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Optimization of Diesel Engine Usage for Multi-Source Nano-Grid

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Abstract - Multi-source electrical systems rely on performing energy management to have a minimal operational cost while satisfying the energy demand. In this paper, an existing hybrid nano-grid composed of PV panels, a diesel generator, and batteries is used for the investigation purpose. The behavior of the actual electrical system is studied through its equivalent model developed in MATLAB/Simulink®. Recently, we noticed space for improvement in the control settings of the multi-source system. To further confirm the impact of these input set points on the usage of the diesel engine, a sensitivity analysis is also performed. An optimization based on a genetic algorithm demonstrates that changing these control set points through the different periods of the year could improve diesel engine usage and help to penetrate more renewable energy from PV modules.

INTRODUCTION

Multi-source electrical systems combine several energy sources such as diesel and photovoltaics into an electrical system. They mix the advantages of reliability and autonomy of thermal engines and the low carbon emission from renewable electrical systems. However, they need to be well-sized and controlled, according to their location [1], to ensure optimal usage of both energies and to minimize greenhouse gas emissions.

In literature, many approaches have been proposed to control this kind of electrical system. As used by [2, 3], optimal set points of battery depth of discharge help to minimize diesel engine pollution and overall system cost. When there is the usage of weather-dependent renewable energy in a multi-source system, like photovoltaic (PV) panels, it is beneficial to use power production prediction algorithms to improve control [4, 5, 6].

Multisource electrical systems are used in many applications such as hybrid vehicles and nano-grids. One of the applications of autonomous nano-grids is to feed telecommunication towers in remote areas with limited access to the electrical grid.

In this paper, we consider a telecommunication base station located in Québec, Canada, that draws its power from a stand-alone hybrid electrical nano-grid composed of PV panels, a diesel engine, and batteries. The operation of the diesel engine is based on the state of charge (SoC) of the batteries. Fig. 1 shows a picture of this installation.

For the investigation purpose, an equivalent model of this telecommunication station has been developed in

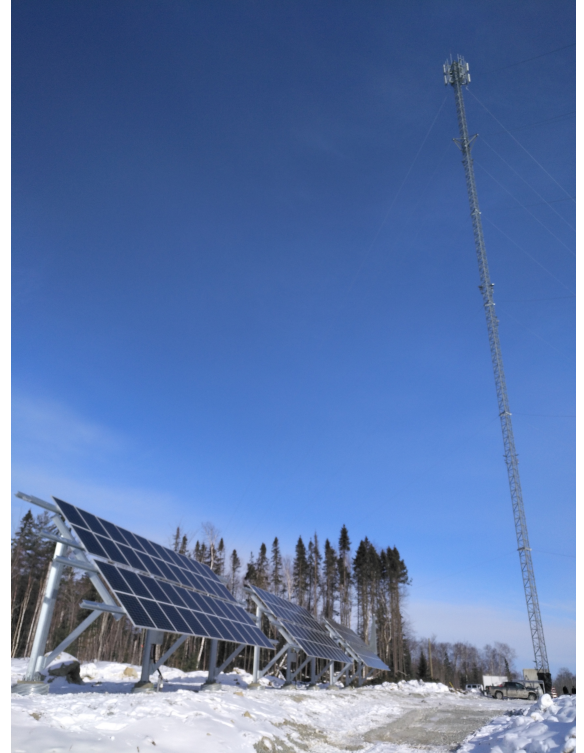


Fig. 1. Picture of the case study telecom station.

MATLAB/Simulink® and is used in this work. This model is then used to first identify sub-optimal energy management situations and second to optimize energy management to minimize diesel generator usage.

A. Modeling of Nano-Grid

The model uses Energetic Macroscopic Representation (EMR) formalism [7] to reproduce the behavior of the studied electrical system. It takes the time series of global irradiance, outdoor temperature, and power profiles of the telecom antenna and the heaters for internal environment control as input parameters. As output, this model can generate the estimation of fuel consumption based on generator power demand and the number of generator start-ups for the specified period from inputs. The diesel generator fuel consumption rate f_{DG} in liters per hour is given by (1) where coefficients α and

β are 0.246 and 0.08145 respectively [8]. P_{DG} is the power of the generator and $P_{DG_{rated}}$ is the 20kW rated power of the diesel generator.

$$f_{DG} = \alpha P_{DG}(t) + \beta P_{DG_{rated}} \quad (1)$$

The PV sub-system of this model considers the global irradiance and outdoor temperature to estimate the available power from PV panels. However, this model does not consider the snow coverage on PV panels.

The storage sub-system is composed of a lithium iron phosphate battery bank modeled by the simple equivalent circuit model.

The energy management system is based on fixed set points related to the SoC of batteries. When the SoC of the battery is below a minimum threshold (SoC_{min}), the diesel generator is set to start and run until the SoC reaches a maximum threshold (SoC_{max}). The control inputs of the energy management system are SoC_{min} , SoC_{max} , and the charge rate of the charger ($Chrg_{rate}$), which is defined as the percentage of the maximum power deliverable by the charger connected to the diesel generator. By default, these parameters are set at 16%, 70%, and 100% for SoC_{min} , SoC_{max} , and $Chrg_{rate}$, respectively. Fig. 2 illustrates the inputs, outputs, and setpoints for the EMR model of the station.

This model has been investigated and validated through a comparison of simulated results with the actual station data acquired for the month of November 2021. It was found that the model can reproduce the results with good accuracy with less than 1% of mean absolute error (MAE) on battery state of charge estimation, less than 1.3% error on PV power production estimation, and less than 0.3% error on generator power production estimation. The details of the base station, its system architecture, its model, and its experimental validation are provided in previous work [9].

B. Problem identification

As this system is working in fixed operation, it leads to over usage of the diesel generator. The generator starts when the battery SoC is 16% and keeps charging the batteries until they reach an SoC of 70%. Also, the charger connected between the generator and the battery is operating at 100% of $Chrg_{rate}$. The situation where this set points combination leads to a non-

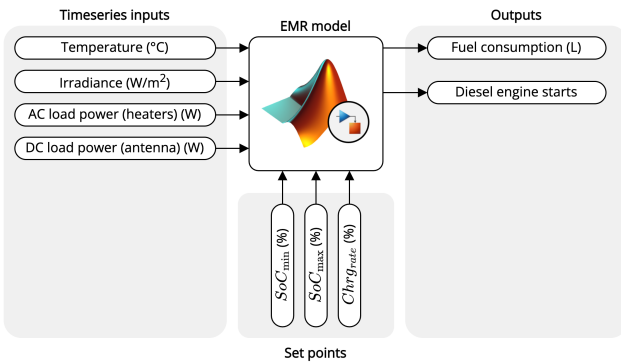


Fig. 2. Model time series inputs, control set points, and outputs.

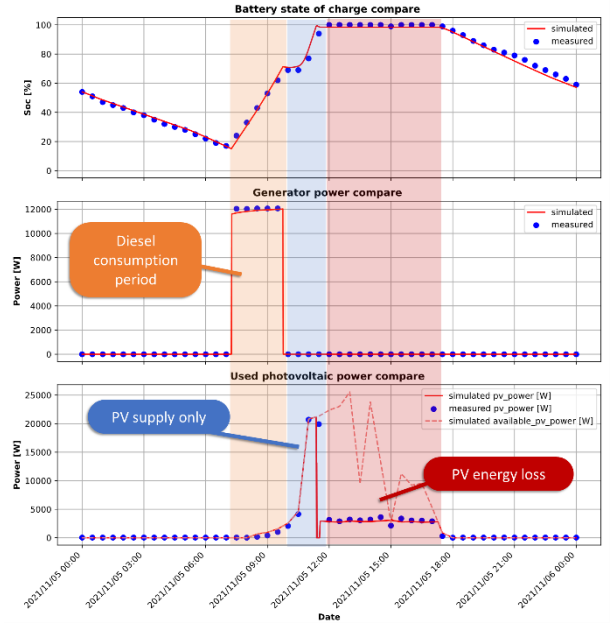


Fig. 3. Typical scenario of generator over usage (example of 2021-11-05).

optimal operation of the generator can be seen in Fig. 3. In this typical scenario, the batteries start to get charged by the generator in the early morning and reach an SoC of 70% at around 10 AM. Then, the PV panels are taking the lead to charge the batteries until they get fully charged during the noon time. At this time, we can see the supply of energy produced from the PV panels must be dumped since the batteries are already full and the load demand is satisfied. Under this scenario, it was estimated that 63.3 kWh of energy available from PV panels was wasted. This amount of energy could be used by the station by stopping the diesel generator much earlier or by reducing the charging rate of the charger. Besides the reductions in diesel consumption, this could help to increase the contribution of electricity from the PV panels.

C. Parameters identification

The energy management system of this hybrid nano-grid has only 3 control input parameters, as illustrated in Fig. 2:

Minimum State of Charge (SoC_{min}): Sets the minimum battery state of charge that will trigger the generator start.

Maximum State of Charge (SoC_{max}): Sets the maximum battery state of charge that will stop the generator operation.

Charge rate ($Chrg_{rate}$):

Controls the power flow from the generator to the batteries by the charger rate.

In this study, the parameters are evaluated in value ranges that respect the hardware specifications, but that don't cover the edge cases of long-term damages. The SoC_{min} range is evaluated at a minimum of 10%, as a low battery SoC can damage batteries [10] and a maximum of 65% as it can't be higher than or equal to the SoC_{max} threshold (70%). For the SoC_{max} parameter, it is considered between 20% and 100%, as it can't be lower than the SoC_{min} threshold and it can't be higher than 100% of batteries SoC. Currently, with a $Chrg_{rate}$ of 100%, the generator is operating at 60% of its rated power.

Indeed, this generator of 20 kW rated power is typically operating at 12 kW, as seen in Fig. 3. For the matter of this study, this $Chrg_{rate}$ parameter is evaluated down to 45%, which corresponds to 27% of the rated power load to see the possibility of gains at low power demand on generator. The long-term damages caused by the low operation of the generator are not considered in this study.

The generator usage analysis is based on the model outputs which are fuel consumption and generator start-ups. To validate the impact of the three adjustable parameters on these outputs, a sensitivity analysis is performed using the available records from February 1st, 2022, to May 1st, 2022. The parameters are swept between the previously defined ranges to see the impact on fuel consumption, the generator start-ups number, and the overall cost combination (defined in the section *Optimization*). The result of this analysis, in Fig. 4, shows that fuel consumption and generator start-ups are significantly influenced by these three inputs.

If the SoC_{min} is reduced from the actual 16% value (Fig. 4(a)), both the generator start-ups number and the fuel consumption are also reduced. Similarly, an increase in SoC_{min} leads to an increase in both outputs. The effect on the generator start-ups is more pronounced than on the diesel consumption with 254% more generator starts when SoC_{min} is increased to 65% while the diesel consumption is increased by 31%. This indicates that reducing SoC_{min} to a minimum value would help reduce diesel generator usage, especially the starts number. However, it may lead to premature usage of batteries, which has not been considered in this study.

The impact of SoC_{max} on diesel generator usage is seen to be different from the one that is noticed for SoC_{min} . As seen in Fig. 4(b), fuel consumption follows the evolutions of SoC_{max} while the generator start-ups number evolves oppositely (*i.e.*, less generator starts when SoC_{max} is increased). It is significant to see that decreasing in SoC_{max} has negatively impacted the generator starts. It is seen that generator would experience 254% more starts with an SoC_{max} decrease to 20%. This indicates that the SoC_{max} must be chosen based on a trade-off between fuel consumption and diesel generator start-ups.

As illustrated in Fig. 4(c), the tuning of the $Chrg_{rate}$ parameter can help to reduce the number of generator's starts by 15% when it is reduced to 45%. On the other hand, this has caused fuel consumption to increase by 38 %. Hence, reducing $Chrg_{rate}$ has a positive impact on diesel generator start-ups, but a bigger negative impact on fuel consumption.

D. Optimization

As we have seen that generator start-ups and fuel consumption are greatly influenced by SoC_{min} , SoC_{max} , and $Chrg_{rate}$, the optimal tuning of these three parameters would significantly be helpful on the generator usage. Aiming at that, an optimization is performed to find the optimal combination of these three set point values for diesel generator usage. As the environmental conditions change throughout the year, this optimization must be evaluated at different periods. For this purpose, we have considered two different seasons: winter and

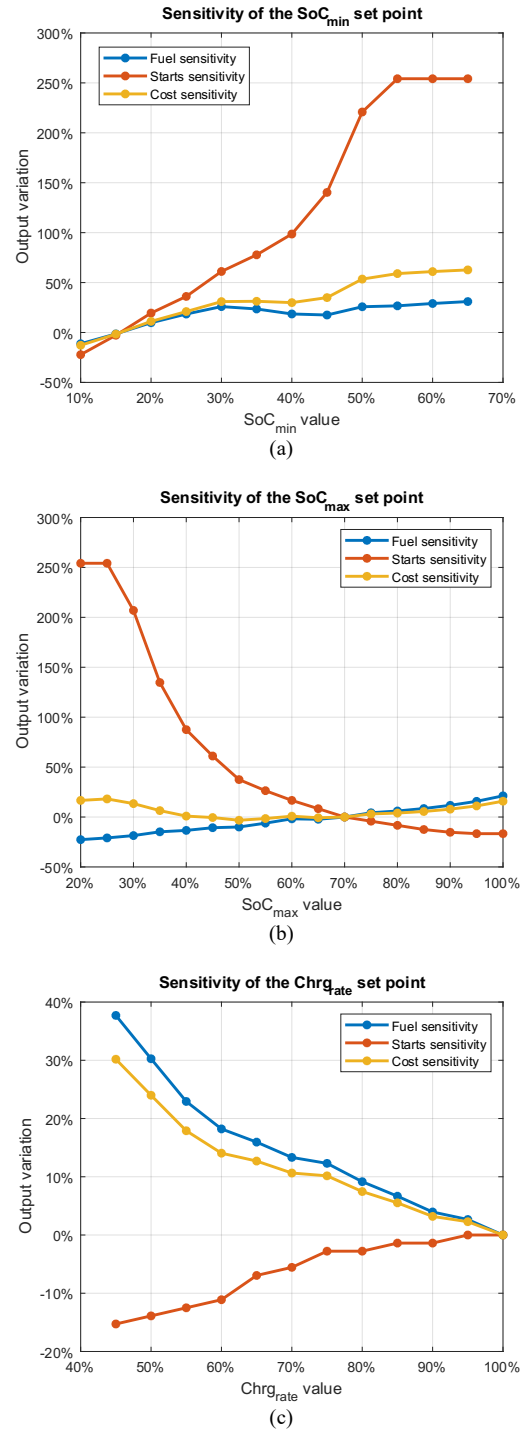


Fig. 4. Set points sensitivity analysis (2022-02-01 to 2022-05-01)

spring. For the objective to optimize, the total fuel consumption f_{DGtot} , which is the integral over simulation time of f_{DG} (1), and the generator start-up number N_{start} are used in a cost function that is aimed to be minimized. The cost of the diesel generator usage, in USD, is defined in (2) where the cost of fuel c_{fuel} is 1 USD/L and the cost of a generator start is 2 USD, as it is applied in [11].

$$CDG = c_{fuel} f_{DGtot} + c_{start} N_{start} \quad (2)$$

The variation of this cost according to the model inputs is also displayed in Fig. 4.

The genetic algorithm is chosen to solve this optimization problem because of its accuracy to find a global optimum for this kind of complex power system modeling [12]. The genetic algorithm available in the global optimization toolbox from MATLAB® is used. The solution to find is the parameter set of SoC_{min} , SoC_{max} , and $Chrg_{rate}$ which has the minimal cost CDG . For the optimization process, these parameters are constrained in the ranges previously defined in the section *Parameters Identification*. Fig. 5 illustrates the integration of the optimization algorithm with the model.

E. Results and discussion

For the winter period, the optimization is done between January 25th and March 20th, 2022, due to the availability of on-site measurement records. The current set points lead to an estimated fuel consumption of 715 L with 58 generator start-ups, which leads to a cost of 754 USD. It is found that optimization saves 55 L of fuel and 11 generator starts if the generator is operated with set points at $SoC_{min} = 11\%$, $SoC_{max} = 71\%$, and $Chrg_{rate} = 95\%$.

For the spring period, the optimization is done between March 20th and May 26th, 2022, due to the availability of on-site measurement records. The current set points lead to an estimated fuel consumption of 334 L with 28 generator start-ups, which leads to a cost of 390 USD. The optimization reduces the cost by 11%, by saving 56 L of fuel if the generator is operated with set points at $SoC_{min} = 10\%$, $SoC_{max} = 39\%$, and $Chrg_{rate} = 73\%$. However, this causes an increase of 6 generator start-ups. These results are summarized in Fig. 6 and 7.

By comparing the results of these two seasons, we see that there is less improvement for winter than for spring. Also, the optimal set point combinations for both seasons are not the same, which confirms the interest in developing an optimization based on a period of the year contrary to assuming fixed parameters set can be optimal for a complete year. Also, in the winter, we see that the new set points have benefits on

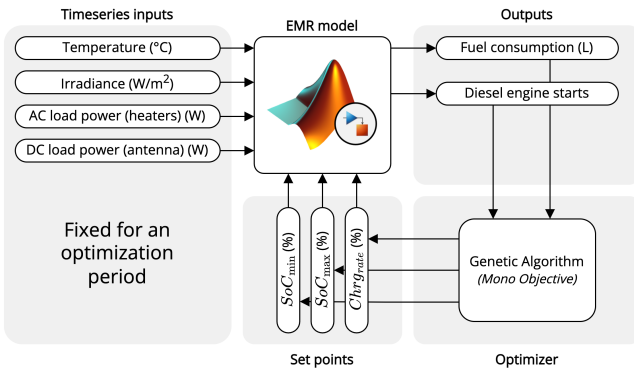


Fig. 5. Interaction of the optimization with the model.

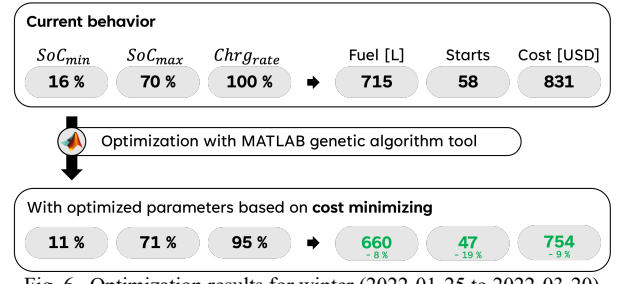


Fig. 6. Optimization results for winter (2022-01-25 to 2022-03-20)

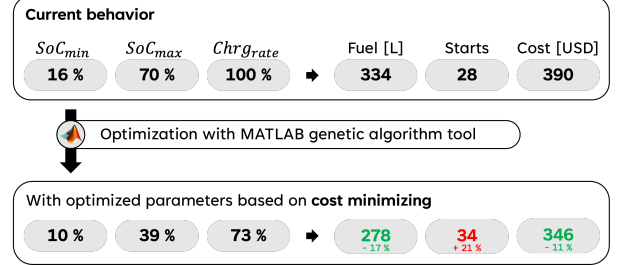


Fig. 7. Optimization results for spring (2022-03-20 to 2022-05-26)

either the fuel consumption or the generator starts, which is not the case for the spring. In fact, for this period, to reach the overall minimum cost, the increase of generator starts must be a compromise to do. For both periods, the SoC_{min} parameter always tends to be close to the minimum boundary, here is 10%, as we saw in the sensitivity analysis where lowering this value is beneficial for the generator usage.

CONCLUSION

We used a model based on Energetic Macroscopic Representation to simulate a nano-grid of a telecommunication base station. A simple energy management system based on the three set points SoC_{min} , SoC_{max} , and $Chrg_{rate}$ that controls this station is presented. We demonstrate that varying these parameters has an impact on the diesel generator usage, i.e., the fuel consumption and the starts number. We demonstrate that SoC_{min} must be minimal to reduce generator usage, while the choice of SoC_{max} depends on a trade-off between the fuel consumption and starts number. The decrease in $Chrg_{rate}$ increases fuel consumption but improves the generator start-ups. A global cost function considering the cost of the generator start-ups and the cost of fuel consumption has been used to find the optimal solution for specific periods such as the winter and the spring.

This paper demonstrates that tuning the input set points SoC_{min} , SoC_{max} , and $Chrg_{rate}$ improves fuel consumption and the generator usage cost. It also supports that changing them through the year must be done to adapt to different weather conditions brought by seasons.

In future work, we will attempt to study the impact of the best date ranges, other than seasons, among which the change of set points would be optimal. For example, we will try to see if an optimization approach based on monthly tuning could lead to better generator usage. Also, as a low battery SoC can deteriorate the batteries, an improved model of battery

degradation can be done to perform a study of the financial impact of operating the system with the previously defined set points. An additional input, such as a weather forecast, could also be considered to perform an online tuning and compare it with the actual offline planning.

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