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A Frequency Response-Based Renewable Resource Hosting Capacity Method for Isolated Grids

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SUMMARY

Diesel-based northern communities have been a focal point of many worldwide initiatives in a drive to reduce dependency on fossil fuel. These communities oftentimes house First Nations reserves deprived of energy resources due to restricted or difficult accessibility. From the electricity standpoint, this means these communities can experience reduced reliability and quality of power that can be traced to the operation of small diesel generators, changing load patterns, or diesel shortage. The development of these areas has been driven by United Nations goals to improve the outlook of their communities. This resulted in uptake of renewable generation in many of such areas. However, integration of grid-tied, inertia-less forms of generation can negatively impact the stability of a system supplied by traditional, rotating forms of generation. If not managed appropriately, rapid variations in the output of renewable generation plants can lead to a sequence of events that ultimately results in unintentional community-wide blackouts that would not occur should this renewable generation not be there. This paper proposes a method to quantify the amount of utility-scale renewable generation that can be integrated in diesel-based isolated grids (i.e., hosting capacity) prior to experiencing misoperation of frequency relays, in turn causing community-wide loss of supply. This method is verified through a case study and field measurements of a real northern community isolated grid.

KEYWORDS

Isolated Grids, Distributed Energy Resources, Frequency Stability

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INTRODUCTION

Canada houses about 300 diesel-reliant northern communities with an aggregate population exceeding 200,000 inhabitants. These communities can be categorized as commercial outposts, villages, hamlets, towns, and cities. Most isolated communities are identified as First Nations [1]. In close alignment with the sustainable development goals of the United Nations, the Canadian federal government has developed programs to incentivize reducing reliance on diesel in these communities, to both increase the electric system reliability as well as to reduce greenhouse gas emissions [2]. This has also been observed in several countries around the globe. These incentives have incited initiatives reduce diesel consumption through increased energy efficiency and adoption of alternative sources of energy.

High inverter-based generation, however, could lead to degraded frequency stability in isolated grids due to the following reasons: (1) lack of inertia, or very low inertia due to their power electronics interfaces, leading to an overall decreased system moment of inertia and increased rate of frequency change, and (2) reduction in the amount of rotating generation units and spinning reserve [3]-[5]. Many approaches have been investigated to overcome these two challenges. For example, [6]-[8] and references therein devoted considerable effort in developing and improving algorithms to implement virtual inertial control for microgrids. While this concept has demonstrated effectiveness in stabilizing frequency within microgrids, it has been mostly confined to wind turbines, and Battery Energy Storage Systems (BESS), with only conceptual adoption in solar central inverters. Solar string inverters, which dominate the application to small isolated microgrids, have not yet garnered such technologies.

Hence, the frequency stability in small community isolated microgrids that do not rely on BESS or microgrid controllers has been managed through limiting hosting capacity of utility-scale inverter-based solar systems [9]-[11]. Reference [10] has proposed limiting the penetration of renewable energy resources by either reducing the installed nameplate or by energy curtailment to ensure energy balance in the system. Reference [11] is more relevant to this paper and has proposed monitoring frequency and voltage excursions and determine the maximum renewable resources penetration based on how well these excursions stay within predefined bands. The research was based on a case study of a small scale northern isolated grid and, while providing insight on system hosting capacity, it was reliant on a case study and difficult to expand to different systems.

In this paper, the author proposes a new hosting capacity method to determine the maximum utility-scale penetration of inverter-based renewable generation. It is based on the capability of the diesel generator(s) to ride through large disturbances caused by rapid reduction in renewable generation production and on typical relay frequency settings for such isolated grids. The result is a set of practical charts that can be directly adopted to guide utility engineers in integrating renewable generation in isolated grids. The charts are developed for a generic system and sensitivity analysis is used to expand their applications to any isolated grid. A real case study is presented, where a real northern isolated community grid was measured and used to validate the proposed charts.

PROPOSED METHOD

The proposed method is based on the frequency recovery of diesel generator(s) to rapid reduction in renewable generation production. This can be illustrated by the generic system shown in Fig. 1. In this system, a number of diesel generators are connected to a common bus. Their terminal voltage is chosen to be 4.16kV as this is the voltage level used at most isolated diesel plants operated by the Canadian electric utility that conducted this study. A solar farm (PV Farm) is connected near the plant, and the size of this solar farm is varied for the study. The total system equivalent load is condensed as shown in the figure. This system is studied by running hundreds of Electromagnetic Transient simulations by using MATLAB/Simulink.

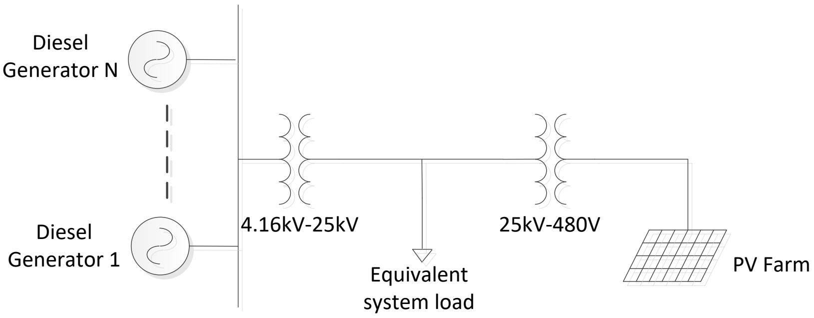

Fig. 1. Simplified system topology.

The purpose of the tests shown in this section is to examine the impact on the system frequency response. Worst case scenarios are used initially. Assumptions are:

1. Only one generator is running at full output.
2. System load is constant power and at unity power factor
3. The PV farm reduces output from ac nameplate to zero in less than one cycle (for example, due to misoperation of a protection scheme, such as anti-islanding, or disconnection).

The result for different PV sizes is shown in Fig. 2, which illustrates expected frequency excursions for different hosting capacity values in relation to the load size. In this simulation, the PV system ceases energization at 5s. The figure suggests that penetration levels as low as 28% can result in frequency nadir nearing 57Hz, and for a penetration level of 83%, the frequency nadir nears 51Hz. Clearly, some of these penetration levels are very likely to cause the diesel generator frequency relay pick-up and trip initiation. This results in a community-wide system blackout, as all generation sources will trip for an event that is considered to be either minor or simply a misoperation that could commonly occur.

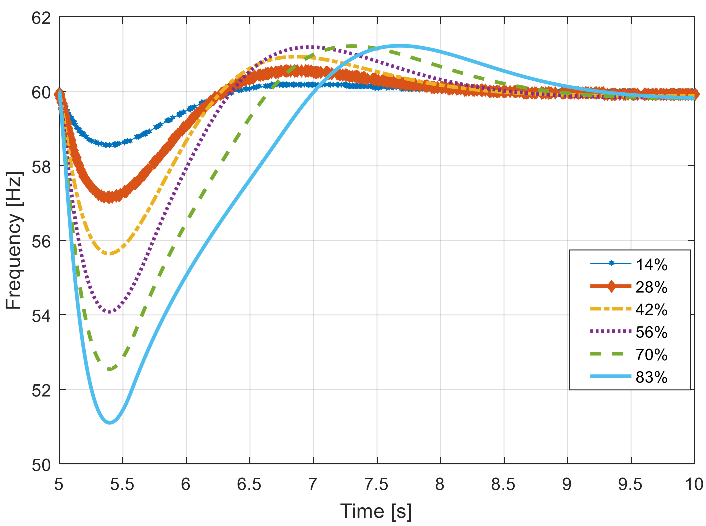

Fig. 2. Frequency response for total loss of PV farm.

Rather than to ascertain whether a frequency relay will pick up or not, this work determines the amount of time the frequency deviates below a certain threshold. Fig. 3 illustrates the time at which the frequency dips below different thresholds (57 Hz, 58 Hz, and 59 Hz) as the PV penetration level increases. To note, the Canadian utility performing this study uses 57 Hz as relay pick-up level in all its isolated communities with a delay of 3 seconds. However, choice is a significant relaxation as compared with the levels specified in the Western Electricity Coordinating Council (WECC) WECC Off Nominal Frequency Requirements (effective December 5, 2003) and OPP 804 “Off-Nominal Frequency Load Shedding and Restoration” that are applicable to the interconnected transmission grid [12].

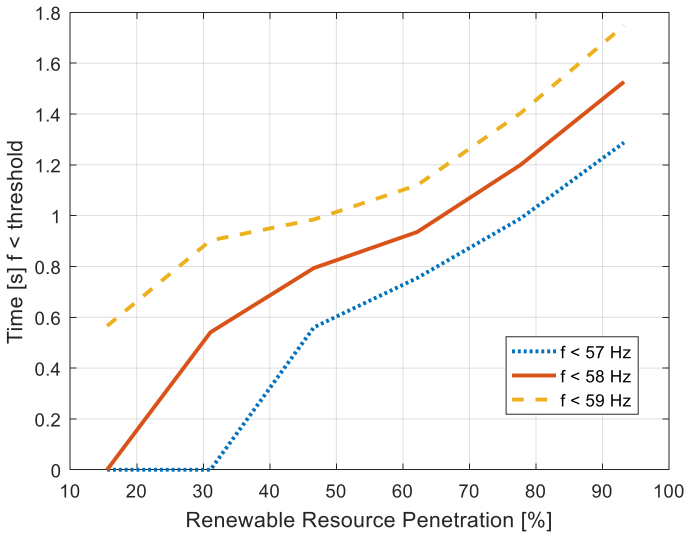

Fig. 3. Timing the frequency dips below threshold at variable penetration levels.

Fig. 3, however, was derived for a real system operated by the Canadian utility conducting the study. To become more adoptable, a sensitivity study that consider typical system parameters is conducted in the next section.

SENSITIVITY ANALYSIS

The diesel generator used in the derivation of Fig. 3 has the system parameters as shown in Table 1. In this table, $P_{nominal}$ is the highest output power the generator can provide, X_d, X'_d, X''_d are the direct-axis steady-state, transient and subtransient reactances, and H is the inertia constant. This is a real generator in operation in the remote community system. The governor and Automatic Voltage Regulator (AVR) were tuned during commissioning and their parameters are not varied in this study.

Table 1. Generator Nameplate

$P_{nominal}$	X_d	X'_d	X''_d	H
1.43 MW	1.56 pu	0.29 pu	0.17 pu	0.6 s

The derivations of the figures presented in this section were obtained by repeating Electromagnetic Transient simulations at each penetration level, for different inertia constants, resulting in hundreds of simulated data stored and plotted in the same graph.

Fig. 4 shows the impact of generator inertia constant [s] on the time the frequency dips below 57 Hz. Reiterating, this is the frequency setting used in the real system, hence its choice. As expected, the lower the inertia constant, the faster the diesel generator will respond to a disturbance, recovering from the frequency dip more rapidly. Larger values of inertia constant result in a slower response, dipping for longer.

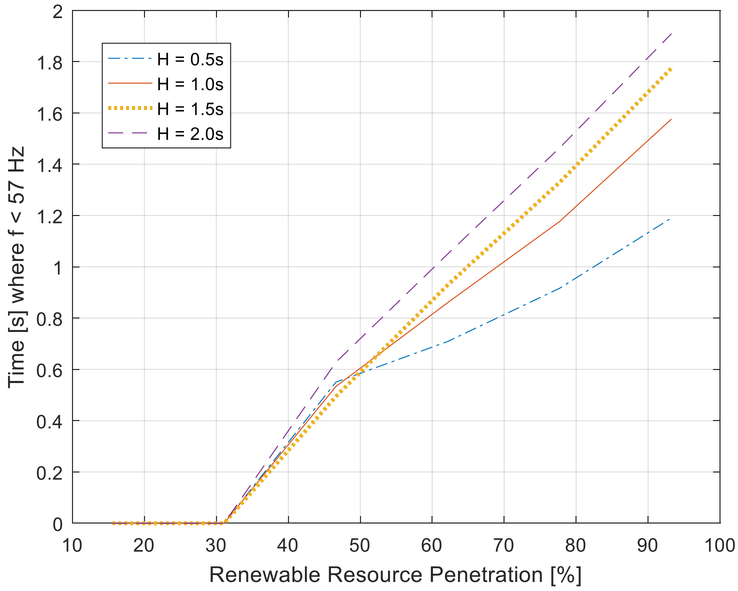

Fig. 4. Renewable generation penetration sensitivity study for different inertia constant values.

The instantaneous diesel generator loading factor is also a very important parameter. While the instantaneous system loading varies, the maximum diesel generator load is routinely controlled by the dispatch strategy and stacking order of the generators in a diesel plant. The electric utility that conducted this study normally does not allow a diesel generator to exceed 90% of its rated output, dispatching a second generator when this output is approached. Intuitively, the more loaded the generator, the less capable it will be to recover from a disturbance. This is quantified in Fig. 5.

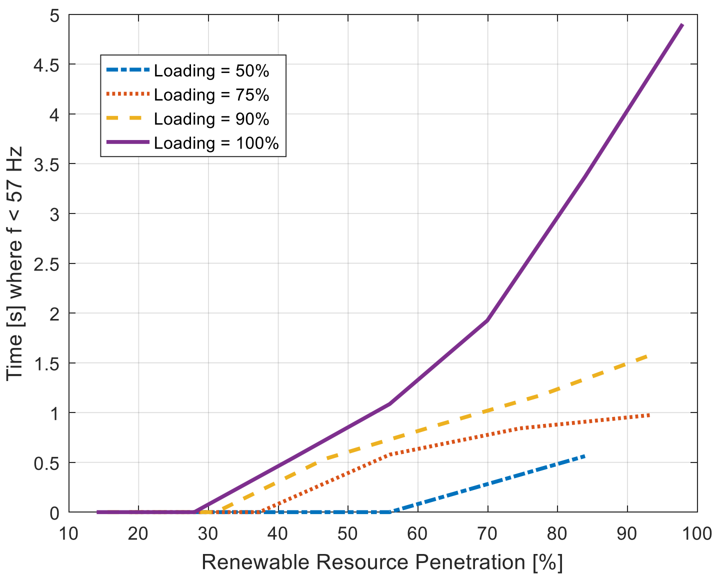

Fig. 5. Renewable generation penetration sensitivity study for diesel generator loading factors.

Finally, the aggregate load power factor is varied to analyze its impact. Intuitively, the lower the power factor (lagging) of a load, will demand the generator to produce VARs, resulting in overexcitation. This overexcitation strengthens the field excitation voltage, increasing stability and causing the generator to respond to disturbances more promptly. This is confirmed by Fig. 6, which shows that as the load power factor is reduced, the frequency dip lasts for less time. This analysis assumes the PV inverters operate at unity power factor, their default factory setting.

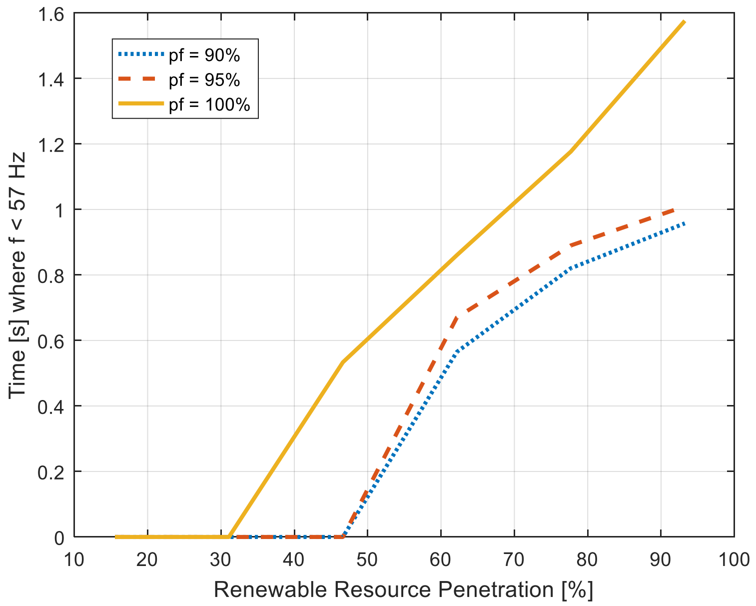

Fig. 6. Renewable generation penetration sensitivity study for different load power factor values.

CASE STUDY AND FIELD MEASUREMENTS

The isolated community under study is one of the oldest European settlements in the province of Alberta. Currently, it houses three First Nations with a total population of close to 900 dwellings. There is no natural gas supply in this community, and residents are reliant on diesel and electricity only. The electricity is generated at 4.16 kV and stepped up to 25 kV. All four diesel generators are identical and rated 1.15MW/1.3MW/1.4MW (nominal/prime/overload ratings). There are some loads served near the plant, but most of the load is located about 8km south of the plant and supplied at 2.4kV. The PV farm was installed early in 2019 and it is located very close to the diesel plant. The PV farm is 600kWdc / 450kWac. Fig. 7 shows a simplified system diagram.

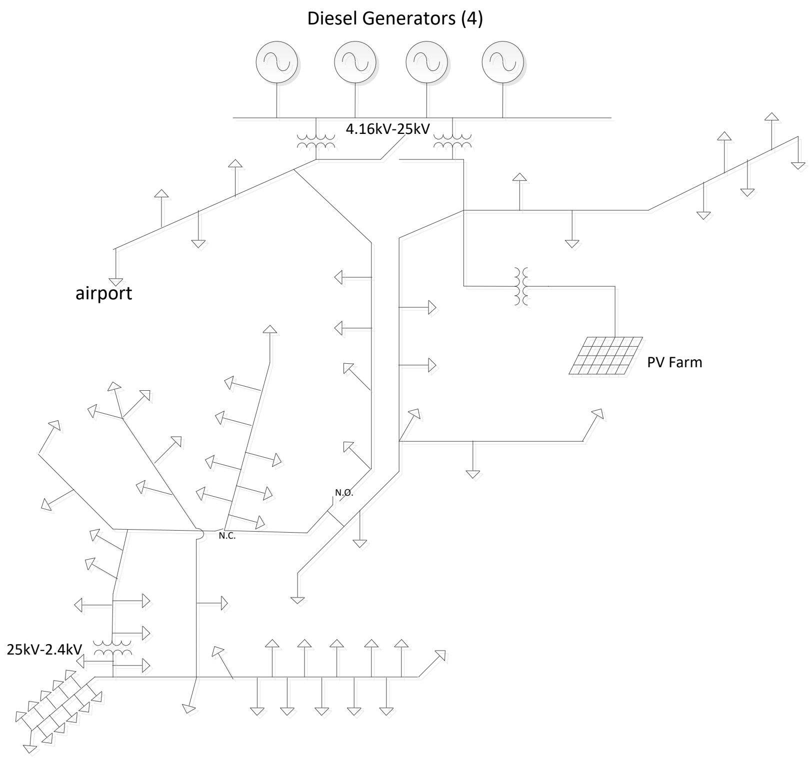

Fig. 7. Simplified electrical system topology.

During the plant commissioning a condition of full PV output (450kW) and two generators running at about 650kW each was captured. Under this condition, the PV plant was intentionally tripped by opening the overhead three-phase interrupter. Measurements were recorded and compared with a similar loading simulated case. This is shown in Fig. 8. While not an exact match, the results are close enough to accept the model used for simulation. The measurements were acquired by using a portable power quality monitor that samples the three phase voltages and currents at a sampling rate of 1,024 samples/cycle. Data post-processing is then carried out by using MATLAB to calculate several system parameters, including frequency.

For the case study, the electric utility determined a safe hosting capacity for its utility scale PV farm would be about 40% of the size of the diesel generator. For most disturbances, the studies contained in the paper deem this penetration level to be safe.

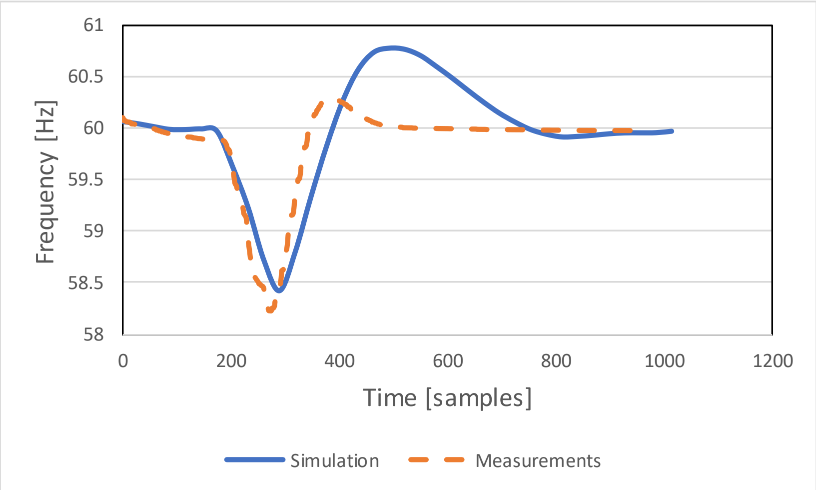

Fig. 8. Simulation and measurements for PV plant disconnection.

CONCLUSIONS

This paper has proposed a method to determine the maximum penetration level of utility-scale inverter-based renewable generation that can be integrated in off-grid isolated systems. The main criteria was frequency response and frequency protection elements. Any further installation of renewable generation can only be accepted if a BESS and microgrid controller are also installed.

The second contribution of the paper is a set of practical charts that can be directly used by utility planners of such systems. By knowing frequency relay settings, these charts present the hosting capacity. If other small scale, residential renewable generation units are present, these do not need to be included in the charts for two reasons:

1. These are generally small and likely to be ignored as compared to the nameplates of utility-scale renewable generation systems.
2. These are unlikely to experience the exact same rate of energy output cessation, due to not being disconected by the exact same protective device.

The author hopes this research, including the presented charts will be of usefulness to utility engineers planning renewable integration in isolated systems where these are not being integrated with BESS and microgrid controllers.

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