A bstract
In this paper, we are studying an innovative solution to reduce fuel consumption and production cost for electricity production by diesel generators. The solution is particularly suitable for remote areas where the cost of energy is very high not only of inherent cost of technology but also due to transportation cost. After a brief description of power generation based on a conventional synchronous alternator, the attention is focused on the Eo-Synchro concept. Then an innovative approach for optimizing the energy is proposed; it is based from the fact that the structure that contains the stator windings of the alternator is mounted on roller bearings which allows its free rotation around the axis of the rotor, consequently stopping the rotor structure from being static and aims to minimize the unit cost of electricity. Our model yields improved performance on fuel saving at all generator load stages compared to the conventional model. Experimental results on a 75kW Diesel Generator (DG) validate the performance of the proposed model.

K eyw ords
Diesel generator, power generation system, electrical machines, control of rotor speed, control of stator speed, Eo-Synchro concept, fuel saving.

1.  Introduction
Most of the remote and isolated communities or technical installations (communication relays, meteorological systems, tourist facilities, farms, etc) that are not connected to national electric distribution grids rely on diesel engines to generate electricity [1]. In Canada, approximately 200,000 people live in more than 300 remote communities (Yukon, Northwest Territories, Nunavut, etc) that use diesel generated electricity, which is responsible for the emission of 1.2 million tons of greenhouse gases annually [2]. In Quebec alone, there are over 14,000 subscribers scattered in about forty communities that are not connected to the main electrical grid. Each community constitutes an autonomous network that uses diesel generators for electricity production [3]. The diesel power generating units, while requiring relatively little investment, are generally expensive to exploit and maintain, particularly when they are functioning regularly at partial load [4]. The use of diesel power generators under weak operating factors accelerates wear and increases fuel consumption [5]. During the past several years, the oil prices have achieved historic highs, peaking at 147$CAD/barrel in July 2008, averaging over 100$/barrel during 2011, averaging over 110$/barrel until October 2014, and then it fell to 80$/barrel. Recently, the oil price is around 45$/barrel. Despite this considerable drop, the diesel fuel prices are losing only a few cents in some provinces in Canada. According to Statistic Canada, in St. John’s Newfoundland, the diesel fuel lost only 5.7¢/L, and in Whitehorse in Yukon increased by 3.5¢/L and in Yellowknife in Northwest Territories was set to rise up to 9.3¢/L in October 2014 compared to 2013. According to Statistics Canada (http://www5.statcan.gc.ca), the decline in crude oil prices is not felt at the pump in this region. However, the pump price gasoline only decreased by 11.8¢/L from a high of $112 per barrel to a low of $35 per barrel in December 2015. Therefore, the decrease in oil prices has not greatly affected the price of diesel fuel, which implies that the electrical energy produced using only oil and energy source will always remain expensive, at any cost per barrel [6]. According to Hydro Quebec, extending the main grid to these isolated areas will cost around (1M $/km), which is impossible to do with the actual economic crisis.

There are two types of DGs. The first type consists of a Diesel Engine (DE) running at a fixed speed coupled with a Synchronous Generator (SG); this solution has the advantage of simplicity. However, there are some drawbacks, including high level of noise regardless of the power level required by the load, high level of greenhouse gases emission (GHG) even when load power demand is low and over dimensioning in case of non-linear or unbalanced loads. The second type of DG operates with a variable speed. In this option the DE is coupled with an electrical generator operating at variable speed. This concept is able to reduce fuel consumption and reduce the cost of DG power generation [7]. Currently, most existing
DGs in remote areas operate at a constant rotational speed due to the restriction of the constant frequency required at the terminals of the generator. This operating mode causes high fuel consumption, as well as increases the maintenance costs [6]. To overcome these drawbacks, variable speed DGs are being proposed as an alternate configuration (Pena et al, 2008). Compared to the fixed speed DGs, variable speed DGs, are more efficient but costly, due to the use of power converters or mechanical transmissions.

In our project, we investigate another possibility that, when coupled to a DG operating in a power unit (Figure 1), the alternator with the Eo-Synchro application features can operate at variable speeds without the need for costly power electronics components to generate a constant frequency at the generator terminals. Per its configuration, the system can compensate for a lower or higher heat motor speed with no perturbation on the wave quality of the electricity being generated. It can operate in instantaneous or prolonged modes, depending on the desired application. The system can therefore be used to compensate for brief speed fluctuations or extended under-speed use while still compensating for intermittent and brief speed fluctuations [7, 8].

![Figure 1 Illustration of alternator with mobile stator (Eo-Synchro application) coupled to heat motor](image)

The project was developed by Concept Fiset Inc and was performed by the project partners Renewable Energy Research Laboratory of University of Quebec at Rimouski. The EoSynchro concept has three international patents including Canada [7, 8], the United States [9] and Australia [10].

### 2. Objectives and methodology

A conventional DG consists of an engine connected directly to a synchronous alternator to produce electricity [11]. Since the electricity produced must be at a fixed frequency, normally 50Hz or 60Hz, the engine must rotate at a constant speed (typically 1,500rpm for 50Hz or 1,800rpm for 60Hz), no matter what the power demand is. One solution to save fuel in a diesel generator is to enable the engine to operate at variable speeds in direct relation to the electrical load demand [12]. In a previous work [13], Peter Dengler and Marcus Geimer from Karlsruhe Institute of Technology demonstrated that using an electronic converter is an easier way to provide a system at variable engine speed but at constant electric frequency (VSCF). These devices are already available on the market for other purposes, but a system with a generator in VSCF technology is still not established in the market as their higher investment costs are not yet proved to be economically justified by lower fuel consumption [13]. The objective of this study is to demonstrate that the EoSynchro application is able to reduce the fuel consumption and to reduce the cost of DG power generation. The structure of the present article is as follows. Section 3. presents the design approach of the active power generation by a synchronous alternator in general followed by the mechanical concept of EoSynchro and its principle control. In Section 4. we present the bench test and discuss the results obtained in order to demonstrate the efficiency of EoSynchro technology for generator applications. In Section 5. we provide a preliminary conclusion of our study and a perspective for future work.

#### 3. The design approach

##### 3.1 Three phase synchronous alternator

The active power which is supplied by a three-phase synchronous generator is given by:

\[
P = \frac{E_0 \cdot E_b}{X_s} \sin \delta \tag{1}
\]

where:

- \( P \) = active power provided per phase (W);
- \( E_0 \) = induced voltage per phase (V);
- \( E_b \) = voltage across terminal per phase (V);
- \( X_s \) = synchronous resistance per phase (Ω);
- \( \delta \) = internal phase difference angle between \( E_0 \) and \( E_b \) in electrical degree.

Parameters \( E_0 \) and \( E_b \) are normally controlled by an Automatic Voltage Regulator (AVR). This unit is integrated with the alternator and maintains the voltage produced by the alternator at a present value [14]. The magnetic field of the alternator must rotate at the rated speed, that is 60Hz in North America. When connecting an alternator to a public electricity grid, the electricity grid one must be considered to be extremely large. Such a grid, to which hundreds of alternators and thousands of various loads are connected, consequently imposes a voltage and a fixed frequency to any apparatus that is connected. According to this principle, when synchronizing an alternator on an infinite grid, the induced voltage \( E_0 \) is equal to and in phase with the voltage \( E_b \) of the grid. Therefore, according to the above equation, the voltages \( E_0 \) and \( E_b \) being fixed by the grid and the reactance \( X_s \) being specific to the structure of the alternator, the only parameter which could modify the active power \( P \) provided by the alternator, is the electrical phase angle \( \delta \) between the stator and rotor electrical field. This electrical angle \( \delta \) is associated with the mechanical angle \( \alpha \) through the following equation:

\[
\delta = \frac{p \cdot a}{2} \tag{2}
\]

where \( p \) is the number of poles.
When the motor develops a torque, the poles of the rotor move backward of the poles of the stator.

In a standard synchronous alternator, the stator is stationary. If a torque is applied to the rotor, its axis has a tendency to deviate from the central axis of the stator. Figure 2 confirms this principle for a synchronous motor however, it is applied as well to a synchronous alternator.

The difference rests on the fact that the torque is applied to the shaft of the machine (generator mode) and is not generated by the machine (motor mode). According to Figure 3 the maximum power provided by an alternator is obtained at an electrical phase difference angle $\delta$ of 90°. However, for stability reasons [14], the wattage rating of an alternator is reached at an electrical phase difference angle $\delta$ of 30°, i.e. a mechanical phase difference angle $\alpha$ of 15° for a 4-pole alternator.

The rotating speed of the electric field is equal to:

$$n_{sync} = \frac{120f}{p}$$  \hspace{1cm} (3)

In the case of a 4-pole alternator which operates at 60Hz, the rotating speed of the electric field inside the stator (also called synchronous speed) is 1,800rpm. In a synchronous alternator, the rotating speed of the stator field must be identical to the rotating speed of the rotor field. The two fields are therefore stationary with respect to one another and rotate at a constant speed. From a mechanical point of view, if free rotation of the stator is possible, the equation which describes the synchronous speed $n$ in rpm is the following:

$$n_{sync} = n_{rotor} - n_{stator}$$  \hspace{1cm} (4)

and by transmutation,

$$n_{stator} = n_{rotor} - n_{sync}$$  \hspace{1cm} (5)

When a negative value of $n_{stator}$ occurs, it means that the stator rotates mechanically in the opposite direction with respect to the rotor [16]. Therefore, to maintain a synchronous speed of 1,800rpm, if the rotor rotates at 1,650rpm, the stator must rotate in the opposite direction at 150rpm so that the resulting speed is 1,800rpm. If the rotor rotates at 1,800rpm, the stator must remain mechanically stationary. If the rotor rotates at 1,950rpm, the stator must rotate at 150rpm in the same direction as the rotor. In a standard alternator, where the stator is stationary ($n_{stator} = 0$ rpm) and the rotor is rotating, the synchronous speed then corresponds exclusively to the mechanical speed of the rotor. Therefore, for a 4-pole synchronous alternator, to have a frequency of 60Hz, the rotor must rotate at a constant and stable mechanical speed of 1,800rpm. In a production generator unit which uses a standard synchronous alternator, control of the mechanical speed of the rotor is therefore of prime importance to maintain an optimum phase angle, with an optimum power supply. In practice, this control is exercised at the level of the opening of the governor valves of a turbine in the case of a hydro-electric power station or from the angle of attack of the blades (pitch) in the case of a wind power turbine for example.

### 3.2 The Eo-Synchro concept as applied to power units

The Eo-Synchro application is a power unit control system with a highly original approach for power generation based on an innovative alternator design. Modifications to the structure holding the stator windings are the leading principle behind the Eo-Synchro application where this structure now rotates freely in reference to the rotor and frame. An auxiliary motor, driven by a dedicated automatic controller, dictates the desired position, speed or acceleration of the stator structure. This concept ensures regular wave quality regardless of speed variations of the rotor. No energy goes through power electronic equipment as in conventional technologies [8, 9, 10].

#### 3.2.1 Rotating stator concept

To generate electricity in a power unit, a synchronous alternator transforms the mechanical energy coming from a heat motor into electrical energy [17]. When this alternator incorporates the Eo-Synchro concept by allowing the mechanical rotation of the stator windings, the synchronous speed of this alternator can remain constant through:

- Control of rotor speed only (existing design)
- Control of stator speed only (new design) [8, 9, 10]
- Control of both speeds simultaneously (new design) [8, 9, 10]
With the Eo-Synchro design, it becomes possible to control the synchronous speed of a 3-phase alternator by controlling the mechanical speed of the stator (control of stator speed only). In addition, because the Eo-Synchro application is entirely independent from the drive mechanism, it can be adapted to any type of rotor speed control and integrated into any type of power generation unit (reciprocating engine, wind turbine, hydraulic turbine, gas turbine, etc).

Figure 4 shows a prototype of the Eo-Synchro alternator, rated at 75kW. Rotor speed can vary from 1,575 to 2,025rpm. The main system components are identified in Figure 5.1 and 5.2.

For this prototype, a three-phase synchronous alternator was modified to allow the stator windings to rotate around the rotor. No other modifications were made on the alternator rotor. The stator windings also remain the same.

The stator drive (compensating motor) is mounted in a casing affixed to the top of the casing of the synchronous motor using an assembly means comprising of brackets and bolts such that the output shaft of the stator drive is aligned in a parallel orientation with the stator shaft [8, 9, 10]. The output shaft of the stator drive and the stator shaft are connected using a timing belt and pulleys. The bottom pulley is fitted to the distal end of the stator shaft extending outside the casing of the synchronous alternator and the top pulley is fitted to the output shaft of the stator drive such that both pulleys are vertically aligned with one another. The timing belt links the two pulleys for one to drive the other.

3.2.2 Stator speed control

In the illustrated system (Figure 6) the controlling unit receives a feedback signal from an encoder which senses the position, or the speed of the stator. In this case, the encoder is positioned on the rotor to sense the position, and thereby the speed, of the rotor. The controlling unit also reads the produced alternating current as a feedback. From the received feedback signal and/or alternating current, the controlling unit produces the control signal which is inputted to the variable speed drive to control the rotation of the stator drive (compensating motor) and thereby of the stator of the synchronous alternator.

The controlling unit may use the feedback signal, the reading of the alternating current, or a combination of both. The
controlling unit can be provided as a programmable logic controller, a computer or any other processing unit for example. The variable speed drive is typically powered using the electric current produced by the alternator and the frequency regulation consequently consumes part of the produced power, but the total balance of produced electric power remains positive. By controlling the rotation of the stator about the rotor, the relative speed, and thereby the frequency of the generated electric current, can be regulated [18]. For example, in a typical wind turbine generator (Figure 7), a 60Hz alternating current is generated in a 4-pole-3-phase alternator that rotates at 1,800rpm [19].

When the wind is strong, the speed of the prime mover, ie the wind turbine, may rotate faster, at 2,000rpm for example. In order to compensate for such a higher rotation speed of the rotor, the stator is rotated at 200rpm in the direction of rotation of the rotor. The relative speed between the rotor and the stator is thus 1,800rpm (2,000rpm -200rpm: 1,800rpm). If the speed of the rotor decreases due to weak winds for example, eg at 1,500rpm, the stator is rotated at 300rpm in the direction opposite to the rotor. The relative speed is thus 1,800rpm (1,500rpm +300rpm: 1,800rpm).

4. **Eo-Synchro application for power units**

In order to demonstrate the efficiency of Eo-Synchro technology for a generator application, we performed bench testing in an R&D pilot facility of an industry leading generator supplier in collaboration with the Renewable Energy Research Laboratory at the University of Quebec in Rimouski, Canada. The following is a summary of the bench test work performed.

4.1 **Description of the test bench**

Figure 8 shows the schematic of the bench test studied. It consists of DE as a prime mover coupled to an SA. A compensating motor mounted on the top of the alternator and coupled to a drive provides the necessary rotation speed of the stator of the SA. The DE was instrumented by a torque sensor and speed sensor. This allowed us to measure the mechanical power supplied to the SA. Also, the output of the SA was instrumented with the global output. We were able to measure the current and voltage of each line with the PF and the total harmonic distortion (TDH) of the current and voltage.

![Figure 7 The Eo-Synchro applied in a wind turbine](image)

![Figure 8 Schematic of the bench test](image)

![Figure 9 Main components of the bench test](image)

4.2 **About the tests**

We started the tests without introducing the compensating motor (stator fixed) in order to evaluate the engine fuel consumption at different applied loads. Table 1 illustrates the different applied loads and fuel consumption in g/kWh. Subsequently, we performed the same tests mentioned above but with the application of Eo-Synchro technology. Table 2 illustrates the fuel consumption results with stator speed control.
### Table 1: Evaluation of fuel consumption with a blocked stator

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Load (kW)</th>
<th>Consumption g/kWh</th>
<th>Engine speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>60</td>
<td>262.7</td>
<td>1655</td>
</tr>
<tr>
<td>90</td>
<td>54</td>
<td>289.6</td>
<td>1585</td>
</tr>
<tr>
<td>80</td>
<td>48</td>
<td>286.7</td>
<td>1550</td>
</tr>
<tr>
<td>70</td>
<td>42</td>
<td>270.5</td>
<td>1550</td>
</tr>
<tr>
<td>60</td>
<td>36</td>
<td>262.5</td>
<td>1550</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>265.3</td>
<td>1525</td>
</tr>
<tr>
<td>40</td>
<td>24</td>
<td>311.7</td>
<td>1500</td>
</tr>
<tr>
<td>30</td>
<td>18</td>
<td>346.7</td>
<td>1500</td>
</tr>
</tbody>
</table>

### Table 2: Evaluation of fuel consumption with Eo-Synchro

<table>
<thead>
<tr>
<th>Load (%)</th>
<th>Load (kW)</th>
<th>Consumption g/kWh</th>
<th>Engine speed (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>60</td>
<td>Uncompleted test, spyder had broken</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>54</td>
<td>265.9</td>
<td>1600</td>
</tr>
<tr>
<td>80</td>
<td>48</td>
<td>266.1</td>
<td>1600</td>
</tr>
<tr>
<td>70</td>
<td>42</td>
<td>270.4</td>
<td>1525</td>
</tr>
<tr>
<td>60</td>
<td>36</td>
<td>263.3</td>
<td>1500</td>
</tr>
<tr>
<td>50</td>
<td>30</td>
<td>250.7</td>
<td>1480</td>
</tr>
<tr>
<td>40</td>
<td>24</td>
<td>272.8</td>
<td>1430</td>
</tr>
<tr>
<td>30</td>
<td>18</td>
<td>312.1</td>
<td>1430</td>
</tr>
</tbody>
</table>

### 4.3 Results comparison

First, it is important to note that both tests were done off-grid and the THD of the output current was below 2%. As observed in Table 1 and 2, when the Eo-Synchro technology is applied, fuel consumption decreases significantly when the engine is running at low load (40% and less). However, we must note that variable speed generators in remote area applications will regularly run at lower loads. Figure 10 illustrates a typical load for a remote area using a DE as a primary electricity source [20].

**Figure 10**: Example of a typical electrical daily load profile in a remote area. The peak load for any community occurs during the daytime hours when residents, businesses and manufacturers consume electricity at their peak demand.

Table 3 shows the fuel consumption difference between the conventional generator model (stator is fixed) and when Eo-Synchro technology is applied. As we can see, results obtained at 60% and 70% of applied loads are highlighted in red because they are very close to a conventional generator with a blocked stator. However, when the load is increased to 80%, we achieved a significant gain of 7% on fuel consumption followed by 8% for a load of 90%. Unfortunately, the test was suspended at 100% when the load was increased to 100% because the spyder had broken.

### Table 3: Efficiency of the consumption variation

<table>
<thead>
<tr>
<th>Loads (%)</th>
<th>Blocked Stator Vs Eo-Synchro</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>90</td>
<td>+8.18%</td>
</tr>
<tr>
<td>80</td>
<td>+7.18%</td>
</tr>
<tr>
<td>70</td>
<td>-0.40%</td>
</tr>
<tr>
<td>60</td>
<td>-0.30%</td>
</tr>
<tr>
<td>50</td>
<td>+5.50%</td>
</tr>
<tr>
<td>40</td>
<td>+12.48%</td>
</tr>
<tr>
<td>30</td>
<td>+9.98%</td>
</tr>
</tbody>
</table>

Figure 11 further illustrates the effect the Eo-Synchro technology can have on improving DE fuel consumption for different loads.

**Figure 11**: Effect of the Eo-Synchro application on fuel consumption.

### 5. Conclusion

This article presented the innovative features of the Eo-Synchro technology which originate from a rotational non-fixed stator design and a fuel savings evaluation for a DE generator application that can be achieved by controlling the rotation of the stator. A decrease of the heat losses to the DE exhaust is facilitated by allowing for lower engine operating speed at low power load with the Eo-Synchro technology. For this reason significant fuel savings of up to 12% can be obtained at low DE generator power loads (40%). The maximum gas pressure in the combustion chamber has to stay below a certain threshold and limits the intake pressure and therefore the fuel savings can be realized. This is why the fuel economy is higher for lower loads. Based on our results, for a 1MW DE generator unit, the fuel saving are projected to be 23g per kWh at 90% load. For an 1MW unit producing 1,000kWh, fuel savings would be 23kg/h. For equivalent purposes, as 1 liter of fuel weighs approximately 0.85kg, we can assume fuel saving of 27 liters/h, which represents...
an annual fuel saving of 216,500 liters (57,190 US gallon) over 8,000 hours of annual operation. However, in the present paper, only an evaluation of fuel consumption based on 75kW DE has been demonstrated. Current estimation aims at bounding the hoped fuel economy for a 1MW DE.

While the present paper presents the original aspect of Eo-Synchro technology and theoretical results that are valid for a small DE, some preliminary experimental results under a 500kW DE were conducted under a new test bench by PhD researchers at University of Quebec in Rimouski and will be published shortly. The published experimental results cover a mathematical model to characterize the generated power model and the results of fuel economy savings obtained.

### Nomenclature

- **DE** Diesel Engine
- **DG** Diesel Generator
- **VSCF** Variable Speed @ Constant Frequency
- **SA** Synchronous Alternator
- **DRV** Drive
- **SG** Synchronous Generator
- **GHG** Green House Gases emission
- **PF** Power Factor
- **TDH** Total Distortion Harmonic

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