Using Electric Water Heaters (EWHs) for Power Balancing and Frequency Control in PV-Diesel Hybrid Mini-Grids

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Abstract: Electricity is usually supplied by diesel generators in remote communities at costs that can reach up to $1.50 per kWh in northern Canada. At these costs, several renewable energy sources (RESs) such as wind and photovoltaic (PV) can be cost effective to meet part of the energy needs. Their main drawback, being fluctuating and intermittent, can be compensated with either storage units, which are costly, and/or by adapting the electrical power consumption (load) to the availability of RESs. Electric water heaters (EWHs) are good candidates for demand side management (DMS) because of their relatively high power ratings and intrinsic thermal energy storage capabilities. The average power consumed by an EWH is strongly related to the set point temperature (*Td*) and to the hot water draw (*Wd*). A 5.5 kW, 50 gallon EWH is modeled in MATLAB-Simulink and a typical 24-hour water draw profile is used to estimate the potential range of power variation offered by an EWH for power balancing purposes. Besides, a strategy for controlling the power consumed by the EWH, by means of *Td*, using a grid frequency versus temperature/power droop characteristic is proposed. In this way, the EWH can be used for power balancing and for assisting with the mini-grid frequency control.

Keywords: *Diesel hybrid system, electric water heater, power balancing, frequency regulation*

Nomenclature

t_{on}	*time period that EWH is ON*	*h*
t_{off}	*time period that EWH is OFF*	*h*
T	*total operation cycle of EWH*	*h*
Tin	*incoming water temperature*	*°F*
Ta	*ambient air temperature outside tank*	*°F*
Td	*reference temperature for the EWH*	*°F*
T_H	*temperature of water in tank*	*°F*
ρ	*density of water*	*lb/gal*
C	*thermal capacity of water the tank*	*BTU/°F*
B	*thermal capacity of water usage*	*BTU/°F*
Q	*energy input rate*	*Btu/h*
Wd	*average water draws per hour*	*gal/h*
Cp	*specific heat of water*	*BTU/lb. °F*
SA	*surface area of tank*	ft^2
U	*stand-by heat loss coefficient*	*Btu/°F. h.* ft^2
$P_{EWH\ average}$	*power consumed by EWH*	*kW*

1. Introduction

Diesel generators sets (gensets) are a relatively expensive way to produce electricity in remote areas when connection the main grid is not feasible. Renewable energy sources (RESs) such as wind and photovoltaic (PV) are an attractive solution to reduce cost of electricity in these systems. They are environmentally friendly and their incorporation into diesel based mini-grids is relatively simple [1] for low penetration levels. They are usually controlled as passive units, injecting as much of intermittent and fluctuating power as possible, while the grid forming unit(s), usually gensets, have to match the power generated and consumed in the system [2]. This is not an easy task considering that remote communities are characterized by highly variable loads with the peak load as high as 5 to 10 times the average load. What is more, gensets should not operate at low load conditions (~0.3-0.4 pu), due to maintenance problems in the diesel engine, and should provide spinning reserve for cases of sudden load surges or renewable generation reduction [3]. It should be noted that diesel gensets are usually Operated in parallel with frequency x power droop characteristics what facilitates active power dispatch. Besides, operation with variable frequency conveys the message of surplus

(higher frequencies) or shortage (lower frequencies) of active power in systems with non-dispatchable renewable sources.
Power balance issues can be overcome with energy storage units but this is a relatively costly solution [4]. Alternatively one can use controllable loads to help with the power balancing and frequency regulation in a diesel hybrid mini-grid. Due to their relatively large time constants, thermal loads such as electric water heaters (EWH) present an energy storage characteristic and are good candidates for power balancing and frequency control [5].
The use of EWHs in load side demand control was introduced in 1934 by Detroit Edison. Timers were employed to cut off energy flow to EWHs during peak periods for four hours [6]. Later, many other control strategies were developed.

This paper discusses the use of EWHs to help balance the active power and assist with the frequency regulation in diesel hybrid mini-grids. A model of 5.5kW-50gal EWH is implemented in Matlab/SIMULIINK in order to observe the impact of varying the set point temperature (*Td*) on the power consumed by the EWH supplying a typical residential water draw (*Wd*) profile. Analytical equations are derived and used for estimating how much power an EWH can take or drop during each hour of the day, by varying *Td*, while keeping the hot water temperature (T_H) within acceptable values.

2. Methodology

2.1. Electric water heater (EWH) model:

The following first-order differential equation, which represents the energy flow in an electric water heater [7], was used to implement a simple model of an EWH.

$$C\frac{dT_H}{dt} = U\,SA(Ta - T_H) + Wd\,\rho C(Tin - T_H) + Q \tag{1}$$

The first part at the right side represents the heat losses to the ambient, the second the heat needed to heat the inlet cold water, and the last one is the input heat energy from the resistive element of the EWH.
By integrating both sides one gets

$$T_H = \frac{1}{\tau}\int (R'GTa + R'BTin - T_H + R'Q)dt \tag{2}$$

Where $G = U\,SA$, $B = Wd\,\rho C$, $R' = 1/(G+B)$ and $\tau = R'C$

By implementing (2) in Matlab/SIMULINK one can see the variation of the temperature of the hot water in the tank (T_H) for various conditions. The heating element of the EWH is turned ON and OFF so as to keep T_H within a tolerance band (+/- Δ) of *Td*. When the heating element of the EWH is ON, T_H rises until it reaches (*Td*+Δ). Then the heating element is turned OFF and T_H decreases until it reaches (Td-Δ), when the heating element is turned ON again. In this study, the rated power of the EWH (P_{rated}) is assumed to be 5.5 kW and *Td* for the base case (Td_b) is set at 120 °F with Δ equal to 2.5 °F. The 24-hour hot water draw (*Wd*) profile used in this paper refers to the hourly profile proposed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [8]. The other main parameters used in the simulations are shown in Table 1.

In this study, the following assumptions are made:

- The hot water temperature in the entire tank is the same.
- The ambient and the inlet water temperature (*Ta* and *Tin*) are constant during the day.
- The variation of *Td* does not affect *Wd*.

The variation of T_H for one day is shown in Fig. 1(a) using the ASHRAE *Wd* schedule shown in Fig. 1(b). The instantaneous power consumed by the EWH is shown in Fig. 1(c). A simulation (time) step of 0.0001 h was considered.

Table 1. Main EWH parameters

Q(Btu/h)	ρ(Ib./gal)	V(gal)	C(BTU/°F)	Ta(°F)	Tin(°F)	G(Btu/ °F.h)
18771.5	8.34	50	417	67.5	60	3.6

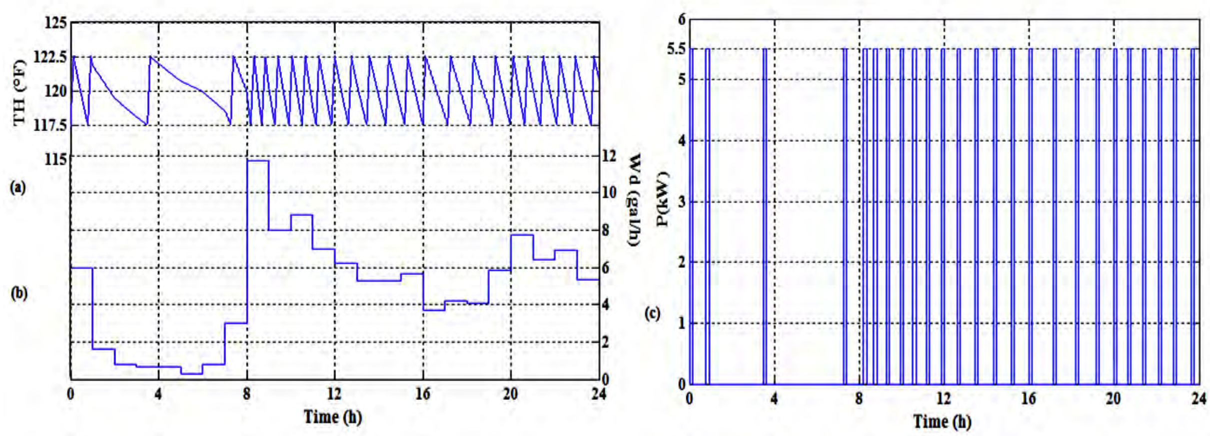


Fig. 1: (a) Variation of T_H (°F). (b) Wd schedule (gal/h). (c) EWH power consumption (kW).

One can see from Fig. 1(c) that t_{on} and t_{off} and the operation period ($T = t_{on} + t_{off}$) of the EWH during the day are not constant. t_{off}, in particular, varies significantly with *Wd*. Table 2 shows the maximum and minimum values of t_{on}, t_{off} and T during the one day period considered.

Table 2. Maximum and minimum on, off and operation period of the EWH.

$t_{on-\max}$ (h)	$t_{on-\min}$ (h)	$t_{off-\max}$ (h)	$t_{off-\min}$ (h)	$T_{\max}$ (h)	$T_{\min}$ (h)
0.1639	0.1143	3.6571	0.3453	3.7714	0.5092

2.2. *Mathematical analysis:*

An equation that describes how T_H varies in time can be obtained by solving Eq. (1) as

$$T_H(t) = T_H(t_0)e^{-(1/\tau)(t-t_0)} + \left(R'GTa + R'BTin + R'Q\right)[1 - e^{-(1/\tau)(t-t_0)}] \quad (3)$$

With the appropriate modifications, it can be used for obtaining expressions to calculate t_{on} and t_{off}. However, exponential equations are not very convenient to use. Alternatively, one can derive linear expressions for t_{on} and t_{off}. This can be done by replacing dT_H by T_{high}-T_{low} (T_{low} - T_{high}) in Eq. (1) when the EWH is ON (OFF) and *dt* by t_{on} (t_{off}). Besides, T_H is assumed equal to *Td* in order to calculate the average heat losses to the ambient and due to inlet cold water replacing the water drawn from the tank. In this case

$$t_{on} = \frac{C\,(T_{high} - T_{low})}{G\,(Ta - Td) + \rho\,Cp\,Wd\,(Tin - Td) + Q} \tag{4}$$

$$t_{off} = \frac{C\,(T_{high} - T_{low})}{G\,(Td - Ta) + \rho\,Cp\,Wd\,(Td - Tin)} \tag{5}$$

With Eq. (4) and (5) one can calculate the operation period of the EWH ($T = t_{on} + t_{off}$) and the average power consumed by the EWH in that operation period ($P_{EWH} = D\ P_{rated}$), where

$$D = \frac{t_{on}}{T} = \frac{G\,(Td - Ta) + Wd\,(Td - Tin)\,\rho\,Cp}{Q} \tag{6}$$

The value of *Wd* for the above equations should be the average water draw for the period under consideration (*T*). As shown in Table 2, for T_{high}-T_{low}=2Δ and with Δ = 2.5 °F, t_{on} is always smaller than 1h what allows the use of the hourly ASHRAE *Wd* schedule for validating Eq. (4). By comparing the values of t_{on} obtained with eq. (4) with those of the simulations one sees that the error were smaller than 0.01%. On the other hand, t_{off} varies more with *Wd* and can be larger than 1 h, usually for low values of *Wd*. In this case, an average value for *Wd* valid for that duration needs to be considered.

The values of *D* obtained from (6), which are equivalent to P_{EWH} in pu, are shown in Table 3 for different values of *Wd* and *Td*. There one sees that P_{EWH} at *Td* = 140 °F is around twice that at *Td* = 100 °F for all values of *Wd*. Besides, operation at low values of *Wd*, limits significantly the variation of P_{EWH} one can get by varying *Td*. Thus, in these cases, the EWH will be less effective as a means for balancing active power in the electric system.

Table 3. Variation of P_{EWH} (pu) with Wd and Td.

Wd(gal/h) / *Td*(°F)	0.25	0.75	1.5	3	6	9	12
100	0.0107	0.0196	0.0329	0.0595	0.1129	0.1662	0.2195
108	0.0131	0.0238	0.0398	0.0717	0.1357	0.1997	0.2637
116	0.0155	0.028	0.0466	0.0839	0.1586	0.2332	0.3079
124	0.0179	0.0322	0.0535	0.0961	0.1814	0.2667	0.3521
132	0.0204	0.0364	0.0604	0.1083	0.2043	0.3003	0.3962
140	0.0228	0.0406	0.0672	0.1205	0.2272	0.3338	0.4404

One important aspect when designing the control scheme of a given system is to identify the sensitivity of a quantity of interest to variations in some of its key parameters. This can be done by means of partial derivatives. For *D*, and consequently P_{EWH}, these key parameters are *Td*, taken here as the control parameter, and *Wd*, assumed as a disturbance in the system. From Eq. (6) one can get

$$\Delta P_{EWH}(pu) = \Delta D = \frac{\partial D}{\partial Td}\Delta Td + \frac{\partial D}{\partial Wd}\Delta Wd = \frac{G + Wd\,\rho\,Cp}{Q}\Delta Td + \frac{(Td - Tin)\,\rho\,Cp}{Q}\Delta Wd \tag{7}$$

For the case under consideration assuming that *Wd* is constant

$$\Delta P_{EWH}(pu) = \Delta D = \frac{3.6 + 8.34Wd}{18771.5}\Delta Td \tag{8}$$

This equation is very useful when one wishes to compute by how much one should change *Td*, for the EWH operating with a given value of *Wd*, in order to change P_{EWH} by a certain value in steady-state. The limit values for P_{EWH} and *Td* are those shown in Table 3.

Another important aspect of the operation of an EWH for active power balancing is the amount of power it can drop or take under transient conditions. Since the EWH operates in an ON/OFF mode, its instantaneous power consumption is either rated or zero. This cannot be changed. However, one can during transient condition values for t_{on} and t_{off} significantly larger than those obtained for steady-state conditions.

Let's consider first the case where the EWH should take additional load. From Fig. 1(a) one sees that T_H increases almost linearly when the EWH is ON and t_{on} is the time required for T_H to increase by 2Δ, 5 °F in this study, when *Td* remains constant. As shown in (4), t_{on} increases as *Wd* increases but it does not vary significantly with *Wd* since *Q* is the dominant element in the denominator of (4). If *Td* is suddenly increased by a value larger than the tolerance band ($\Delta Td > 2\Delta$), the EWH will be turned ON immediately and remain ON until the value of T_H increases by at least ΔTd. Based on this, one can estimate that the increase in t_{on} during transient conditions, with respect to the previous value in steady state, for a given ΔTd on average, for $T_H = Td$, as

$$\Delta t_{on}(\%) = \frac{\Delta Td + \Delta}{2\Delta} \tag{9}$$

Table 4 shows the maximum values of t_{on} that one can have during each time of the day, assuming the ASHRAE *Wd* schedule, as one changes *Td* from an initial value, either 120 °F or 100 °F, to 140 °F. Td_b = 120 °F is the base case, when one does not expect the need to take or drop power during the next few hours. However, if one knows that there will be a need to take as much load as possible, due to a typical surge in production of wind power or due to a decrease in the regular electric load in the system, then one could operate with *Td* = 100 °F.

Table 4. t_{on_max} for different values of initial Td using the ASHRAE Wd schedule. Case #1 (Td=120°F, ΔTd=20°F, Δt_{on}=4.5.) Case#2 (Td=100°F, ΔTd=40°F, Δt_{on}=8.5).

Time (h)	0	1	2	3	4	5	6	7	8	9	10	11
Wd(gal/h)	6.0	1.6	0.8	0.7	0.7	0.3	0.8	3.0	11.7	8.0	8.8	7.0
ton(h), Case1	0.646	0.537	0.522	0.519	0.519	0.512	0.522	0.568	0.876	0.712	0.743	0.677
ton(h), Case2	1.221	1.016	0.986	0.981	0.981	0.966	0.986	1.074	1.656	1.346	1.403	1.280
Time(h)	12	13	14	15	16	17	18	19	20	21	22	23
Wd(gal/h)	6.25	5.30	5.30	5.65	3.70	4.20	4.10	5.85	7.73	6.38	6.90	5.30
ton(h), Case1	0.654	0.626	0.626	0.636	0.585	0.597	0.595	0.642	0.702	0.658	0.674	0.627
ton(h), Case2	1.236	1.183	1.183	1.202	1.105	1.128	1.124	1.213	1.327	1.244	1.274	1.185

An useful expression for Δt_{off} cannot be obtained in a similar way because the curve for T_H decreasing does not resemble a straight line. Nonetheless, one knows that t_{off} is usually long enough for power balancing operation. Therefore, in this case, one can define a worst case conditions (*Wd* =11.7 gal/h) for which t_{off_min}= 2.3337 (4.4081) h when *Td* = 120(140) °F.

2.3. Temperature Control Using Frequency Droop

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

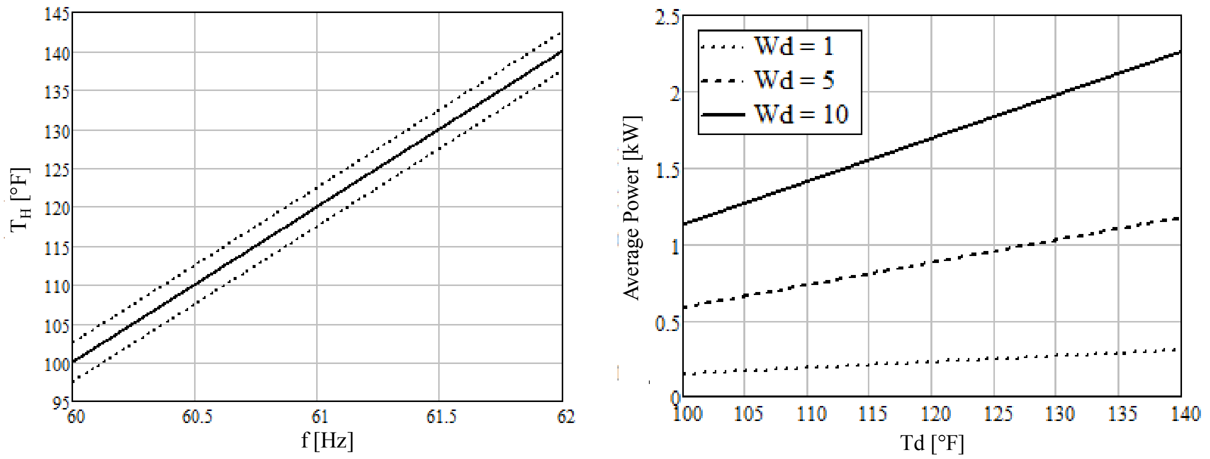
$$P_g = s_p(f_{nl} - f) \tag{9}$$

Where P_g 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) [3].

As the actual loading of the genset is proportional to the frequency, it is proposed that the power consumed by the EWH to be controlled by means of the *Td*, using the frequency versus temperature droop function

$$Td = Td_b + m(f - f_c) \tag{10}$$

Where m is a slope factor equivalent to s_p and f_c is the center frequency (Hz). *Td* is equal to half its total excursion. Fig. 2 (a) shows the frequency x temperature droop function with m = 20 °F/Hz, Td_b=120°F, and f_c = 61 Hz. The value of T_H will vary within *Td* ±Δ as shown with the dotted lines. The action of droop is limited to when *Td* is within acceptable limits of temperature; in this case it was limited between 100 °F and 140 °F. From Eq. (9), when the load increases, the frequency of the generator decreases. This frequency reduction will cause *Td* in the EWH to decrease, while when the generator load decrease the frequency will increase making *Td* increase. Varying *Td* during steady and transient condition will affect the average power consumption, as can be seen on Fig 2 (b) for different values of *Wd*, for the EWH described on Section 2.1. Varying *Td* between 140° F and 100 °F would result in a 1.13 kW variation in the average power consumed. However for periods of lower water draw (*Wd* ~ 1 gal/h) this variation is limited to 0.15 kW, which makes this control strategy sensitive to the water draw condition. It is important to note that have been reported in the literature that the electricity consumption is directly related to water consumption [9], what makes the effect on peak load shaving improved with this strategy.



(a) (b)

Fig. 2: (a) Frequency x temperature droop variation (b) Average power consumption variation with Td for different average water draw.

3. Results

A mini-grid with a genset feeding a network with 20 houses in a single phase connection where only two of the three outputs of the genset are used is presented in [3] and is used in this paper to evaluate the impact of the frequency x temperature droop control in the loading of the generator and grid frequency. The genset is rated at 95kW on a three phase basis, however in practice it means that only about 2/3 of the generator power is available. The droop parameter of the genset are s_p = 29.4 kW/Hz and f_{nl} = 62.3 Hz.

A residential load profile for a house without EWH based on [10] was scaled to have a daily energy consumption of 20 kWh and used as reference for all 20 houses to determine the 24 h load profile of the mini-grid. Fig. 3 (a) presents the single house load profile used and the power consumption profile of the EWH with *Td* = 120 °F. The *Wd* schedule considered was the one presented in Fig. 1 (b). Two cases are considered, first the EWH operates with constant *Td*, base case, and the second one using the frequency x temperature droop strategy (Tdroop) with m = 20 °F/Hz and f_c = 61 Hz. Fig. 3 (b) presents the genset load for each hour of the day. The load variation is reduced with the droop approach. The peak load from this day decreases from 56 kW to 52 kW, while in the lower load region, the load increases from 8.3 kW to 9.5 kW. This small difference in the low load region is due to the fact that varying *Td* for controlling the power is sensitive to the water profile that during that period was low. Fig. 4 presents the frequency variation regarding the change in the genset load (a) and the variation on *Td* due to the frequency droop implemented.

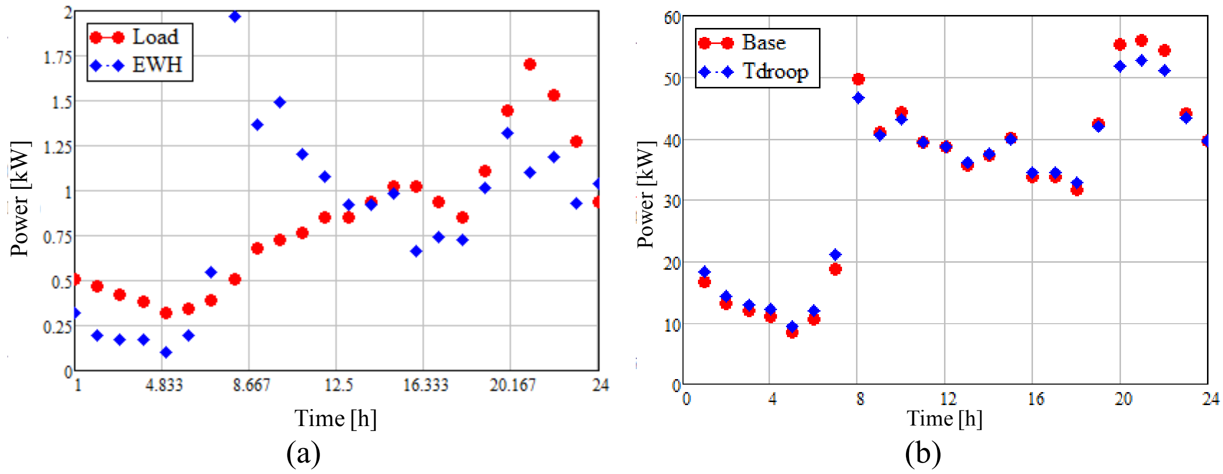
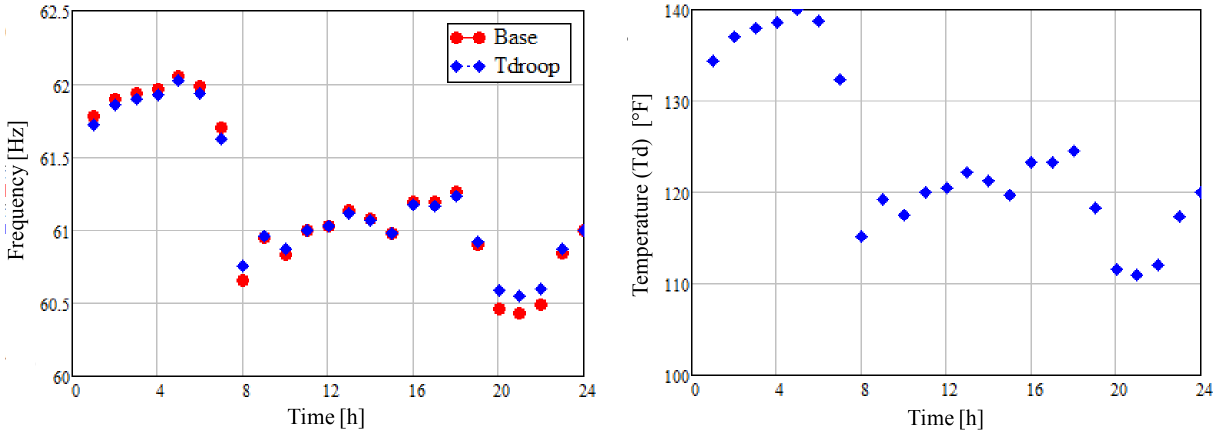


Fig. 3. (a)Load Profile and EWH Power Profile for Td = 120° F and (b) Genset power.



(a) (b)

Fig. 4. (a) Minigrid frequency and (b) individual EWH Td during the 24 h case study.

4. Conclusions

This paper presented EWHs as candidates for DMS due to the fact that the average power consumed is strongly related to the set point temperature (*Td*) and to the hot water draw (*Wd*). A mathematical model was obtained for the EWH. It was proposed a strategy for controlling the power consumed by the EWH, by means of *Td*, using a frequency versus temperature droop characteristic. A 5.5 kW, 50 gallon EWH was modeled in MATLAB-Simulink and a typical 24-hour water draw profile was used to estimate the steady state performance in a 95 kW diesel based mini-grid. Results showed that with the proposed control strategy power variations in the mini-grid can be reduced; however it is strongly dependent on the values of water draw from the houses.

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