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The potential of variable speed diesel application in increasing renewable energy source penetration

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Abstract

Integration of renewable energy source (RES) generation to displace diesel generation can present clear economic, environmental and social benefit. While low level RES integration is relatively easy to achieve, both the cost and complexity escalate as systems target increasing RES penetration. A key barrier to greater RES penetrations remains the inefficiency of diesel generation to operate at low or partial loading. To achieve low or partial loading, conventional fixed speed diesel technologies must rely on prescribed purge routines, which serve to increase emissions intensity and fuel consumption. Fixed speed constraint remains the primary barrier to increased engine flexibility and improved partial load efficiency. This paper investigates redesign of the diesel generator to achieve variable speed operation. A suitable design basis is developed, with laboratory testing used to validate unit performance, ahead of economic evaluation. Economic modelling is presented to explore the improve engine flexibility, required of hybrid diesel applications. Variable speed application is shown to reduce diesel fuel consumption by up to 40 % in comparison to conventional hybrid diesel applications.

Keywords: hybrid diesel, isolated power system; partial load; renewable energy; variable speed diesel.

1. Introduction

Globally diesel represents the majority of generation within remote and isolated power system [1]. Diesel generation provides this market an accessible, reliable and proven generation technology [2]. Unfortunately, the pollution and high operating cost make continued reliance on diesel generation undesirable [3]. Alternative renewable generation technologies, such as wind and solar photovoltaics are increasingly be integrated to realise

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clean and cost competitive generation options [4]. As diesel-based power systems are hybridised in support of renewable integration a number of technical challenges present, principally power security.

When integrating renewable technologies, the variability of the renewable resource requires careful consideration [5]. Renewable technologies, such as wind and solar photovoltaics can exhibit large resource variability, adding to the integration challenge. To balance supply and demand, as required to manage the system frequency without curtailment, the renewable generation requires pairing with a flexible generation source [6]. Diesel generation is a logical partner, given the technology is often preexisting and dispatchable. However, while the diesel engine is easily scheduled to parallel with renewable generation, the operating characteristics of the diesel constrain partial load approaches. For fixed speed diesel applications, as the load decrease, so does engine efficiency. The condition increases both emissions intensity and fuel consumption, with engine loading below 30% of rated generally prohibited to preserve engine condition [2, 7]. Both load limits and engine efficiency serve to restrict engine flexibility and limit hybrid operability [8].

To increase system flexibility a battery energy storage systems (BESS) is commonly integrated. Batteries facilitate high penetrations of renewable energy yet add significant cost and complexity to the system. Numerous researchers have investigated these integration challenges via optimisiation of the sizing and/or control of the BESS [9-12]. While a wide range of BESS applications exists (bulk energy supply [13], ancillary services [14-16], transmission/distribution augmentation, or consumer services [17-19]), diesel application remains either on [20, 21] or off [22, 23]. Existing research favours diesel off functionality, with very little investigation of coordinated diesel generator response undertaken [24]. In contrast, continuous diesel operation, discuss further within this paper, remains the more accessible application [2]. In improving RES penetration without fully replacing diesel service, continuous operation provides an important transitional stage to reduced diesel reliance. Under continuous diesel methodologies the flexibility of the diesel generation to run at partial load becomes a key determinant of successful renewable energy source utilisation.

As an alternative to BESS integration a number of approaches exist to improve the flexibility and partial load efficiency of diesel generation. All approaches target improved combustion efficiency within the cylinder environment, either via primary or auxiliary system redesign. Auxiliary measures involve modification to the engine's heating and ventilation systems. Auxiliary measures may include load variable cooling or air charge treatment, however, as these approaches do not address the fixed speed performance constraint, there impact is limited [1]. Primary measures involve modification of the engine's combustion or timing. These measures offer superior results, but also add complexity and expensive. Approaches are either mechanical, for example integration of a gearbox between the generator and the engine, or electrical, conditioning a variable frequency variable voltage output to serve a fixed frequency load [25]. Of the two approaches, electrical concepts offer improved flexibility and efficiency for reduced complexity and cost [1] and are the focus of this paper.

The paper is structured as follows; an introduction to variable speed diesel application is presented, section two. Case study comparison of conventional fixed speed and variable speed diesel configurations are then described, section three, with case study results discussed in Section four. Conclusions and further research discussion are presented in section five and six respectively.

2. Variable Speed Diesel

Modern diesel engines permit short term partial load application; however, low load efficiency is poor, constrained by the fixed speed design basis. For fixed speed applications, as load reduces, engine speed is held constant. The result is an increase in fuel consumption per kWh generated. Unchecked, partial loading can also result in engine damage, via cylinder glazing and, in extreme cases, piston seizure [2]. Small and medium sized diesel generators are particularly sensitive to partial load operation, presenting elevated partial load fuel consumption, Fig.1. The response from industry has largely been to avoid partial load applications, however, the advent of RES technologies has generated increased interest in the practice. Subject to renewable pairing, diesel assets face increased partial load exposure as the available load is shared. Accordingly, hybrid diesel application requires increased flexibility of the diesel generator, with variable speed configurations one possible solution.

Wind turbine technologies face a similar technical challenge, how to operate efficiently as the wind resource varies, yet remain connected to a fixed frequency network. To exploit the improved generator efficiency of variable speed generation, rectification and inversion of generation is undertaken via a partial or full power converter. The approach allows variable frequency output from the wind turbine yet complies with the fixed frequency of the network. Variable speed approaches are equally applicable to diesel generation, allowing the diesel engine to vary speed subject to load changes. For variable speed diesel generation, a power converter can also be used to condition a variable frequency variable voltage supply for network compliance. Variable speed diesel generation allows the diesel engine to select the most engine efficient speed for the required load. The controller allows the engine speed to reduce as engine load reduces. The practice maintains a higher cylinder fuel load per cycle, as required to maintain the thermal characterisation of the engine at partial load. Of note, the controller also permits the engine to increase speed above rated loading, allowing the engine to exceed its rated power output by permitting an increase to the rated engine speed. Accordingly, both the low and high load operating range of the engine is increased under a variable speed control methodology. Across this extended capacity range variable speed diesel generation is able to achieve improved part load efficiency, extended service life, reduced emissions intensity and reduced acoustic emissions [26, 27].

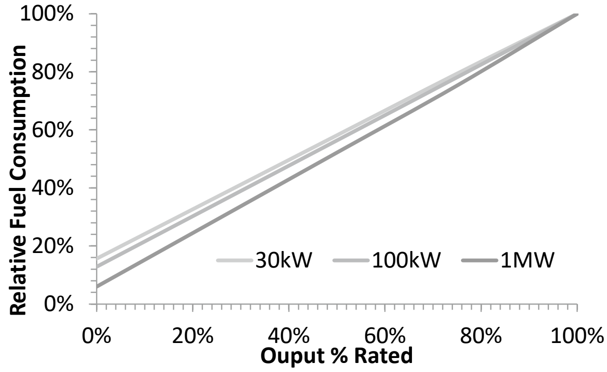

Fig. 1.Fixed speed diesel generator fuel consumption for various generator capacities across partial and full load applications

The preferred design basis adopted for this variable speed diesel study adopts a permanent magnet generator (PMG), with full power converter. The power converter consists of a PWM rectifier, DC link and PWM inverter, Fig. 2.

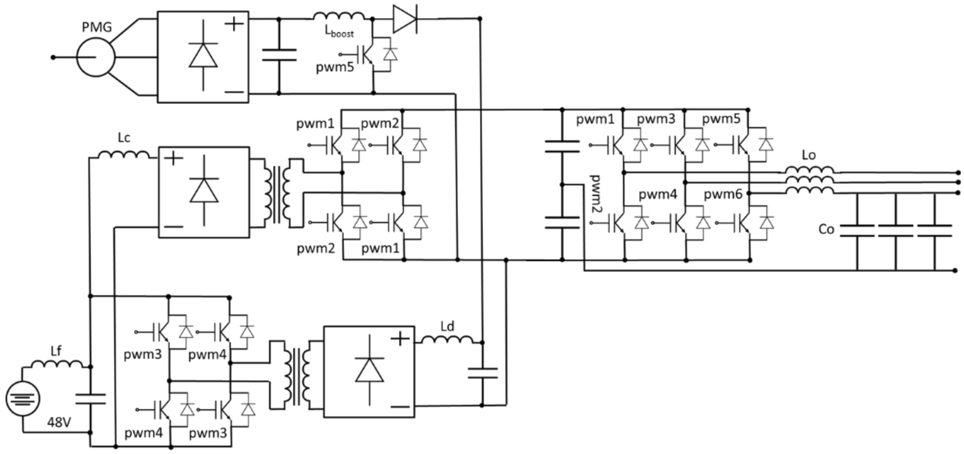

Fig. 2. Variable speed diesel generator electrical basis of design

The advantage of using a PMG generator configuration, as opposed to a doubly fed induction generator [25, 28], is the ability of the PMG full power converter solution to offer higher partial load efficiency, improved reactive power generation and low voltage ride-through capabilities. The disadvantage in using a PMG involves the cost of the full power converter, however, it is likely that the cost of this technology will reduce with experience curve of wind, solar and battery technologies. A 48V battery is incorporated into the variable speed diesel technology tested to provide improved transient response, as proposed in [29].

3. Experimental Setup

The experimental setup consists of an 11kW variable speed diesel generator, designed around a Perkins 403A-15 diesel engine and a custom permanent magnet generator manufactured by Integrated Electric Company. The 1.5 liter, 3 cylinder engine is indirect injected and naturally aspirated, with a compression ratio of 22.5. A digital signal processor controller is responsible for variable speed regulation of the engine's electronic governor. The specific fuel consumption of the diesel generator at fixed kW output was measured using a resistive load bank to provide a stable AC load, Fig. 3.

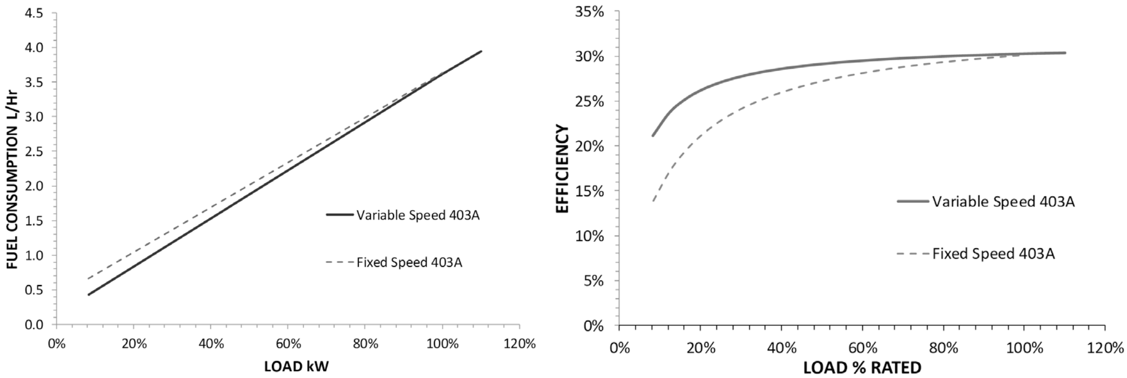

Fig. 3. Fixed speed versus variable speed generator performance

Comparing the performance of both fixed speed and variable speed diesel technologies a number of observations are relevant. At full load, engine efficiency is comparable, with variable speed applications operating at, or close to, fixed speed ratings. At rated load, variable speed technologies effectively replicate fixed speed operation. The advantage of variable speed approaches at high loading remains their ability to exceed unit rated power, exploiting the benefits of higher rpm to extend an engine's maximum duty. At partial load, dramatic improvements in engine efficiency are evident, with the unit adopting a lower rpm to improve combustion efficiency, Table 1. Improved engine efficiency is delivered as load reduces via preservation of both cylinder fuel loading and accordingly cylinder temperature. Notably, as load reduces injector leakage, convective engine cooling and mechanical engine losses all remain as fixed values, and represent an increasing burden for partial load application. At lower rpm this issue is addressed via higher cylinder fuel loading and reduced mechanical and cooling losses.

In addition to the efficiency gains, both the acoustic and emissions intensity improve proportionally. The primary emission gases of concern for diesel generation are NOx and particulate matter PM. NOx is directly linked to combustion temperature, with NOx emissions reducing with load. Accordingly, for both fixed speed and variable speed diesel application partial load NOx compliance is not a primary concern. In contrast, partial load PM emissions significantly increase, given the need to routinely purge the engine of carbon accumulation. Purging consists of running the engine at elevated load and temperature for a sustained period. One hour purge, ever eight to twelve hours of load below 30% rated is typical for fixed speed applications [30, 31]. For variable speed application the requirement to regularly purge your engine is eliminated, with reduced occurrence of internal carbon and soot accumulation. Accordingly, PM emissions are significantly reduced under variable speed applications. As both NOx and PM capture or treatment technologies add cost and complexity to the diesel generator, an ability to run without after treatment approaches serves to improve the economics of diesel generation in regulated markets.

Table 1. Variable Speed Diesel Speed Control

Load		Engine Speed		Fuel Consumption	
Load kW	Load % rated	RPM	speed % rated	L/Hr	L/kWh
1.47	13.8%	911	61%	0.84	0.57
2.98	27.9%	915	61%	1.19	0.40
4.56	42.7%	985	66%	1.64	0.36
6.04	56.6%	1111	74%	2.03	0.34
7.62	71.4%	1300	87%	2.67	0.35
9.13	85.6%	1472	98%	3.09	0.34
10.67	100.0%	1675	112%	3.60	0.34
12.17	114.1%	1760	117%	4.21	0.35

4. Kondey Island Case Study

Case studies simulation has been used to assess the economic viability of variable speed diesel application for remote island electrification. The case study presented considers the island of Kondey, located within the Republic of Maldives. The Republic of Maldives represents a vast island nation consisting of 199 inhabited islands. The islands are formed on a chain of 26 coral reef atolls situated within the Indian Ocean, 800km due south west of Sri Lanka. Approximately a third of inhabited islands have populations of less than 1000 people [32]. All islands are primarily serviced by diesel generation, with the more remote islands facing some of the highest cost and lowest reliability electricity generation. Cost for energy within the Republic of Maldives have historically exceeded $400/MWh, with smaller and more remote loads paying considerably more for diesel supply and transport [33]. In recognition of increasingly volatile diesel fuel pricing, and the adverse impacts of climate change on the low lying atoll community, the Government of Maldives is planning to become a low to carbon neutral economy within the next decade [34]. The most suitable technologies for the Republic of Maldives include wind and solar PV, however space is strictly limited in most applications, with communities tasked to maximise the capacity factor or efficiency of each installation. Within this context, variable speed diesel application holds the potential to increase both the efficiency of the existing diesel generation, but also to increase renewable energy penetration from existing wind and solar assets. Importantly, the approach would not require any additional land area.

Kodney Island is situated within Huvadhu Atoll, to the south of the island archipelago. Kodney was one of the first islands to include wind and solar PV integration, as identified within United Nations and Asian Development Bank feasibility studies [35, 36]. The hybrid power system was developed for Kodney in 2007, consisting of two diesel generators,17kVa and 32kVa, 10.8kW of wind generation, 5kW of solar PV and a 96kWh battery [37]. At the time of development, the daily average Kodney load was 127 kWh/day with a 26kW peak. The daily load profile for Kondey Island is shown below in Fig. 4, exhibiting a typical twin peak profile at 7am and 7pm. Renewable energy and storage integration successfully reduced the annual system fuel consumption from 18,400 liters to 11,900 liters, a 35% reduction. The system achieved a 25% renewable penetration to deliver a 15.4% reduction in cost of energy. The performance of the Kodney hybrid power system have been used to validate a modelling methodology, able to extend consideration to variable speed diesel application. The modelling input are defined below in Table 2.
Assessing a variable speed diesel configuration for Kondey Island, we observe that further cost of energy reductions are possible, Table 3. Interestingly, cost savings are not achieved exclusively via reductions in the diesel fuel consumption. Instead, the increased flexibility of variable speed diesel generation, allows a reduce battery utilization without performance penalty. The ability of variable speed application to rationalise the required BESS capacity, permits further reduction to the cost of energy, achieved both via removal of the BESS and improved diesel efficiency. Fuel consumption remains similar to the fixed speed diesel plus BESS system performance, however without the cost and complexity of BESS integration. The modelling suggests that BESS integration was not the lowest cost RES enabling technology.

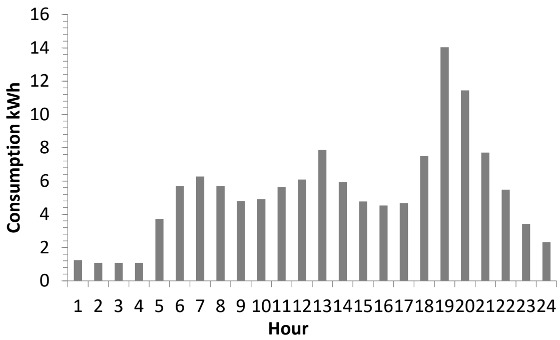

Fig. 4. Fixed speed versus variable speed generator performance

Table 2. Economic model inputs.

Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
Discount Rate	8%	Fuel Curve Slope	0.306 -0.324	Wind CAPEX	$1250/kW	BESS Roundtrip Losses	8%
Project Life	25 years	Diesel Fuel Cost	$1.11/L	Wind Turbine Lifetime	25 years	Solar PV CAPEX	$1000/kW
Diesel CAPEX (17kVa/32kVa)	$7,000/ $15,000	Diesel Heating Value	43.2 MJ/kg	Average Hub Height (10.4m) Wind Speed	4.4 m/s	Solar PV Derating Factor	88%
Diesel Maintenance Costs	$.3/h	Diesel Density	820 kg/m^3	Rotor Diameter	3.72 m	Solar PV panel efficiency	16.8%
Diesel Lifetime	20,000 h	Diesel Low Load Limit	0-25%	BESS CAPEX	$500/kWh	Average GHI	5.82 $kWh/m^2/day$
Fuel Intercept Coefficient	.21-.39 L/h	Variable Speed CAPEX Premium	6-14%	BESS Replacement Cost	$500/kWh	Converter CAPEX	$300/kW

The advantage of variable speed diesel technologies as a low cost, low complexity approach to RES integration is further highlighted when we assess the current day performance of Kondey Island. The island's load has grown substantially since 2007 and by 2012 represented a total annual consumption of 130MWh, an annual increase of approximately 20% per year. [38]. During this load growth RES capacity/generation has remained fixed, and subsequently has reduced the observed renewable penetration from 25% to under 10% per annum. Load growth has served to invalidate both the technical and commercial justification for BESS integration. Modelling renewable energy penetrations for the revised load illustrates the absence of instantaneous renewable generation surplus. As such, the battery becomes a stranded assets, inflating the cost of energy to consumers for no appreciable benefit. Had a variable speed diesel methodology been adopted initially, without a reliance of energy storage, energy costs would now be 8% lower, offering improved system resilience to load variation via the systems lower capital expenditure. Considering both the original business case and the current Kodney Island system performance, the ability of variable speed diesel methodologies to reduce total diesel consumption, improve RES penetrations and mitigate the need for BESS integration has shown to offer Kodney Island reduced energy costs and improved system flexibility under load growth. BESS are likely to have an important role on Kodney Island should significant additional RES generation be integrated, however, until such time, they do not currently offer the system optimal technical or economic performance.

Table 3. Fixed Speed Vs. Variable Speed Comparison

	Fixed Speed Application			Variable Speed Application		
	Fixed Speed Diesel Only	Plus Renewable Generation	Plus Energy Storage	Variable Speed Diesel Only	Plus Renewable Generation	Plus Energy Storage
Cost of Energy $/kWh	$0.59	$0.54	$0.50	$0.56	$0.49	n/a
Fuel Usage L	18,341	15,202	11,908	16,847	12,676	n/a
Renewable Penetration %	n/a	16.16	24.87	n/a	27.49	n/a

4. Conclusion

Fixed speed diesel applications have failed to provide the flexibility required of modern hybrid diesel power systems. The advent of renewable energy source generation has exposed these systems to increased generation variability/volatility, a scenario for which fixed speed diesel generation is poorly suited. While additional enabling technologies, such as battery energy storage systems, can be introduced to address the challenges of renewable energy source integration, these technologies themselves add cost and complexity to the system. As an alternative to battery integration, this paper explores the ability of variable speed diesel generation to provide improved generator flexibility, thus eliminating the need for batteries. Experimental testing of a variable speed diesel generator is shown to provide fuel efficiency gains of up to 40% at partial load, promoting both increased renewable energy utilisation and reduced diesel fuel consumption. Subject to load growth, variable speed diesel technologies are also shown to provide system resilience, in contrast to BESS integration which can become obsolete as RES penetrations reduce. Accordingly, variable speed diesel approaches are recommenced as a precursor to energy storage integration, representing a transitional technology, able to efficiently reduce the cost and complexity burden to RES integration

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