

# Diesel Plant Sizing and Performance Analysis of a Remote Wind-Diesel Microgrid

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**Abstract**— This paper introduces an energy-flow model developed for performance analysis and unit sizing of an autonomous wind-diesel Microgrid. A remote community in Canada is used as the study system, for which a medium penetration wind power plant has been integrated into a system served by a diesel plant with three equally sized diesel generators. Based on field observations and monitored data for almost two years of operation, an energy-flow model is developed which incorporates operating constraints and control requirements of the autonomous wind-diesel system. The model is employed to analyze the interaction of wind and diesel power plants in order to identify alternative unit sizing approaches that improve wind-energy absorption rate of the wind plant, fuel savings and overall efficiency of the diesel plant. Optimization criteria for unit sizing of the diesel plant in the presence of the wind farm are discussed and system performance for several configurations based on multiple units with a reduced-size diesel unit are investigated. The simulation results from the energy-flow model for two operation scenarios are compared with the field observations and an optimum combination of multiple diesels with reduced-size units is suggested.

**Index Terms**— Autonomous wind-diesel, unit sizing, distributed generation, energy flow, Microgrid.

## I. INTRODUCTION

Traditionally, remote communities in Canada have been supplied electricity almost exclusively by diesel units, due to the reliability and confidence in the technology. The Ramea wind-diesel project is the first medium penetration wind installation integrated to a diesel generator based power supply system in Canada [1]. The project has been used by CANMET Energy Technology Center as a pilot project site and benchmarking system to further advance the wind-diesel integration technology and analyze real-world operation of these systems in the context of remote Microgrids. Reference [2] provides a RETScreen® case study for economical pre-feasibility analysis of the project that demonstrates financial aspects of remote wind-diesel systems.

The remote Microgrid and Mini-grid projects aim to investigate autonomous operation of the isolated power generation and distribution systems which use multiple energy sources to supply a community load. The immediate applications are for electrification of non-integrated areas and geographical islands based on alternative energy generation technologies, particularly with high penetration of renewable resources. The principal issues to consider are: optimal sizing of the power generation plant, control strategies; technologies to

maintain grid stability; short-term power balancing and long-term energy management; power quality and reliability of the power supply system.

Integration of renewable energy (RE) sources into fossil-fuel based power generation systems for remote areas can offer attractive economical and environmental merits including considerable fuel savings and carbon dioxide emission reductions. However, intermittent aspect of RE sources along with highly variable nature of load demand for these applications may lead to significant degradation of RE utilization due to the excess RE energy losses. The RE energy losses is considered as a portion of the energy that cannot be delivered to the system. The RE losses are more significant for medium to high penetration depth of RE sources, especially when no electric energy storage is used. Reference [3] discusses various configurations and operating strategies for small wind-PV-diesel systems with and/or without energy storage. However, the issue of RE energy losses and sizing requirements are not addressed since the study focus is on small systems (below 100-kW). In the case of autonomous wind-diesel systems that operate based on continuous utilization of one or more diesel generators without energy storage, various operating limits are imposed on the wind energy import to maintain adequate level of loading on the diesel generators for safe and reliable operation, [4], [5]. The excess wind energy has to be dumped when the diesel plant operates at the minimum loading.

The main objective of this paper is to develop a design methodology and analysis approach for unit sizing of an autonomous wind-diesel system. Historically, the wind power plant is integrated to an existing diesel-based power supply system in which diesel generators are normally oversized with respect to the load. Hence, maintaining a minimum loading requirement for diesel units in operation drastically reduces the overall wind energy contribution to electricity supply of the network during low load periods and/or high wind conditions. Re-sizing of the diesel units with respect to the wind plant and implementation of appropriate cycling strategies to optimize spinning capacity of the diesel plant can help improve the wind energy contribution.

The autonomous wind-diesel system of the Ramea island in the province of Newfoundland, Canada is used as a base to verify a model for energy-flow analysis and evaluate the diesel plant sizing methodology. After almost two years of field observations and collection of an adequate amount of data, the studies on the impact of wind integration on daily performance of the system and investigation of methods for optimization of the power plant can provide valuable knowledge and help support future development of similar projects.

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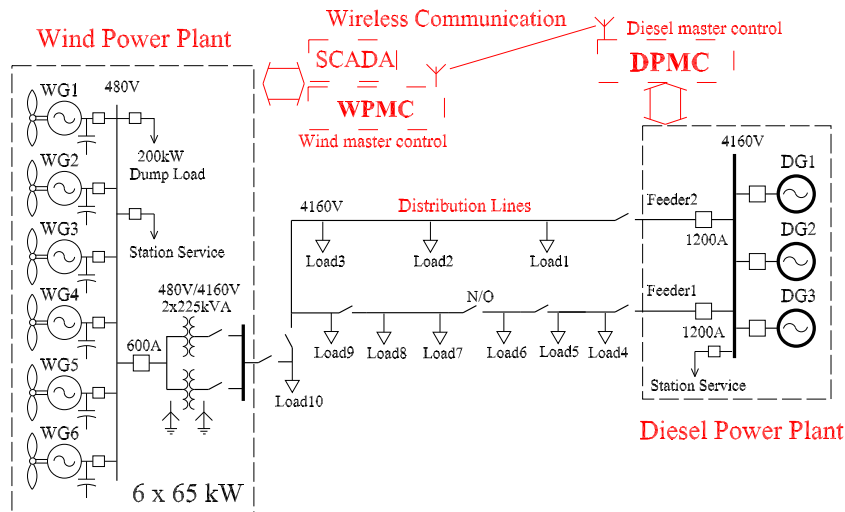


Fig. 1. One-line diagram of the remote wind-diesel distribution network

This paper considers a selected set of commercially available diesel generators and uses the annual load duration curve of the system to determine optimal diesel unit sizes that meet the following objectives:

- To improve overall diesel plant efficiency and maximize the fuel savings,
- To maximize total wind energy contribution to the grid (or equivalently minimize dumped wind energy),
- To introduce a diesel cycling and dispatch strategy that maintains adequate loading on multiple diesel sets while minimizing the number of diesel on/off cycling.

The study approach of this paper is to use an energy flow and dynamic power flow model of the autonomous wind-diesel network to investigate the daily and monthly performance of the network under various wind and load regimes. The paper is structured as follows. Section II describes the remote wind-diesel system of this study. The rationales for diesel plant sizing are discussed in Section III. Section IV introduces the energy-flow model. Section V presents a discussion on diesel plant control and operating constraints for the model. The performance analysis of the autonomous wind-diesel system based on three case studies are presented in Section VI. The summary and conclusions are stated in Section VII.

## II. STUDY SYSTEM

The Ramea wind-diesel project is the first medium penetration wind installation integrated to a remote diesel generator based power supply system for a geographical island in Canada. The wind developer, Frontier Power Systems, with support from governmental funds from the Technology Early Action Measure (TEAM) program [6], integrated 390 kW of wind into a community with a peak load of 1.2-MW. Good wind resources, correlation with high-load periods, and community acceptance and support have made this island a favorable site for development of a medium penetration wind energy system. While the utility, Newfoundland and Labrador Hydro, remains ultimately responsible for supply of the load, wind generation from this independent power producer (IPP)

can feed its power generation into the system, as long as the diesel units are loaded above a certain level. A fully automated digital control system facilitates the smooth integration of wind and ensures inter-operability with the existing remote grid.

Fig. 1 shows the one-line diagram of the Ramea distribution network including a diesel power plant, a wind power plant and two 4.16-kV feeders. The diesel power plant consists of three Caterpillar D3512 diesel engines, each with rated capacity of 925-kW at 1200 rpm. The wind power plant is composed of six identical Windmatic WM15S wind turbines with rated capacity of 65-kW at a rated wind speed of 14 m/s (50 km/h). The wind power plant also employs a load regulator to control imported wind power generation at light-load conditions in order to always maintain the loading of diesel generators at least at 30%. The network load varies in the range of 200-kW to 1200-kW with an average of 550-kW and annual energy consumption of about 4300-MWh.

### A. Diesel power plant

Three Caterpillar D3512 diesel engines are the main power generation sources of the remote wind-diesel power plant. Diesel generators are 4.16-kV, 1200 rpm and 925 kW with power factor of 0.85. Each of the diesel units is equipped with an automatic voltage regulator and a governor system. Two frequency control modes are used including: (1) a speed-droop characteristics for fast load following capability, and (2) an isochronous mode for load sharing and frequency regulation. One or two of the three diesel generators are normally required to supply the local community load. Parallel operation and cycling periods of the diesel generators are coordinated by the diesel generators' master controller.

The fuel consumption characteristics of the diesel engines are given in Table I at different load values [7]. Table I illustrates that fuel consumption of a diesel engine increases by about 23% for operation at 25% loading in comparison to the rated load. This may be identified as an important factor in determination of the minimum loading constraint of

TABLE I  
FUEL CONSUMPTION FOR CAT D3512 DIESEL ENGINE

Load % / kW	Engine Power kW	Fuel Rate Litres / hour	Fuel Efficiency kWh / litre
100 / 925.0	983.2	233.0	3.97
90 / 832.5	886.0	209.2	3.98
80 / 740.0	789.8	186.6	3.97
75 / 693.8	742.0	175.9	3.94
70 / 647.5	694.2	165.2	3.92
60 / 555.0	599.0	144.0	3.85
50 / 462.5	504.4	123.0	3.76
40 / 370.0	413.1	102.8	3.60
30 / 277.5	319.6	82.3	3.37
25 / 231.3	272.0	71.9	3.22
20 / 185.0	223.7	61.4	3.01

TABLE II  
WIND-TURBINE SPEED CHARACTERISTICS FOR WINDMATIC WM15S

<b>Cut-in speed (turbine start-up)</b>	4 m/s ( 14.4 km/h)
<b>Wind speed for rated output</b>	14 m/s (50.4 km/h)
<b>Cut-out speed (turbine shut-down)</b>	22 m/s (79.2 km/h)
<b>Restart speed (after shut-down)</b>	19 m/s (68.4 km/h)
<b>Tower height</b>	25 meter

the diesel generator. However, the determinate factor is that operation under light-load conditions significantly increases the risk of engine failure, and can cause premature ageing of the diesel generator. Operation at light load also reduces the load following capability of the generator, although the response time of the generator is highly dependent on the type of controls and the load characteristic. The minimum loading constraint of a diesel generator is normally set between 30-50 percent.

### B. Wind power plant

The wind power plant consists of six Windmatic wind turbines, a 200-kW controllable dump load, and six capacitor banks. The Windmatic WM15S is a horizontal axis, two-speed, up-wind turbine which uses two induction generators, a 65-kW unit and a 13-kW unit for the energy conversion and direct connection to the distribution system. The smaller unit is used for start-up and turbine roll over, switching to the larger unit at high wind speed, about 7 m/s. The wind-turbine speed characteristics are given in Table II. A 30-kVAr fixed capacitor bank is connected in parallel with the output of each wind turbine to partially compensate for the reactive power needs of the induction generators, Fig. 1. The start-up of the wind turbines is currently assisted by the diesel plants; each wind turbine operates as a motor until it is accelerated beyond synchronous speed, at which point it begins to generate power. The diesel plant also provides the balance of the reactive power, while the capacitor banks are switched on/off to correct the wind plant's power factor to above 0.9. However, transient reactive power support and the fine tuning is provided by the synchronous generators.

### C. Wind-Diesel control

A wind-diesel integrated control system (WDICS), designed by the Atlantic Wind Test Site [8], has been used to control

and supervise operation of the wind turbines, to facilitate its integration into the system, which is controlled and primarily supplied by diesel generator plant. The WDICS configuration, Fig. 1, is composed of (i) a diesel plant master controller (DPMC), (ii) a wind plant master controller (WPMC), and (iii) a SCADA system with internet access for monitoring and data acquisition. DPMC is a fully integrated and digital automatic controller that supervises the overall wind-diesel network operation as well as synchronization, load sharing, and load following control of the diesel generators. WPMC performs automatic control and protection of the wind power plant including start-up of the wind turbines when the wind speed rises above 4 m/s (14.4 km/h), and shutdown of the turbines for wind speed beyond 22 m/s (79.2 km/h). It also communicates with DPMC to report power generation of the turbines and to update the maximum limit for wind power import. The communication link between DPMC and WPMC is a 1-km wireless connection.

## III. DIESEL PLANT SIZING

Optimal unit sizing of a diesel power plant requires careful consideration of several factors including detailed analysis of daily and seasonal load fluctuations, annual load growth, and incorporation of practical constraints for feasible and reliable diesel operation. If diesel units are only sized based on peak and/or average load values, on an annual base, with some safety margins and additional capacity for future expansion, the diesel plant will generally be very oversized. The reason is that remote community loads are normally characterized as being highly variable, with the peak load as high as 5 to 10 times the average load [4]. A practical approach is to employ multiple units, e.g. a set of two or three diesels, with various sizes and apply a diesel cycling and dispatch strategy to optimize the loading of each unit to achieve maximum fuel efficiency.

Fig. 2 shows the fuel efficiency curve for several commercial size diesel generator reported in the manufacturer catalogue. The fuel curve for each generator is depicted between 25% and 100% of the rated capacity with diesel loading normalized to a 1-MW base. The dash-line curve shows the fuel efficiency for the 925-kW Caterpillar D3512 currently utilized in the Ramea diesel plant as a base for comparison. According to Fig. 2, in general, fuel efficiency of a diesel generator drastically reduces when the loading goes below 30-40% of the rated diesel capacity. Supplying the load with a 925-kW unit, the diesel generator should be replaced with a 635-kW unit at about 530-kW loading and/or with a 560-kW unit when the loading goes below 450-kW as the total load demand reduces. This is to maximize the fuel efficiency of the diesel plant, if multiple units with different sizes are used. The given thresholds are determined according to the intersection points of the corresponding fuel curves in Fig. 2.

A challenging aspect of an autonomous wind-diesel system with no energy storage is maximizing the wind energy absorption rate, or the amount of wind energy imported, which also affects diesel fuel efficiency. For reasons associated with risk of failure, premature generator ageing and adverse impact on

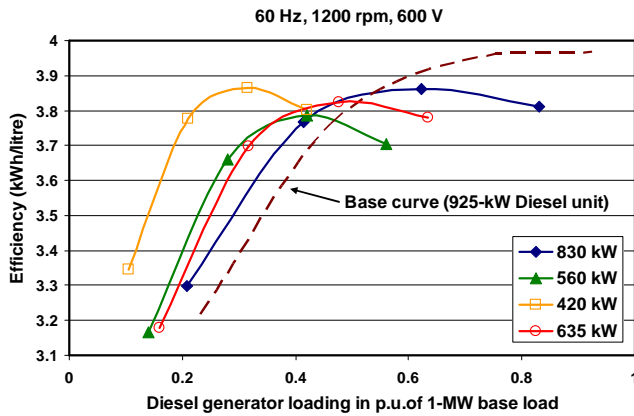


Fig. 2. Fuel curves for commercial size Detroit diesel generators based on manufacturer data sheets, [9]

fuel consumption, the minimum loading of each unit is limited to 30%. Consequently, the excess wind power is dumped when load demand is low. Managing the diesel loading based on multiple units with different sizing and applying an optimal running strategy can effectively reduce the dumped wind energy and provide substantial fuel saving. However, the dispatching strategy has to be technically reliable, practically feasible, and economically viable. This paper investigates an alternative approach for the Ramea diesel plant configuration by replacing one of the three diesel units with a smaller size diesel unit. The selection is between a 560-kW and/or a 635-kW diesel by comparing the fuel curves in Fig. 2 and the previous discussion.

An investigation of diesel loading coverage based on annual load duration curve for selected sizes are performed. An effective loading coverage of a diesel unit is defined as the area between the minimum loading constraint (MLC) and the spinning reserve constraint (SRC). Fig. 3 shows monthly variations of the minimum, average and maximum load values for the remote community based on 2005 data. MLC and SRC thresholds are also shown in Fig. 3 for three diesel generators of 925-kW, 635-kW, and 560-kW. MLC thresholds for the latter two units, based on 30% of the rated diesel capacities, are below the minimum monthly load of the network (200-kW for 2004 and 2005). However, a 635-kW unit with a SRC of 540-kW suitably meets the average load (550-kW). Analysis of the annual load duration curve based on collected data for 2005 also illustrates that the load is in the acceptable range of a 635-kW diesel generator 57% of time, compared to 39% for a 560-kW unit, [2].

The above rationales can suggest a decision in favor of considering a 635-kW unit as the optimal unit size. However, due to the positive correlation between community load and power generation of the wind plant, detailed daily and seasonal analyses of the wind-diesel power system performance are required to ensure the right selection for concurrent operation of wind and diesel plant. An energy-flow model is developed and used for this purpose.

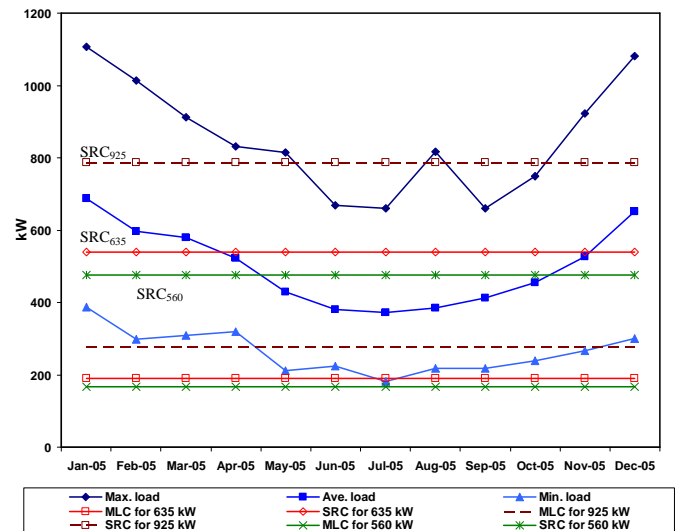


Fig. 3. Comparison between monthly variations of load demand, and MLC/SRC thresholds for each diesel units (Load: minimum, average, and maximum values; DG: 925-kW, 635-kW, and 560-kW)

#### IV. ENERGY FLOW MODEL

A dynamic energy-flow model of the wind-diesel power delivery network is developed for analysis of daily, weekly, and monthly performance of the autonomous system. A block diagram representation of the model is shown in Fig. 4. The model consists of several blocks including (i) diesel power dispatching and on/off cycling control with fuel consumption and efficiency estimate, (ii) gross wind power generation and dumped energy calculation, and (iii) generation/load balancing block. The model uses 1-minute time step for analysis. Inputs to the model are wind-speed and load demand values generated from two sets of collected field data from system operation in 2004 and 2005. The available data includes monthly collected 15-minute averages and daily monitored 1-second data that are used to generate 1-minute load and wind-speed information. The various elements of the energy flow model are explained in the following subsections.

##### A. Wind power calculation and import

Power generation of each wind turbine is calculated by applying adjusted wind-speed data per turbine,  $v_{\omega_1}$  to  $v_{\omega_6}$  in Fig. 4, to a generic power-speed curve for the turbines, [2]. The effective wind speed for each turbine is calculated by multiplying the recorded wind-speed averages from the site with corresponding wind-speed coefficients that represent relationships between average wind-power generation of turbines and their geographical distributions in the area. The total wind generation is then given by,

$$P_{WG}^{total} = P_{WG1} + P_{WG2} + \dots + P_{WG6}, \quad (1)$$

where  $P_{WG1}$  to  $P_{WG6}$  are the real power outputs of the six wind turbines. The reactive power requirement of each turbine is also determined based on a curve that represents power factor variation of the 65-kW induction generator, as the interface medium of the turbines, as a function of real power output.

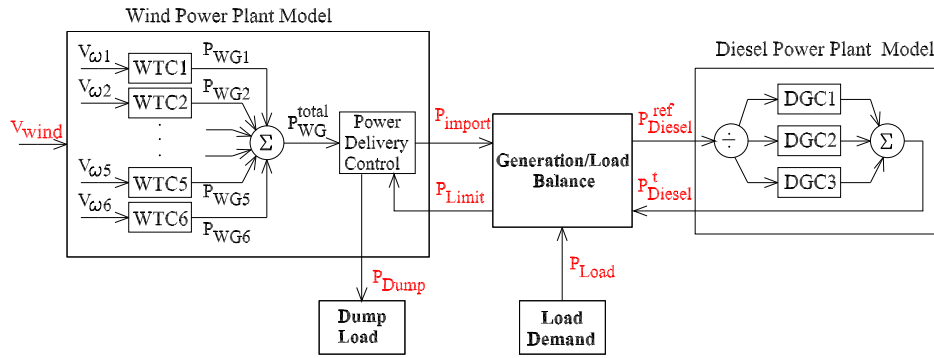


Fig. 4. Block diagram of the energy-flow model for the autonomous wind-diesel system of Fig. 1

In the next step, the wind power import and dumped load values are calculated based on the minimum loading requirements for the diesel units and the corresponding limit imposed on the maximum wind power import from the wind plant. The wind power limit is updated at each time step based on variations in load demand and diesel generators loading, as explained in Section IV-B. The difference between the wind power generation and the wind power import determines the control set-point for the dump load. The wind power import and dumped load values are given by,

$$P_{import} = \begin{cases} P_{WG}^{total} & \text{if } P_{WG}^{total} \leq P_{limit} \\ P_{limit} & \text{if } P_{WG}^{total} > P_{limit} \end{cases} \quad (2)$$

and

$$P_{dump} = \max((P_{WG}^{total} - P_{import}), \text{ and } 0), \quad (3)$$

where  $P_{import}$ ,  $P_{limit}$ , and  $P_{dump}$  represent wind power import, limit on wind power delivery, and the excess wind power to be dumped, respectively.

It should be mentioned that start-up and shut-down intervals for wind turbines are not considered when the energy-flow model uses a 1-minute time step.

### B. Generation and load balancing

The generation and load balancing block in Fig. 4 specifies total real and reactive power generation of the diesel power plant at each time step based on the input data for load demand, the calculated wind power import and reactive power of the wind plant. Hence,

$$P_{Diesel}^{ref} = P_{load} - P_{import} \quad (4)$$

$$Q_{Diesel}^{ref} = Q_{load} + (Q_{WG}^{total} - n \times Q_{cap}), \quad (5)$$

where  $P_{Diesel}^{ref}$  and  $Q_{Diesel}^{ref}$  are total real and reactive power generation of the diesel plant. Also,  $Q_{WG}^{total}$  and  $Q_{cap}$  are total reactive power of the six wind turbines and reactive power of a capacitor bank, respectively.  $P_{load}$  and  $Q_{load}$  represent lumped values for real and reactive power of the community load including power losses of distribution lines. In (5),  $n$  represents the number of 30-kVar capacitor banks ( $Q_{cap}$ ) required at each step to partly compensate reactive power of the wind plant.

A power limit value ( $P_{limit}$ ) is determined and applied to the next step of calculations.  $P_{limit}$  is equal to the difference between total power generation of the diesel plant and MLC. For this analysis, the MLC value is set to 30% of total real power capacity of diesel generators in operation. Hence,

$$P_{limit} = \max((P_{Diesel}^{ref} - 0.3 \times P_{Diesel}^{rated}), \text{ and } 0), \quad (6)$$

where  $P_{Diesel}^{rated}$  is the rated real-power capacity of the diesel plant based on diesel units in operation as determined in Section V-B.

After calculating the total loading of the diesel generators, the diesel plant master controller, DPMC in Fig. 1, performs the task of generator cycling, as required, to update the diesel generators operating status, turn on/off of additional generators, share the power among multiple generators, and calculate fuel consumption of each unit based on the given fuel curves in Fig. 2.

### V. DIESEL PLANT CONTROL AND OPERATING CONSTRAINTS

The diesel power plant is the main generation source of the remote electricity network of the island. Although the community load fluctuates in a wide range and may drop to 200-kW, the wind generation plant is not designed to operate independent of the diesel generator. Hence, under any load and/or wind power generation condition, the diesel plant controller needs to secure operation of at least one diesel generator with adequate spinning reserve capacity to support sudden load changes and wind power fluctuations. Two indications of the load at each time step are used for decision making and to compare the diesel loading with the operating constraints: (i) 1-minute load values which is entered to the model as inputs and interpreted as instantaneous load, since the time step is also 1-minute, and (ii) 5-minute load averages updated at each step.

The following operating constraints are incorporated into the diesel plant control model as part of the energy flow analysis:

- Minimum loading constraint (MLC), which is set at 30% of the total real power capacity of the diesels ( $P_{Diesel}^{rated}$ ),
- Spinning reserve constraint (SRC), which is determined based on the 5-minute average loading and set at 0.85 % of the rated real-power capacity of the diesel ( $P_{Diesel}^{rated}$ ).



- Maximum power constraint (MPC), which is defined based on instantaneous power of the diesel plant and incorporates both real and reactive power supplied by the diesel plant. MPC is set to 0.95 % of the total apparent power of the diesel plant ( $S_{Diesel}^{rated}$ ) that includes a safety margin when a 1-minute time step is used. However, diesel generators can momentarily tolerate up to 10% overload.
- Minimum operating time for each unit (MOP), which refers to a minimum on-time requirement for a diesel generator after each start-up to avoid short periods of switch on/off and minimize cycling. Previous studies have shown that an optimal cycling can be achieved for MOP greater than 20 minutes [10].

The limit on wind power import is only dictated by the MLC. However, if either the SRC or MPC thresholds are reached, an additional generator or a generator with larger capacity should be brought online.

#### A. Diesel cycling and dispatch strategy

Based on the current structure of the diesel plant with three equally sized diesel generators and the annual load duration curve of the network for 2004-2005, [2], a 925-kW diesel generator can supply the community load 88% of time. One of the other two 925-kW generators would be needed to meet high-load intervals. Considering the proposed diesel sizing approach based on a reduced size generator and two of the current 925-kW generators, various combinations of diesel operations can be achieved.

Table III shows the possible combinations of three diesel generators, one with a reduced size (DG1) in comparison to other two generator of equal size (DG2 and DG3). The first column in Table III identifies the logical states corresponding to on/off status of the diesel generators as specified in the following three columns of the table. The next two sets of columns identify upgrading and downgrading states, respectively, based on the rated capacity of the diesel plant at each state and possible choices for an upper state with higher capacity or a lower state with smaller capacity. The upgrading and downgrading states are derived from a logical cycling diagram for the diesel plant as shown in Fig. 5. The logical cycling diagram of Fig. 5 maps the relationship among the seven states and illustrates possible changes for a state based on increase and/or decrease in capacity and switching constraints. It should be noted that the cycling diagram of Fig. 5 is valid, independent of the selected size for DG1 and DG2/DG3.

An upgrading transition is required when the total loading of the diesel plant surpasses the MPC and/or SRC thresholds for the current state. A satisfactory state is the one with lowest capacity among the two available upgrading choices, given in Table III, for which the 5-minute average and instantaneous load values are below the MPC and SRC, respectively.

A downgrading transition is performed to optimize total capacity of the diesel generators in operation and select an appropriate combination with higher total loading for the diesel plant. To initiate downgrading, a medium loading threshold

TABLE III  
OPERATING STATE OF THE DIESEL POWER PLANT BASED ON GENERATORS COMBINATIONS

Logical state	Diesel 1 (DG1)	Diesel 2 (DG2)	Diesel 3 (DG3)	Upgrading states		Downgrading states	
1	On	Off	Off	2	6	1	1
2	On	On	Off	7	7	1	3
3	Off	On	Off	2	4	2	2
4	Off	On	On	7	7	3	5
5	Off	Off	On	6	4	6	6
6	On	Off	On	7	7	1	5
7	On	On	On	7	7	2	4

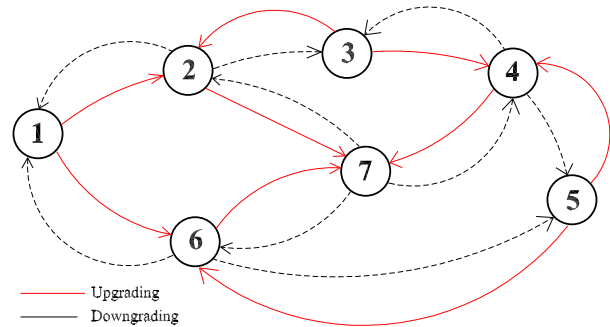


Fig. 5. Logic cycling diagram for three diesel units

(MLT) is assigned to each state that defines the loading condition at which a downgrading transition is required. The MLT values are determined based on the intersection points of the fuel curves in Fig. 2. However, downgrading does not occur if the operating duration of a targeted generator for switch-off is less than MOP, a minimum operating time of 20-minutes.

#### B. Load sharing

Normally, one or two units of the fleet of three diesel generators operate together. In a rare loading condition, addition of the third unit may be required. Diesel plant master controller (DPMC) supervises start-up, synchronization and parallel operation of the diesel units. This process is typically introduced as a delay in the energy-flow model. The corresponding delay may vary in the range of a few seconds to one or two minute, depending on a generator capacity and its controls. Fig. 6 shows a paralleling and load sharing process between two 925-kW generators, based on the the collected 1-Hz field data, for an operating point of the network in which the load demand reached about 850-kW. The average time required, based on several observations, is less than a minute; therefore, the delay does not affect the energy flow-model with an analysis time step of 1-minute.

The total loading of the diesel plant is shared among diesel units proportional to their rated capacities. The rated capacity of the diesel plant is calculated based on the diesel generators in operating position identified by the state number given in Table III. Hence,

$$S_{Diesel}^{rated} = \sum (S_{DG_i} \times Status_i) \text{ for } i=1 \text{ to } 3, \quad (7)$$

where  $S_{Diesel}^{rated}$  is the rated apparent power of the diesel plant based on diesel units in on-position.  $S_{DG_i}$  is the apparent

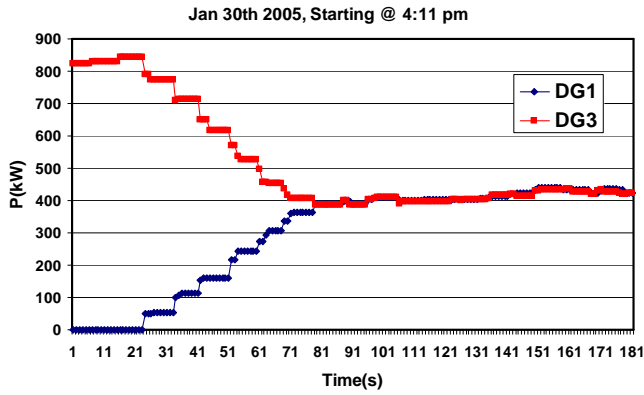


Fig. 6. Typical diesel generator paralleling and load sharing process based on field observations (Jan. 2005)

power of the  $i$ -th unit. Also,  $Status_i$  identifies the operating status of the  $i$ -th diesel unit with  $On = 1$  and  $Off = 0$ . The loading of each diesel unit with  $On$  state is given by

$$P_{DG_i} = P_{Diesel}^{ref} \times \frac{S_{DG_i}}{S_{Diesel}^{rated}} \text{ if } Status_i = 1, \quad (8)$$

where  $P_{DG_i}$  is the loading of the  $i$ -th diesel generator.

## VI. PERFORMANCE ANALYSIS

The energy model in Fig. 4 is used to analyze daily and monthly performance of the autonomous wind-diesel system, with various diesel sizes. Three cases based on DG1 sized at 560-kW, 635-kW, and 925-kW are considered. The diesel plant configuration for each study cases are as follows:

- **Case I:** Three diesel generators of the same size, i.e.  $DG1 = DG2 = DG3 = 925$ -kW,
- **Case II:** A 560-kW unit ( $DG1$ ) with two 925-kW units ( $DG2$  and  $DG3$ ),
- **Case III:** A 635-kW unit ( $DG1$ ) with two 925-kW units ( $DG2$  and  $DG3$ ).

System performance in terms of total wind energy import, and energy contribution of the small DG unit versus the 925-kW units for each case on a monthly basis are compared.

Figs. 7(a-c) show the results from energy contribution analyses for three months of operation in 2005, namely, April, June, and December. The selected months represent different load coverage characteristics for three cases. The average load of the system, based on Fig. 3, for June and December are either within the load coverage areas for reduced-size units represented by Case II and Case III (Fig. 3c), or above SRC thresholds of both cases (Fig. 3a). The average load for April 2005 is within the loading coverage of a 635-kW, but it is higher than the SRC threshold of a 560-kW, Fig. 3b. Comparing the wind energy contributions for Case II and Case III with the ones for Case I in Figs. 7(a-c) illustrates the effective impact of the size reduction of one diesel unit on the increase in total wind energy import. The wind contribution of Case III is also higher than those of Case II and Case I by an order of 7 to 20 percent higher dependent on the wind resource availability and system loading.

TABLE IV

FUEL CONSUMPTION IN LITERS FOR A THREE-MONTH ANALYSIS OF FIG. 7

	Case I	Case II	Case III
<b>December</b>	108,040	105,190	104,780
<b>April</b>	77,281	71,933	72,463
<b>June</b>	91,853	88,225	88,237

An essential conclusion from Fig. 7 is that a reduced-size diesel unit significantly reduces the fuel consumption as shown in Table IV. Although a 635-kW diesel unit is used more frequently than a 560-kW unit, the fuel saving in Case III is similar to Case II with slightly higher saving in winter, when peak load is higher, Table IV.

To investigate the impact of reduced-size diesel unit on overall performance of the diesel plant, two operating scenarios are considered:

- **Scenario A:** Diesel plant operation without energy contribution of the wind turbine.
- **Scenario B:** Diesel plant operation with the wind farm.

The no-wind operating condition of Scenario A is modelled by dumping the total wind energy harvested.

Table V presents results for a typical month of analysis (December 2005) based on Case I and Case III. Table V also provides a comparison between the model results for Case I-B with the field observations extracted from electricity sale data for the remote wind-diesel system. The last column in Table V provides a cross-comparison between wind-diesel operation performance for Case I, current operating practice of the system, and the proposed Case III in percentage of the change in corresponding values.

From the diesel plant perspective, Case III with a reduced-size 635-kW unit has significantly improved fuel efficiency and reduced fuel consumption for the same loads and wind-speed conditions, Table V. Using a diesel with smaller size increases the wind absorption rate by 6.7% and correspondingly reduces the amount of the wind energy dumped by about 30%. An adverse effect of reduced diesel size is that the total number of start/stop cycles of the diesel generators is increased by 50%. The change in number of cycling periods may impose further mechanical limitations and maintenance requirements for the diesel plant operation and needs further investigation and consultation of the diesel manufacturers. It should be also noted that the number of on/off cycles is very sensitive to the selected value for the minimum operating time (MOT) for the diesel units and can be adjusted based on operating requirements.

## VII. CONCLUSIONS

An energy-flow model for unit sizing of a remote wind-diesel Microgrid was introduced in this paper. The model was validated using field observations and monitored data for an autonomous wind-diesel system of a geographical island in Canada. The current design and operating characteristics of the autonomous wind-diesel system was used as the base case study. Alternative unit sizing and configuration approaches

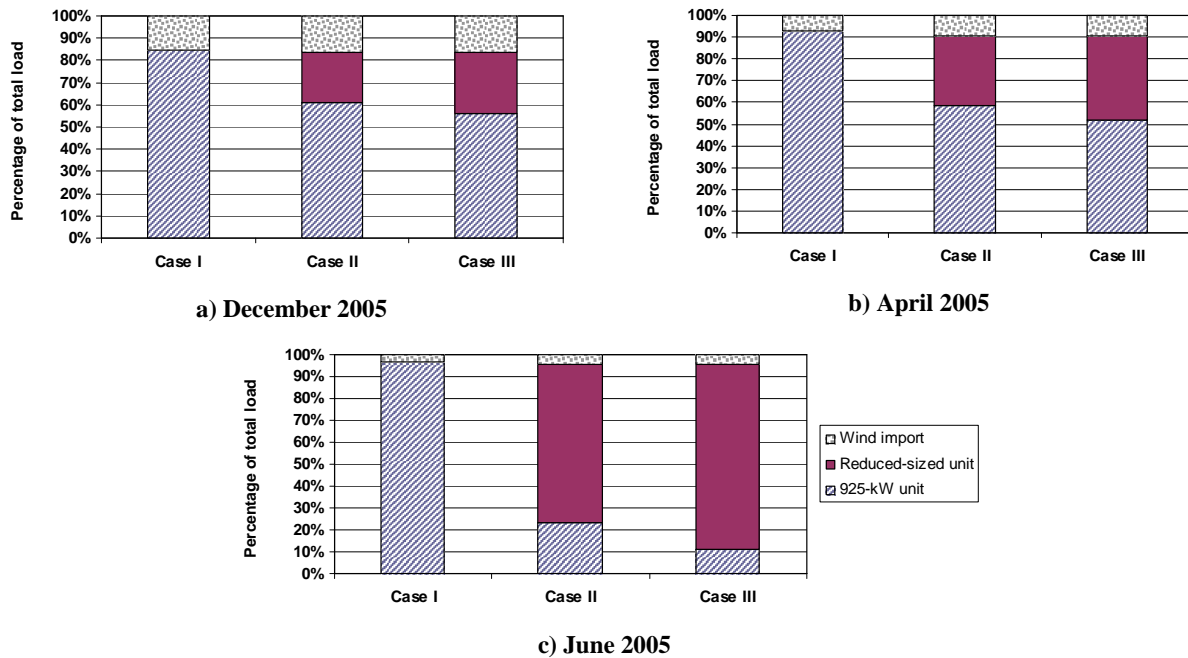


Fig. 7. Energy contribution of diesel units and wind plant for three months of operation based on study Case I to III, (Note - a reduced-sized DG is either a 635-kW unit for Case III or a 560-kW unit for Case II)

TABLE V

WIND-DIESEL SYSTEM PERFORMANCE IN DECEMBER 2005 - COMPARING CASE I AND CASE III FOR DIFFERENT OPERATING SCENARIOS

Study Scenarios	Case I			Case III		
	A: No wind	B: with wind	Field (sale data)	A: No wind	B: with wind	Change in % of Case I-B
Total load (MWh)	483.98	483.98	482.57	483.98	483.98	0
Wind import (MWh)	0.0	75.269	62.160	0.0	80.279	+ 6.7% (improved)
Dumped wind energy (MWh)	91.686	16.412	Not Available	91.686	11.402	- 30.5% (improved)
Fuel consumption (Litres)	127,930	108,040	116,158	125,730	104,780	- 3 % (improved)
Fuel efficiency (kWh/litre)	3.783	3.778	3.73	3.849	3.853	+ 1.99 % (improved)
Diesel cycle start/stop	198	124	Not Available	286	298	+ 51 %

were investigated to look at the possibility of enhancing system performance based on several optimization criteria including: (i) wind energy absorption rate, (ii) diesel fuel consumption, and (iii) overall fuel efficiency of the diesel plant. Using the energy-flow model, monthly and seasonal performance of the system for alternative approaches based on a diesel plant with multiple units at different sizes were analyzed. Comparison of the performance indicators extracted from study results with those of the base case showed that diesel plant configurations with a reduced capacity diesel can significantly improve the fuel consumption and efficiency.

It should be noted that using a smaller diesel may affect the power quality of the network when the wind plant is designed based on older generation of wind-turbine technologies. The main concerns are diesel capability for fast real/reactive power compensation during wind fluctuations and sudden start-up

and/or shut-down of the wind turbines. However, the implementation of soft-starting methods and application of new turbine technologies using a power-electronic interface can effectively correct any potential power quality impacts and even lead to performance improvements.

## VIII. ACKNOWLEDGEMENT

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