# Investigating the impact of electric hot water load control on low voltage distribution networks

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## Abstract

Decarbonising domestic loads is seen as critical in reaching global net zero carbon targets by 2050, thus, electrical networks are rapidly changing to keep pace with the decarbonisation of the energy sector. Water heating (WH) represents ~25% of household energy consumption, meaning that the transition from gas water heating (GWH) to electric water heating (EWH) will place additional stresses on the grid. This study analyses the grid power flows, identifying the most stressed bus/sub-station before and after WH electrification. This is critical as the voltage stability affects the need for expensive infrastructure upgrades. When EWH loads are added, voltages commonly drop below the acceptable limits. This demonstrates the critical need for advanced WH designs and controls using the thermal storage potential in WHs to stabilise network voltages, reducing the requirement for grid reinforcement.

## Introduction

Increasing awareness of the impacts of climate change has led to a diversification of power generation sources, with countries switching from 100% fossil-fuel-based generation to a combination of renewables and fossil fuel [1, 2]. The increased penetration of renewable energy generation coupled with increasing loads on distributed electrical networks have resulted in larger frequency and voltage instability in electrical grids, and as a result, more significant financial resources are dedicated to frequency and voltage regulation by network service providers (NSPs) [3, 4].

The application of demand response mechanisms to provide network regulation services has been investigated through several studies, examining the impact of electric vehicles, heat pumps, and EWHs on electrical networks [5, 6]. Research in [7] employed probabilistic modelling to assess the impact of plug-in electric vehicles on low-voltage distribution networks at varying penetration levels. Voltage degradation was observed, and their study indicated that probabilistic analysis was more effective at producing detailed results of voltage levels, compared to deterministic methods of analysis. This study was compounded by [8], further assessing the best method to determine the impact of the vehicle-to-grid (V2G) injection on the voltage profile of a distribution network.

Moreover, as WH represents approximately 25% of household energy consumption, investigations into WH load control present formidable opportunities to mitigate the negative grid impacts of electrification. A study in [9] used a two-stage control to schedule WH operation, the first being a dispatch reference using linear programming, with short-term refinement using a reducing horizon and mixed-integer linear programming. Whilst this study focused on maximising the utilisation of renewable energy generation, it did demonstrate that voltage excursions can be reduced by up to 28%, indicating that demand response of WHs could solely play a large role in stabilising network voltages. There is a greater volume of studies investigating the low-voltage impact of heat pump WHs [10-12], however, their inability to rapidly respond to network conditions, coupled with a comparable smaller electrical load, result in limited demand response potential.

To support the achievement of decarbonisation targets, generous incentives are available to substitute gas/fuel water heaters (GWHs/FWHs) with heat pump water heaters (HPWHs) [13]. Any increase in electrical load from WH may further stress existing network infrastructure leading to either capital investments or restrictions on energy use. A relevant study [14] investigated fuel substitution using heat pumps by applying probabilistic methodologies based on Monte Carlo simulations to assess the impact of electric heat pumps on low-voltage distribution networks. This study used electro-thermal load modelling techniques, conducting low voltage network analysis by integrating three-phase unbalanced power flow solution engine OpenDSS with developed electric heat pump models. Whilst this study made suggestions for network design improvements, they didn't address the possibility of WH load control that can operate sympathetically with the network.

Our study investigates the electrification of WH systems using real field data to identify the most stressed bus/sub-station in a low-voltage network. The voltage profiles are obtained for the entire annual cycle. Firstly, the simulation is performed with solely domestic GWH, and then substituting GWHs with simple storage EWHs. The potential impact that electrification may have without the intelligent demand response has been quantified and then the intelligent WH controls are suggested that sympathetically support network voltages and frequencies.

This research represents a continuation of previous studies [6, 15-17] in which the consumer benefits of smart load control of thermally stratified EWHs were investigated. This paper focuses on the next steps of the investigation and will begin to assess the impact of EWH load control on voltage profiles of a low-voltage distribution network.

## Methodology

Annual electricity consumption data was obtained from 380 residential houses in South Australia from the South Australian Power Network (SAPN) [18], with this network having ~1 kWp/person of rooftop PV, making it the highest global concentration of residential PV [19-21]. The residential electrical data was filtered to capture residential profiles with controlled loads representing WH consumption. The control strategy used by the SAPN permits WH load control to mainly operate overnight, which was illustrated in the raw data that showed the exact hours during the night in half-hourly increments where WH load control was operational for each residence throughout the year. This resulted in 81 profiles with controlled WH loads extracted in 30-minute increments for 1 year. For comparison and analysis, the net energy consumption (excluding WH loads) was obtained for the corresponding 81 residential profiles to represent residential profiles with GWH consumption instead of EWH. The data for the remaining 299 homes without controlled WH loads were not used as part of this study but were retained for possible future use as part of a larger distribution network to be studied.

A model 546-bus low voltage (0.4kV) distribution network was derived from a larger power network model in DIgSILENT PowerFactory. Characteristics of the network are shown in Table 1.

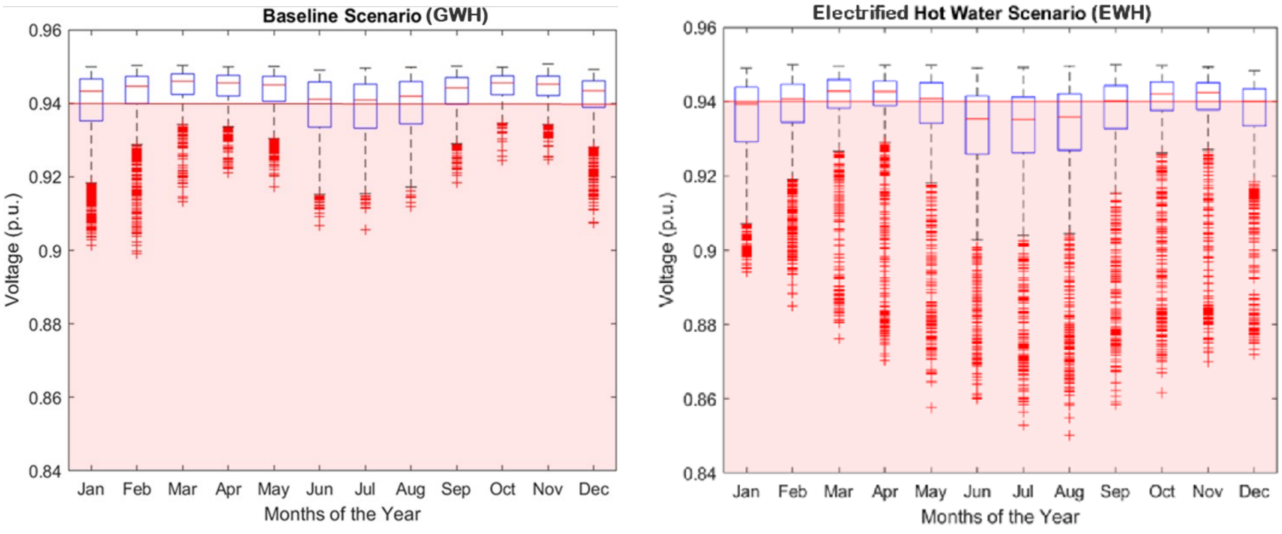
**Table 1 Characteristics of the Low Voltage Distribution Network**

| | |
|---|---|
| Transformer specification | 10 kV/0.4 kV Low Voltage Three Phase Transformer<br>Rated Power 630 kVA; Nominal Frequency 50 Hz |
| Lines | 6 Cable types; Rated Voltage 1 kV; Nominal Frequency 50 Hz<br>Rated Current (in ground): range from 0.58 – 0.309 kA<br>Rated Current (in air): range from 0.14 – 0.268 kA |

Two scenarios were established with the intention to initially focus on a small and manageable number of residential profiles that reflect typical loads of a small, low-voltage distribution network. Firstly a baseline/GWH scenario was developed from the 81 residential profiles with controlled loads that were extracted from the South Australian data [18]. The net energy consumption for the profiles (excluding WH load) was used to represent residential profiles with GWH consumption, therefore ensuring no electrical consumption for WH use was included. The batch of 81 residential profiles representing GWH profiles were assigned to the 307 buses in the low voltage distribution network establishing a baseline case, since it is not unusual to have similar electricity profiles for multiple households. The second scenario, which is the electrified hot water scenario includes the same 81 residential load profiles used in the baseline/GWH scenario with their corresponding controlled WH loads added to their net consumption to represent profiles with EWH consumption. In this case, the 81 residential EWH profiles were allocated to 307 buses in the same low voltage network and configuration as the baseline/GWH scenario, ensuring that baseline/GWH and EWH scenario comparisons are based on realistic and actual data as recorded in the field by SAPN and to maintain the integrity of the data. The data for both scenarios were imported separately into DIgSILENT PowerFactory software to perform power flow simulation of 30-minute intervals over the entire annual cycle. The simulation results were further processed in MATLAB to determine the critical bus (the bus with the lowest voltage profiles) and corresponding bus voltage for each scenario.

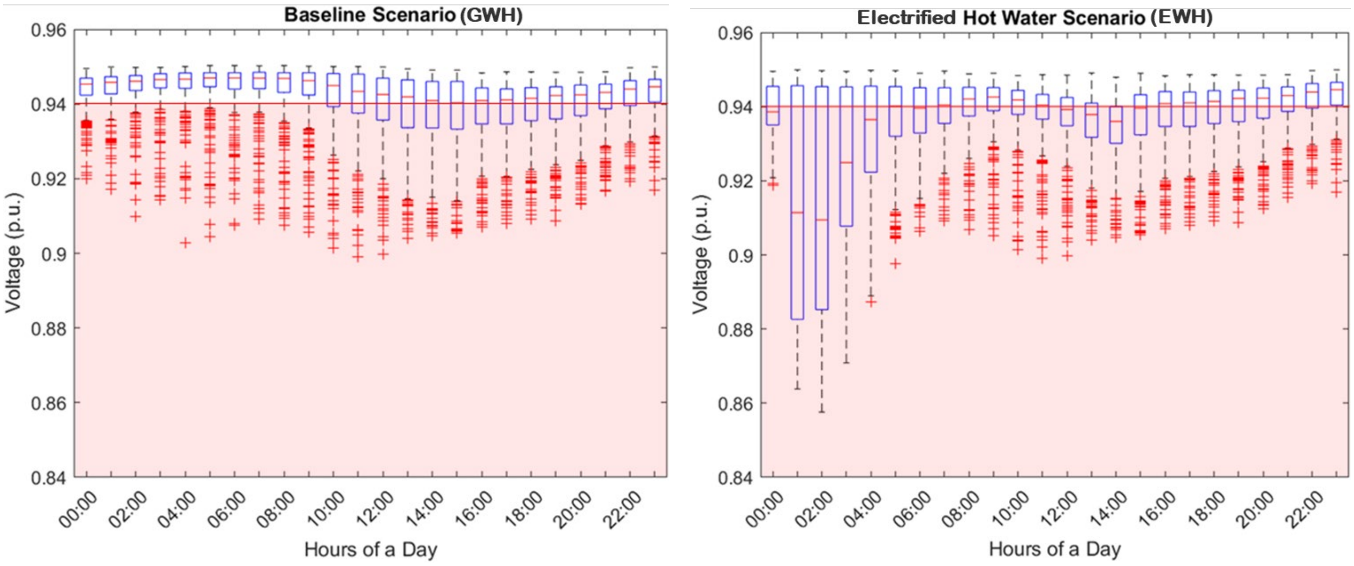
## Results

The simulation results from DIgSILENT PowerFactory software represented voltage magnitudes in per unit (p.u.) that are typically used in electrical network studies, based on the nominal voltage of the connected terminals. The results show voltage magnitudes in the range of 0.84 to 0.99 p.u. The results, when processed in MATLAB, were analysed with voltage magnitudes below 0.94 p.u. (which is the minimum acceptable operating voltage in Australian distribution networks) [22] to identify the critical bus with the minimum voltage. In both the baseline/GWH and the EWH scenarios, the same critical bus was identified. The distribution of the voltage magnitudes for the critical bus for each scenario is illustrated using a box and whisker plot, in which the maximum and minimum voltage magnitudes are shown at the end of the top and bottom whiskers; the median voltage mid-point is represented by the red horizontal line dividing the box into two; and the upper and lower quartiles demarcate the top and bottom 25% of the data values. Figures 1(a) and 1(b) illustrate a comparison of the monthly voltage distribution of the critical bus for the baseline/GWH scenario and the EWH, while Figures 2(a) and 2(b) illustrate a comparison of the hourly voltage distribution for the same critical bus and scenarios.



(a) (b)

**Figure 1 Comparison of monthly critical bus voltage (p.u.) for baseline/GWH scenario (a) and EWH scenario (b), with outliers in red and shaded below 0.94 p.u. voltage limit.**



**(a)** **(b)**

**Figure 2 Comparison of hourly critical bus voltage (p.u.) for baseline/GWH scenario (a) and EWH scenario (b), with outliers in red and shaded below 0.94 p.u. voltage limit.**

## Discussion

The monthly voltage distribution of the critical bus in the baseline/GWH scenario shows median values above 0.94 p.u. for all months of the year indicating there was no violation of the voltage limit, although June and July present as most at risk of violating this limit. Furthermore, the interquartile ranges are wide from June to August and January, with the largest differences between the maximum and minimum voltage occurring during this period, indicating limited voltage control. This likely corresponds with seasonal changes in consumer energy consumption during the summer season (December to February) and winter season (June to August), caused by increased space cooling or space heating, and higher occupancy levels. A non-symmetrical negatively skewed distribution is also observed throughout the year, which indicates dangerously low voltage levels overall, even before the electrification of hot water services (as shown in Figure 1(a)). The EWH scenario under the current typical demand control exacerbates the voltage profile situation, as it exhibits a generally lower critical bus minimum voltage (as shown in Figure 1(b)). The months of January, July, August, and September show median voltage magnitudes below 0.94, in violation of acceptable voltage limits. May, September, December, and February show medians just above the 0.94 p.u. limit. As expected, this is due to the incremental load of WH with the largest loads evident during the southern hemisphere Winter (June to August).

The above observation demonstrates the seasonal impact on WH loads, mainly driven by a lower temperature of the cold water, as shown in Figure . It is therefore expected that the larger thermal load in winter will exacerbate the seasonal voltage excursions on the critical bus.

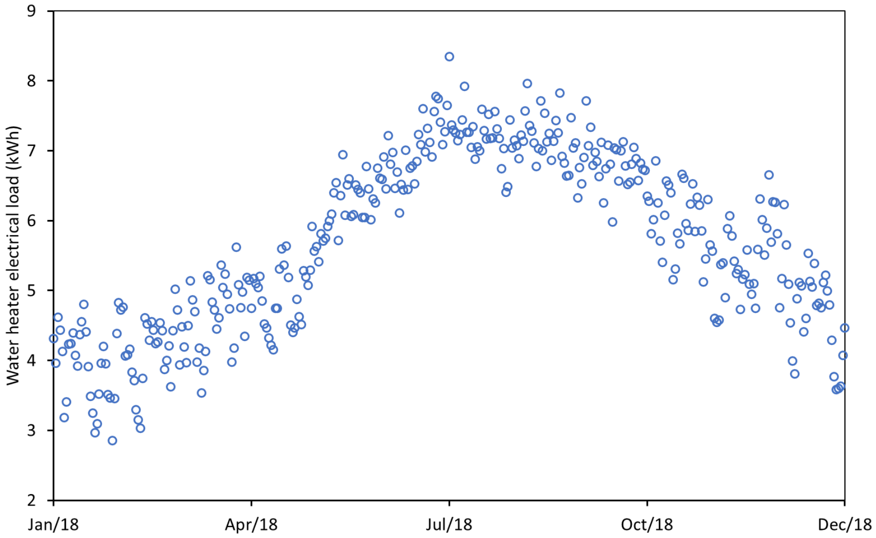


**Figure 3 Average hot water electrical consumption from 81 SAPN houses**

The hourly critical bus voltage distribution (Figures 2(a) and 2(b)) within the baseline/GWH scenario illustrates decreases in voltage from afternoon to early evening that align with the peak network loads and a general lack of renewable generation in this period. Figure 2(a) illustrates voltages below the critical limit of 0.94 p.u. occurring once daily compared to 13 times daily as shown in Figure 2(b) for the EWH scenario, with minimum voltage as low as 0.86 p.u. The distribution of voltage in both scenarios is negatively skewed, and in the case of the EWH scenario, a wide dispersal of values is observed particularly at midnight for several hours when existing control measures are active.

Generally, the voltage levels are on the verge of violating acceptable limits for 17% of the year for the baseline/GWH scenario, which may be recoverable using tap changes at sub-stations. In contrast, the simulated critical bus voltage in the EWH scenario demonstrates significant reductions in bus voltages, whereby the voltage is at the lowest acceptable voltage limit or below for 50% of the year, with peak reductions shown as WHs concurrently operate for all houses despite an active control strategy. The difference between the results of the two scenarios demonstrates the potential for negative impacts of excessive or uncontrolled electrification and highlights the limitations of the conventional control strategies shown in the case of the SAPN field data. Whilst this is recorded as a significant problem with the electrification of domestic WH loads, the inherent thermal energy storage within a WH can be exploited to separate times of electrical energy consumption and thermal delivery.

## Conclusion

The results of the study emphasise the need for better or more efficient control strategies such as intelligent and smart controls used by the NSPs, particularly as efforts are made to shift to EWH. Exploring the most effective WH load control strategies instead of the conventional fixed overnight control strategy could optimise the thermal energy storage benefits to minimise voltage excursions. These are preliminary results for the first part of our study. The next part of the study will explore the impact of distributed solar PV on the same network as well as the use of different control strategies and their effect on voltage and grid performance. We will look at an intelligent schedule of WHs that consider the urgency to heat, and network conditions along with rooftop PV generation, with the anticipated net results being enhanced low-voltage network stability and increased PV hosting capacity, all expediting the energy transition to 100% renewables.

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