm Optimization Algorithm

The Adaptive Inertia Weight Particle Swarm Optimization (AIWPSO) algorithm is a metaheuristic method in the field of swarm intelligence. It has several advantages that other metaheuristic methods do not have, such as reliable calculation speed and accuracy, efficiency in maintaining diversity and a search mechanism that is more efficient and is still used today (27,40,41).

The Particle Swarm algorithm mimic the movement behavior of a bird looking for food to track its evolution. It possesses a particle figure that can generate a swarm. For this model algorithm, the particle tries to change its position based on what it knows and what its neighbors know, and it uses the best position it and its neighbors come up with. Consider x and v to be the position and constant velocity of the particle in the search space, respectively. At k iterations, the particle's position and velocity can be estimated using the following Equation 5 and Equation 6.

$$v_i^{(k+1)} = w \cdot v_i^k + c_1 \cdot r_1 (xBest_i^k - x_i^k) + c_2 \cdot r_2 \times (gBest_i^k - x_i^k) \quad (5)$$

$$x_i^{(k+1)} = x_i^k + v_i^{(k)} \quad (6)$$

where k is the iteration step, i is the particle, c_1 and c_2 are the constants used to measure the contribution of the cognitive and social components, AIWPSO determines the state of the particles and improves convergence by adaptively updating inertial weights respectively, r_1 and r_2 are random values [0–1] where stochastic elements are included in these algorithms and parameters are independent of time; and each is the best position of the individual and the group. w is the weighting factor, the range of inertial weights is [0, 1]. AIWPSO determines the state of the particles and improves convergence by adaptively updating inertial weights.

Inertia weights were introduced for the balance between global and local traceability. In general, the inertia weight parameter (w) is obtained by using the following Equation 7:

$$w = w_{max} - \frac{w_{max} - w_{min}}{k}\, iter \quad (7)$$

where w_{min} is the initial weight, w_{max} is the final weight, k is the maximum number of iterations and *iter* is the number of existing iterations.

AIWPSO computational process steps are described in the framework shown in Figure 5. The AIWPSO algorithm will choose the best curve by determining the appropriate objective function. Particles look for an objective value as the best solution, which is when the equivalent fuel flow rate is lowest by introducing a mechanism to adaptively update the inertial weight (w) during the optimization process.

The following are the detailed steps for the AIWPSO algorithm:

1. Initialize the swarm and control parameters, including the number of particles, maximum number of iterations, acceleration coefficients, and initial velocity.
2. Set the maximum and minimum values for the inertia weight.
3. Diesel engine parameter receive rpm position particle (1) & (2)
4. Evaluate local best update criterion.
5. Initialize the velocity of each particle to a random value within a specified range.
6. For each iteration, update the velocity and position of each particle using the following Equation 5, Equation 6
7. Update the inertia weight using the following Equation 7
8. Evaluate the fitness of each particle and update the personal best and global best positions if necessary.
9. Repeat steps 3-7 until the maximum number of iterations is reached.
10. Return the best solution found.

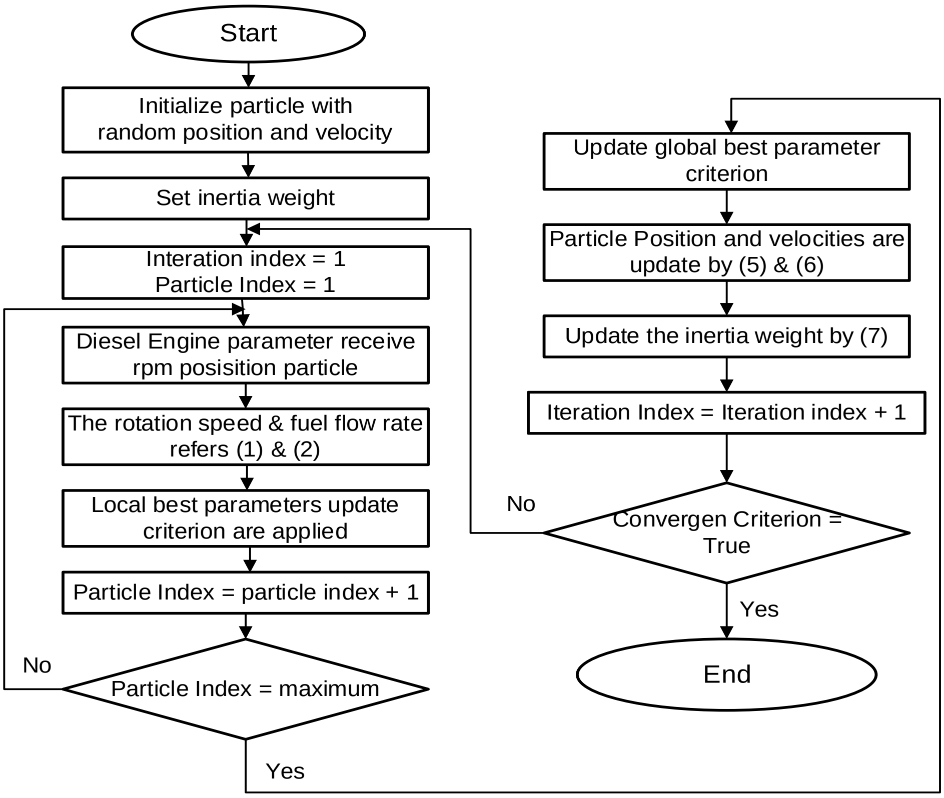

Figure 5 Algorithm of AIWPSO method for minimal fuels consumption

3. Results and Discussion

This section describes the results and analysis of system simulations designed according to the design plan. Using the SFC curve as a reference, it is possible to determine the minimum fuel consumption at each operating point. MatLab/Simulink is utilized to simulate the designed model in order to evaluate its performance.

Figure 6a depicts the reference line for linear model speed control in the contour map graph, which is based on prior research (20). Using an imaginary reference line that connects two points that have been chosen, the upper point, where the rotational speed is 1500 rpm and the torque is 5600 Nm, and the lower point, where the rotational speed is 1070 rpm and the torque is 1800 Nm. Figure 6a also displays the computational results of the AIWPSO algorithm to minimize fuel flow. The steps of the AIWPSO algorithm used to minimize fuel flow refer to Figure 4. The AIWPSO method uses the following initialization values: i = 8, k = 100, w_{max} = 0.9, w_{min} = 0.9, $c_1 = c_2$ = 1.4, and $r_1 = r_2$ = 0.4.

In Figure 6b, the machine operating points from the linear control model and the AIWPSO algorithm model are shown which are plotted on a contour map. It can be seen that in the AIWPSO control model, the set of machine operating points tends to be more upright compared to the linear model. As a result, the AIWPSO algorithm model improves fuel consumption efficiency better than the linear model.

The simulation results of the rotational speed control operation are shown in Figure 6c. Overall, the graph demonstrates that the engine speed varies less and is more stable when the speed control using the AIWPSO algorithm approach is applied, as compared to when the linear line control model is employed. For example, observed in the fifth hour with a load of 290 kW, the speed value obtained using the AIWPSO control algorithm was 1,036 rpm while the speed value referring to the linear line was 1,271 rpm.

Furthermore, Figure 6d shows a comparison of fuels flow rate between the two models. It can be seen that the AIWPSO model has a lower value fuels flow rate than the linear line model. This occurs because the AIWPSO algorithm minimizes fuel use according to the power required by the load. This is one of the reasons why the AIWPSO algorithm provides improved fuel efficiency.

Further, Figure 6e shows that the difference in fuel consumption between the two models at the same load is greater when the load is low. For example, at the sixteenth hour for a load of 245 kW, when using the AIWPSO control, the amount of fuel used is 63.3 liters/hour, whereas when using the linear control, the amount of fuel used is 64.4 liters/hour.

The recapitulation of the fuel usage calculation results for the two models is shown in Figure 6f. It is known that the ASD-SG system with the AIWPSO speed control model uses 1,678 liters of fuel per day. Meanwhile, using the linear approach, fuel consumption is 1,693 liters per day. Therefore, AIWPSO provides savings of 15 liters per day or 450 liters per month. This is in accordance with the statement (21) which states that control with a global optimum algorithm, in this case using the AIWPSO approach, will provide good efficiency, which is consistent with the observed trend of savings. The application of the AIWPSO algorithm has great potential in increasing efficiency and reducing operating costs in the use of diesel generators. In order for this technology to be optimally applied in the actual world, obstacles such as computational complexity, convergence speed, and parameter sensitivity must be considered. Therefore, further research and development of new technologies is required in the future to eliminate these obstacles.

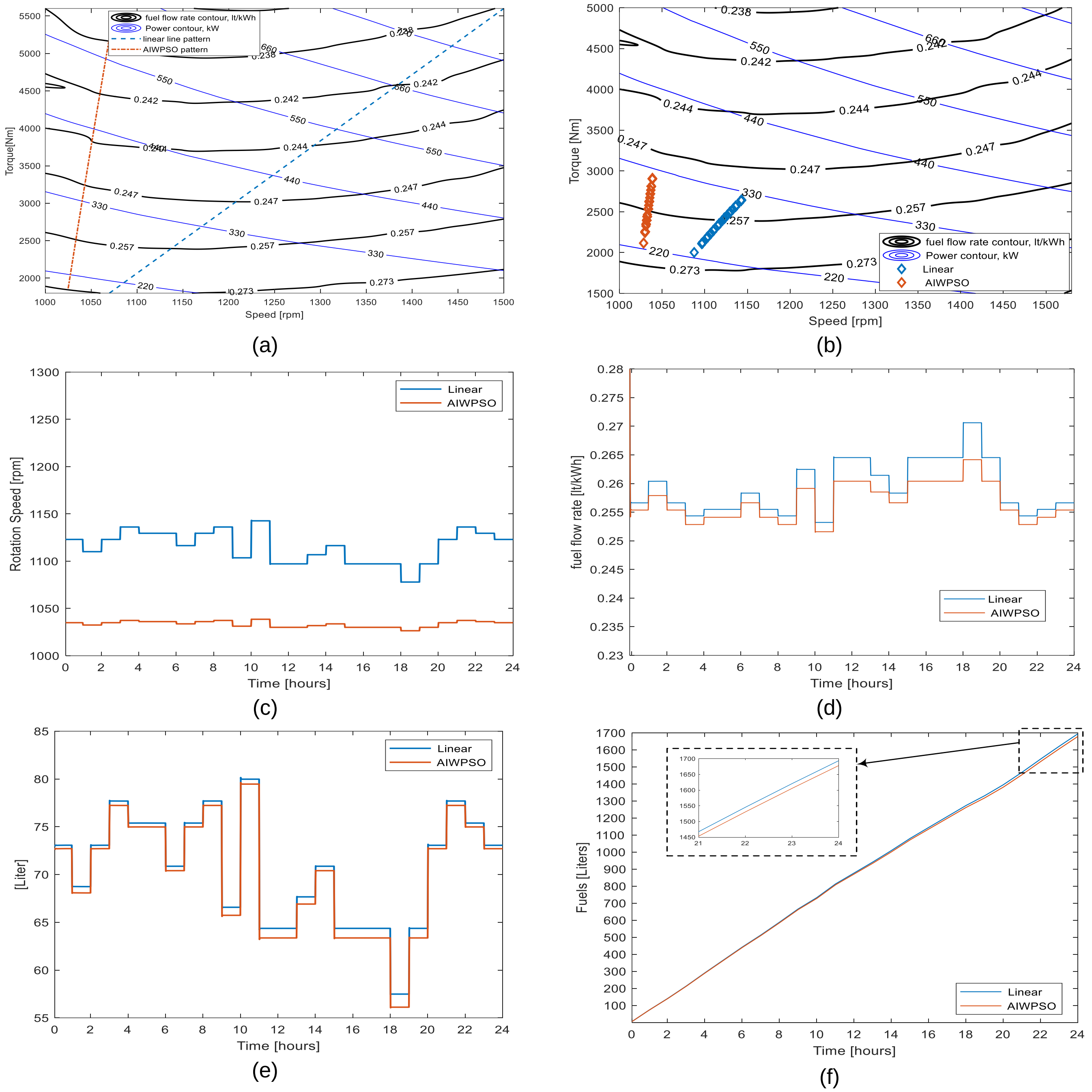

Figure 6. Results of System Performance Simulations with Variable Speed Using Linear Models and AIWPSO (a) Reference Line Pattern for Both Model, (b) Comparison of Machine Operating Point, (c) Comparison of Diesel Engine Speeds, (d) Comparison of Fuels Flow Rate, (e) Comparison of Fuel Consumption, (f) Comparison of Accumulated Fuel Consumption

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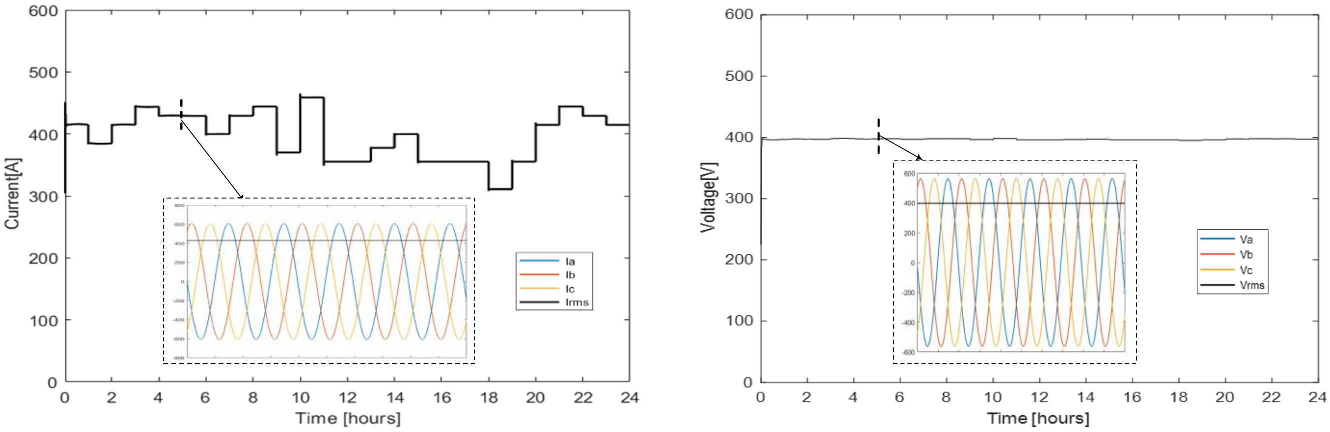
Referring to subchapter 2.1, the simulation results of the ASD-SG converter system are then presented. According to these results, it is known that the two models can adapt to the electrical load demand. The converter in this system is an AC/DC/AC converter that converts the variable frequency input voltage and current into a constant and stable frequency quantity.

Figure 7a depicts the output current form of the inverter. There are three phases of the current each having a similar wave pattern but a different phase than the others. This current can vary depending on the load and produces a three-phase output that matches the load requirements. Meanwhile, the output voltage is shown in Figure 7b. According to this graph, the converter system has a maximum voltage of 565.7 volts. Therefore, the rms voltage is 400 Volts (Vmax/sqrt(2)). On a review of both these current and voltage measurements, it appears that the ASD-SG system performs better than the system proposed by (42).



(a) (b)

Figure 7. Output of the Inverter (a) Current, (b) Voltage

4. Conclusion

In this study, a fuel economy model for the ASD-SG system has been developed and simulated. This model utilizes engine rotational speed control based on the fuel consumption curve of the engine. In this model, the control of the engine speed uses the Adaptive Inertia Weight Particle Swarm Optimization (AIWPSO) algorithm, while the comparison model uses linear control. The amount of fuel saving per day is 15 liters, or approximately 1%, as a result of improving the control system without adding equipment. The simulation results generally show that the model with the speed control method using the AIWPSO algorithm has a smoother rotational variation and is more fuel efficient than the comparison model. AC/DC/AC power electronic converters using Vienna rectifiers and inverters have proven to be successful in meeting load needs and can operate normally on both models. This control system, with the AIWPSO algorithm, produces very effective results in the computational process of obtaining fuel savings and smoother engine speed configurations.

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