ENHANCED PART LOAD OPERATION OF DIESEL HYBRID MINI-GRIDS WITH HIGH PENETRATION OF PHOTOVOLTAICS

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Abstract. *Renewable energy sources such as wind and photovoltaic (PV) have great potential for reducing fuel consumption in diesel-based mini-grids in remote communities. However, the fluctuating and intermittent nature of these sources can give rise to a number of problems in mini-grids with high penetration of non-dispatchable renewables with reduced or non-existent storage units. This paper proposes the use of a frequency x power droop control strategy for curtailing the output power of PV inverters during periods of excess of power in a diesel-dominated mini-grid. This approach reduces the operation of the diesel genset under part (light) load conditions, reducing frequency variation, and avoids overvoltages in the mini-grid. The theoretical analysis is verified by means of digital simulations with PSCAD.*

Keywords: *diesel driven generators, load frequency control, photovoltaic power systems, power distribution.*

1. INTRODUCTION

More than 200,000 Canadians live in Canada's 310 remote communities (Kim Ah-You and Greg Leng 1999). These are not connected to the main electricity grid and usually depend on oil from the south for heating and for electricity. Energy supply in these communities is thus characterized by high costs and a high degree of dependence on fossil fuel. Most communities rely on diesel generators for producing electricity at costs that vary between \$0.15 and \$1.50 per kWh. At these costs, several renewable energy technologies (RETs) such as photovoltaic (PV) and wind can be cost effective to meet part of the energy needs in many remote communities.

In principle, the incorporation of RETs into a diesel-based system is relatively simple and they operate as passive generation units, with no participation in the control strategy of the mini-grid (Lopes, Moreira et al. 2006; Katiraei, Iravani et al. 2008). They usually inject the maximum amount of energy that can be converted from the wind and solar irradiance using some sort of maximum power point tracking (MPPT) strategy. However, the energy of these fluctuating and intermittent non-dispatchable RETs is not an asset if it is not consumed when produced. Power smoothing of RETS can be achieved with energy storage devices (Barton and Infield 2004; Abbey and Joos 2007; Black and Strbac 2007) but conventional battery storage happens to be the most expensive mini-grid component over its life-time. In storage-less systems, dump loads are frequently used to burn excess power. As a result, the impact on RETs on fuel displacement on hybrid mini-grids is usually modest (Katiraei and Abbey 2007).

It should also be noted that many remote community systems are characterized by highly variable loads, with the peak load as high as 5 to 10 times the average load. Thus, the power balancing task of the grid forming unit(s), usually one or more diesel gensets, is even more demanding. Mini-grids, by definition, represent weak grid conditions. Sudden variations of reasonable amounts of power generation/consumption may deteriorate the power quality and stability of the mini-grid. Large variations of frequency and voltage can lead to tripping of sources and loads. This problem is even more critical during high penetration of RETs and with the system operating with reduced amounts of rotating masses due to low combined generator inertia. Lastly, large amounts of fluctuating power will complicate power dispatch, load sharing, unit cycling and associated functions of the supervisory control system of the diesel plant.

It is worth mentioning that operation of gensets at part (light) load conditions, below 0.3 pu, can result in increased carbon build up in the diesel engine (James B. Malosh, Ronald Johnson et al. 1985), which can significantly affect the maintenance costs and even the life time of the genset. A common solution is the use of dump loads with further waste of costly fuel. In mini-grids with frequency droop controlled gensets, dump loads usually reduce the frequency rise, which is a global quantity, but not necessarily the voltage rise, which is site dependent, mostly if the electrical distance between dump loads and the point of common coupling (PCC) of the RETs is long.

Alternatively, one can employ active power curtailment (APC) of RETs based on locally measured variables what has the potential to address, the low loading condition of the genset (Tonkoski, Lopes et al. 2009), overfrequencies as well as overvoltages. Recall that diesel power plants in mini-grids are usually composed of a number of gensets operating with power vs. frequency droop control.

This paper discusses the potential of power curtailment of RETs during periods of energy surplus in a diesel dominated mini-grid for improving the steady-state performance. The output power of PV inverters will be varied using the well-known frequency x power droop control. The proposed technique suitability is verified by means of simulations.

2. DIESEL-DOMINATED PV HYBRID MINI-GRID

An elementary PV-diesel hybrid mini-grid is shown in Figure 1 (a). It consists of a grid-forming diesel power plant which can include one or more droop controlled gensets operating in parallel. The PV inverter is rated at a fraction of the diesel plant and is located away from the diesel plant. They supply a non-controllable lumped load representing the customers' loads. Although not shown in Fig.1, an on-off dump (controllable) load is often employed in such a system to provide a minimum load to the genset(s) thus avoiding operation of the genset(s) at light load. It is usually placed close to the diesel power plant and is dispatched by the supervisory control system of the diesel plant. There are no energy storage units in this system.

3 BASIC CONCEPTS

3.1 Droop control

Droop control is a well-known technique used for operation and power sharing of power generators connected in parallel. The relationship between frequency and power can be described by

$$P_{gen} = s_P(f_{nl} - f) \tag{1}$$

for $f \leq f_{nl}$. There, P_{gen} is the output power of the generator (kW), s_P is the slope of the curve (kW/Hz), f_{nl} is the no-load frequency of the generator (Hz) and f is the operating frequency of the system (Hz). In case of two droop controlled generators (sources) supplying a common load (P_{load}) the relationship with the frequency would be,

$$P_{load} = P_{gen\_1} + P_{gen\_2} = s_{p\_eq}\left(f_{nl\_eq} - f\right) \tag{2}$$

where

$$s_{p\_eq} = s_{p_1} + s_{p\_2} \tag{3}$$

$$f_{nl\_eq} = \frac{s_{p\_1}f_{nl\_1} + s_{p\_2}f_{nl\_2}}{s_{p\_1} + s_{p\_2}} \tag{4}$$

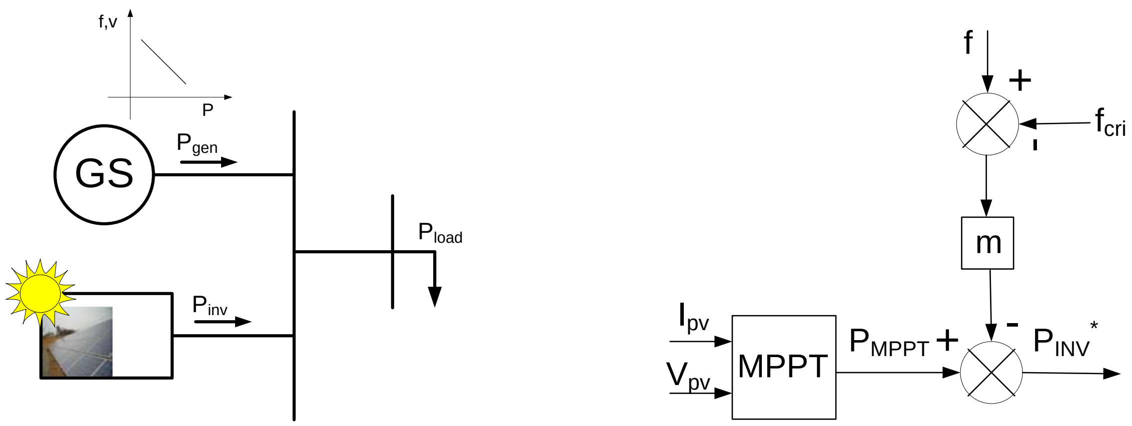
For a given value of load power, one can calculate first the system frequency with (2) and then the output power of each generator with (1).

3.2 Droop controlled PV inverter

Usually grid-tie inverters are controlled with MPPT and as current sources. Alternatively, the power injected by the inverter can be controlled (reduced) as a function of the system frequency according to

$$P_{inv} = P_{MPPT} - m\,(f - f_{cri}) \tag{5}$$

for $f \geq f_{cri}$. This is valid as long as $P_{inv} \geq 0$, if the inverter is connected directly to the PV array (no battery storage in an intermediate dc bus) as assumed in this paper. There, P_{MPPT} is the maximum power available in the PV array for a given solar irradiance (kW), m is a slope factor equivalent to s_p and f_{cri} is the frequency (Hz) above which the power injected by the inverter is decreased with a droop factor. For $f < f_{cri}$ the inverter injects P_{MPPT}, as most PV inverters do. This value should be selected based on the genset droop characteristics, so as to minimize the reduction in genset loading above this frequency and consequently the frequency rise. The logic used to implement (5) is shown in Figure 1 (b).



(a) (b)

Figure 1 – (a) Grid connection of PV panels, (b) Droop based APC of the PV inverter.

3.3 Diesel PV hybrid system characteristics

The droop characteristics of the diesel PV hybrid system can be obtained by substituting (1) and (5) in (2). After some manipulations one obtains

$$P_{load} - P_{MPPT} = s_P(f_{nl} - f) + m\,(f_{cri} - f) \tag{6}$$

for $f_{cri} \leq f \leq f_{nl}$. In the left hand side, one sees a "frequency independent" load and a "frequency independent" source. In the right hand side there are two "frequency dependent" (droop controlled) elements. One is a source (genset) and the other is a load (power curtailed from the PV inverters). Although these have the same format, they have opposite signs since the system frequency (f) is always below f_{nl} and PV inverter power curtailment only occurs for $f \geq f_{cri}$. For $f < f_{cri}$, the frequency dependent load is not active (zero) and the inverter supplies as much power as available in the PV array.

A numerical example is used to illustrate these two operating regions. The key parameters of the system are shown in Table I.

Figure 2 shows the droop curve of the genset (0 kW ≤ P_{gen} ≤95 kW) and also the frequency vs. power curve of the diesel PV hybrid system, which is divided in two segments. In the first, for $f < f_{cri}$, the PV inverter operates with MPPT and the grid forming genset supplies the difference between the load, assumed to be 50 kW in this example, and the PV inverter power that varies with the solar irradiance. Any increase in the power supplied by the PV inverter will result in an equivalent decrease in the genset output power. The system frequency increases according to the droop curve of the genset. As the solar irradiance increases, or load power decreases, the system frequency tends to increase and when it becomes larger than f_{cri}, the output power of the PV inverter begins to be curtailed. In this second segment, the system frequency will vary according to a new curve defined by the droop characteristics of the genset and of the APC of the PV inverter, as discussed in Section 3.1. The diesel PV hybrid droop curve presents a smaller slope than that of the genset. For instance, for $m = s_p$, it is half the slope of the diesel genset curve. Note that the *slope* is numerically equal to the inverse of the s_p and m parameters when the frequency vs. power droop characteristics is shown with the parameter frequency in the vertical axis.

Figure 2 shows that when the solar irradiance is at its rated value (P_{MPPT} = 43.5 kW) the system frequency, according to the diesel PV hybrid droop curve (6), is equal to 61.74 Hz. At this frequency, using (2) the genset load is equal to 17.5 kW (~ 0.18 pu) and the power curtailed from the PV inverter (P_{droop}) is around 11 kW. Alternatively, if the PV inverter was allowed to inject maximum power into the system, the genset load would be reduced to 6.5 kW (~0.07 pu) what should have a significant impact on the carbon build up in the diesel engine and on its maintenance costs. It should be noted that for the droop parameters selected for the APC of the PV inverter, discussed in Section 4.2, and the load level considered in this case (50 kW), there would be no power curtailment until P_{MPPT} reaches 21.5 kW and f reaches f_{cri} = 61.37 Hz. Beyond this point, PV power would be curtailed, as the frequency increases, at the same rate as the genset power is reduced, since they present the same droop factor (slope). Mathematically, for this case, one can say that

$$P_{droop} = \frac{P_{MPPT} - P_{MPPT\_cri}}{2} = P_{gen\_cri} - P_{gen} \tag{7}$$

Where all PV powers (P_{MPPT}, P_{MPPT_cri} and P_{inv}) are shown from right to left in Fig. 2, starting at the load power level (P_{load}). As mentioned in previous sections, a dump load is often used in practice to avoid operating the genset below ~0.3 pu. Another approach suggested by genset manufacturers is that when they are required to operate at low loading conditions, they should run at full load for 1-2 hours to get rid of the carbon accumulated along the day. This leads to high costs in fuel and offsets part of the gains with the installation of renewable energy resources. A compromise between maintenance costs and the cost of power curtailed should be established in order to design optimum APC parameters for a specific mini-grid, which is not in the scope of this paper.

Table I. Main parameters of the diesel PV hybrid system.

	Diesel genset	PV inverter
Rated power	95 kW	43.5 kW
Droop factor	29.4 kW/Hz	29.4 kW/Hz
No-load frequency	62.34 Hz	-
Critical frequency	-	61.37 Hz

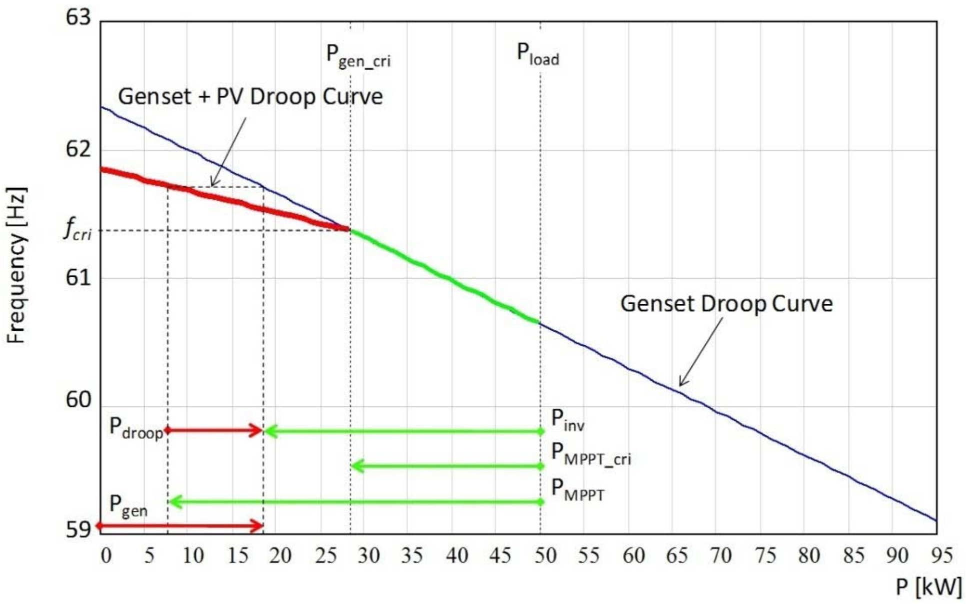


Figure 2 – Diesel-PV hybrid system frequency variation.

4. SYSTEM DESCRIPTION AND RESULTS

4.1 Benchmark

To validate the proposed technique a benchmark of a rural isolated system based on the one developed by CANMET Energy - NRCan (Katiraei, Turcotte et al. 2008; Turcotte 2009) and (Tonkoski, Turcotte et al. 2010) were adapted by the authors to study mini-grid operation and implemented in PSCAD©. The benchmark scheme is presented in Figure 3.

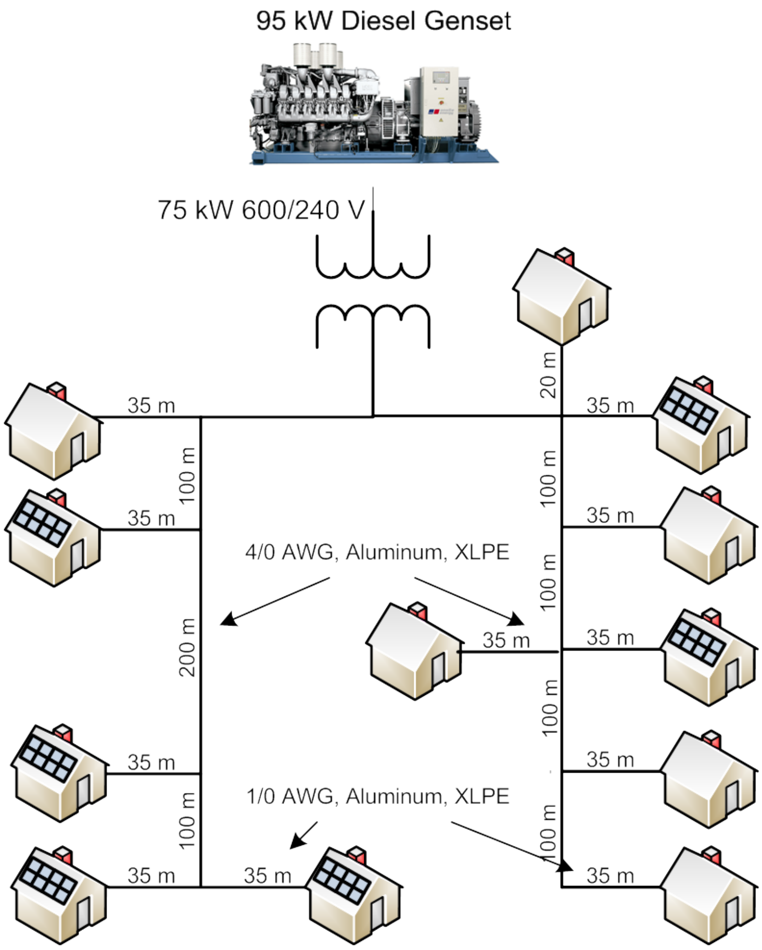


Figure 3 – Rural Mini-grid benchmark.

A 95k W genset feeds the network in a single phase connection where only two of the three outputs of the genset are used. As this genset is rated at 95 kW on a three phase basis, in practice it means that only 2/3 of the generator power is available. The frequency and voltage curves of the 95 kW diesel genset are shown in Figures 4 and 5.

The power distribution is accomplished through low-voltage single-phase overhead lines. The voltage is brought from 600 V to 240 V using a standard 75 kVA distribution transformer next to the diesel power plant. There is no tap changer or other voltage regulation means except the manual tap adjustment in the primary of the 75 kVA transformer in steps of 5 % of the rated voltage.

The 240 V line is a typical wood pole line. It is wired using 4/0 AWG Aluminum, XLPE for both line and ground and the drop lines are wired with 1/0 AWG Aluminum, XLPE. The cable and transformer parameters are presented in Tables II and III. They were chosen based on system planners guide lines for rural mini-grids.

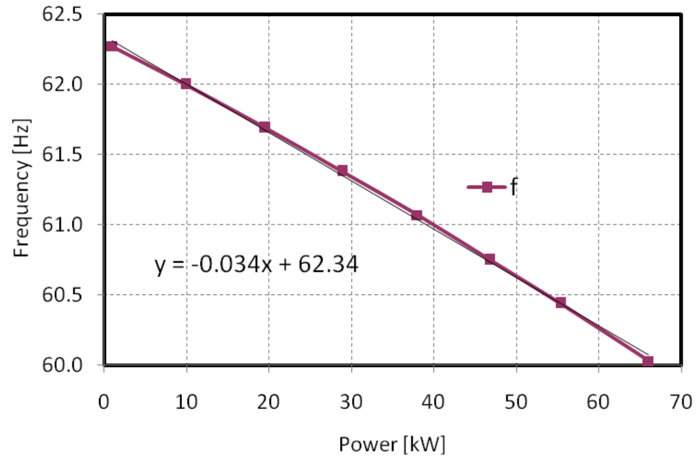


Figure 4 – 95 kW Diesel genset frequency vs. power droop characteristic.

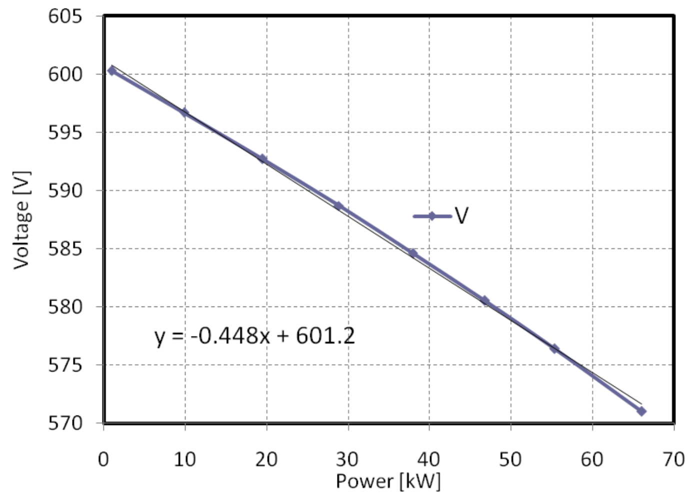


Figure 5 – 95 kW Diesel genset voltage variation with output power.

Table II – Single-phase PI section lines parameters (per line conductor)

	Drop Lines	Pole-Pole Lines
R	0.549 Ω / km	0.27 Ω / km
L	0.23 mH / km	0.24 mH / km
C	0.055 µF / km	0.072 µF / km

Table IIII – Transformer's Simulation Parameters

	Transformer's Simulation Parameters
Rated Power	75 kVA
Primary Voltage	600 V
Tap	0.95:1
Secondary Voltage	240 V
Copper Losses	0.045 pu
No Load Losses	0.002 pu

	Transformer's Simulation Parameters
Leakage Reactance	0.045 pu

4.2 Design of droop-based APC

The droop-based APC is designed so that power curtailment starts, based on local frequency measurements, when the genset load falls below 0.3 pu. Until this point, no curtailment is used and all the PV power is injected into the mini-grid. The output power of the PV inverter is reduced linearly by the APC as the frequency increases and when the genset load reaches 0.2 pu, 0.1 pu of inverter power is curtailed. These values were selected so that one can compare the impact of the APC scheme with the use of a simple 0.1 pu dump load that represents the conventional approach for dealing with part load operation of gensets. The design of the PV droop coefficients uses these two set points as reference. The value of f_{cri} is obtained manipulating equation (1) and considering the frequency as the APC starts to act. Equation (8) presents the design for the 95 kW genset.

$$f_{cri} = f_{gen\ 0.3pu} = \left(f_{nl} - \frac{P_{gen\ 0.3\,pu}}{s_P}\right) = 61.37\ Hz \tag{8}$$

The coefficient m is obtained by equation (9). Considering that 0.1 pu of PV power should be curtailed linearly when the genset is operating between 0.3 pu and 0.2 pu, the m coefficient is obtained dividing the power to be curtailed in this period by the frequency variation.

$$m = f_{gen\ 0.3pu} = \frac{0.1\ P_{rated}}{f_{gen\ 0.3pu} - f_{gen\ 0.2pu}} = 4.9\ \frac{kW}{Hz} \tag{9}$$

Where P_{rated} is the rated power of the genset (kW).

4.3. Simulation results

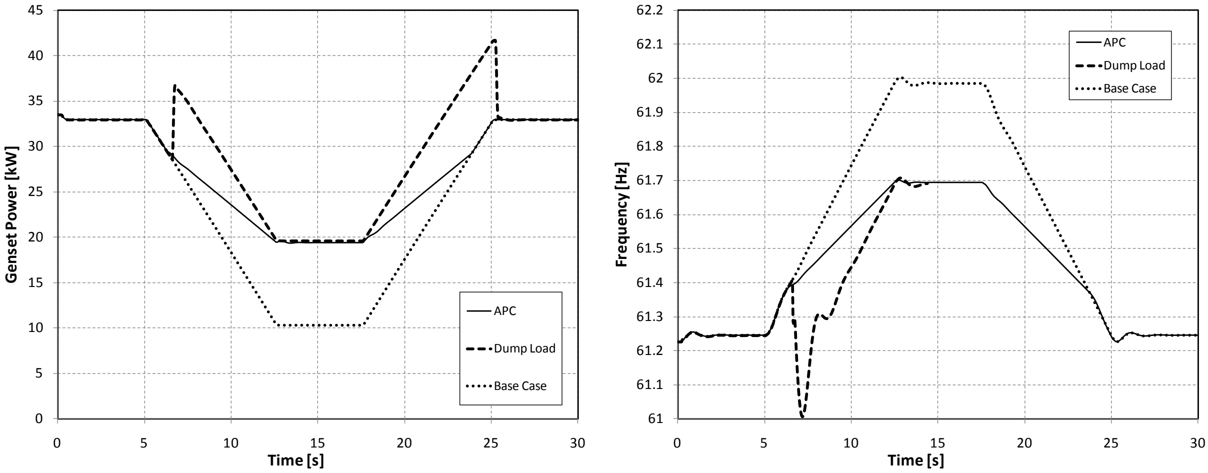
In all the simulations shown below, the load is assumed constant at around 50 kW (0.52 pu) and is equally distributed among the twelve houses of the system (4.2 kW each). 6 houses have installed 7.25 kW PV systems, for a total of 43.5 kW of PV, as shown in Figure 3. The objective of the simulations is to investigate the effect of the solar irradiance variation on the mini-grid operation. The fuel consumption rate was estimated by the information provided by one manufacturer of a 95 kW system and using an exponential regression. The equation used is fuel rate = $6.105e^{0.015P}$.

Three case studies are considered considering that the PV power available (P_{PV}) goes from 3.25 kW to 7.25 kW.

Case #1, base case, presents the simulation results for the system operating with MPPT and variable solar irradiance. There, the genset load decreases when the PV penetration increases. The genset load starts at 33 kW (0.34 pu) for a PV generation of 19.5 kW (44% of total PV capacity). In Figure 6 (a), the PV generation goes from 44 % to 100 % in t = 5 s. The genset load falls to 10.3 kW (0.11 pu) increasing its frequency of operation to 61.98 Hz (Figure 6 (b)). Although it reaches a low fuel consumption state (Figure 7 (a)), this low power operation results in carbon build up in the combustion engine as mentioned earlier. The voltage in the farthest house of the left feeder reached 1.069 pu (Figure 8 (a)), well beyond the accepted voltage levels for distribution feeders in Canada, as recommended by the (CSA R2006), which establishes a maximum of 1.058 pu for extended operation. At t = 17.5 s, the solar irradiance and PV generation start to decrease, reaching 44 % of their rated value at t = 25 s.

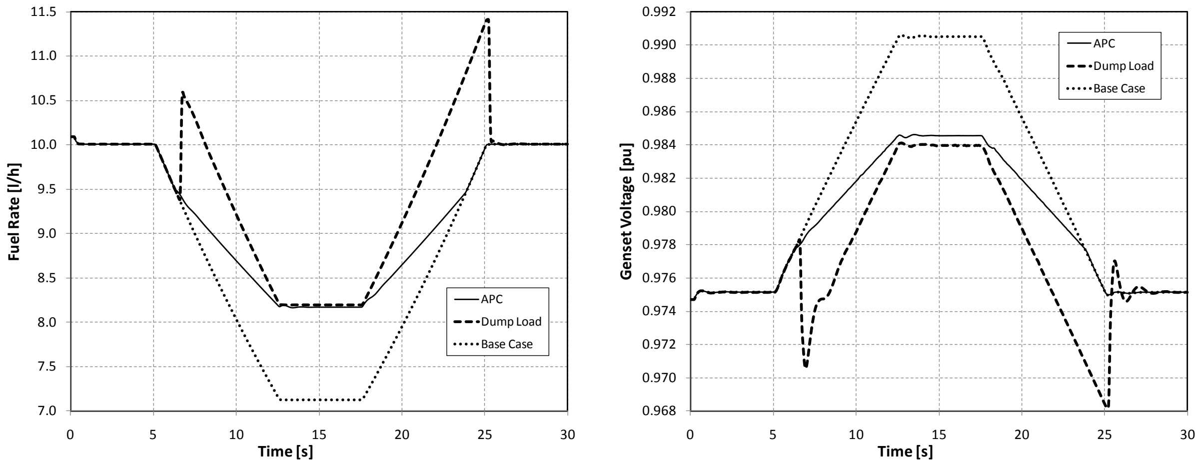
In Case #2, shown in the items (b) of Fig. 6 and 7, a 36 Ω dump load (about 10 kW at 600 V) is used to compensate for the decrease in genset load. It is connected whenever the genset power is below 28.5 kW (0.3 pu) and disconnected when the genset power reaches 32 kW (0.33 pu). On Fig. 6, at rated solar irradiance, the use of the dump load resulted in a genset loading at 19.6 kW (0.2 pu), higher than in the base case, and a frequency of 61.7 Hz, lower than the base case. Just after the dump load is connected, the genset power goes to about 37 kW and is decreased by the PV generation increase. This happens as dump loads mostly operate in steps and would hardly match the exactly desired load condition. If the genset load falls below 0.3 pu, the energy burned/wasted at the dump load is the same, regardless of the power produced by the PV. Although the genset power is above 0.2 pu, the voltage in the left feeder, is still beyond the acceptable value (CSA R2006). The voltage at the last house reached 1.062 pu because of the reverse power flow in this feeder section. No overvoltages occur in the right feeder.

In Case #3, no dump loads are used and the droop controlled inverters provide the power curtailment to regulate the genset operation. The parameters used in the droop controllers are f_{cri} = 61.37 Hz and m = 4.9 (kW/Hz). The power curtailment is done proportionally to the frequency rise above f_{cri}, in order to make the genset to operate above 0.2 pu for a 50 kW load and at rated solar irradiance. Figure 6 (a) shows that the genset load is kept to the same 19.6 kW (0.2 pu) as compared to the dump load case. The frequency increases linearly to 61.7 Hz, curtailing 1.6 kW per PV inverter (Figure 9). Comparing fuel consumption, with dump load there is a single point where it will have the same fuel consumption performance. The APC provides overall better fuel consumption performance and keeps the genset load leveling closer to the 0.3 pu most of the time. This is clear comparing performances in Figure 7 (b), just after the dump load is connected, in that moment, with APC, the fuel consumption is 9.46 l/h while with the dump load it went to 10.6 l/h, burning unnecessary fuel. Also, the voltage rise in the farthest house in the left feeder was limited to 1.045 pu, below the recommended 1.058 pu from (CSA R2006), avoiding the overvoltage occurrence. This is due to reducing the reverse power flow in the left feeder, as compared with the dump load case.



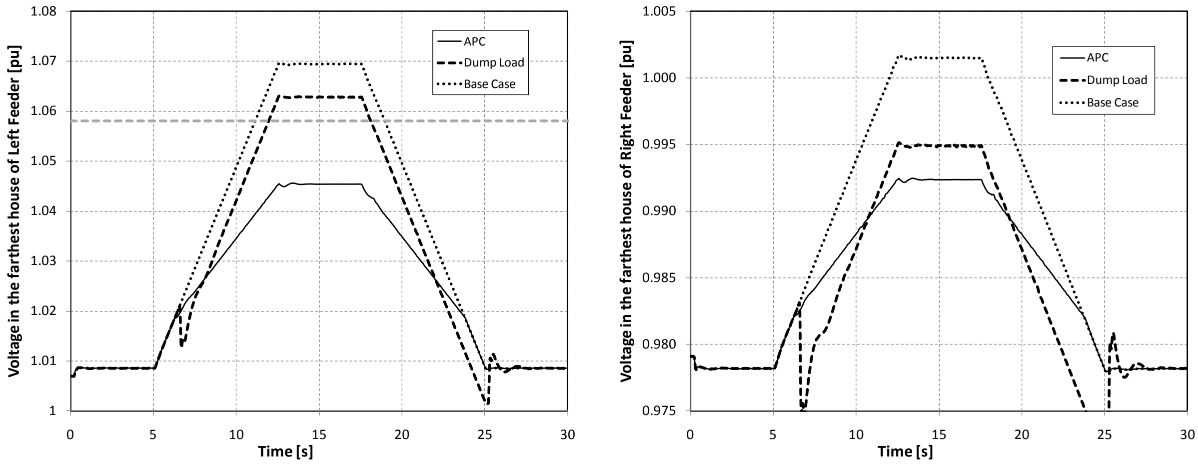
(a) (b)

Figure 6– Diesel genset output power and frequency.



(a) (b)

Figure 7– Fuel Consumption flow rate (a) and genset's output voltage (b).



(a) (b)

Figure 8 – Voltage in the last houses of (a) left feeder and (b) right feeder.

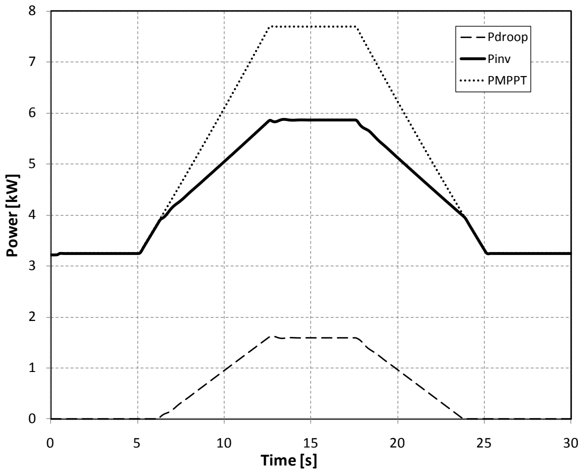


Figure 9 – Inverters output power and droop.

5. CONCLUSION

This paper has discussed the use of APC of PV inverters in PV-diesel hybrid mini-grids as a means for reducing frequency variation, ensuring minimum loading of the diesel genset(s) and indirectly avoiding overvoltages in LV feeders. It has been shown that the main parameters of the droop control scheme (m and f_{cri}) offer a good degree of flexibility for improving the system performance not available when a conventional dump load is used. Also the fuel consumption is optimized during low load and high penetration periods as compared with dump loads that are adjusted to operate at a specific set point.

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