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PV Integration and Peak Load Shaving Using Energy Storage Feasibility Study

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PV Integration and Peak Load Shaving Using Energy Storage Feasibility Study

by

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Abstract

Energy storage system (ESS) is a growing technology in distribution systems. ESS is used in different application such as peak load shaving, system upgrade deferrals, and improving renewable energy integration. A photovoltaic system (PV) is wildly used in the distribution system, and it has given good results in reducing the amount of consumed electrical power from the grid during the daytime. Yet still, it may cause some problems for the network. The intermittency problem because the generation of power is related to weather conditions, another issue is voltage fluctuation especially with high penetration of photovoltaic systems in the network. using energy storage device along with PV system to mitigate such problems. In this thesis an investigation of the impact of installing a photovoltaic system to the part of the University of Calgary distribution network. Utilizing a properly sized energy storage system with PV to manage peak load on the university campus.

Acknowledgements

I would like to express my deepest gratitude and thankfulness to my supervisor Professor Andy Knight for his helpful guidance, support, patience, kindness, and encouragement throughout the period of my Master's degree.

I would like to thank my lab group for providing such a nice work environment.

My sincere thanks and appreciation go to my parents and my wife, I would not have been able to get to this point in my academic career without their encouragement and support.

Dedication

I dedicate This thesis to my parents my wife, my daughter, my son, and all my family.

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Chapter 1: **Introduction**

1.1 Solar Energy on Campus

Calgary is considered to have one of the highest Solar irradiance levels in Canada. This leads to the idea of using solar energy on campus. Using solar energy would be a good source of green energy, and it supports the university in reducing emissions by using PV to generate a clean power. The idea of utilizing solar energy on campus has become more appealing especially with the new carbon tax in Alberta. In other words, solar energy will not only contribute to generating power locally but also will reduce relying on traditional power sources which leads to fewer emissions and lower carbon tax.

1.2 Solar Energy and Energy Storage Potentials

Solar energy is viewed in general to be a very good alternative to traditional energy sources which have been used in the power system. It is also considered an environmentally friendly because PV generates energy free of emissions. Photovoltaic panels can be used in the distribution system on the rooftop of buildings to minimize the consumption of energy and the electrical bill. The PV panels would deliver power during the daytime to the load, which will relieve the network during the peak time. However, one of the main drawbacks of photovoltaic power is its power generation depends on weather condition and location. Weather intermittency, for instance, could result in uncertainty in the amount of energy production which can be different than what is expected. The above-mentioned drawback could be overcome by including battery energy storage into the system. The local consumption of PV produced energy could be boosted by storing surplus energy at times of peak production and using this energy when it is not enough or not existing. Batteries are frequently used with PV systems for compensating the power during outages and for the purpose of storing excess energy generated by the PV modules. The stored energy in batteries can be delivered to electrical loads when it is needed (during the night and intermittent weather conditions).

1.3 Problem Statement

High power consumption during peak hours is costly, and it may cause line congestion because of high demand. Another issue is the need for system upgrades due to growing high demand which may exceed the system capabilities. At university campus, long peak load period is an issue, where high power is being consumed between 8 AM and 9 PM.

In order to overcome the aforementioned problems, PV can be used to reduce the consumed power by generating some portion of the demand locally.

However, campus load profile has long peak hours which makes PV incapable of helping with peak load shedding when the sun is down. In order to deal with this issue, it is proposed to use energy storage system to mitigate this issue. Battery storage gains ground among the electric utilities as a PV integration measure, mainly due to the versatile services that it can offer. A battery storage system can relieve the network overloading by peak-shaving when PV is not generating power. Proper sizing the battery of a grid-connected PV system is essential, by having a low sized battery can be cheap in price, but it maybe not feasible from an engineering point of view.

The proposed solution in this thesis is an integration of PV and ESS to reduce peak load of the University of Calgary distribution system.

1.4 Research Methodology

In this section, the most important research method and, objectives are summarised for ease of reference.

- Develop model for the system under study in EMTP-RV to run time-domain simulation
- Develop PV model which will be used in the simulations on campus.
- Develop ESS model using EMTP-RV and MATLAB to investigate the feasibly of using ESS for peak load shaving application.
- Investigate potential problems associated with using PV on campus.
- Test different ESS sizes and determine a proper ESS capacity for peak load shaving application.
- Investigate different scenarios of utilizing PV with or without ESS in managing peak load.

1.5 Thesis Outline

The rest of the thesis is structured as follows:

Chapter 2 presents the essential background of microgrids, energy storage technologies, and their characteristics, application of energy storage in the distribution system.

Chapter 3, presents the modeling of the case study, PV modeling, ESS modeling, and sizing. Data processing is also presented in chapter 3.

Chapter 4, simulation results are presented, different scenarios are considered in this thesis, and discussion about the obtained results.

Chapter 5 presents a summary of the thesis, the main contributions, and the potential for future work are discussed.

Chapter 2: **Literature Review**

2.1 Introduction

The installation of a photovoltaic system in a distribution system would yield positive results in reducing the amount of electrical power consumed from the grid during the daytime. It is considered an environmentally friendly approach, yet still, it carries some problems in regard to the network, and one obvious one is the problem of intermittency and rising voltage. A solution to this problem is to install an energy storage device along with a photovoltaic system to mitigate this problem. In the following literature review, examination articles that deal with installing energy storage systems in grids connected to photovoltaic systems (PVs) will be presented.

Literature review structure:

- Grid-connected microgrid
- Grid-connected PV problems
- Energy storage systems
- Peak load shaving using ESS
- Fluctuation smoothing, improving penetration and mitigating voltage rise issues
- ESS optimization and power management

2.2 Microgrids

The large-scale deployment of distributed generator (DG) units in distribution systems have led to the development of the concept of microgrids. The microgrid system comprises a group of loads and small-scale sources of energy that operates as a single entity. Each microgrid controls its resources to meet its demand at the distribution level. These resources include dispatchable DG units such as microturbines, fuel cells, and renewable energy sources such as hydro-electric, PV and wind. In addition to these components, energy storage systems are essential elements in microgrids. Microgrids can operate as isolated systems and balance their demand via the available resources, or they can be connected to the main grid at the point of common coupling (PCC) for the bidirectional exchange of energy. The characteristics of microgrids are different than conventional power systems since they have highly dynamic operations due to their dependency on DG units which are closer to the load [1]. Consequently, microgrids are usually equipped with the state-of-art power electronics or protection devices, and are reinforced by two-way communication systems to accommodate the generation resources at the distribution level, and maintain the system reliability in the presence of the bi-directional power flow. Controlling these components is performed by the microgrid's energy management system which ensures optimizing the microgrid operation while ensuring reliability at least cost. The microgrid is connected to the main grid and usually operates in grid-connected mode. However, in the case of faults, the microgrid may operate as an isolated system, or it can be connected to another temporary PCC [2]. Grid-connected PV systems are the most popular PV based systems in the industry. These are two basic types of grid-connected PV systems: with or without batteries. Furthermore, these systems can be categorized into three main size ranges: large, medium and small. Mainly small and medium-sized PV systems are installed on the rooftops of households and commercial buildings.

2.3 Grid-Connected PV Problems

Introducing photovoltaic systems into the distribution system carries a lot of benefits such as clean power and eliminate the dependence on fuel, there are many articles in the literature about renewable energy applications in different areas [3]. Of these, solar energy technology is the most appropriate for residential applications because of physical size and safety issues, but it has some issues too, for example, the solar intermittency issue, voltage rise, reverse power flow, and high penetration issues to overcome those problems an energy storage device are used [4].

Many types of energy storage systems have been proposed in the literature. Primary technologies include batteries, flywheels, pumped hydro, and compressed air. Other storage systems include thermal energy storage systems such as underground thermal energy storage and ice storage systems [5]. Now, batteries appear to be the best option because of economic considerations [6]. Many types of batteries are available on the market such as lithium ion, zinc bromine, nickel-cadmium, sodium-sulfur, sodium-nickel chloride and lead-acid system [7]. However, the advantages of low maintenance requirements and cost-effectiveness indicate that lead-acid batteries are still the best choice, especially for residential applications [8]. Compared with other battery technologies, the significant drawback of a lead-acid battery is the relatively short service life [9].

2.4 Energy storage systems

Energy storage system can be used to help mitigate the PVs effect on the distribution system, peak shaving and can be used to differ network expansion [10] [11]. Figure 1 shows different types of energy storage technology. Not all are suitable for distribution systems [12].

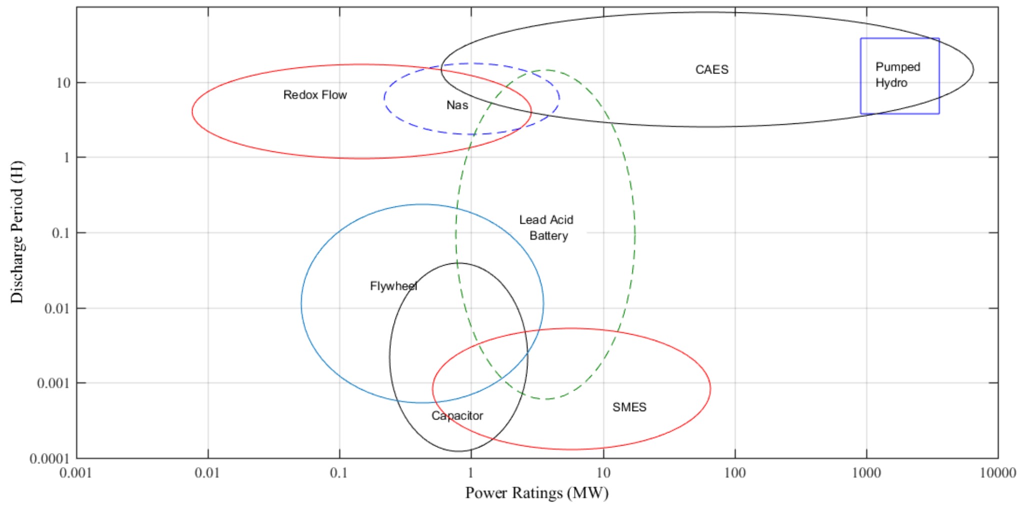

Figure 2.1 different types of energy storage technologies [12]

In batteries, bidirectional electrochemical reactions are used to convert electric energy into chemical energy for charging, and the opposite for discharging. There are various types of chemical substance used in batteries, providing different characteristics such as energy density, power density, number of cycles, and cost. Compared to flywheels, some types of batteries can store more energy, and at the same time be used in power quality applications.

2.5 Battery Characteristics

In this section, a brief description of the battery parameters, and characteristics will be presented and discussed.

2.5.1 Battery Power and Energy Size

The size of a battery is identified by its rated power and the maximum energy that can be stored. The power size of a battery is defined as the rate at which the energy storage can discharging/charge power continually. In normal operation, the maximum injected/drawn power is the nameplate rating of the system, however, some types of energy storage can discharge more power than their rated value for a short period during contingency situations. Also, in most technologies, the charge rate is usually less than the discharge rate. The energy size represents the maximum amount of energy that can be stored for a certain time. The capacity is expressed usually in kWh or MWh. It can also be represented in Ah when the voltage across the energy storage is not assumed to be fixed. The relationship between the power and energy size for a certain energy storage technology is known as the E/P ratio, and it is defined as follows:

$$\frac{E}{P} = \frac{Energy\ Capacity}{Rated\ Power} \tag{2.1}$$

2.5.2 Battery Charge/Discharge Time

Charging and Discharging Rate The amount of charge added/extracted from the battery per unit time is known as charging/discharging rate, which is measured in Amp, though the charging/ discharging rate is also defined in terms of the hours that takes to fully discharge the battery.

Charge/Discharge Time is the maximum duration for which the energy storage can charge/discharge at rated power, and is expressed as follows:

$$\text{Charge/Discharge Time} = \frac{Available\ Capacity}{Rated\ Power} \tag{2.2}$$

It is to be noted that while discharge time depends on the available energy capacity or the DOD, the E/P ratio considers the entire energy capacity. In other words, if the energy storage is allowed to utilize its full capacity, then the discharge time equals the E/P ratio, otherwise, the discharge time is always less than the E/P ratio.

2.5.3 Battery Lifetime

Most energy storage technologies suffer from degradation which affects their performance and reduces their lifetime.

The maximum discharge limit is expressed as the DOD of energy storage (%). It is noted that the level of energy to which the energy storage is charged is known as the state of charge (SOC), expressed in kWh in this thesis. Accordingly, the DOD of energy storage is defined as follows:

$$DOD = \frac{Battery\ Capacity - Minimum\ State\ of\ Charge}{Battery\ Capacity} \times 100 \tag{2.3}$$

2.5.4 Battery State of Charge (SOC)

The percentage amount of energy stored in the battery with respect to the nominal battery capacity is known as the state of the charge of the battery. This is the main parameter that reveals the current battery energy which stored in the battery. This is basically the opposite of the depth of discharge.

2.5.5 Battery Efficiency

The efficiency of the battery is described in two ways that are coulombic efficiency and the voltage efficiency. Coulombic efficiency is the ratio of the amount of charge that enters the battery when it is charging for the amount of charge that can be extracted from the battery when it is discharging. The voltage efficiency is the ratio of the discharged average voltage to the charged average voltage.

2.5.6 Battery Round Trip Efficiency

The loss of energy due to the conversion from grids to energy storage systems and vice versa is represented by the round-trip efficiency. It is the amount of energy that can be discharged from energy storage for a given amount of energy charged. In some cases, the charging efficiency associated with energy conversion in charging process is different than the discharging efficiency. The round-trip efficiency is the multiplication of both of them. Energy storage technologies have a different range of round-trip efficiencies.

Table 2.1 describes the applications and characteristics of some of energy storage technologies.

Table 2.1 advantages and disadvantages of some ESS [12]

Storage type	Power (MW)	Capacity (MWh)	Energy Density (Kwh/m^3)	Efficiency (%)	Lifetime (cycles)
Lithium Ion Batteries	0.001-0.1	0.25-25	300	85-100	1000-4500
Sodium Sulfur Batteries	1-50	<300	150-250	75-90	2500
Lead Acid Batteries	0-40	0.25-50	20	70-90	500-1000
Redox Flow Batteries	0.03-7	<10	10-30	75-85	12000
Compressed Air	5-300	<250	30-60	60-79	8000-12000
Pumped Hydro	<3100	5000-140000	0.28@100m	65-82	10000-300000

2.6 Peak load shaving using ESS

In this application of ESS, it is mostly used in residential PVS systems in order to match the load and the generation. The generation peak is shifted thanks to the ESS, and energy can be used when required by the load. The ESS, therefore, works as an energy buffer to the PVS system at times of a power surplus [13].

Using ESS to help with peak shaving and reducing the losses is another use of ESS [13]. ESS is used to handle this task with an optimal control method that focuses on peak load shaving and reducing the losses, Figure 2.2 shows an example of peak load shaving using ESS.

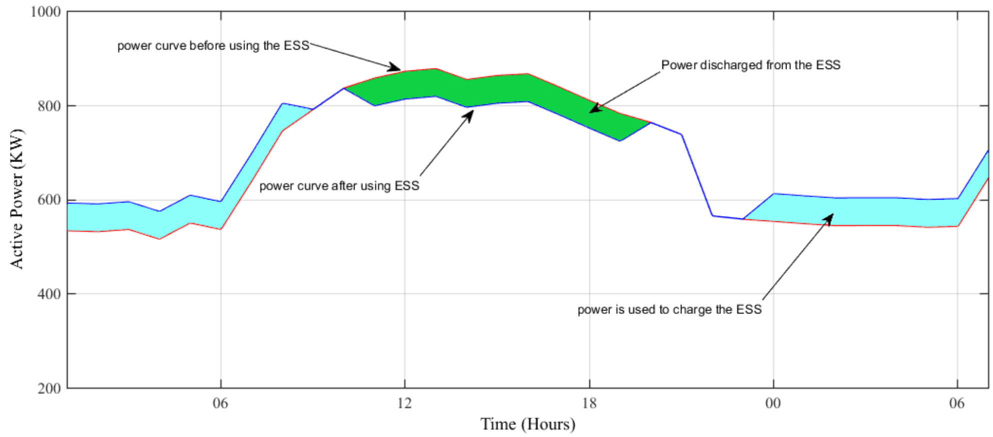

Figure 2.2 peak load shaving using ESS

The idea of shifting the production peak in time was used by [11] in which the author proposed to charge the battery when off-peak times and then discharge during peak times. Using load information, it was possible to size up a suitable ESS. A similar idea was used in [6] when optimizing the energy storage capacity and the power of an ESS for a peak load shaving application. The method assesses a customer load profile and finds the optimal ESS size which helps reduce the electricity bill.

Another method is used in [14], where model predictive control is proposed to operate the ESS basically operating in the schedule based on predictions.

Also, one day ahead operation strategy was developed for operating ESS with PVS to reduce the costs of operating the ESS and reducing the costs of energy drawn from the grid by optimally scheduling the operation of ESS with the PVs in the network [15]

Using ESS with PVs to improve the efficiency of the distribution system uses two options. In the first, the battery is being charged with energy from the photovoltaic system and the load is consuming power from the public grid. Depending on the loading conditions, the battery is discharged. In the second option, during the day the load is being fed from the grid and the photovoltaic system together, the battery is being charged only during the night period when the power is cheap [16]

In another study, the author proposed an optimal operation of ESS along with a PV unbalanced distribution system for a multi-objective function that is then used to do peak load shaving and reduce the losses [13].

2.7 PVs fluctuations smoothing, improve PV penetration, and mitigating voltage rise issue using ESS

An interesting use of ESS is as energy buffer in order to mitigate the intermittency of PV energy generation. The main idea is to eliminate the destabilizing effects of solar irradiance intermittency in the grid and provide a smooth generation curve. The study proposed that the control system injects the PV energy into the grid or stores it in the ESS. The ESS will then release the energy when needed, in order to maintain a stable injection curve. Therefore, the ESS helps to provide a smooth generation curve of the PV system [17], [18].

Another version of ESS as the buffer is the one developed in [19]. Similar to the system described above, the energy from the PV panel can be stored in the ESS or injected into the grid. The ESS itself can provide the energy injection if needed, regardless of solar panels. The difference with the previous configuration is that the ESS can be charged from the grid if required.

A different approach the author proposed was to use small-scale energy storage devices to smooth the photovoltaic fluctuation it takes in account the sizing of energy storage devices to mitigate the power fluctuation in PV plant before dispatching it to the grid [18]. As suggested by [20] the procedure and configuration of the power control differ for sunny days when the production is stable and on cloudy days when there are no predictable values of irradiance [20]. This fact points out the essentiality of improvement in the weather forecast service and the need for analyzing differently the seasons of the year.

Using ESS to help with the PV penetrations limits on the system is another goal that has been discussed in the literature. Energy storage devices are used to help mitigate the voltage rise resulting of high penetration of PV into the system based on optimized operation strategy, it shifts the extra generated power by the PVs during peak PV generation periods to the ESS and by charging this power the voltage stays at stable levels [21] [4] [22].

In [10], voltage control is considered using ESS to get more PV penetration to the network and mitigating voltage rise issue also. Several papers proposed to use ESS to regulate the voltage and mitigate the voltage rise in PVs grid-connected systems. Figure 2.3 shows the voltage rise issue, which is caused by PVs high generation during peak hours of the day.

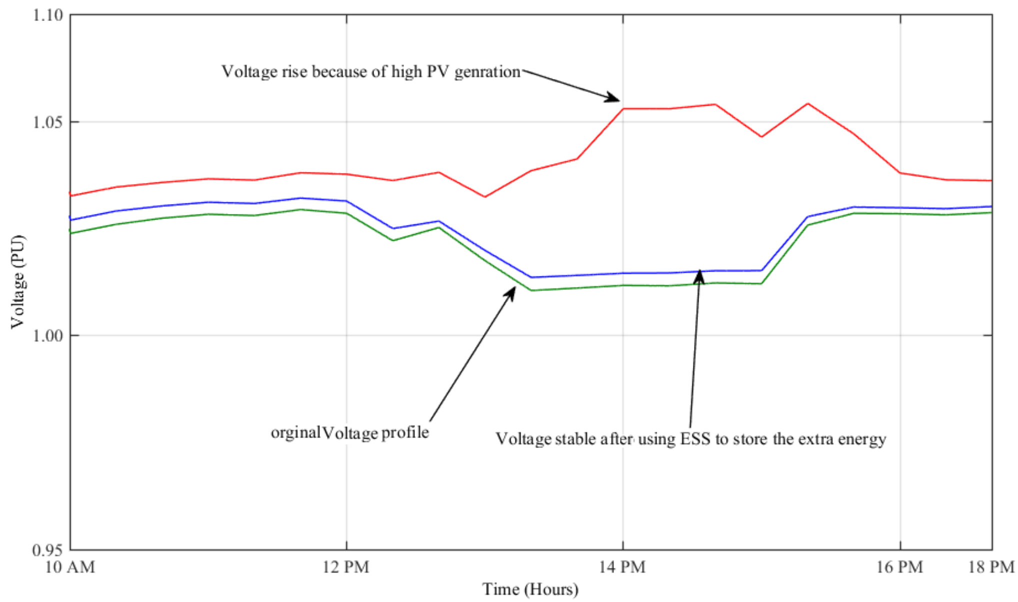

Figure 2.3 voltages profile with PVs connected to the grid and when ESS is used

Some publications focused on finding the optimal allocation of ESS. In [23], system reliability improvements are gained by optimally locating the ESS in the network. On the other hand, the optimal location of ESS is a problem discussed by using GA optimal sizing and location of ESS is addressed to help with system upgrade deferrals [24], using GA to find the optimal location of the battery to help with high penetration of PV in the network, or using multi-objective GA, which takes in account the battery cost and lifetime of it to get accurate results [25].

2.8 ESS Optimization and Power management

Optimal sizing, control, and energy management strategies are known as important research issues. First, several methods for optimal sizing have been proposed in the literature. Some of the authors use the artificial intelligent (AI) methods such as genetic algorithm (GA), whereas others utilize the iterative method to find the optimal configuration of a microgrid which satisfies the optimal operation strategy. Second, the optimal for microgrid energy management is also presented in some research. The rule-based method, optimal global methods (Linear programming (LP), Mix-Integer-Linear-Programming (MILP), and dynamic programming (DP), as well as the artificial intelligent (AI) methods, are all used to find the optimal energy management for a microgrid. Last, the local controllers for DER can enhance the efficiency of microgrid operation by using the conventional methods (single master (centralize control), master/slave and droop control). Furthermore, the variations of conventional droop control are also addressed in some publications.

The optimization of the grid-connected microgrid has been presented in the recent literature. For instance, in [6], a method is proposed to determine the size of battery storage for grid-connected PV system. The objective is to minimize the cost considering the net power purchase from grid and the battery capacity loss. Similar work has been done by comparing four different types of batteries in [26] - the model is linear, and it was modeled in in GAMS.

The author proposed an optimal sizing of a PV energy storage system to be installed on the demand side for three different cases. It takes cost and CO2 emissions into account the sizing method is based on changing the forecast error [27].

A methodology for the optimization sizing and the economic analysis dedicated to PV grid-connected systems with ESS is presented in [6], in which, the author is considering the profit that can be gained from selling energy to the grid. Dynamic active power optimal power flow is used to optimize the operation of the ESS in [15]

In [28], the aim is to find the optimal allocation of energy storage units for grid support. A large-scale system was studied, and improving the reliability of the distribution system was also achieved in [28]. In [24], the author uses GA to determine the optimal allocation and sizing of PV grid-connected systems. On the other hand, the alternating direction method of multipliers with optimal power flow is used for optimal sizing and allocation of the ESS in [29].

In a grid-connected microgrid, energy management system is needed to impose the power allocation among the system components, the cost of energy production and emission. The operational objectives are considered to optimize the energy management, are given as follows:

- Economic option
- Technical option
- Environmental option
- Combined objective option.

Some algorithms for the optimization of microgrid energy management are proposed [30] [31] [13]. The optimal energy management of ESS is presented in [13], by using optimal power flow with multi-objective function in the unbalanced system to optimize the operation of ESS. The operation of the system depends on the linear programming (LP) and second cone programming (SCP), which are used to find the optimal energy management in [26] [11]. This method gives good results; however, the main limitation is known as the need for a specific mathematical solver. In [32], the optimal energy management of ESS is addressed by using an iterative algorithm, with excellent results achieved. A combination of droop-based control and a consensus algorithm optimization module is used to search the optimal size and the charging/discharging control [33]. The achieved results are proved the efficiency of these methods [34].

Although the peak load shaving is a main point of study when sizing ESS in this thesis, another goal also keeps voltage profile at the acceptable level. It should store the energy surplus at some point in the day and release it when required by the injection pattern. The ESS sizing ideas presented above will not directly match what is required in this case. The local climate and the injection special conditions required motivating the creation of a new sizing format.

Chapter 3: **System Modeling and Data Basis**

3.1 Introduction

In this chapter, the system model including the photovoltaic (PV) system, storage system, loads and distribution lines will be presented in detail.

Details of data acquisition and processing will be discussed in this chapter. The data used this study is obtained from different sources dependent on data type and availability.

For the computations in this thesis MATLAB program, and EMTP-RV is used.

3.2 System Description and Components

This system being studied in this thesis is a part of the university network, the original network without PVs and ESS is shown in figure 3.1, the system consists of three buses with five balanced three phase loads. Feeder voltage is 13.8KV line to line and, the feeder length is 1555 m.

In this chapter, details of modeling of each component of the system using EMTP-RV software, mathematical equations and data for each component will be presented.

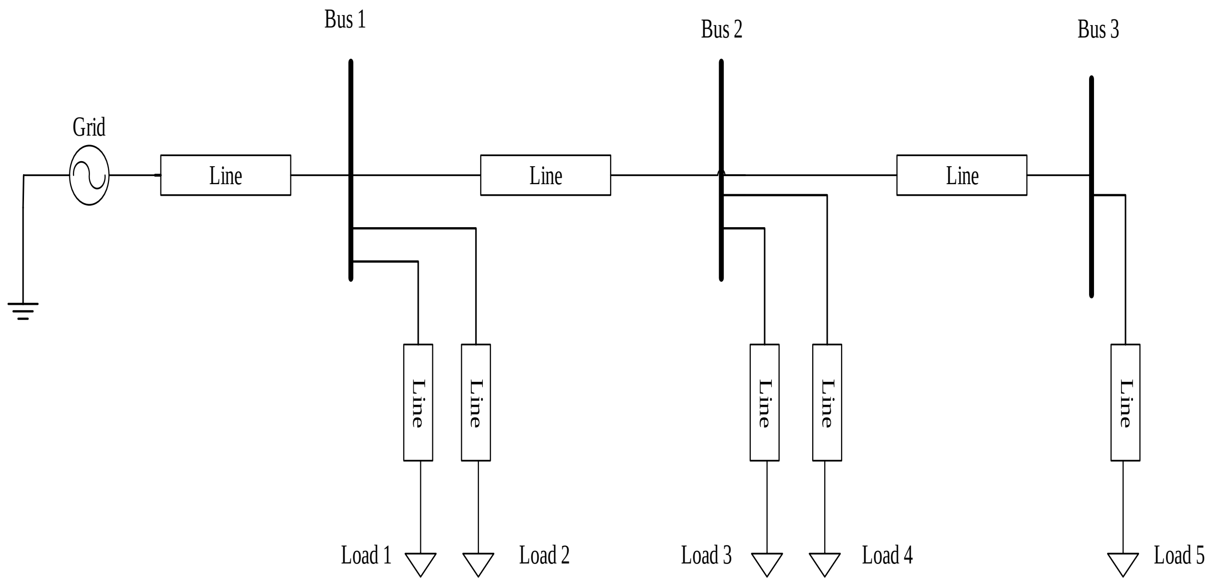

Figure 3.1 single line diagram of the original system under study

Figure 3.2 shows the PVs and ESS connection to the system, however, it must be noted here that choosing an optimal location is beyond the scope of this study. Both PV and ES systems are connected to the same bus, in another word three PV system and three ES systems are used one is assigned to each bus.

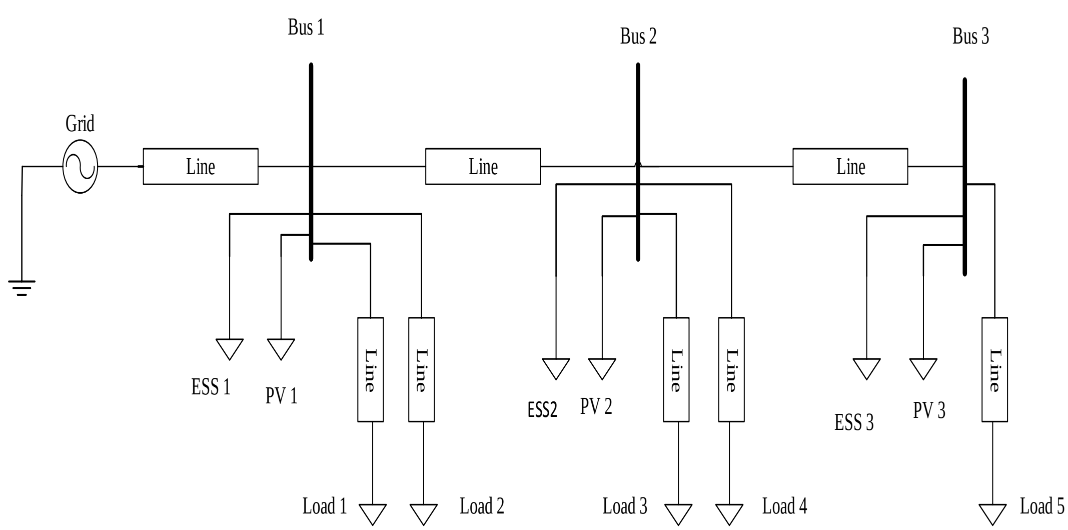

Figure 3.2 Diagram of the proposed system scheme

3.2.1 Loads and distribution lines

For this study, it is required to have a dynamic load, i.e. time-varying loads EMTP-RV has two types of the load in its library and both are constant loads. A current controlled source is used to overcome this issue to work as a variable load. The model is available in one of the EMTP-RV examples and it has been modified to work for this study.

A pi equivalent component is used to represent the distribution lines. It is taken from the components library of EMTP-RV, the positive and zero sequence is calculated based on the following equations

$$[Z_{abc}] = \begin{bmatrix} Z_{aa} & Z_{ab} & Z_{ac} \\ Z_{ba} & Z_{bb} & Z_{bc} \\ Z_{ca} & Z_{cb} & Z_{cc} \end{bmatrix} \tag{3.4}$$

Z_{ia}, $E_{bb,}$ and Z_{ac} are the self-impedances, and Z_{ab}, Z_{ac}, Z_{ba}, Z_{bc}, Z_{ca}, Z_{cb} are the mutual impedances.

For a transposed line Z_{aa}=Z_{bb} = Z_{cc} and Z_{ab}=Z_{bc}= Z_{ca}. also, the matrix will be Symmetric, this gives:

$$[Z_{abc}] = \begin{bmatrix} Z_{s} & Z_{m} & Z_{m} \\ Z_{m} & Z_{s} & Z_{m} \\ Z_{m} & Z_{m} & Z_{s} \end{bmatrix} \tag{3.5}$$

Here Z_s is the self-impedance and Z_m is the mutual impedance. The symmetrical component matrix is given by:

$$[Z_{\text{symmetrical}}] = [A][Z_{abc}][A^{-1}] \tag{3.6}$$

When the off-diagonal terms of the phase impedance matrix are equal, the off-diagonal terms of the sequence impedance matrix will be zero, and the symmetrical component matrix turns out to be:

$$[Z_{\text{symmetrical}}] = \begin{bmatrix} Z_s + 2Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix} \tag{3.7}$$

In the symmetrical component matrix, the diagonal terms are the zero-, positive-, and negative-sequence impedance of the line. Note that the off-diagonal terms are zero which indicates that there is no coupling between the zero-, positive-, and negative-sequence networks for the transposed line. The zero-, positive- and negative sequence components of the impedances are Z_0, Z_1, and Z_2.

$$Z_0 = Z_s + 2Z_m \tag{3.8}$$

$$Z_{1,2} = Z_s - Z_m \tag{3.9}$$

3.2.2 Photovoltaic model

Three PVs are included in the model with one PV system at each bus, and all the PVs are assumed to be identical because their situation is in the very small georgical area. The block diagram in figure 3.4 shows the PV system components, which are:

- PV array
- Inverter
- Maximum power point tracker

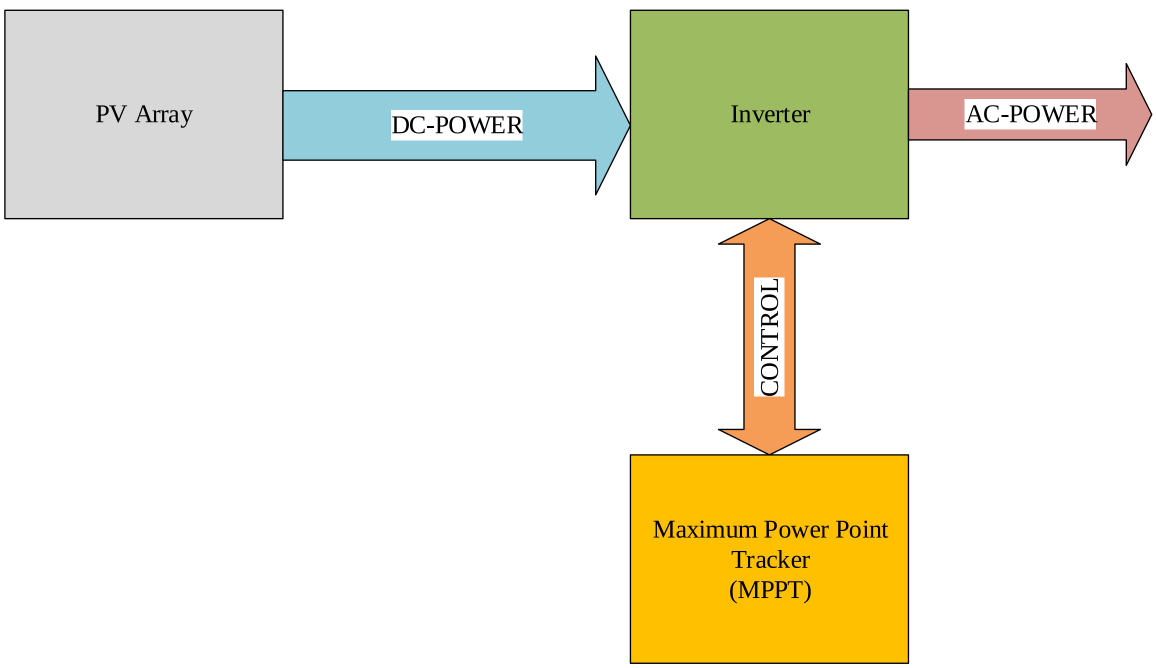

Figure 3.3 block diagram of the PV system

PV array generates DC power only so it is connected to the grid through an inverter. In this configuration, all PV arrays are connected to one inverter, the inverter converts the DC power to AC power and therefore it can be used to feed the loads in the grid.

PVs require a control device to get the maximum power generated by the PV always a maximum power point tracker (MPPT) is doing this task.

The inverter is assumed to be operating with unity power factor, this way only active power generated by the PV is used to feed the loads.

3.2.3 PV system sizing

Details of PV sizing is out of scope in this thesis, and the information obtained from [35] is used to calculate the size of the PV array. Based [35] the available area for putting the PV system is 700 m^2 at each building this area can support 100kW PV system.

3.2.4 PV system Modeling

The PV simplifier system model is given as an injected current source with an active and reactive power control. The purpose of this control is to impose the output active and reactive power following the setpoint value $P_{p.}$ and Q_{pv}, respectively. the P_{pv} is determined by the MPPT of PV module and Q_{pv} is zero.

For simplicity, it is assumed that PV system is working with maximum power point tracker and it will not be modeled in this work also the inverter will not be modeled and only be assumed as constant conversion ratio and unity power factor. The equations in the following give the mathematical theory for the model used in this thesis [13].

$$P_{PV-DC}(t) = \frac{G(t) \times A \times \eta_{PV}}{100} \tag{3.10}$$

Where,

P_{PV} (t) Output power of PV panel [kW]

G (t) Sun Irradiation [kW/m2]

A Area of the PV module [m2]

η_{PV} PV system efficiency [%]

The PV system will be connected to the grid using an inverter also the inverter so the previous equation can be written as:

$$P_{PV-AC}(t) = P_{PV-DC}(t) \times \eta_{INV} \tag{3.11}$$

Where

$P_{pv\text{-}DC}$: DC Power output from the PV panel (kW)

$P_{pv\text{-}AC}$: PV power at the AC bus (kW)

η_{INV} : PV inverter efficiency (%)

3.3 Energy storage system

For this study batteries will be used as energy storage because they are suitable for the peak load shaving application [34] [11], the block diagram in figure 3.5 shows the energy storage system components, which are

- Battery
- Inverter
- Charge/Discharge controller

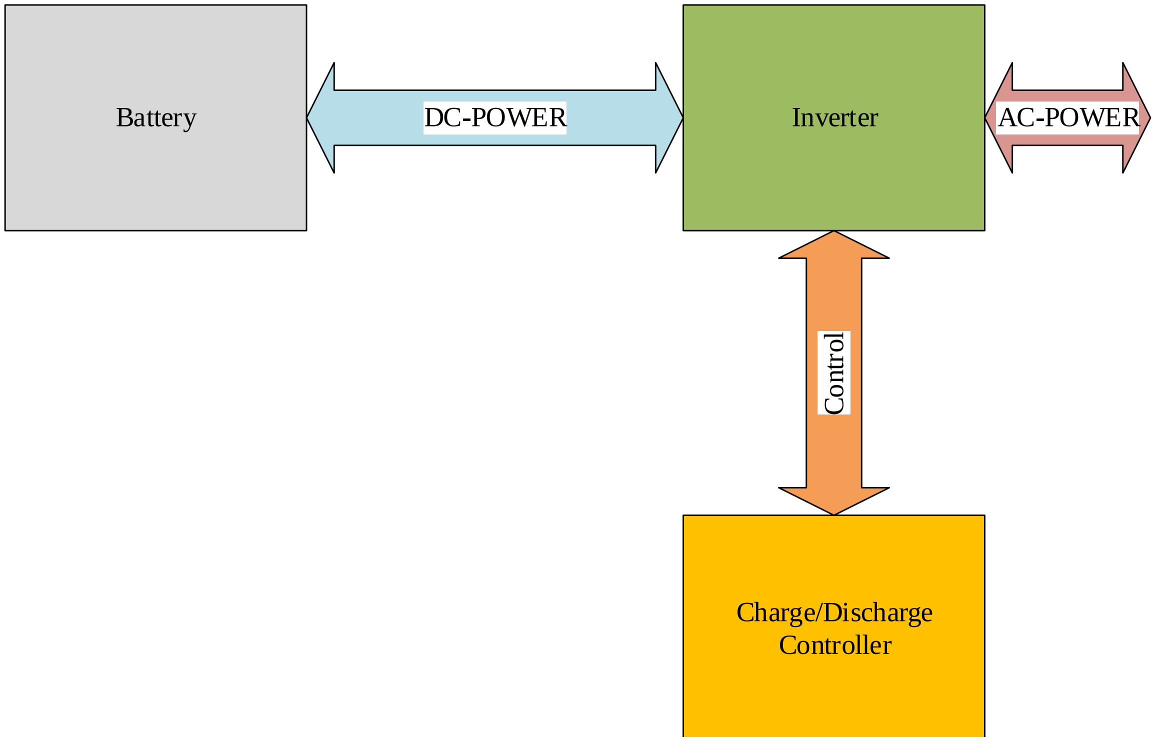

Figure 3.4 block diagram of the Energy storage system components

Battery stores DC power only so it is connected to the grid through an inverter, the inverter converts the DC power to AC power. The battery can be used to feed the loads in a grid by discharging energy when it is required, however, this energy is charged again to the battery when it is available. Charging and discharging of the battery is the responsibility of charge controller which a control device that signals the inverter to which direction energy should flow.

3.3.1 Battery Modeling

The battery is modeled as a controlled current source with its active power and reactive power are the input. These values are generated using MATLAB script, the MATLAB script is based on the following equations [7].

The energy stored in the battery is described in the equation

$$\frac{dE_{batt}(t)}{dt} = P_{batt-DC}(t) \tag{3.9}$$

$P_{batt\text{-}DC}$ Charge/Discharge power of the battery (kW)

E_{batt} Stored energy in the battery (kWh)

The charge and the discharge power can be written into the equation.

$$P_{batt-DC}(t) = \frac{E_{batt}(t) - E_{batt}(t - \Delta t)}{\Delta t} \tag{3.1012}$$

Where,

$P_{batt\text{-}DC}$ Charge/Discharge power of the battery (kW)

E_{batt} Stored energy in the battery (kWh)

When the battery is charging, the stored energy of the battery is also increased and vice versa, when the battery is discharging, the stored energy of the battery decreased.

To connect to the grid, the battery is connected to an inverter to convert the DC power into an AC power the efficiency of the inverter will be assumed to be constant to simplify now the charging and discharging AC can be written as

$$P_{batt-AC}(t) = \begin{cases} P_{batt-DC}(t) \times \eta_{batt}\,, & P_{batt-DC}(t) < 0 \\ \dfrac{P_{batt-DC}(t)}{\eta_{batt}}\,, & P_{batt-DC}(t) > 0 \end{cases} \tag{3.13}$$

Where,

$P_{batt\text{-}AC}$ Charge/Discharge rate of the battery on the AC bus (kW)

$P_{batt-DC}$ Charge/Discharge rate of the battery (kW)

η_{batt} Battery inverter efficiency (%)

The charge state of the battery is updated each sampling hour with the charging and discharging of power to and from the battery is based on the following [36].

$$SOC(t) = SOC(t - \Delta t) + \Delta SOC \quad (3.14)$$

And

$$\Delta SOC = \frac{\mathrm{P}_{\mathrm{batt-DC}}(t)}{\mathrm{C}_{\mathrm{batt}}(t)} \Delta t \quad (3.15)$$

where,

C_{batt} Usable battery capacity (kWh)

SOC is subject to

$$SOC_{min} \geq SOC(t) \geq SOC_{max} \quad (3.16)$$

Where:

SOC_{max} is the maximum state of charge

SOC_{min} is the minimum state of charge

If the SOC is equal to SOC_{max} or SOC_{min} the battery will be in idle mode i.e. $P_{batt-AC} = 0$.

3.4 Data basis

When optimizing energy storage, the data used in the process must be accurate and reliable. Therefore, with the availability and access to hourly solar data and load data throughout a year, I have chosen to use as the basis for this study part of the university network.

During the year, summer period is considered as from 1st May – 31st October and the remaining months of the year are considered as winter period. During the day, the peak hours are defined as 8 a.m. to 9 p.m. All the remaining hours are considered as off-peak hours.

3.4.1 Load Profile

The hourly varying electricity load profile of the university during the year 2015 is obtained from the university, some of the data has an error in the reading so I modified the errors by taking the average between two hours one before and the second one is the error reading also some 15-min data had to be changed to an hourly data to fit with the rest of data profile. Figure 3.6 shows load curve for winter day and summer day.

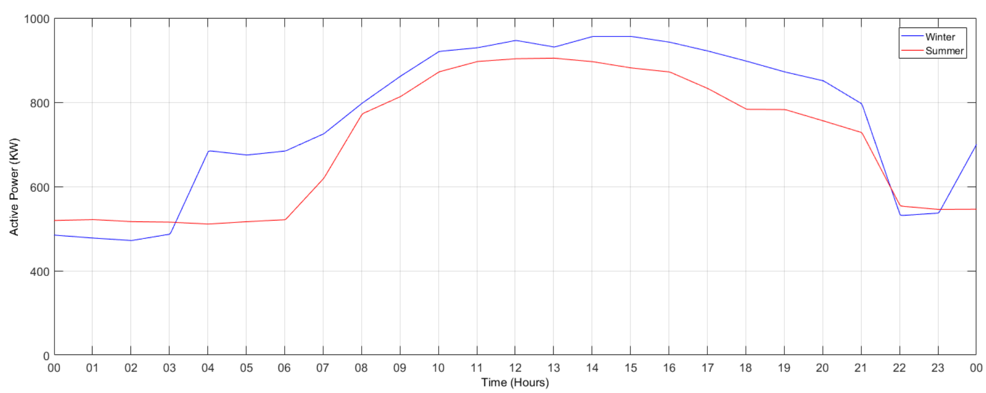

Figure 3.5 shows the load profile of the system during a typical winter day VS typical summer day

3.4.2 PV Profile

PV output data of the system is generated by using the PV system size and the global horizontal irradiance data at the university location. the PV system size, which is installed at the part of the university under study, Then the relevant area of the PV panel is calculated by using the PV watts calculator of the National Renewable Energy Laboratory [35].

The table shows the calculation parameters and data used to calculate the PV output at each bus, figure 3.7 shows the average PV output profile during the winter and summer days respectively.

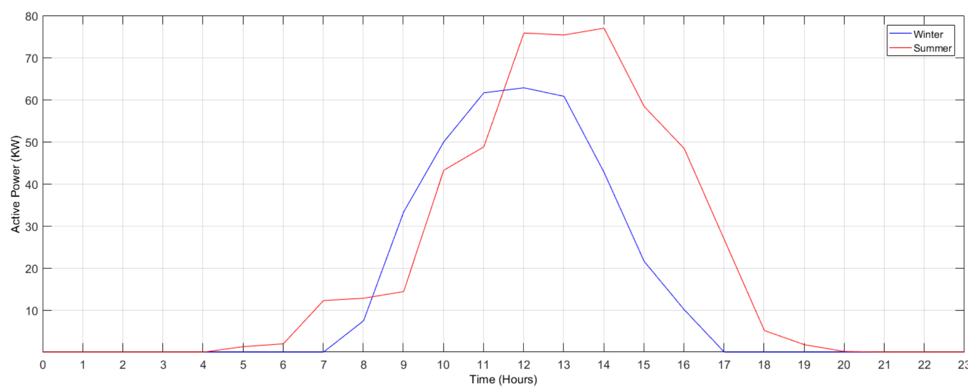

Figure 3.6 shows the PV profile of the system during typical winter day and typical summer day

Table 3.1 PV data

Parameter	Value
PV system size (kW)	100
Array type	Fixed-open rack
Tilt angle(dig)	45
Azimuth (deg)	180
System Losses (%)	14
PV inverter efficiency	97%
DC to AC Size Ratio	1.1
System Type	Residential
Module Type:	Standard

3.4.3 ESS Profile

In this study, different sizes of battery capacities are being used for comparison. In every case, the battery specifications are considered with respect to Fullriver deep cycle battery bank [37]. The table below shows the specification of the battery used for this study, the battery profile is generated using MATLAB script figure 4.8 shows flowchart of process used to generate ESS profile which based on the ESS model discussed in section

Table 3.2 ESS data

Parameter	Value
Nominal cell voltage (V)	2 V
Capacity (C)	1040 AH
Minimum charging/ discharging time (t_{min})	10 hours
Minimum state of charge (SOC_{min})	10%
Maximum state of charge (SOC_{max})	90%
Battery inverter efficiency (η_{inv})	97%
Number of batteries (N)	24 batteries

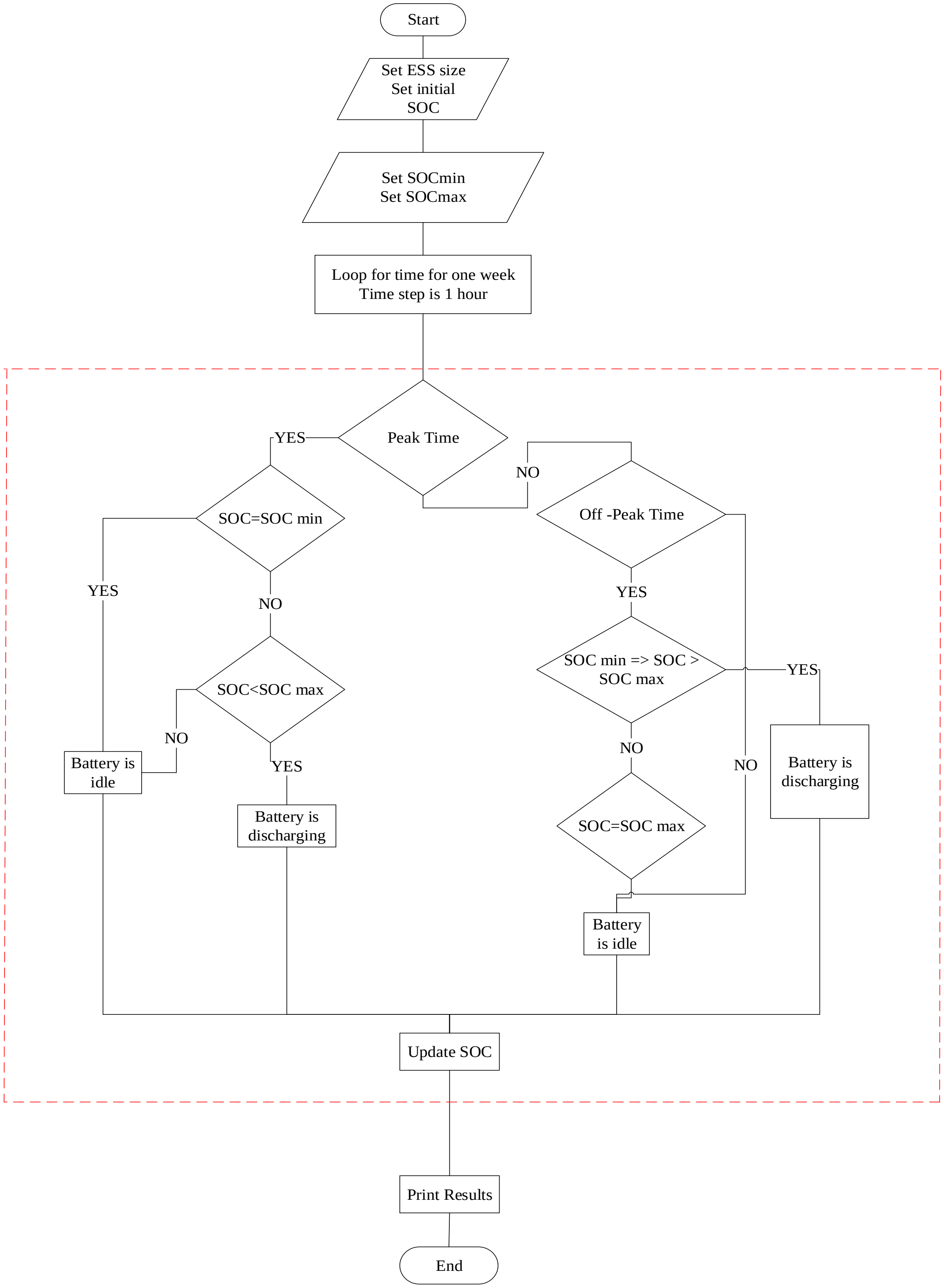

Figure 3.7 flow chart of MATLAB script used to generate ESS profile

3.5 Determination of ES Capacity

An important factor is to find a proper battery size for a grid-connected PV system to do peak load shaving. it has been accomplished by managing the energy flow schedule/decision of this system. In this method, the economic side was ignored and just focused on engineering part only.

In winter, the hourly average power drawn is 706.5 kW, and the maximum demand during the week was at 972 kW. On the other side during summer the hourly average power consumption is at 685.25 kW with a maximum demand of 904 kW, which is due to the fact that there are fewer students and activities on campus during the summer.

Power consumption for the campus is different than regular loads such as corporations the highest amount of power is being drawn between 8 am 8 pm for both summer and winter. With long peak hours, it should be taken into account when managing the operation time of the Energy storage system.

Because the system consumes high power during peak hours it is requiring high capacity ESS to be able to discharge high power and for several hours it is determined that size of ESS must be able to handle this task.

Four different sizes were simulated, and the first three ESS sizes were based on the PV system 50 kWh, 100 kWh, AND 200kWh to get an idea how each size would perform with and without using PV system.

It turns out that all those sizes had little effect on reducing the peak load alone, and could not maintain the same level of reduction as the PV system once the sun is down.

So, overcoming his issue required using different size and different time schedule to keep the same level of peak load reduction once the sun is down i.e. there is no or low PV generation.

On average PV system produces a total of 900kW on a winter day and 2000kW on a summer day.

In winter PV system would produce power for 64 hours over a typical week and it would generate power for 108 hours during summer week. To keep up with the PV system an ESS with the size of 1050 kWh is needed to generate 150 kW of DC power for seven hours starting at 02 PM and until 09 PM which is the best time to discharge the ESS according to results obtained in Chapter 4.

To summarise the size of ESS is chosen based on average PV system generation to maintain the same level of power consumption reduction when the sun is down or when the PV generation is low. The size considered the losses of power transforming from DC to AC and the charging-discharging efficiency.

3.6 Assumptions and Limitations

The scope of this thesis is limited when considering all the minor parameters which are not highly affected by the final result of the simulations. While performing the key objective of minimizing the peak load of the system, the process should keep some parameters as constants. All of those which considered as assumptions and limitations have been described in below.

PV system is connected to the grid using one inverter at each bus, the inverter is assumed to work with unity power factor this way PV system generates active power only. Active power is the main concern under study by utilizing hourly result ion the PV output would be smooth. The size of the PV system installed on the building is taken as a 100 kW-DC system at each bus which due to available area limitation being of 700m^2 at each location. ESS is also connected through unity power factor inverter, only active power is being charged or discharged only which is justified due to focus on active power in the simulations.

Load profile as shown in figure 3.5 sets Peak hours are between 8 AM and 09 PM, off-peak hours are between 11 PM and 08 AM. the battery is discharging during peak time for eight hours and it is charging during an off-peak time for eight hours. Long charging and discharging period justifies the SOC limits, which are SOC_{Max} =90% SCO_{Min}=10% and during the hours out of peak /off-peak hours. Operating time of the battery is 16 hours there is no power transfer from or to the battery during the rest eight hours i.e. battery stays idle.

The simulation conducted using hourly resolution data which due to limited data sources however it is still considered acceptable for peak load shifting study. A typical week is consisting of five working days and normal two holiday days. Simulations conducted for two seasons winter and summer. Energy losses in the system like power transmission loss and loss due to heat are assumed to be zero

Chapter 4: **Simulation Results**

4.1 Introduction

In this chapter simulation results will be presented, these results obtained from the EMTP-RV simulation program, also MATLAB program was used to generate the battery data. The simulation is base on hourly data, two seasons are considered by simulating typical in winter and typical week in summer. in this study three scenarios are considered first is using PV only second is using both PV and ESS and the last one is using ESS only. The first scenario has only one case where the other two scenarios have three different ESS sizes, the simulation process is shown in figure 4.3.

Figure 4.1 shows the system under study also shown the connection of the PV and ESS on each bus. In this study all the PVs integrated at each bus are identical same also goes for ESS used at each bus. The loads, PVs, and the ESS are simulated as current controlled sources depending on active and reactive power as inputs as shown in figure 4.2.

The first step is to set up the load data, PV data, and the battery data this process is based on the method discussed in chapter 3. The second step is choosing the season to be simulated in this thesis it is winter or summer, choose the simulation scenario, and then conduct the simulation using the model developed in EMTP-RV.

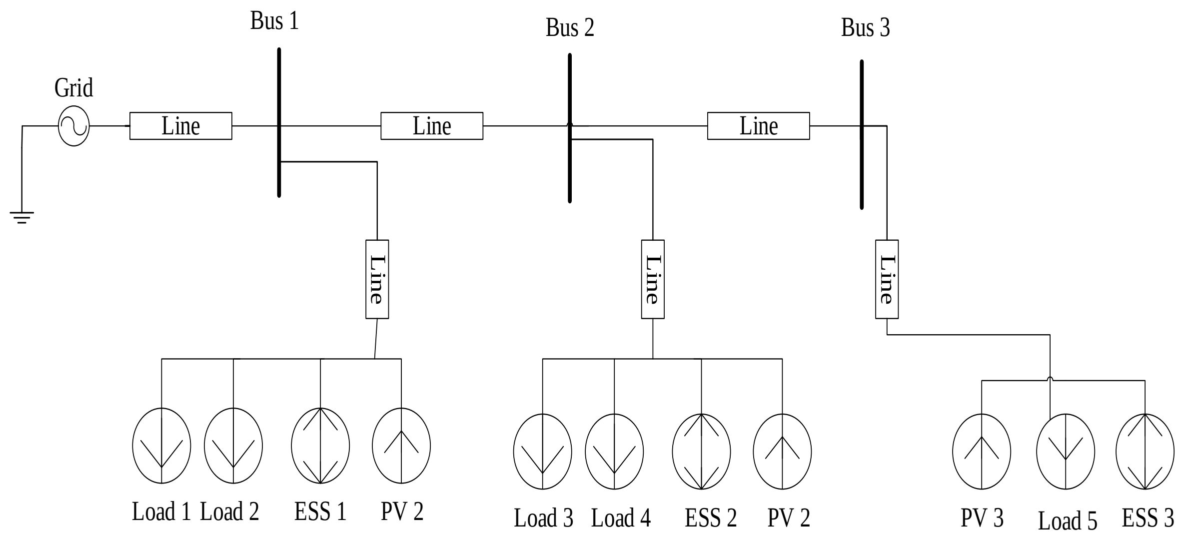

Figure 4.1 single line diagram of the system and the integration of PV and ESS

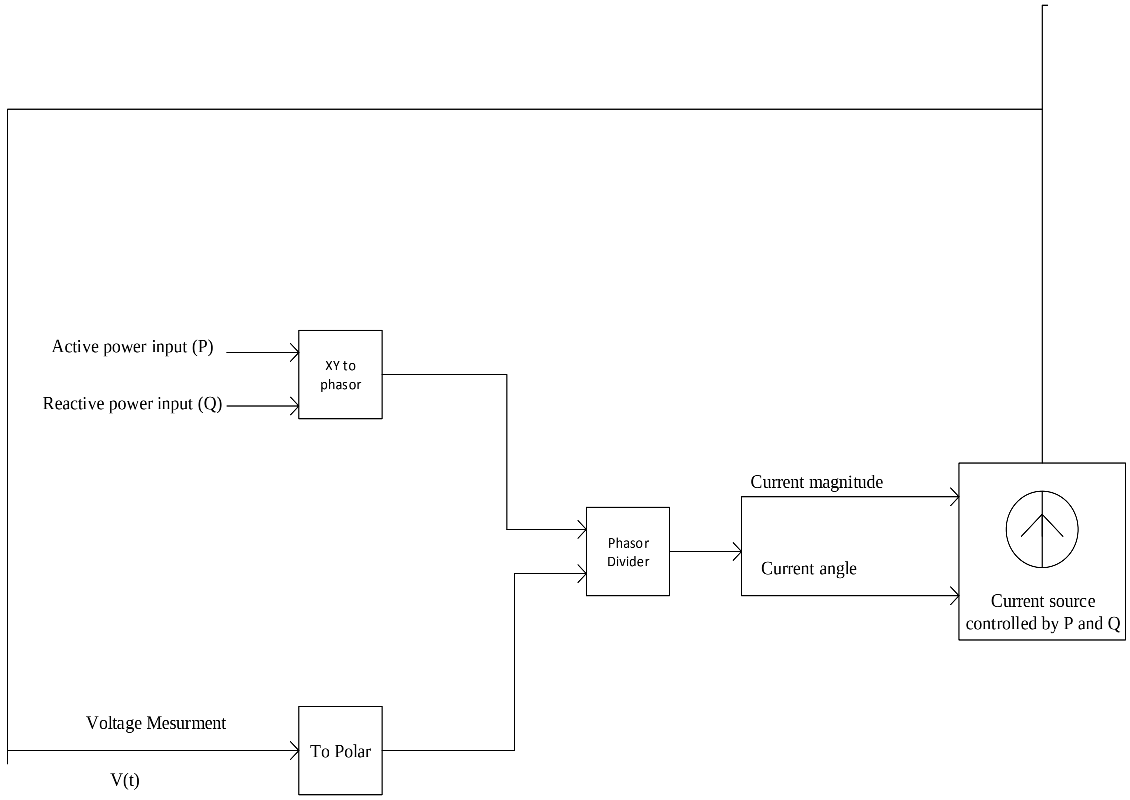

Figure 4.2 single line diagram of the current controlled source

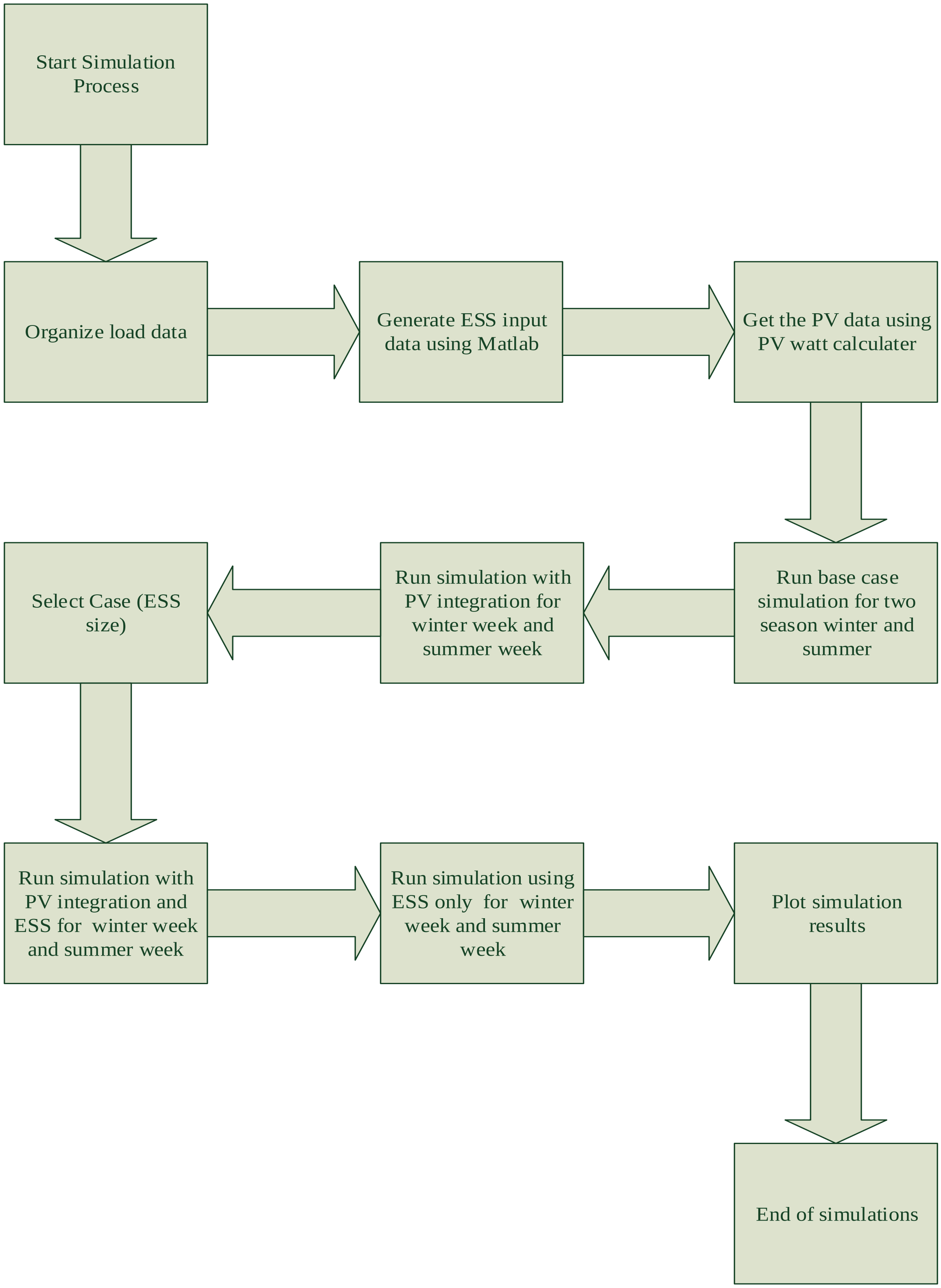

Figure 4.3 block diagram of simulation process

4.2 Base case

Simulation of the original network for a typical week in winter and a typical week in summer with hourly resolution data is conducted using EMTP-RV based on the modeling process discussed in chapter3, first figure 4.4 shows the real power consumed for the total network during winter and summer week, starting Monday to Sunday for each case.

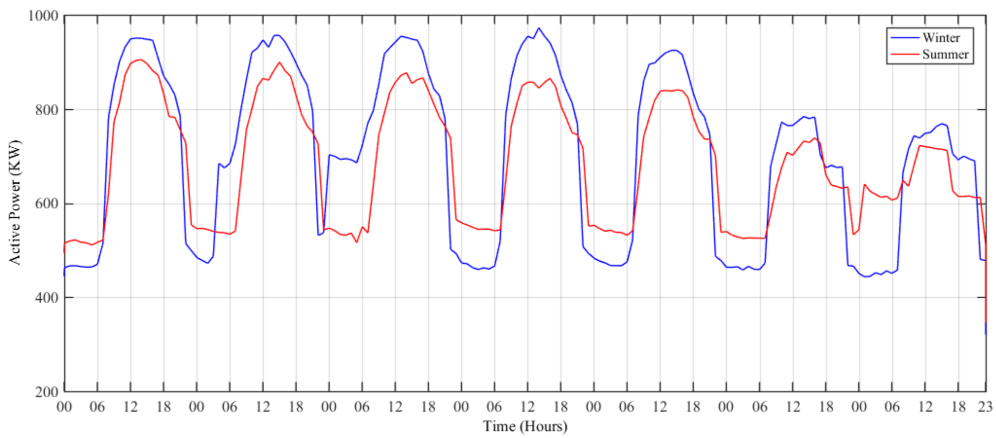

Figure 4.4 power drawn from the grid: typical week in winter and summer

Looking to figure 4.4 gives an idea about load profile, for instance, the power causation during winter is higher which is due more activity on campus, low temperature , and more dark hours than summer, on the other hand during summer power consumption can go up to 900 kW during peak hours where in winter it reaches almost 1000 kW, for off peak hours in winter the power consumption drops down to 450 kW and as low as 500 kW during summer, figure 4.5 show power factor results for both seasons with over sized distribution transformers on campus there is low power factor problem especially at bus 3 where during off peak hours it can go to the poor ratio of 0.6 this due low active power consumption , and it goes up to 0.96 during peak hours where this is high consumption of active power, this effects power quality of the network, for other buses the pattern is the almost the same but still much better than the case of bus 3 . figure 4.6 is shown reactive power curve in winter and summer. high reactive power is causing poor power factor this due to oversized transformers used on campus.

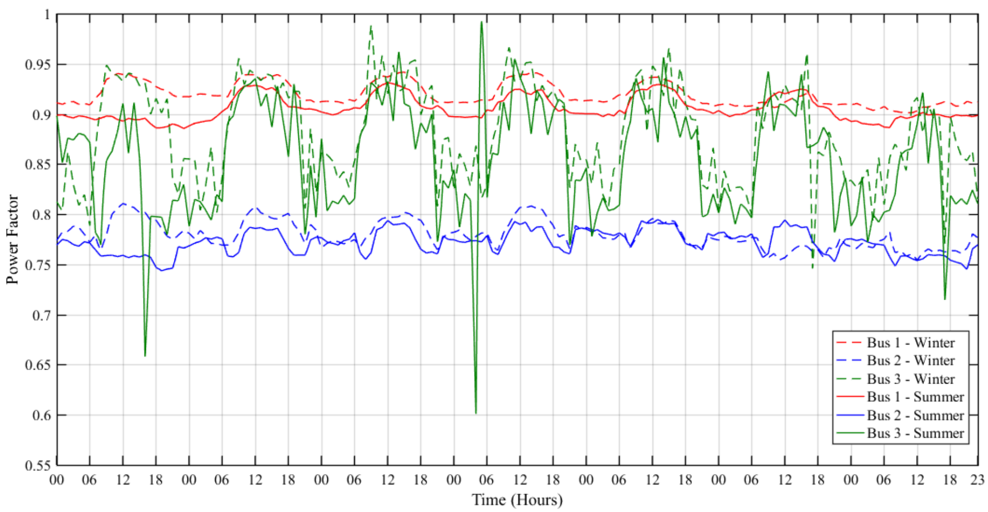

Figure 4.5 Power Factor: typical week in winter and summer

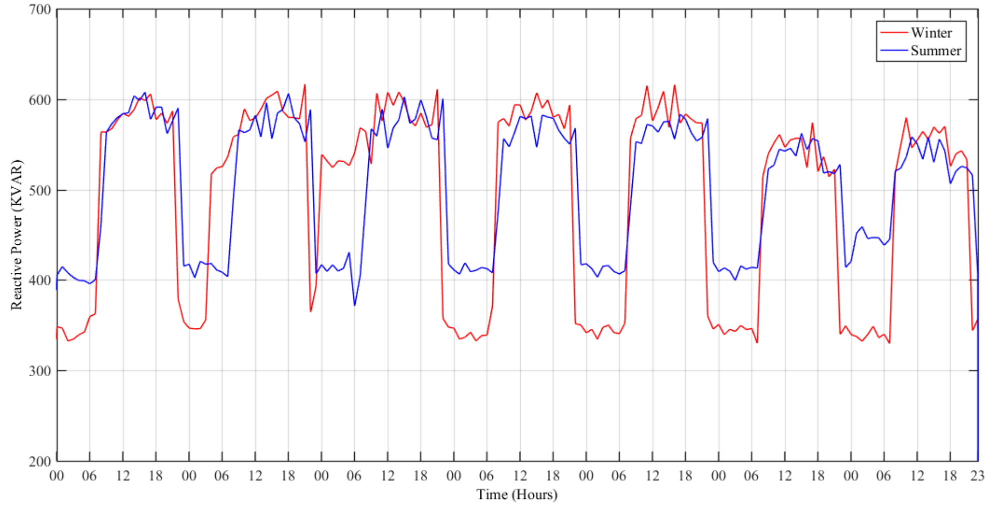

Figure 4.6 reactive power curves in typical winter and summer week

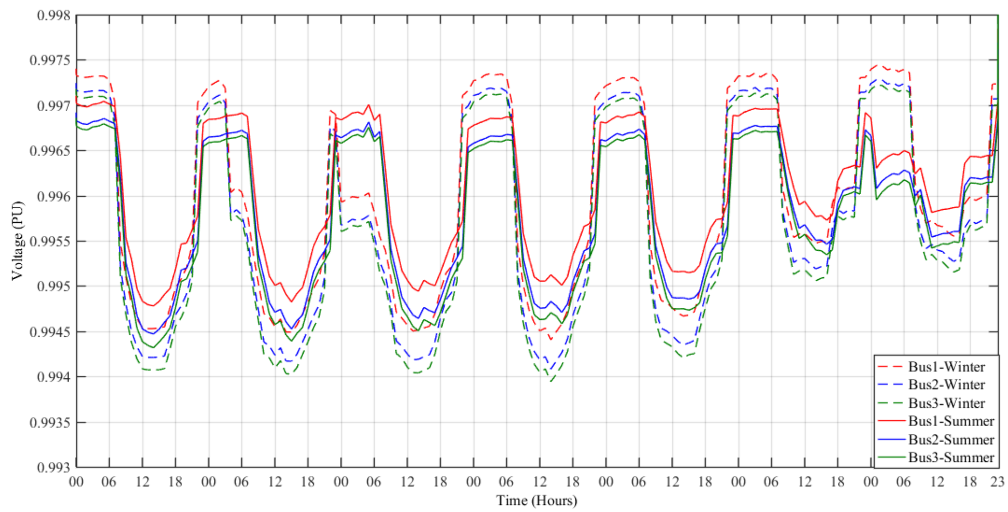

Figure 4.7 voltage profile for typical winter and summer week

voltage profile is shown in figure 4.5 for both summer and winter these results is based on hourly data of the load, it is obvious how stable the system is during both seasons where the voltage at each bus is changing in very little amount , voltage is basically at 0.99 PU for all buses which very stable .

the only thing is that voltage going a little bit high during off-peak hours which is due high reactive power been drawn by the loads, and this related to low power factor and oversized transformers.

In figure 4.6 showing the currents for power source and the three buses in winter and summer, in winter current source is ranging between 69 A for peak hours and 34 A at off-peak periods,however in summer is a little lower in peak hours to reach as high as 65 A,and to drop to low as 40 A during off-peak hours.

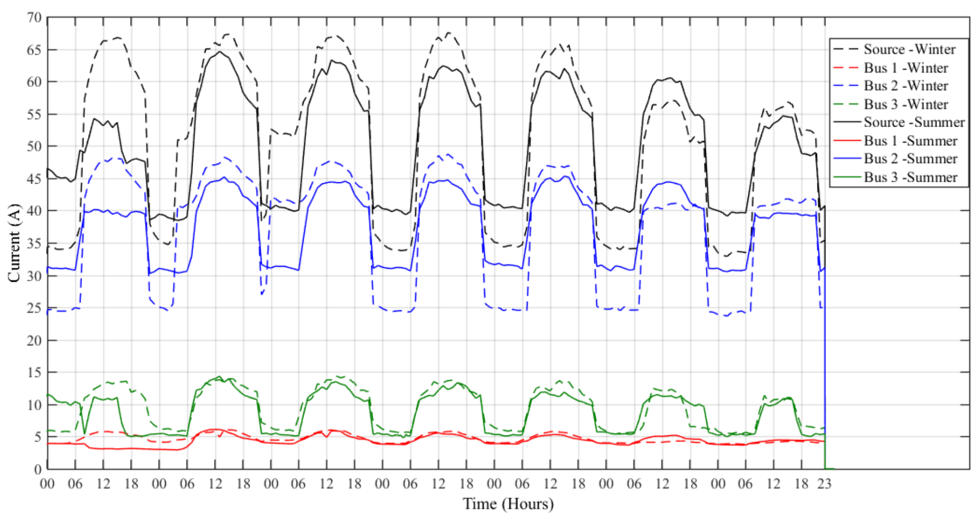

Figure 4.8 currents curve: typical week in winter and summer

For the rest of chapter 4, each simulation will be compared to the original system which will be referred to as Base Case, one for winter and one for summer.

4.3 PV System Integration

In this section simulations results of integrating PV system into the grid are discussed for the two periods discussed in the previous section.

As mentioned in chapter 3 a 300 kW DC PV system with 100 kW DC system at each bus is available to be installed based on the available area. Figure 4.6 shows power consumption in typical winter week with PV system installed, and it is compared to the original case without PV. The simulation has shown good results in reducing power consumption from the grid during daytime with an average of 100 kWh of energy available from the whole PV system even with short day in winter.

For power factor figure 4.10 show the power factor profile for the base case and with PV because of local active power generation at each bus this while reactive power still generated by the grid this has a negative impact on power factor, it should be mentioned that for all rest of cases in this chapter only bus 3 power factor will be discussed because it is already having poor power factor.

An important issue that might result of integrating PV to the grid is the increase of voltage especially at the end of the line, figure 4.11 shows the results of voltage profile for the base case and with PV integration, the results have shown that the voltage stays stable with slight rise during high PV generation periods as expected at bus 3 voltage has the highest value, but it is very little and does not affect the system stability at all.

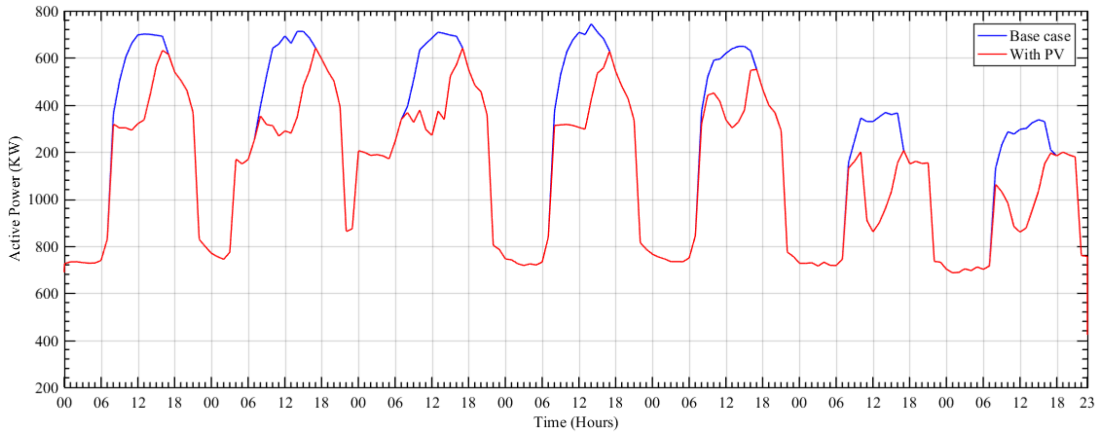

Figure 4.9 power drawn from the grid for base case and with PV: typical week in winter

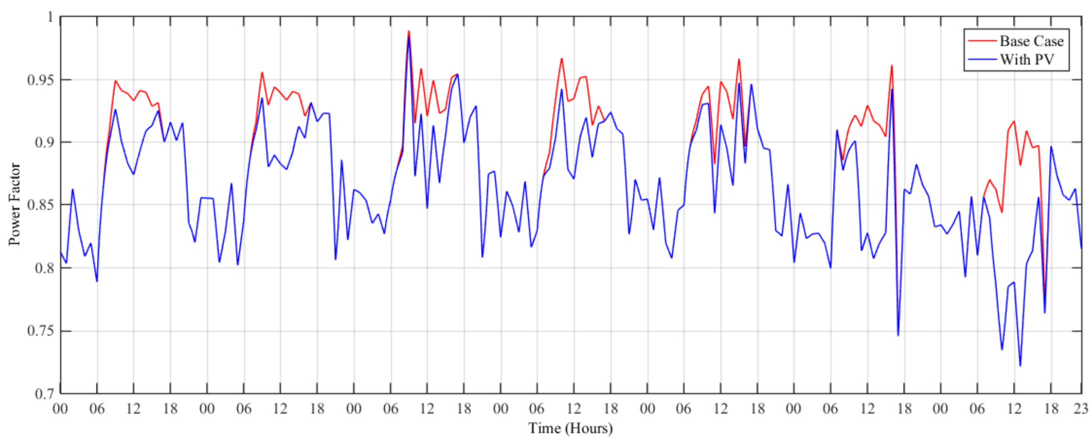

Figure 4.10 Power Factor at Bus 3: typical week in winter without /with PV

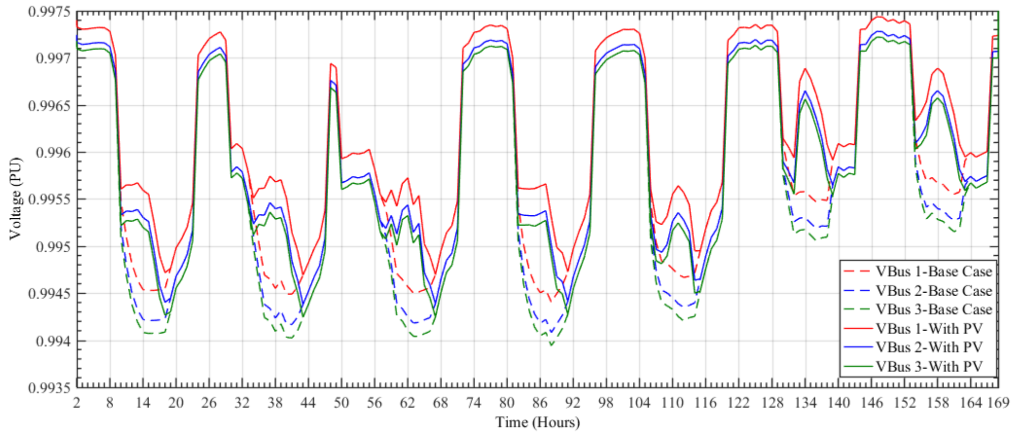

Figure 4.11 voltage profile: typical week in winter without /with PV

For the current profile, results are shown in figure 4.12, with low active power drawn from the grid the current also drops from 69A to 55A at the source.

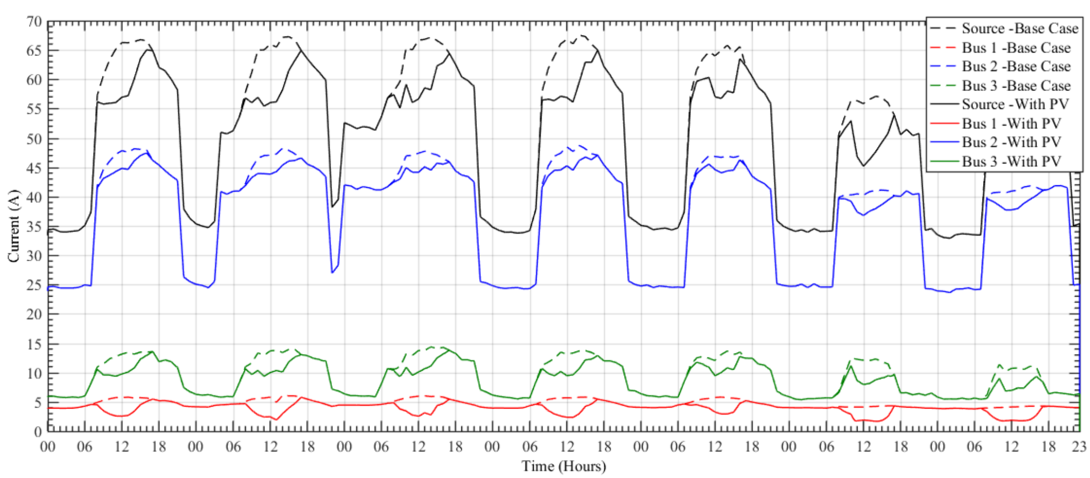

Figure 4.2 current profile: typical week in winter without /with PV

Although in winter season there are the short day and the low temperature effecting PV system, but the PV system has a good generation profile for at campus location, to get the whole picture simulation result of summer week is shown in figure 4.13 with both base case and after installing the PV in this case much better performance of the PV is shown, which due to better weather conditions, and long daytime.

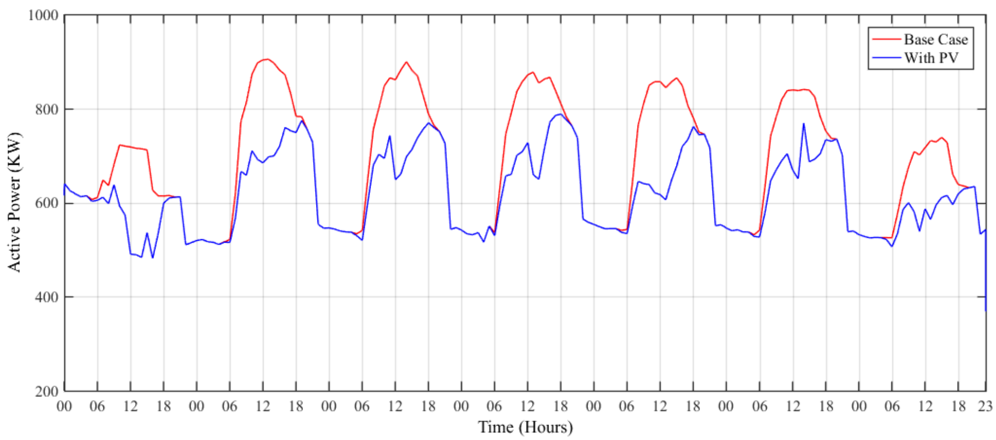

Figure 4.3 power drawn from the grid for base case and with PV: typical week in summer

As for power factor at bus 3, the result shown in figure 4.14 has revealed much negative effect than the winter case with because more active power is being generated locally this cause the power factor to drop too low.

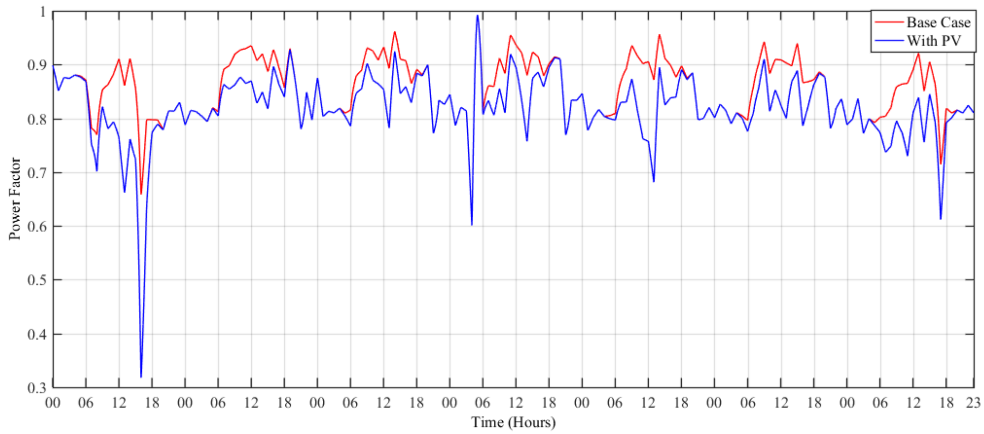

Figure 4.4 Power Factor at Bus 3: typical week in summer without /with PV

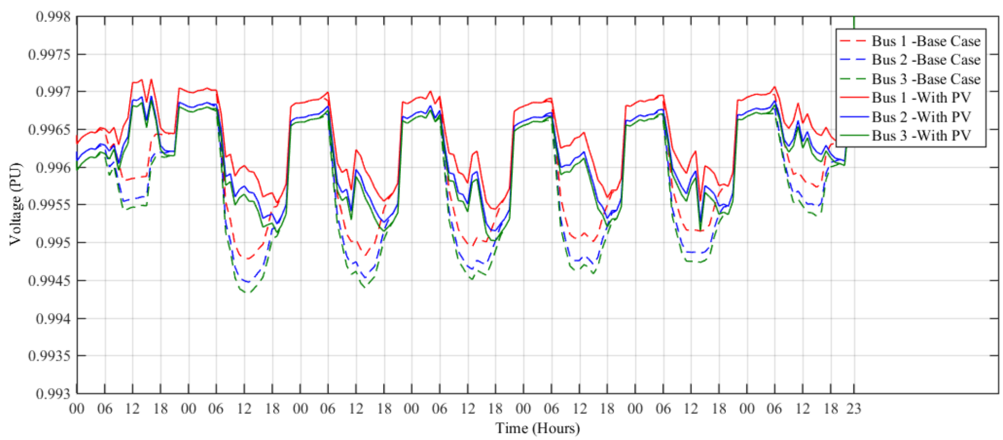

Figure 4.5 voltage profile: typical week in summer without /with PV

Figure 4.15 is showing voltage results in PU, high PV generation during mid-day had affected the voltage on all the buses, the most effects was one bus 3, however, it is still very small effect, and it is not affecting voltage stability.

In the summer, more power is being generated locally by the PV system this means less current is being drawn from the grid figure 4.16 show current profile both base case and

PV case during summer, for example, source current has dropped from 65A in the base case to 55A during working days, and from 55A to 45A during the weekend.

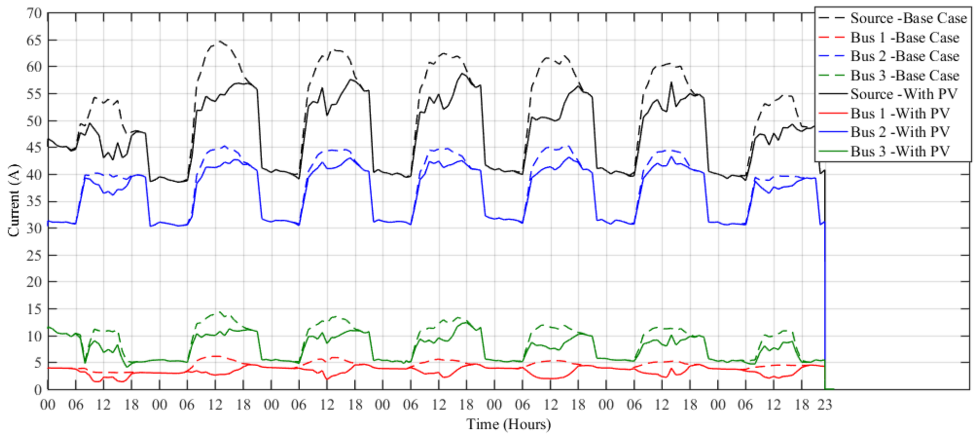

Figure 4.6 current profile: typical week in summer without /with PV

Installing PV system in the network has reduced the power drawn from the grid, however it might disturb the voltage profile of the system as it was mentioned in Chapter 2, fortunately in this case the voltage did not get affected by the installed PVs, Figures 4.10 and 4.15 give an illustration of voltage changes due the installation of the PV in both cases winter and summer the voltages at each bus did not change in a significant amount, actually it was really a very small change which does not affect the system at all.

4.4 Peak load shifting using ESS with/without PV presence

One concern of this thesis is to investigate peak load shaving at university campus using energy storage system. Four cases were simulated were only the size of ESS is changed except for the last case table 4.1 shows the changes on ESS in every case. Each case is divided into two sub-cases first sub-case is using ESS with PV, the second sub-case is using only ESS without PV.

Table 4.1 ESS size and hours of operation

Case	Energy storage size (kWh)	Energy storage hourly rated DC power (kW)	Discharging time	Charging time
Case A	150	15	10 AM to 06 PM	00 AM to 08 AM
Case B	300	30	10 AM to 06 PM	00 AM to 08 AM
Case C	600	60	10 AM to 06 PM	00 AM to 08 AM
Case D	1050	150	02 PM to 09 PM	11 PM to 06 AM

In this section, all the results are taken from the EMPT-RV program by including the battery energy storage to the grid-connected PV system. different battery capacities were tested to determine which capacity can give better results. The battery discharging sequence in this simulation is the same for all different batteries.

In first three cases, the ESS is set to work on a fixed schedule, therefore in between 10 am and 06 pm the ESS is set to discharge mode during this time high power is being drawn from the grid so it is the best time to discharge the ESS, so it can help with load shaving, on the other hand, the ESS is set to charge starting from 12 am to 08 am this is off-peak time so it is the best time to charge the ESS. Figure 4.17 shows the SOC of the battery during the entire week, it must be noted that staring SOC is set equal to 40%.

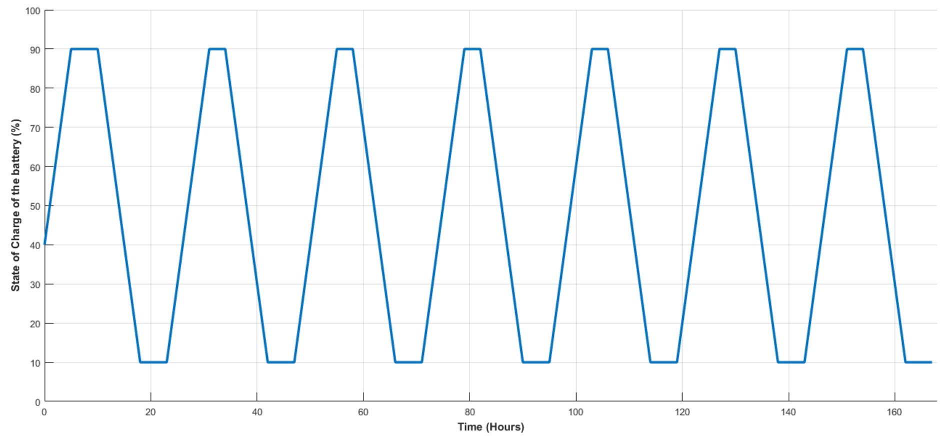

Figure 4.7 state of charge of the battery: typical week operation

Figure 4.18 shows the ac power charged\discharged by the ESS for all four case this result is obtained from MATLAB script also.

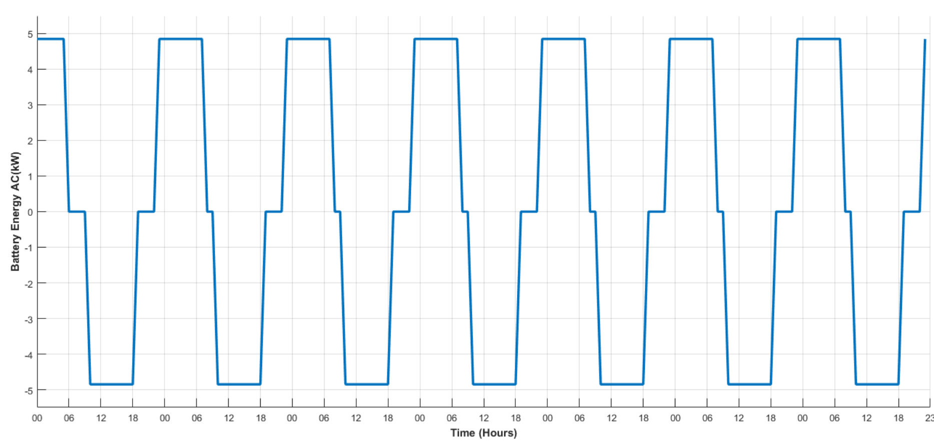

Figure 4.8 power of the battery: typical week operation

4.5 Case A 150 kWh ESS

Case A ESS size is 150 kWh to i.e. one battery pack sized at 50 kWh at each bus. discharge/charge time of 10 hours this means total energy dispatched or consumed is equal to 15 kWh DC at each hour depending on charging \discharging mode.

4.5.1 Case A1 using PV with ESS

Figures 4.19 and 4.20 show the power drown from the grid with PV and ESS installed and comparing this results to the base case in winter, with ESS along with PV more power is generated locally, however, the battery is charging power back during off-peak hours, ESS is also reducing power consumption after the sunset for two more hours, in summer with long daytime PV is counion supplying power when ESS is in idle condition.

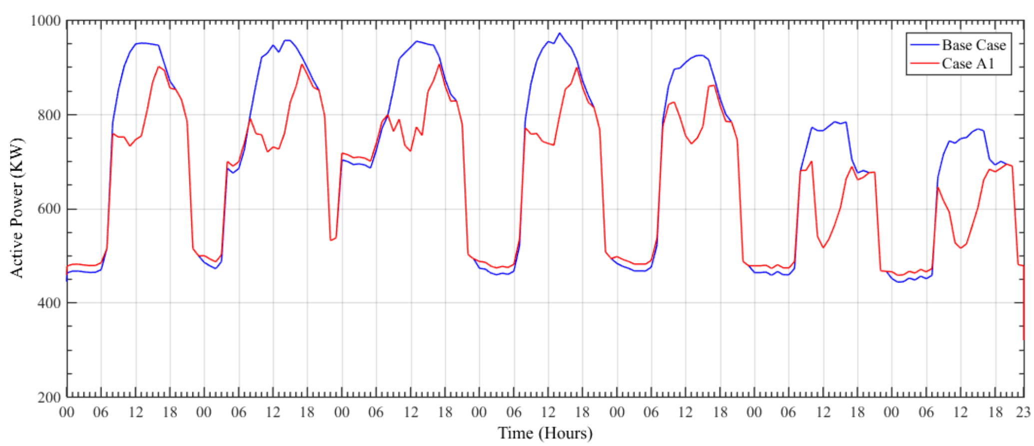

Figure 4.9 power drawn from the grid for base case and Case A1: typical week in winter

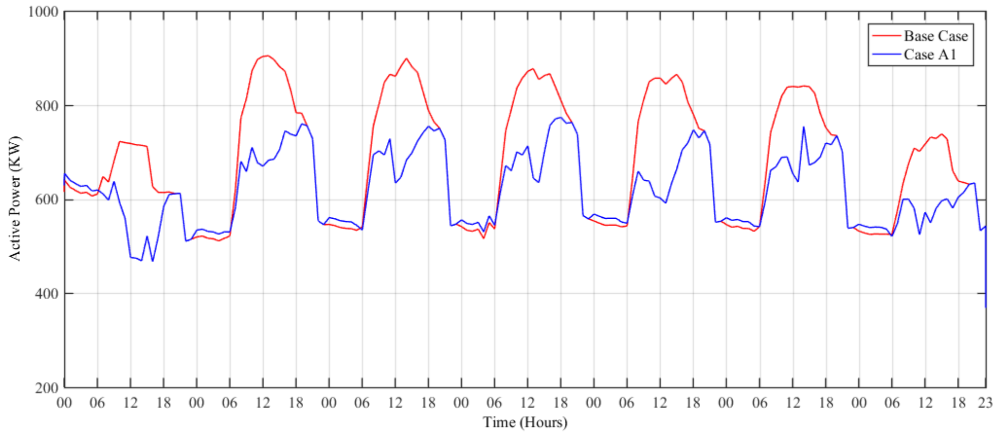

Figure 4.10 power drawn from the grid for base case and Case A1: typical week in summer

Power factor at bus 3 is changing between charging and discharging mode, during discharge mode where less active power is drawn from the grid power factor is dropping even more than the case with PV only to reach 0.7 in winter, and it is dropping to below 0.3 in summer, on the other hand, while charging the battery power factor is improving because more active power is being drawn from the grid.

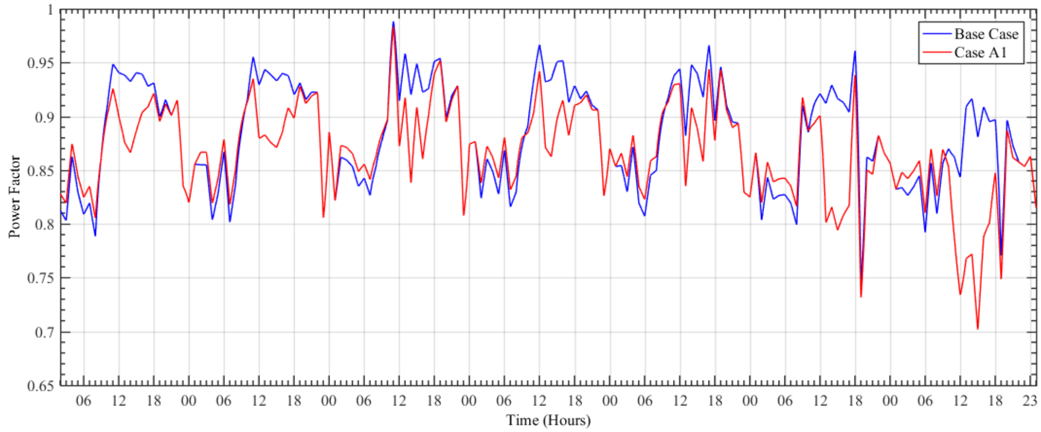

Figure 4.11 Power Factor at Bus 3: base case and Case A1 typical week in winter

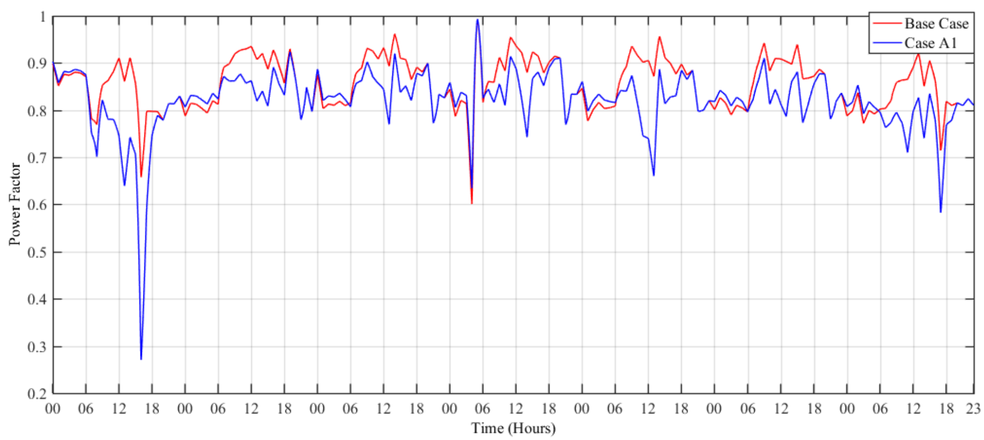

Figure 4.12 Power Factor at Bus 3: base case and Case A1 typical week in summer

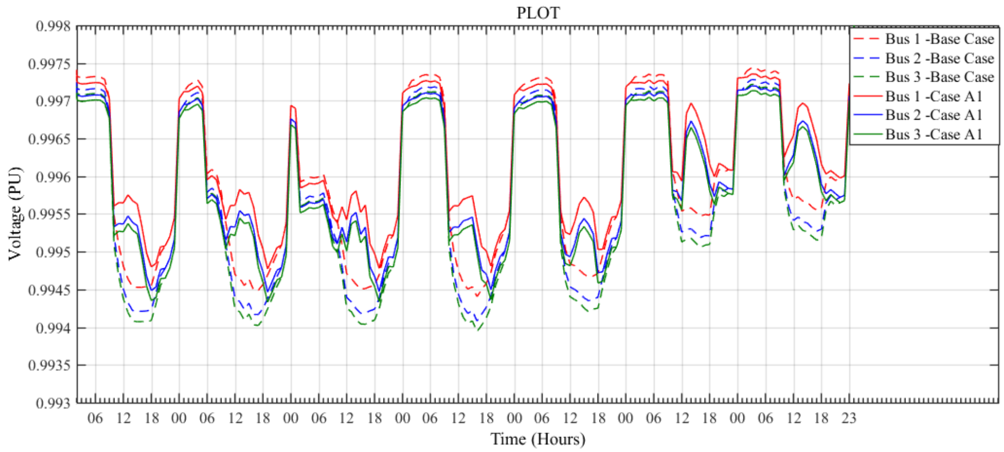

Figure 4.13 voltage profile: base case and Case A1 typical week in winter

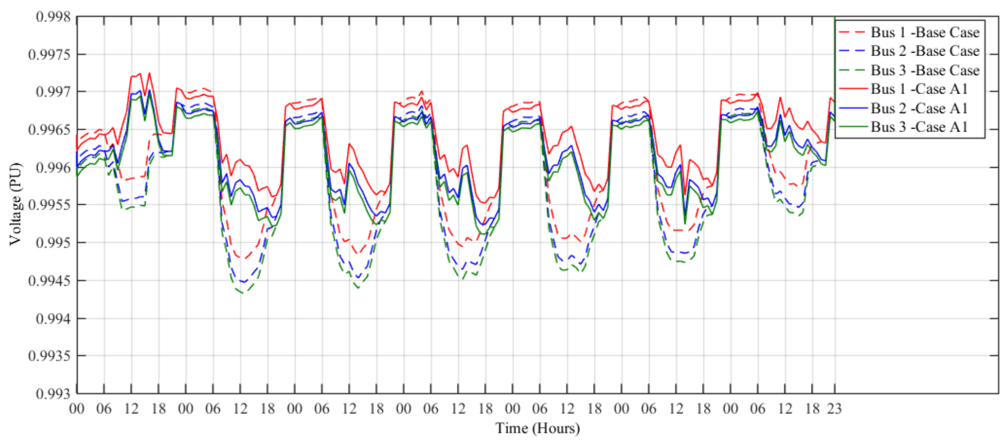

Figure 4.14 voltage profile: base case and Case A1 typical week in summer

Figure 4.23 and figure 4.24 show voltage profile for both seasons, while battery discharging voltage is increasing but still very small amount, and when the battery is charging slight drop in voltage is noticed, in overall putting ESS with did not affect voltage stability, as for current while discharging mod less current is being drawn from the grid but it is very small change, figures 4.25 and 4.26 illustrates current profile for winter and summer, while the battery is charging more current is drawn to feed the battery during off-peak hours.

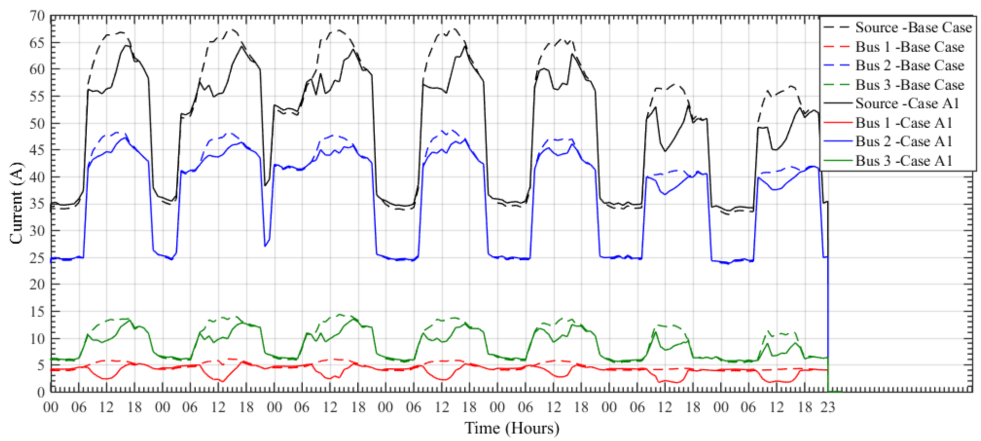

Figure 4.15 current profile: base case and Case A1 typical week in winter

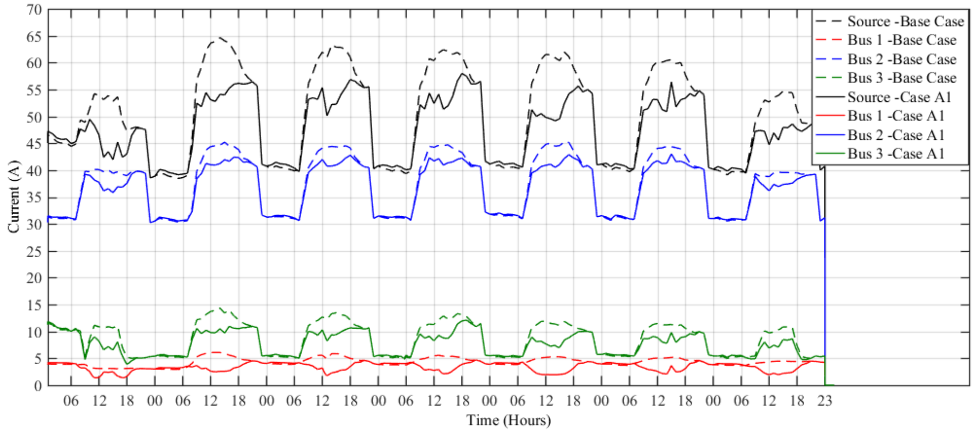

Figure 4.16 current profile: base case and Case A1 typical week in summer

4.5.2 Case A2 using ESS only

Figures 4.27 and 4.28 presents the case of using energy storage system without PV in winter, and summer it clear that very small active power amount has been shifted during peak hours,

Looking at power factor at bus 3 while the battery is charging the power factor is improved because more active power is going through, however, it is the opposite case when the battery is discharging even so because of the size of ESS the drop is not significant.

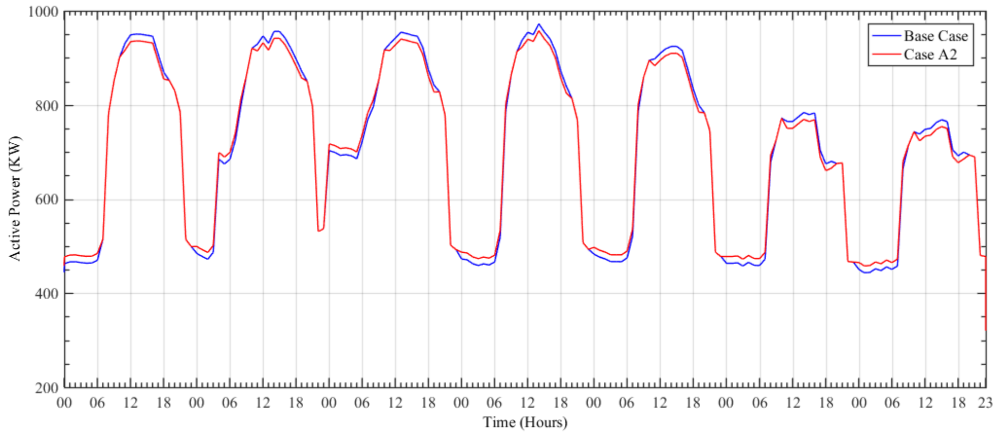

Figure 4.17 power drawn from the grid for base case and Case A2: typical week in winter

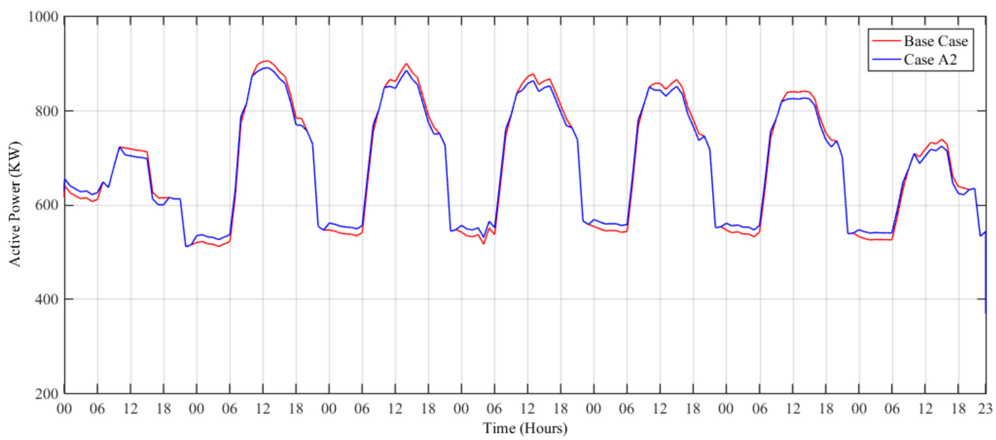

Figure 4.18 power drawn from the grid for base case and Case A2: typical week in summer

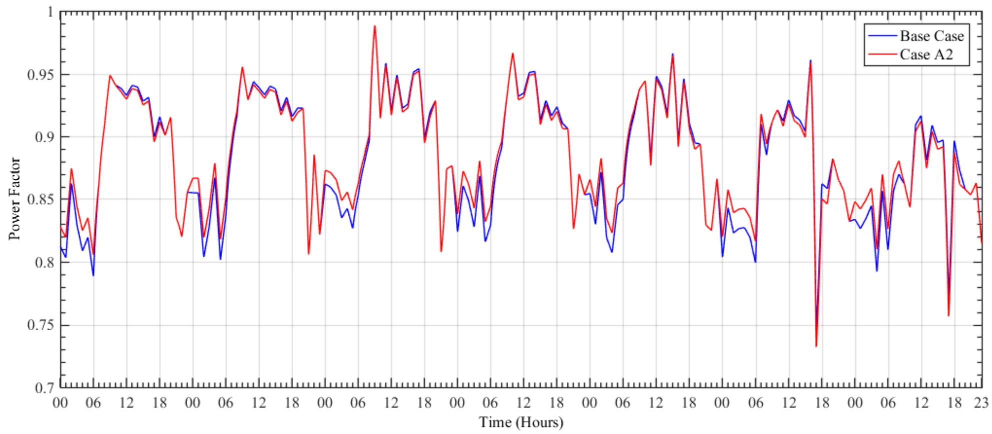

Figure 4.19 Power Factor at Bus 3: base case and Case A2 typical week in winter

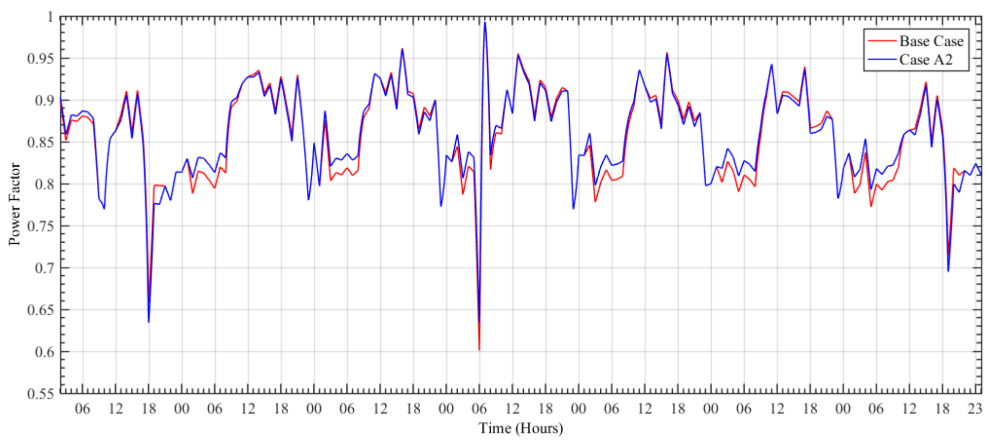

Figure 4.20 Power Factor at Bus 3: base case and Case A2 typical week in summer

Regarding voltage and current the results is shown in figures 4.31, 4.32, 4.33 and 4.34 respectively as the battery discharges voltage has increased by a very small amount, this increment is not affecting voltage stability, while it is the other way for the current, small decrease in current drawn from the source which goes for all buses this because the battery is releasing some of the demand locally.

When the battery is charging the voltage is decreased slightly, and the current is increased due more power is consumed from the grid.

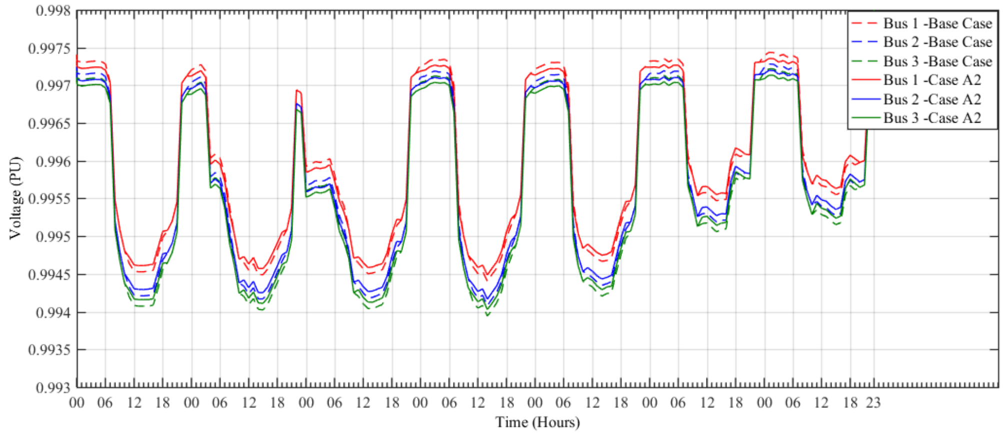

Figure 4.21 voltage profile: base case and Case A2 typical week in winter

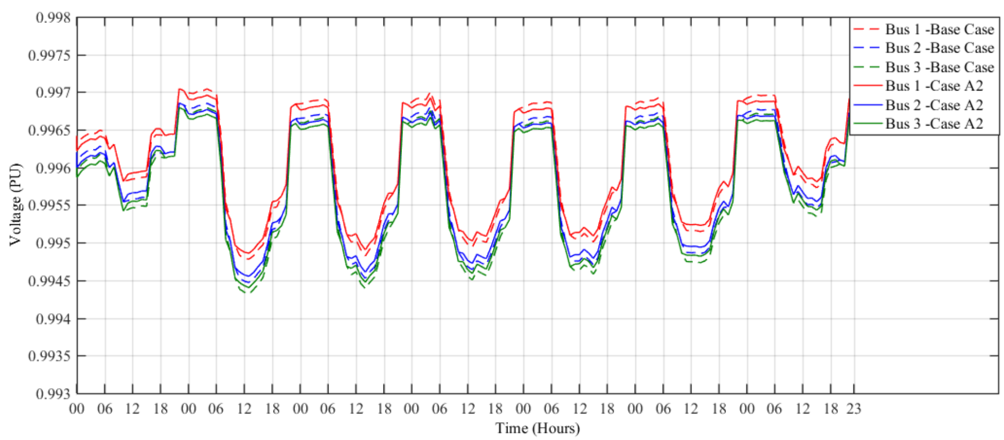

Figure 4.22 voltage profile: base case and Case A2 typical week in summer

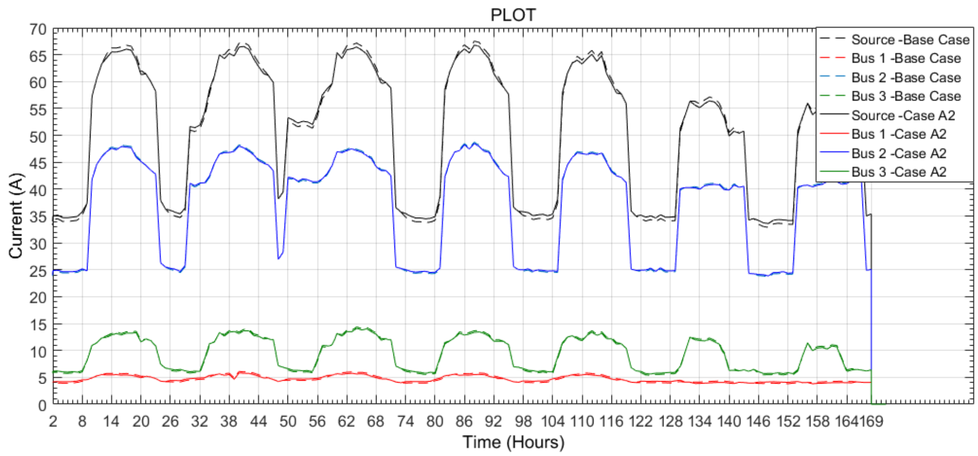

Figure 4.23 current profile: base case and Case A2 typical week in winter

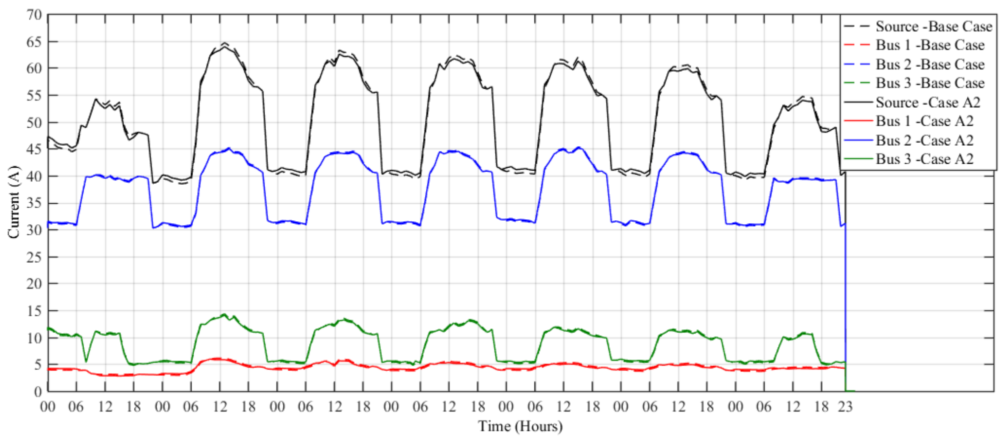

Figure 4.24 current profile: base case and Case A2 typical week in summer

Using 150 kWh ESS has helped with reducing active power consumption during peak hours, yet it is relatively very small compared to demand to produced satisfying results.

4.6 Case B 300 kWh ESS

Case A results have shown that going with relatively small battery size is not practical to do peak load shifting, there for using a bigger size, ESS is more practical solution to shift the peak load.

4.6.1 Case B1 using PV with ESS

in figures 4.35, and 4.36 shown the results of using 300 kWh ESS with PV on the power consumed from the grid during peak hours in winter and summer, for winter more power is shifted after sunset where there is no PV generation which helps reduce power consumed during peak hours, for summer case much better performance for ESS because there is PV generation where the consumed power from the grid is reduced in good amount.

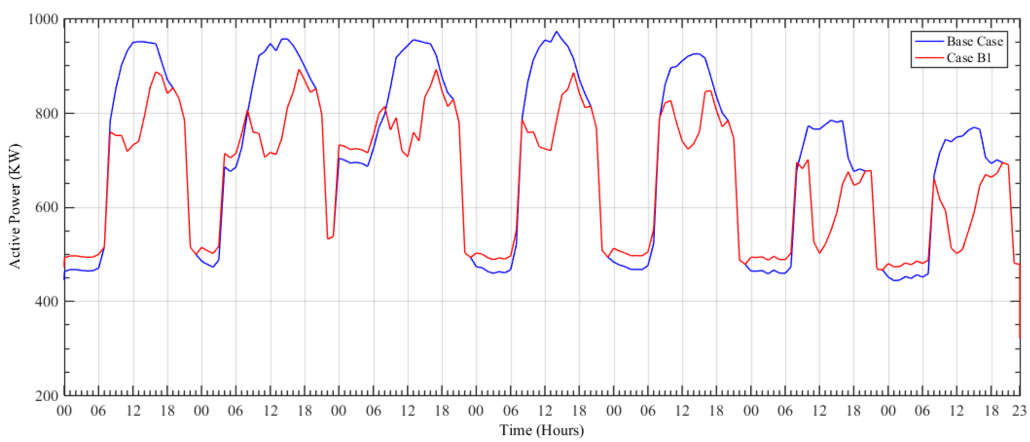

Figure 4.25 power drawn from the grid for base case and Case B1: typical week in winter

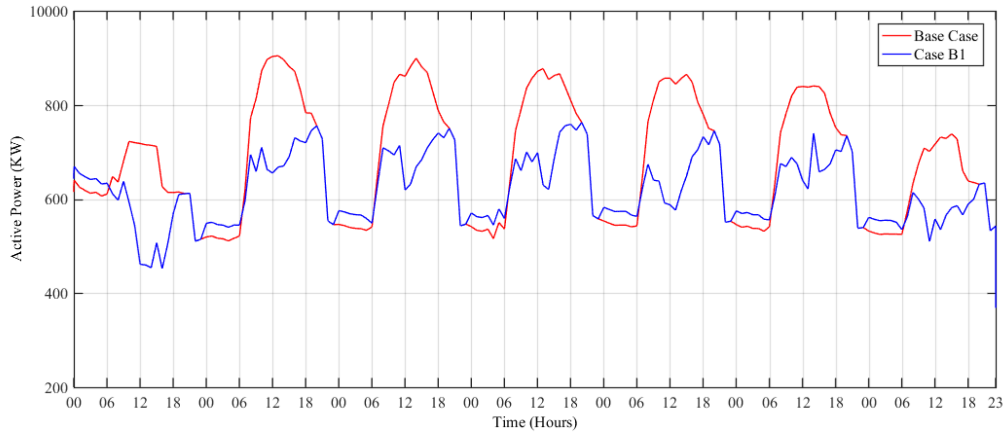

Figure 4.26 power drawn from the grid for base case and Case B1: typical week in summer

Although more power is being locally generated with bigger size ESS this has a negative effect on power factor especially on Sundays for both season where in the winter weekend it drops to below 0.7 in summer weekend it drops to reach 0.22, this due high PV generation and more power discharged from the ESS, never the less some improvement is achieved while the battery is charging during off-peak hours as shown in figures 4.37, and 4.38.

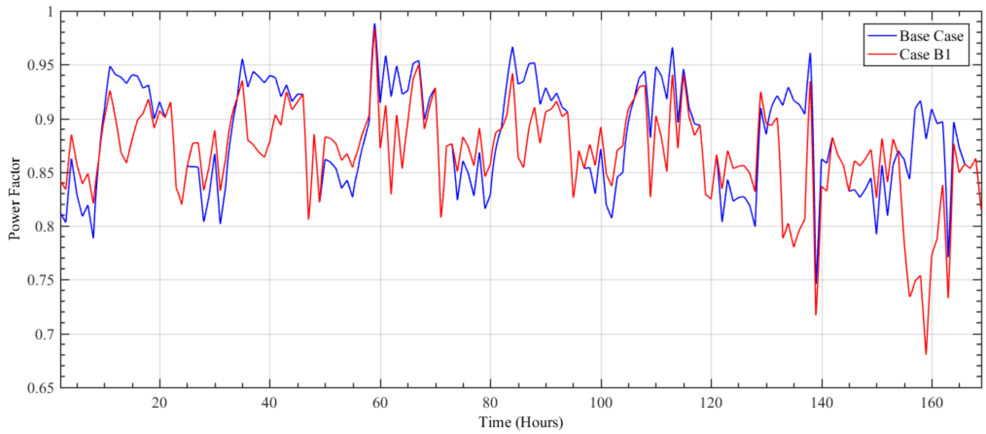

Figure 4.27 Power Factor at Bus 3: base case and Case B1 typical week in winter

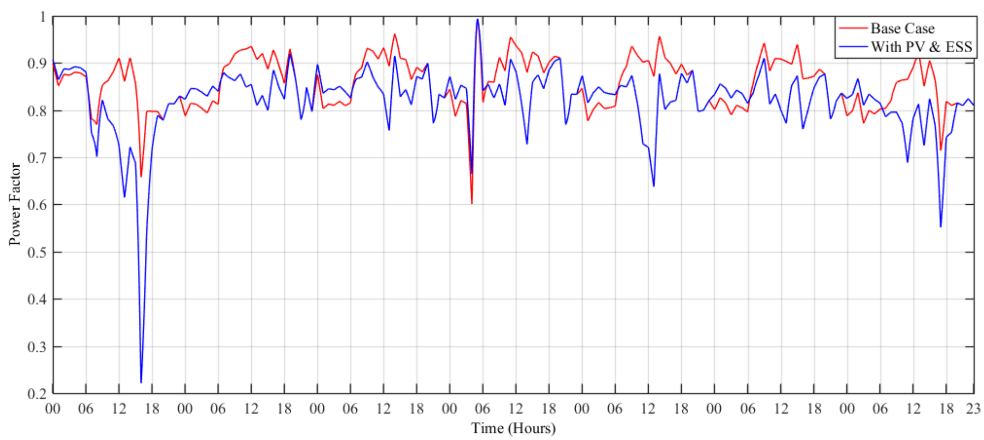

Figure 4.28 Power Factor at Bus 3: base case and Case B1 typical week in summer

As for voltage profile it generally stable with slightly rises but very limited and small for both season as it appears in figures 4.39, and 4.40 the voltage is increasing by very little amount while high PV generation and it is decreasing while the battery is charging, figures 4.41, and 4.42 show the current profile it is clear how bigger size ESS has effected the current drawn from the grid where it is decreasing during the discharge of the

ESS and also while there is PV generation this is faced by and increase in currents during charging time of the battery.

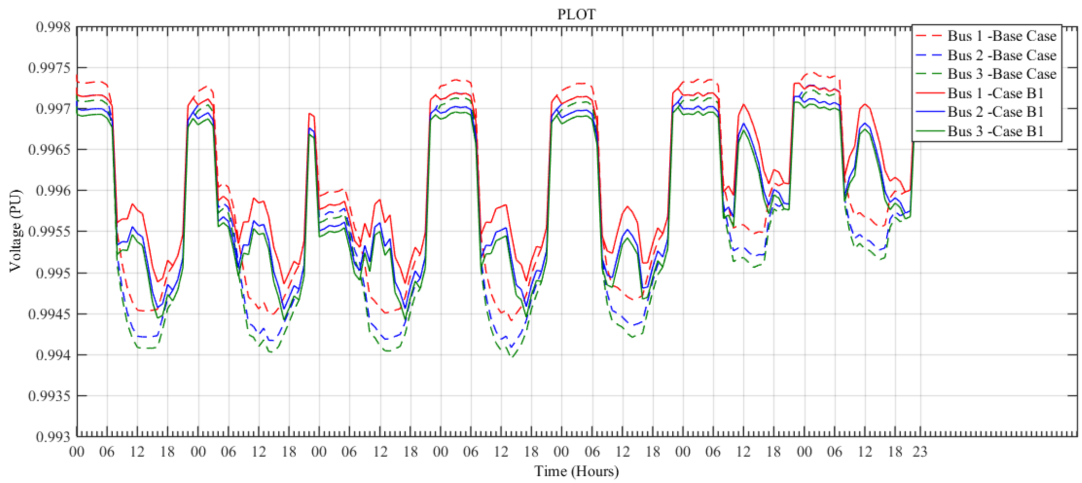

Figure 4.29 voltage profile: base case and Case B1 typical week in winter

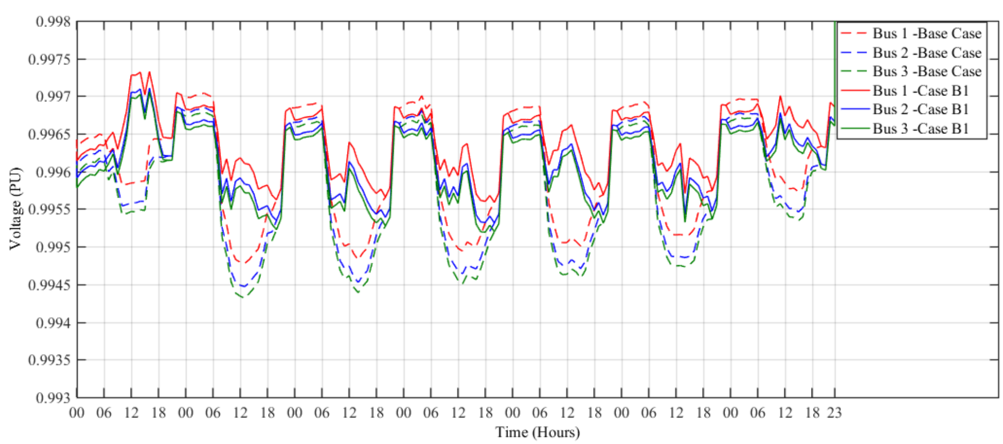

Figure 4.40 voltage profile: base case and Case B1 typical week in summer

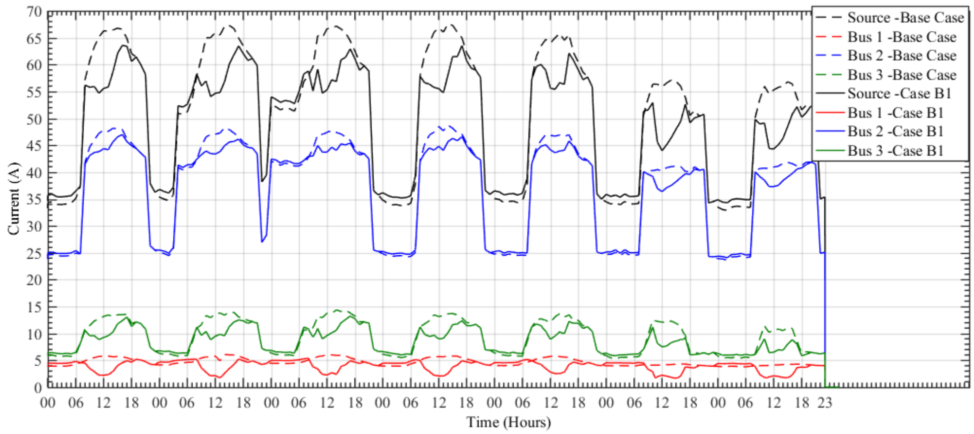

Figure 4.41 current profile: base case and Case B1 typical week in winter

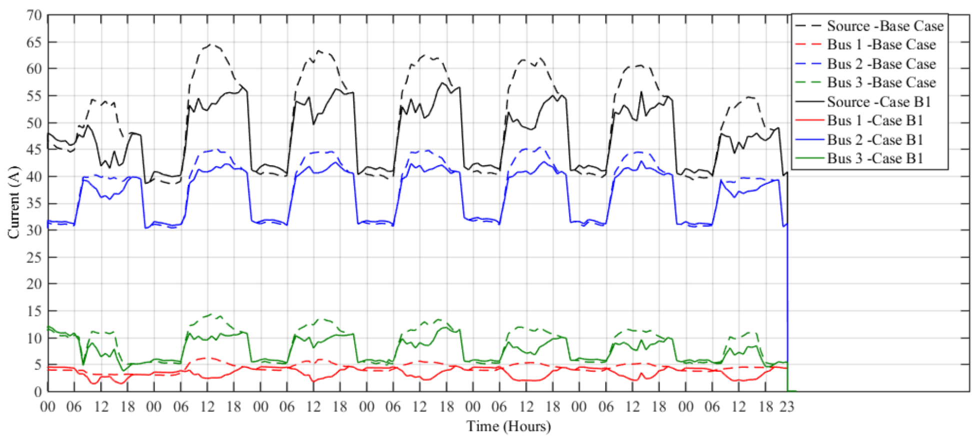

Figure 4.30 current profile: base case and Case B1 typical week in summer

4.6.2 Case B2 using ESS only

Next simulation of using only ESS in the system was conducted in order to get a better understanding how the ESS would effect the system, figure 4.43, and 4.44 show the power drawn from the grid for winter and summer cases while using only ESS, it is clear that using the bigger size of ESS has much better results the Case A, because there is extra 15 kWh of DC power to help with peak load shaving, while charring during off peak the battery starts to discharge at 11 AM and continue until 07 PM, it helped reduce power consumption for that period in a better way than Case A.

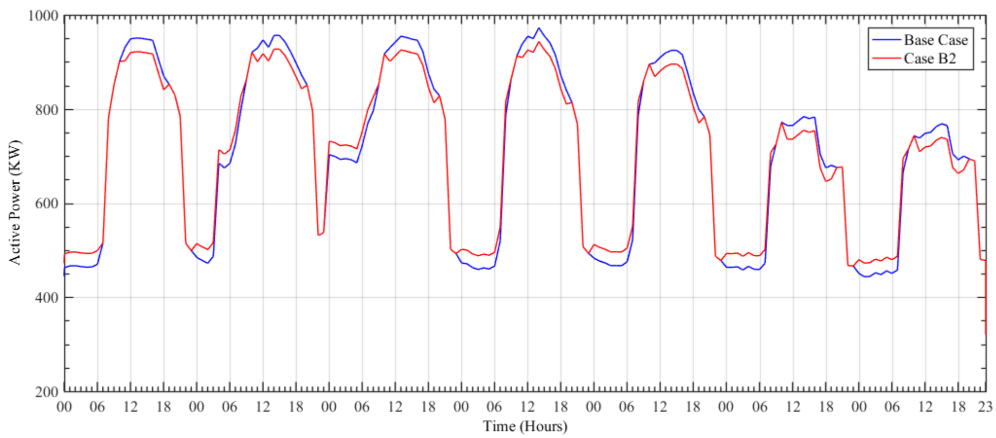

Figure 4.31 power drawn from the grid for base case and Case B2: typical week in winter

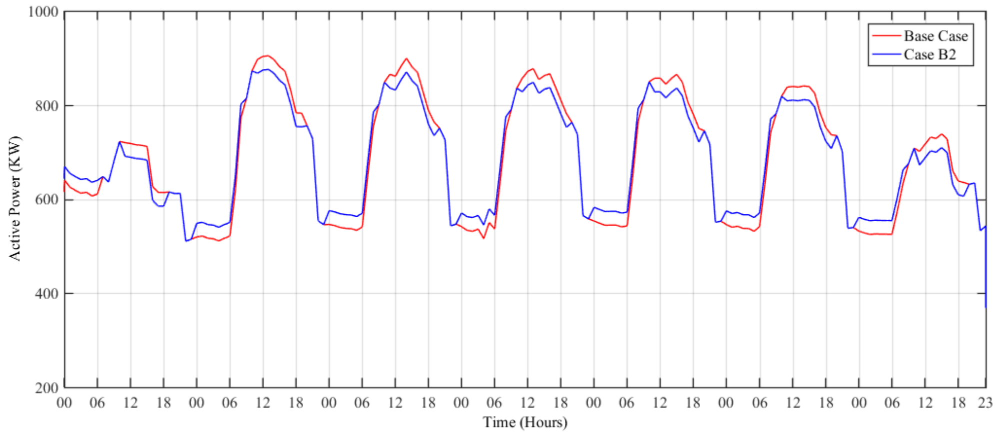

Figure 4.32 power drawn from the grid for base case and Case B2: typical week in summer

Figure 4.45, and 4.46 showing power factor at bus 3 for winter and summer some improvement is noticed at power factor while the battery is charging but it still has caused it to drop while discharging.

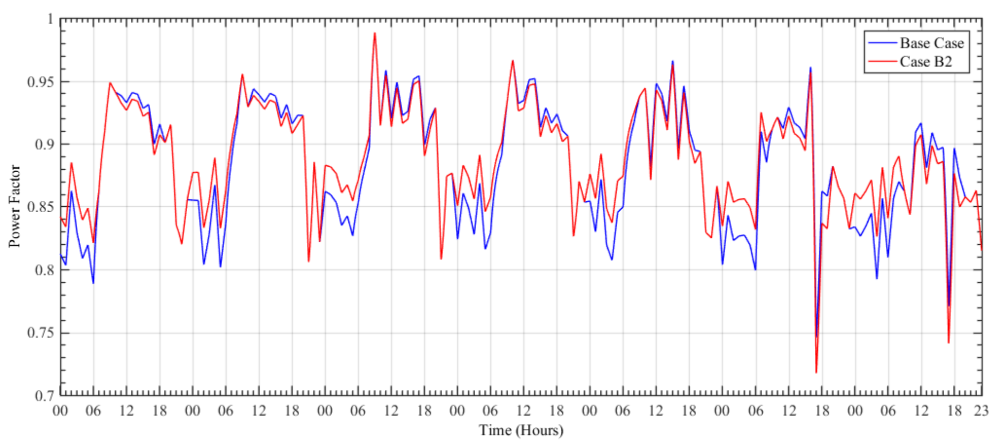

Figure 4.33 Power Factor at Bus 3: base case and Case B2 typical week in winter

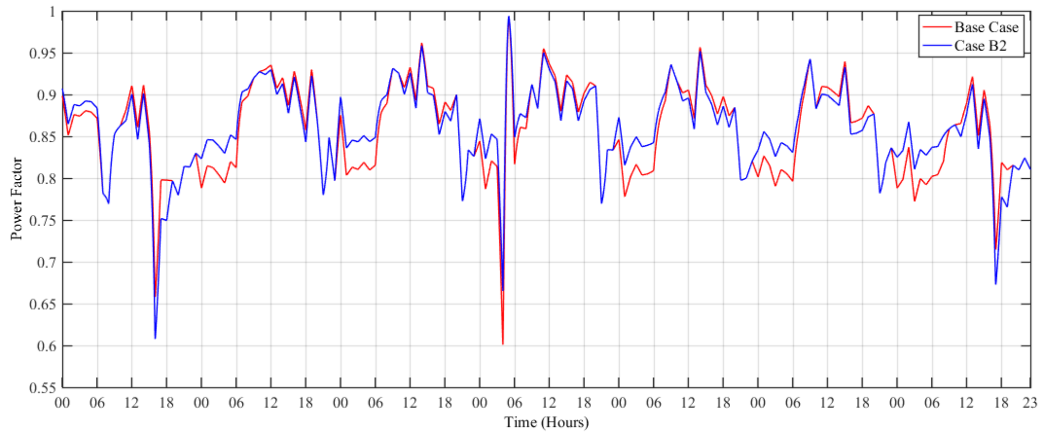

Figure 4.34 Power Factor at Bus 3: base case and Case B2 typical week in summer

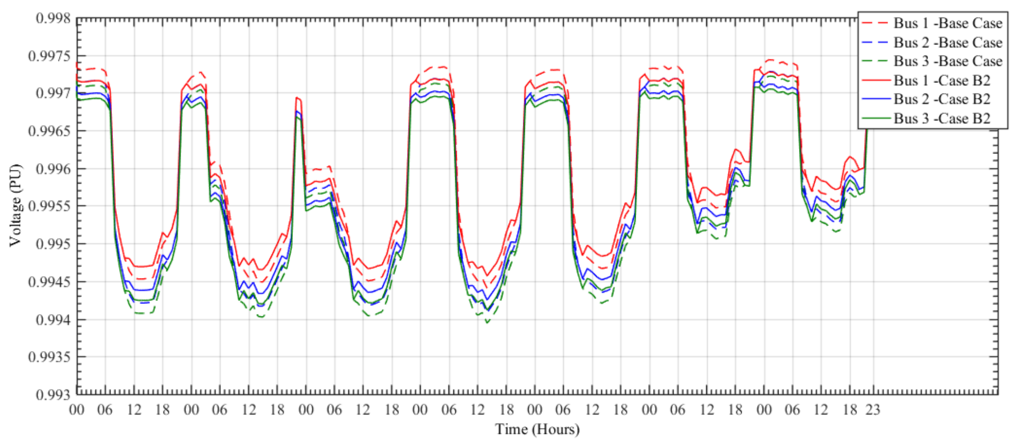

Figure 4.35 voltage profile: base case and Case B2 typical week in winter

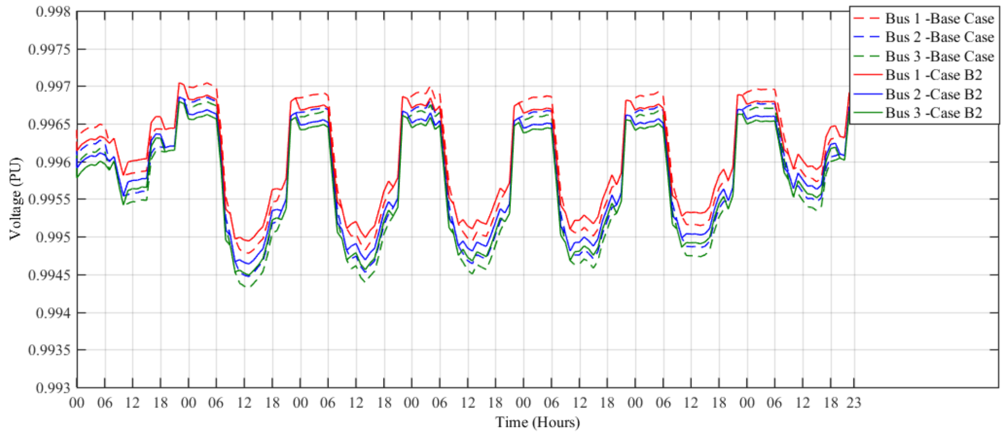

Figure 4.36 voltage profile: base case and Case B2 typical week in summer

Figure 4.47, and 4.48 show the voltage results for both seasons, discharging ESS has a very similar effect like PV it makes the voltage to increase but it is the very small amount, while charging the voltage drops a little bit than a normal case, although there is some effect on the voltage it barely changing, and it’s not considered as a disturbance to the system.

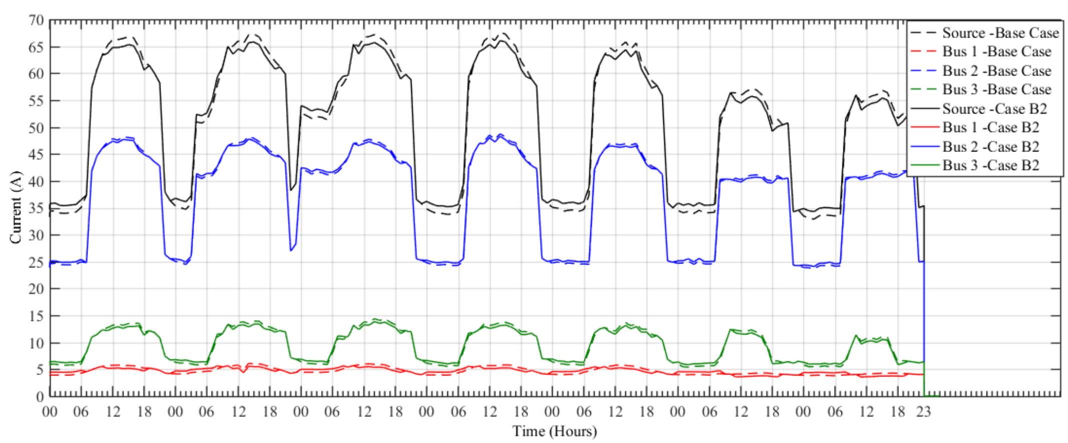

Figure 4.37 current profile: base case and Case B2 typical week in winter

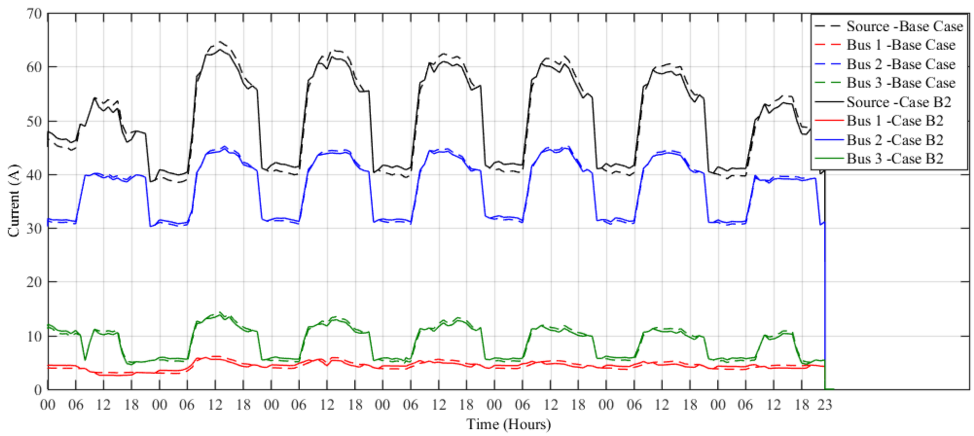

Figure 4.38 current profile: base case and Case B2 typical week in summer

Current profile is shown in figure 4.49, and 4.50 ESS has a different effect on current than the voltage it is the opposite so while the battery is charging the current goes up because more demand is required, and the currents drop down while discharging as less power is being drawn from the grid.

Generally, the results obtained from Case B, have shown much better results than Case A with more power is shifted from peak time to off-peak hours and no effects on voltage system stability yet still bigger size is required to get satisfying results.

4.7 Cass C 600 kWh ESS

Case B managed to reduce some the power drawn from the grid with higher power discharged from the battery along with PV generation, after reviewing the above-mentioned two cases to get good peak load shedding a larger size ESS is needed to handle this task.

4.7.1 Case C1 using PV with ESS

Figure 4.51, and 4.52 show power consumed from the grid with PV and ESS in winter and summer, by comparing it with the base case it is has shown very good result doing peak load shifting, during winter PV with ESS have produced enough power to reduce the peak load from 950 kW to almost 700 kW which very good power saving, also in summer with longer day even much power has been reduced from the grid.

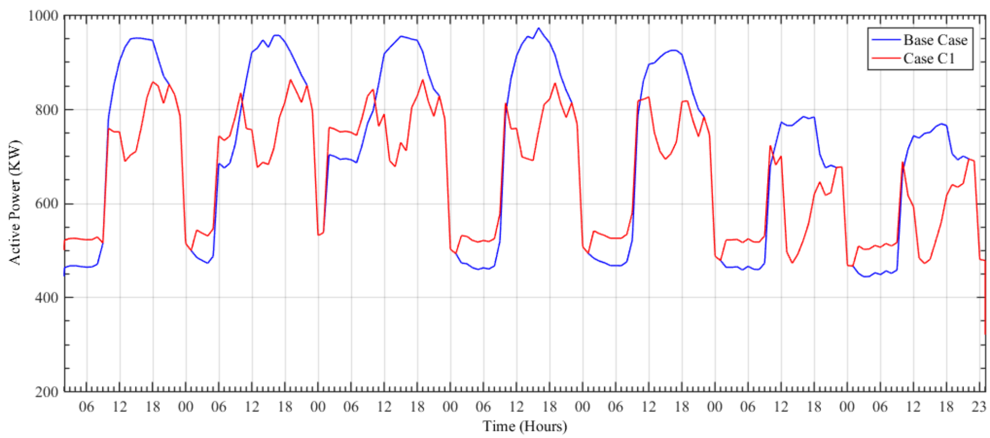

Figure 4.39 power drawn from the grid for base case and Case C1: typical week in winter

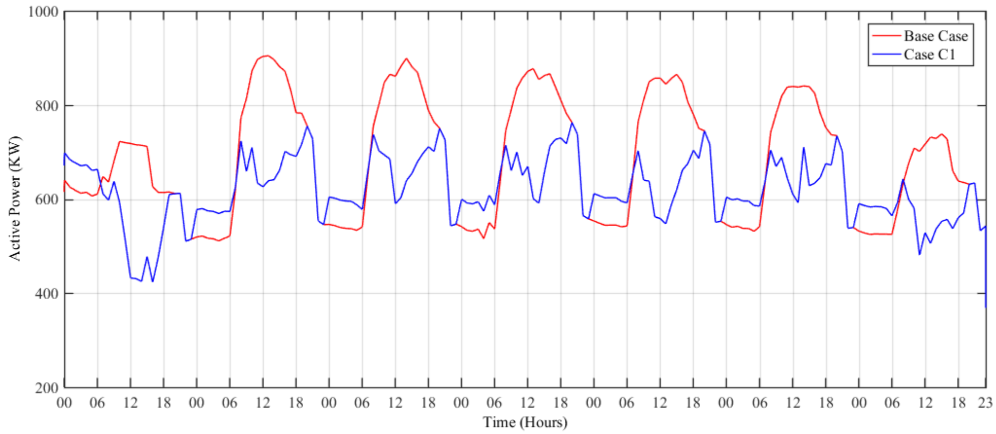

Figure 4.40 power drawn from the grid for base case and Case C1: typical week in summer

Figure 4.53, and 4.54 illustrate results of power factor at bus 3 in winter and summer, ESS has helped with reducing the amount of power consumed from the grid but it is still had impacted the power factor in a negative way because the battery is producing active power while discharging and the load is still drawing reactive power same as the original this led to drop in power factor, and it is even lower in the summer, on the other hand, while ESS is charging the power factor has improved during charging times because more active power is being drawn from the grid.

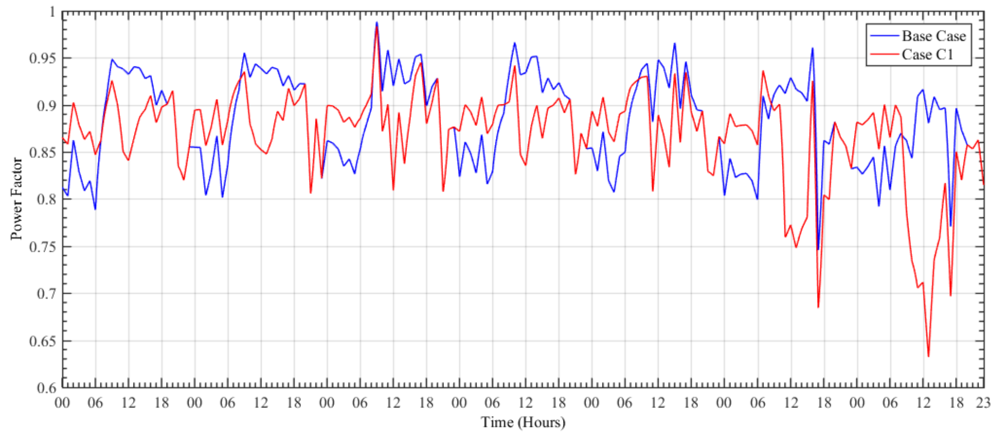

Figure 4.41 Power Factor at Bus 3: base case and Case C1 typical week in winter

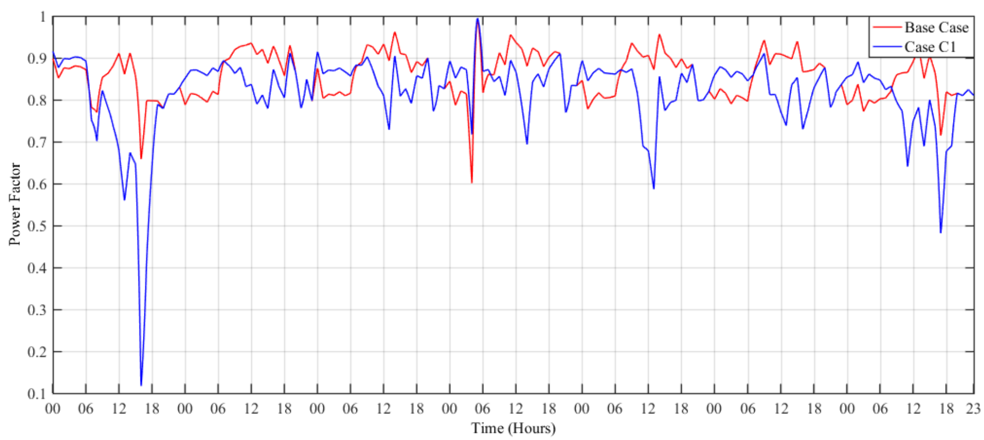

Figure 4.42 Power Factor at Bus 3: base case and Case C1 typical week in summer

Looking at figures 4.55, and 4.56 showing the voltage profile for both seasons voltage rises when battery charging, and it reaches its highest when PV generation is at maximum, but while the battery is charging the voltage is dropping down to its lowest, however, these changes are very small and it is not affecting the system at all.

Current profile is showing in figure 4.57, and 4.58 it is clear how the ESS effected the current drawn from the grid while discharging the current is decreasing as less power being transferred through the distribution line, and when the battery is charging the current is starting to increase because more power is being transferred to the load however it is still less than the peak value of the current during the original case.

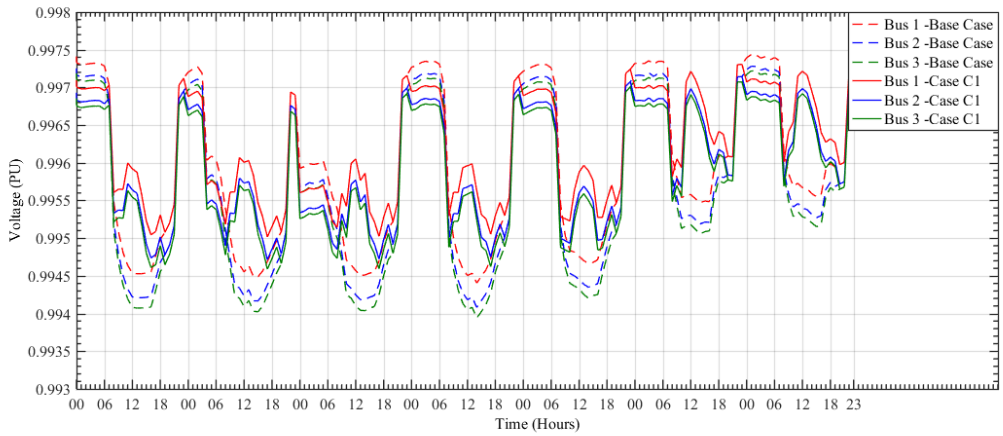

Figure 4.43 voltage profile: base case and Case C1 typical week in winter

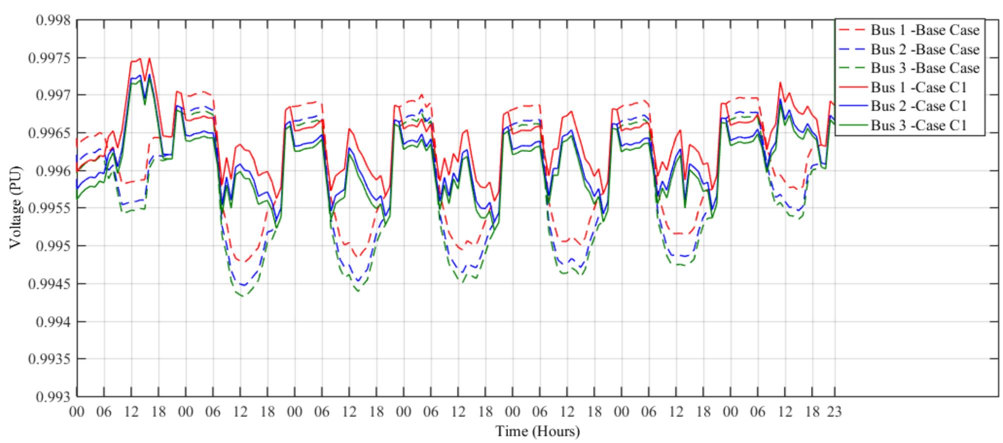

Figure 4.44 voltage profile: base case and Case C1 typical week in summer

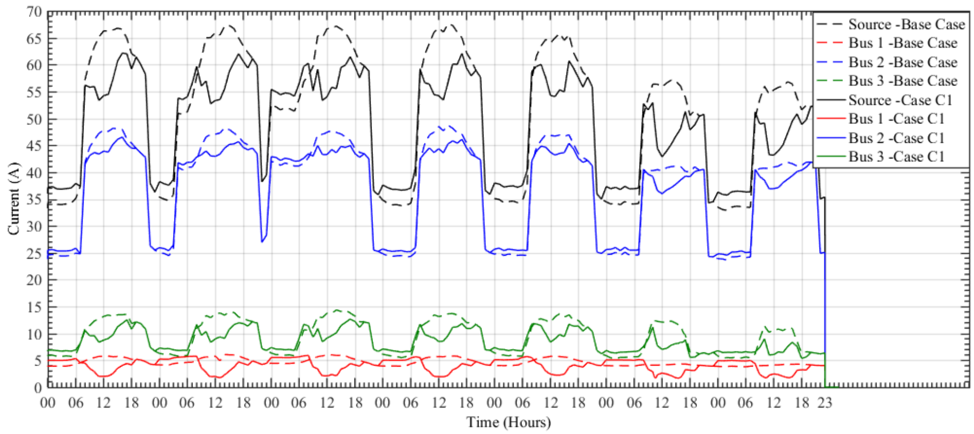

Figure 4.45 current profile: base case and Case C1 typical week in winter

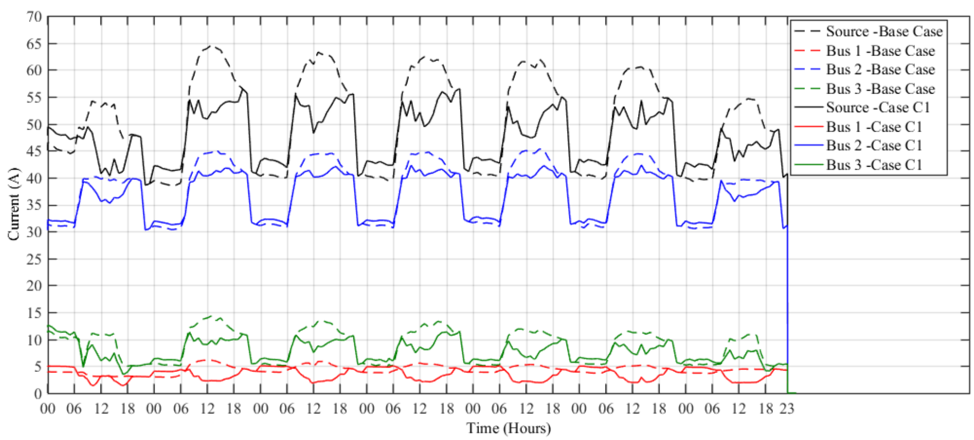

Figure 4.46 current profile: base case and Case C1 typical week in summer

4.7.2 Case C2 using ESS only

The simulation result of only using ESS with out PV is discussed in the following , With 200 kWh ESS alone to help do peak load shaving it has got very good results in doing so, figure 4.59, and figure 4.60 show the results obtained for typical winter and summer , by comparing this result with base case curve it is obvious how the curve is shifted from peak hours to off-peak hours for both seasons, with using ESS the peak load has dropped 50 kWh while the battery is discharging, and then start charging the battery during off peak times.

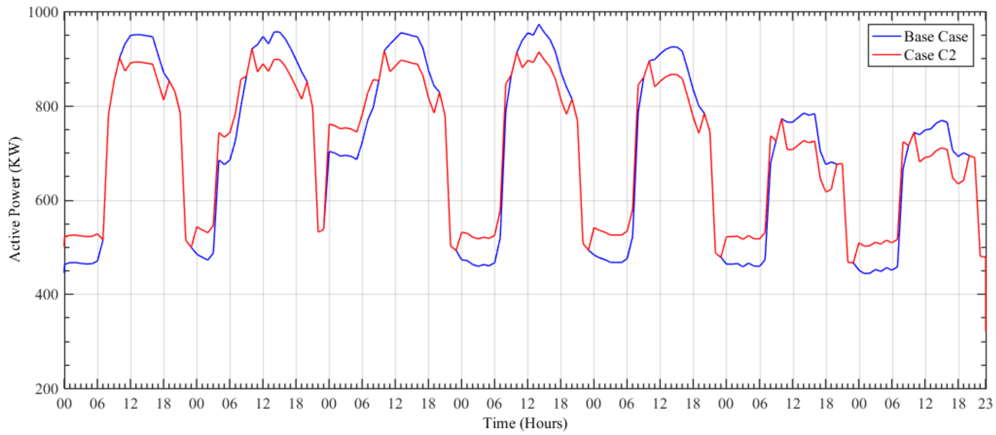

Figure 4.47 power drawn from the grid for base case and Case A2: typical week in winter

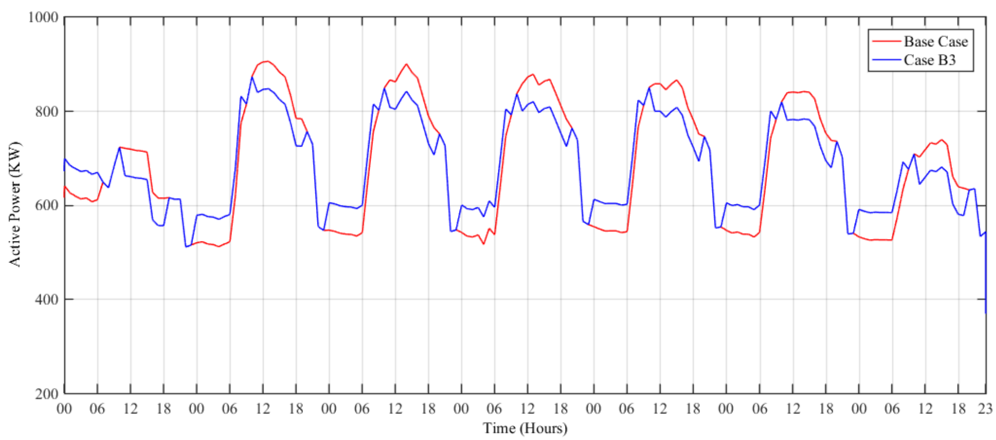

Figure 4.48 power drawn from the grid for base case VS ESS: typical week in summer

Power factor at bus 3 is changing in both way, while the battery is discharging it is dropping down, for instance, its lowest is 0.68 in winter weekend, but in the summer weekend it even lower, in the other hand while the battery is charging the power factor goes up and improves compared to base case this because more active power is being drawn from the grid as shown in figures 4.61, and 4.62.

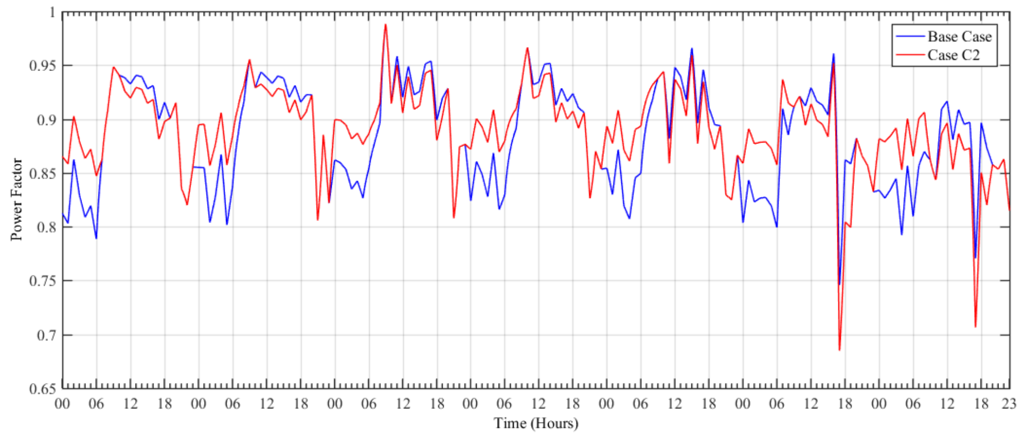

Figure 4.49 Power Factor at Bus 3: base case and Case C2 typical week in winter

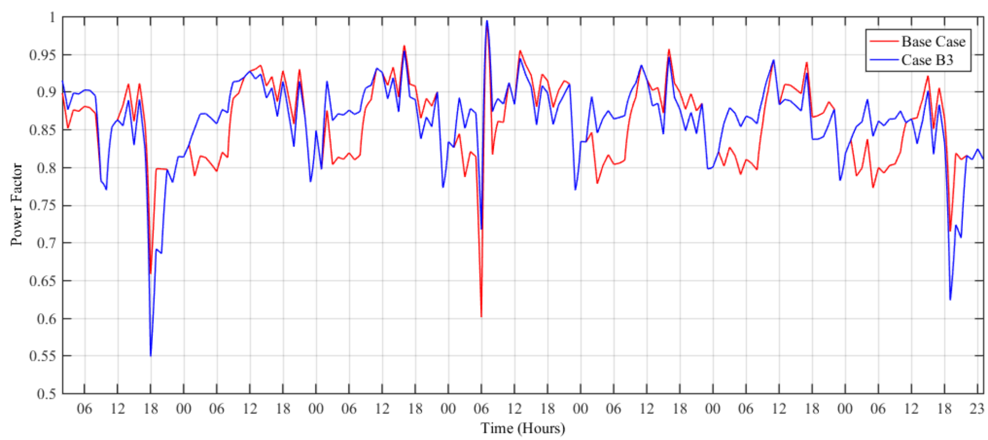

Figure 4.50 Power Factor at Bus 3: base case and Case C2 typical week in winter

Voltage also is changing based on battery charging mode, so while charging voltage is decreasing with more power going to the feed the loads and the battery, but when the battery is discharging the voltage is increasing as less power is drawn from the grid, anyhow those changes in voltage are very insignificant and not affecting the system.

Current profile showing figure 4.65, and figure 4.66 illustrate the current behavior while changing in between charging and discharging so while charging battery higher current goes through the diminution line, the opposite is happening when the battery is discharging less current is going through.

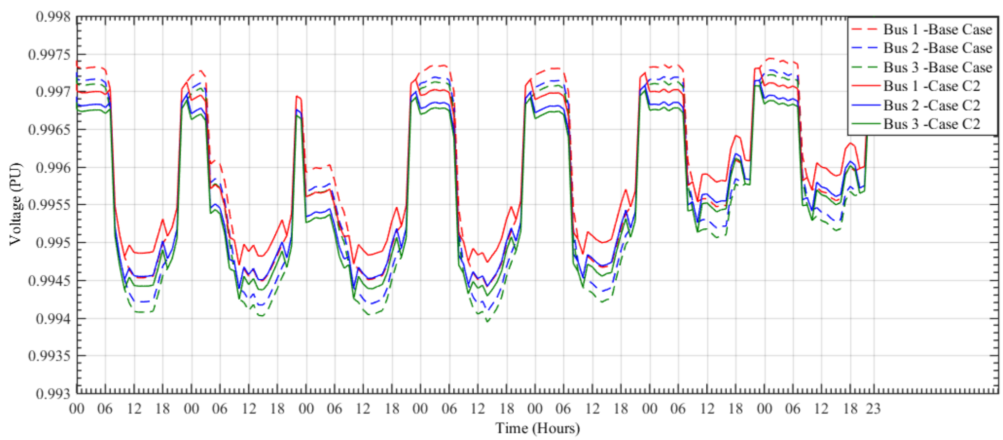

Figure 4.51 voltage profile: base case and Case C2 typical week in winter

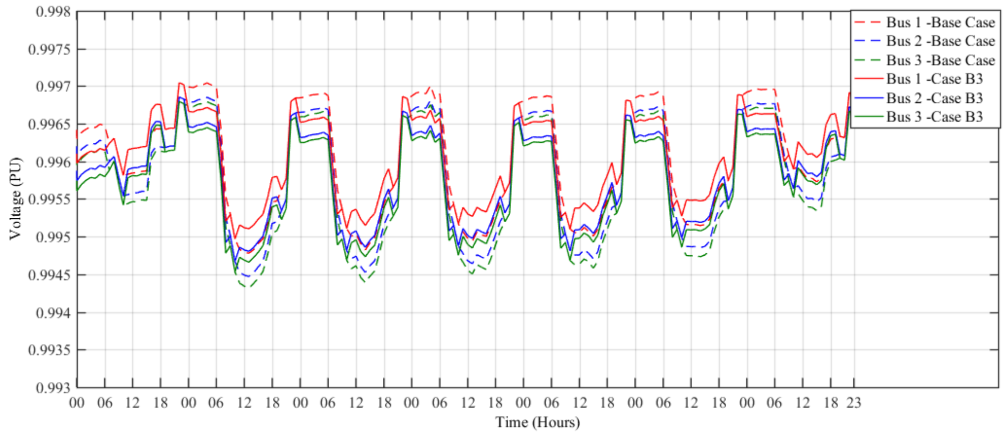

Figure 4.52 voltage profile: base case and Case C2 typical week in summer

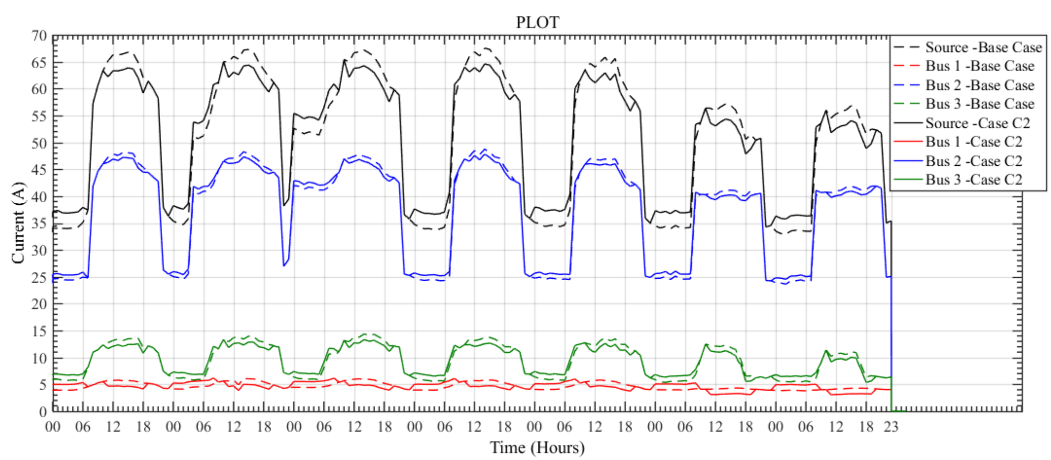

Figure 4.53 current profile: base case and Case C2 typical week in winter

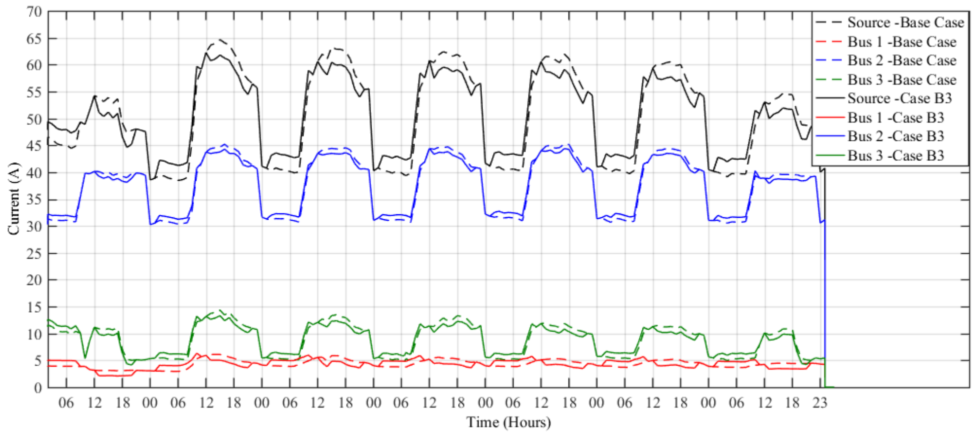

Figure 4.54 current profile: base case and Case C2 typical week in summer

4.8 Case D 1050 kWh ESS

All previous three cases were done to get a good understanding of how different sizes of ESS would impact the peak load. It is obvious that for all the three cases little or insignificant impact has been achieved when using the ESS alone. While the PV system did a good job reducing power consumption the size of the ESS was not good enough to keep up reducing the peak load when the sun is down.

In the following illustration and comments on the simulation results of using the proposed size of the total ESS is 1050 kWh.

4.8.1 Case D1 using PV with ESS

In this case simulation results of operating PV with ESS to reduce power consumption between 08 AM and 09 PM. Figures 4.66 and 4.67 shows the active power curve for both winter and summer. in winter PV has limited time to generate power because of the short day, therefore the ESS is set to start discharging at 02 PM until 09 PM to mitigate the short-day issue.

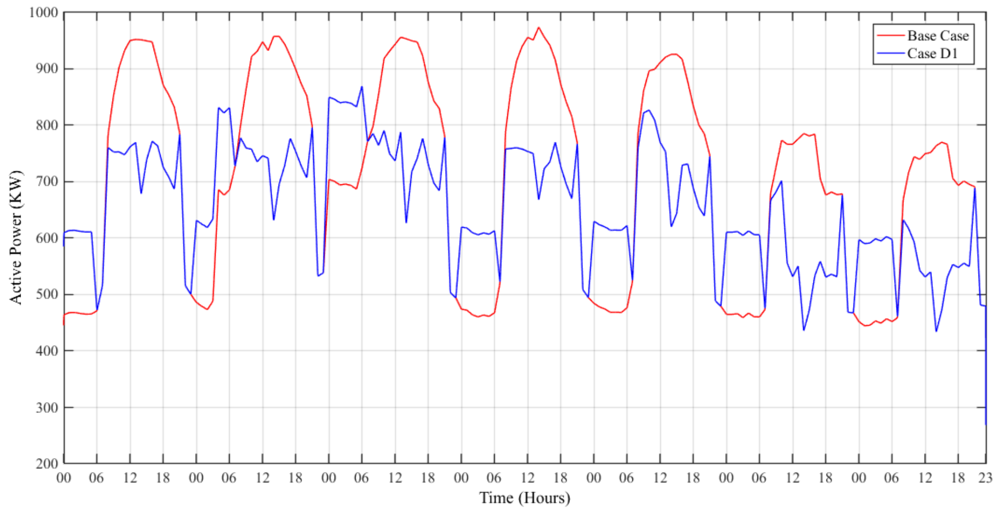

Figure 4.55 power drawn from the grid for base case and Case D1: typical week in winter

However, in the summer even with the long day, the PV production is not enough, so the ESS is helping with peak load shaving with the same schedule as in winter case.

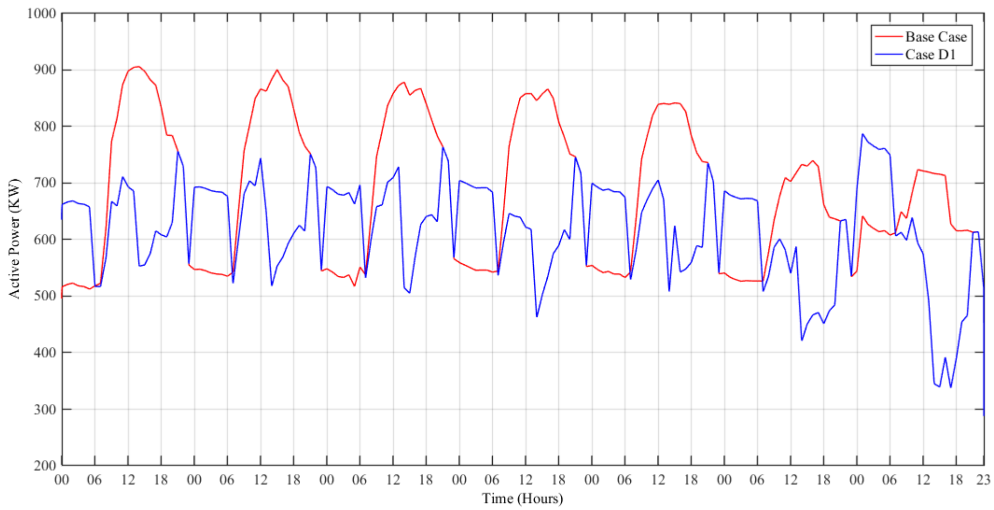

Figure 4.56 Power Factor at Bus 3: base case and Case D1 typical week in summer

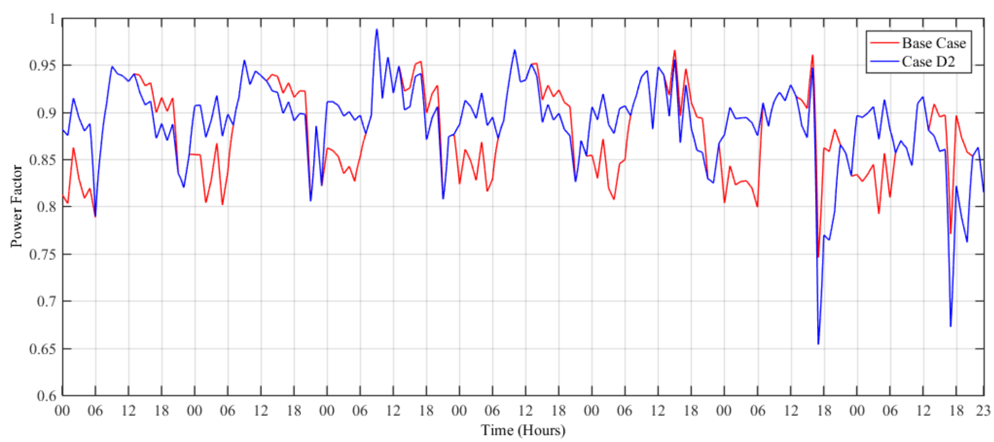

Figure 4. 57 Power Factor at Bus 3: base case and Case D1 typical week in winter

Power factor results are shown in figure 4.68 for winter and in figure 4.69 for summer. In winter with higher active power has been discharged from the ESS less active power is drawn at the same time this cause the power factor to drop to worse value. However, the power factor is improving during charging periods which is due to more active power has been drawn and no change to the reactive power values. On the other hand, the summer results have shown that ESS has more impact on power factor causing it to drop during discharging time although it is improving when ESS is charging.

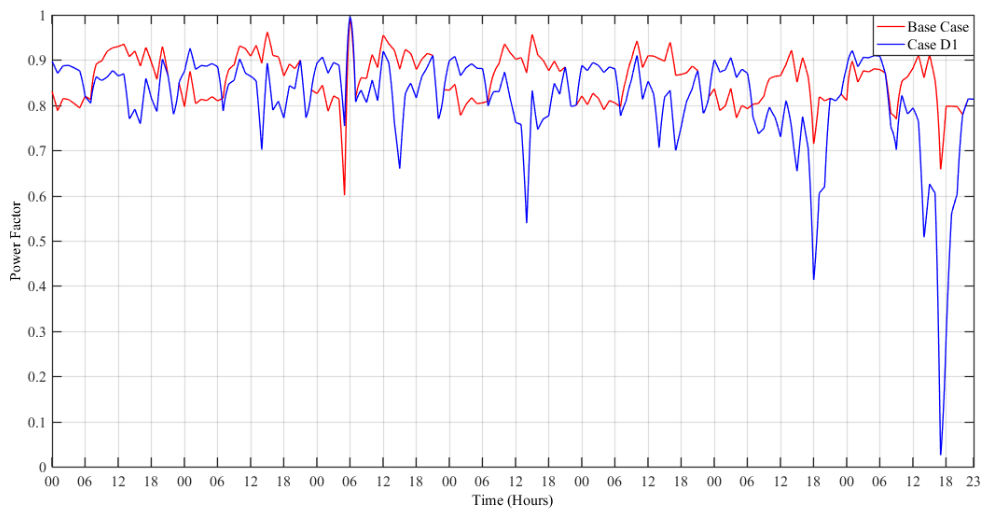

Figure 4.58 Power Factor at Bus 3: base case and Case D1 typical week in summer

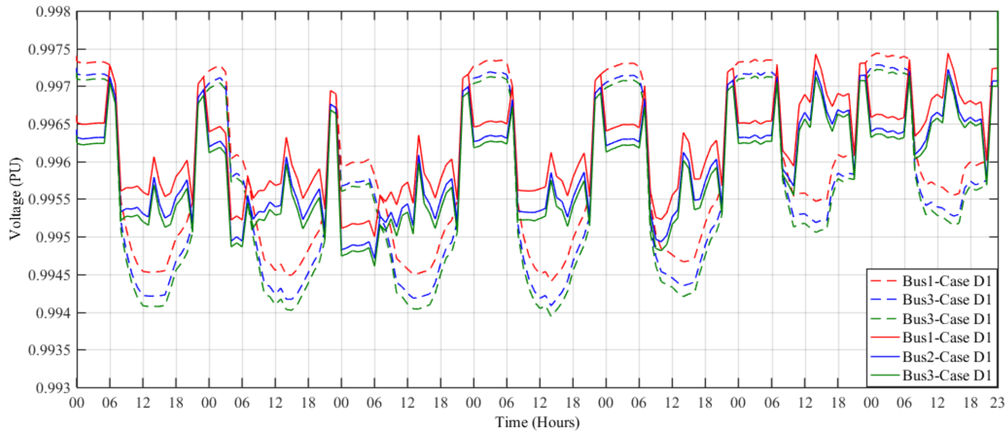

Figure 4. 59 voltage profile: base case and Case D1 typical week in winter

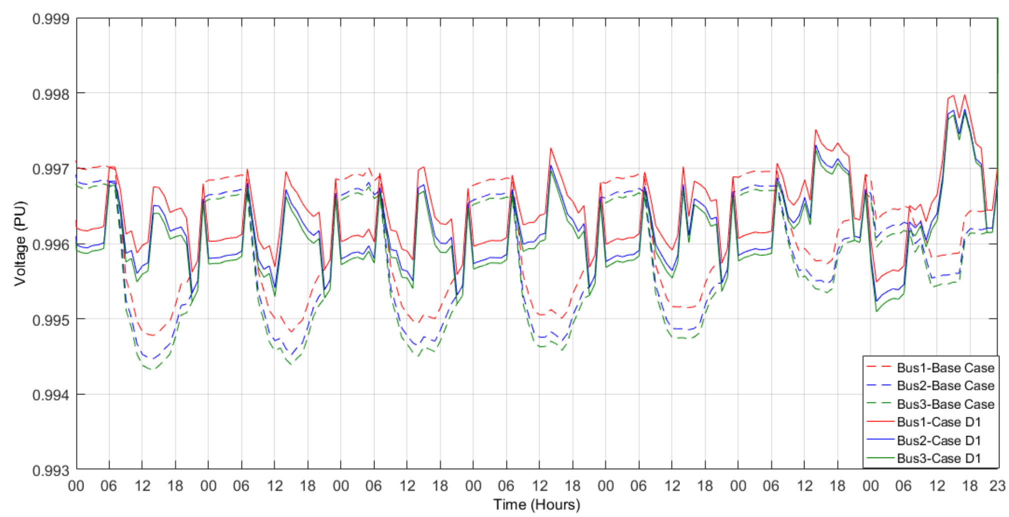

Figure 4.60 voltage profile: base case and Case D1 typical week in summer

Although bigger size ESS is used in Case D this means more power is being injected locally, but it did not affect the voltage profile stability for both seasons.

A significant drop in current drawn from the grid is noticed as shown in figures 4.72 and 4.73 shows that ESS is keeping the current level at the same level when the PV is working alone.

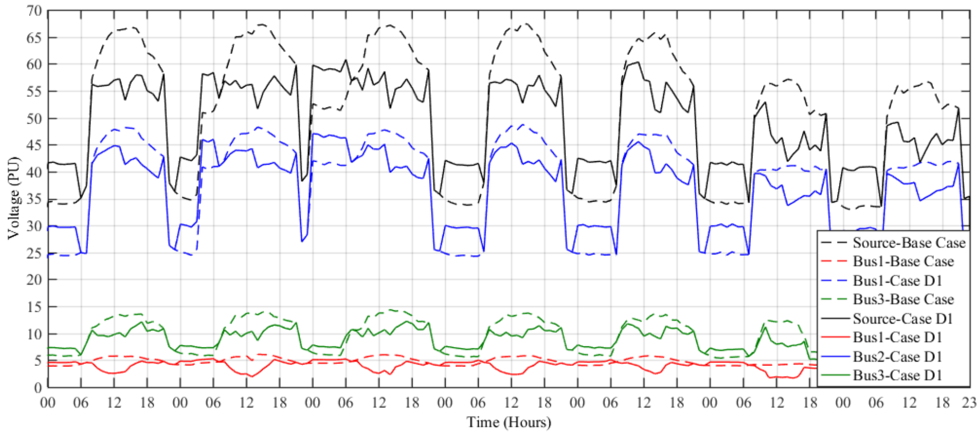

Figure 4.61 current profile: base case and Case D1 typical week in winter

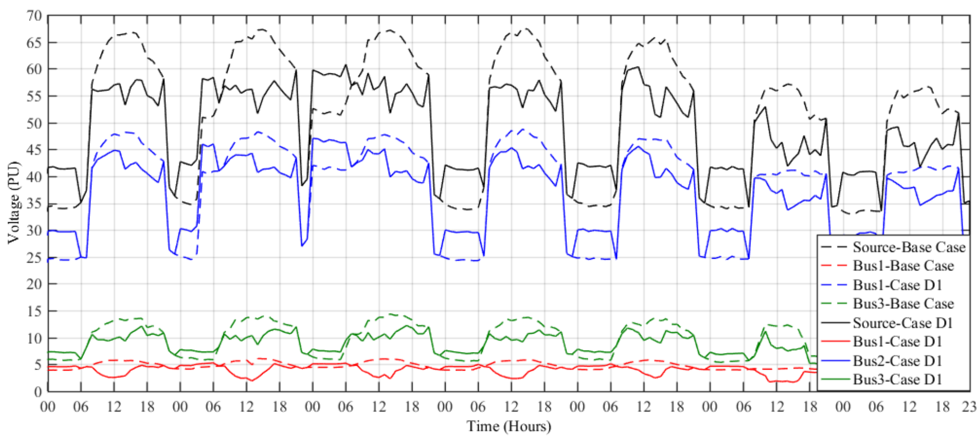

Figure 4.62 current profile: base case and Case D1 typical week in summer

4.8.2 Case D2 using ESS only

ESS, in this case, is operated by itself with the same schedule as Case D1 to do peak load shading. Look at figure 4.74 and figure 4.75 showing the demand curves for winter and summer ESS manages some of the peak load only which is due to its long peak hours, nevertheless, ESS has shown a good reduction in peak load even though in part only.

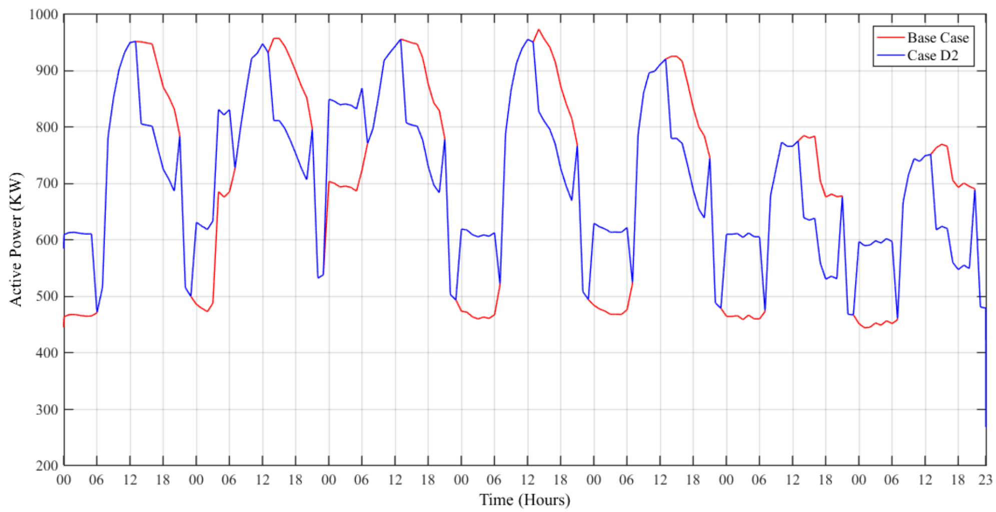

Figure 4.63 power drawn from the grid for base case and Case D2: typical week in winter

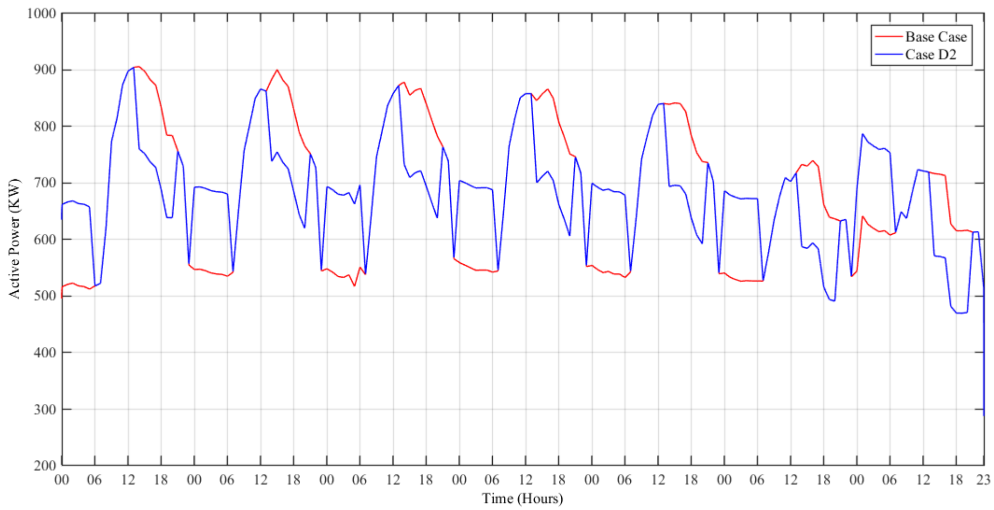

Figure 4.64 power drawn from the grid for base case and Case D2: typical week in summer

Decreasing in power factor occurred while the battery is discharging as it is shown in figure 4.76 and figure 4.77. the power factor drops to reach 0.65 in winter and reaches 0.5 in the summer. However, improvement in power factor is achieved when the battery is charging because more active power is drawn.

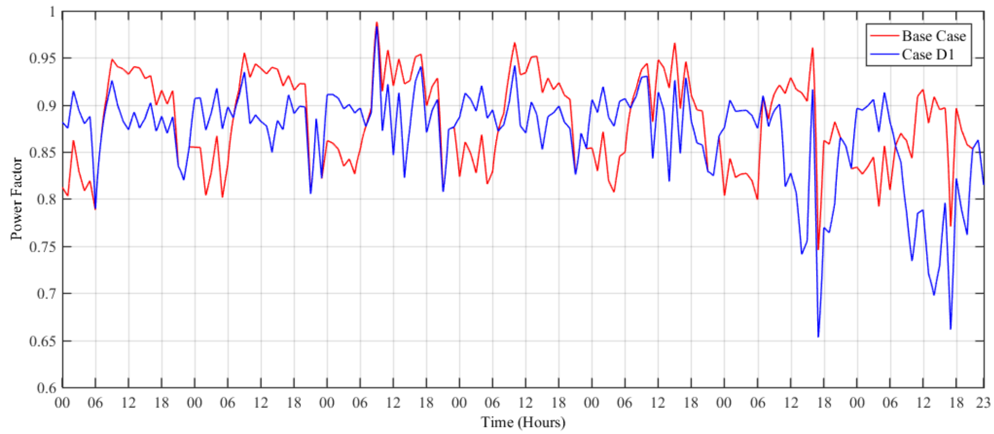

Figure 4.65 Power Factor at Bus 3: base case and Case D2 typical week in winter

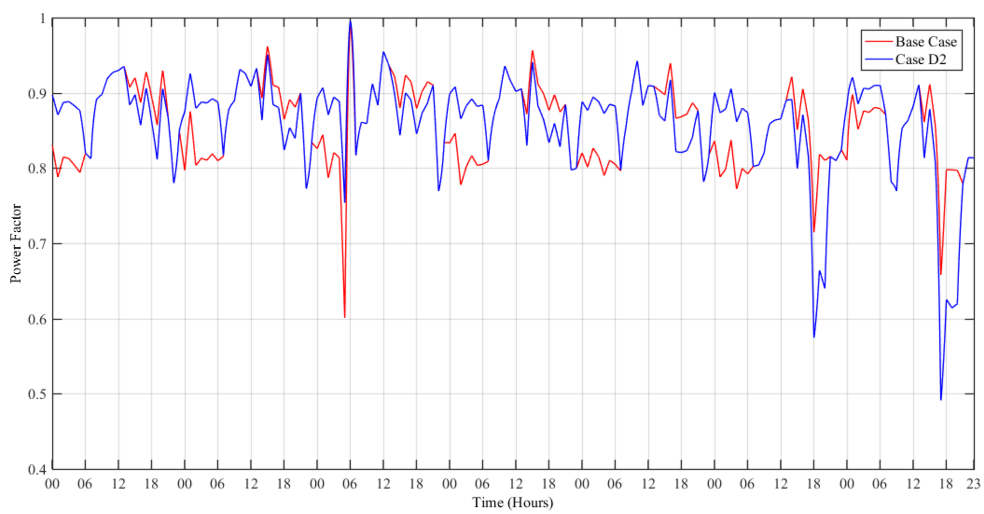

Figure 4.66 Power Factor at Bus 3: base case and Case D2 typical week in winter

Reviewing figures 4.78 and 7.79 which presents voltage profile it is clear that voltages did not change in a significant way. Some voltage rise is noticed when the battery is discharging which is due less active power being drawn from the grid, on the other hand, small voltage drops when the battery is charging that is related to more active power being drawn from the grid.

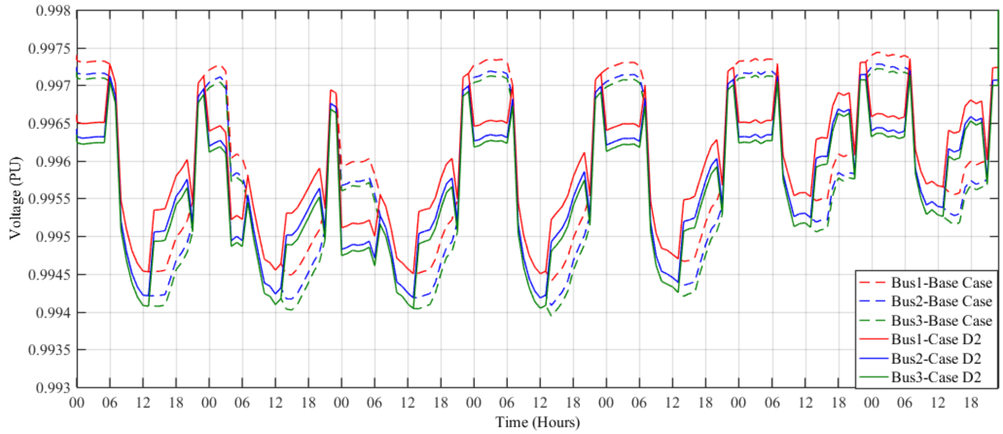

Figure 4.67 voltage profile: base case and Case D2 typical week in winter

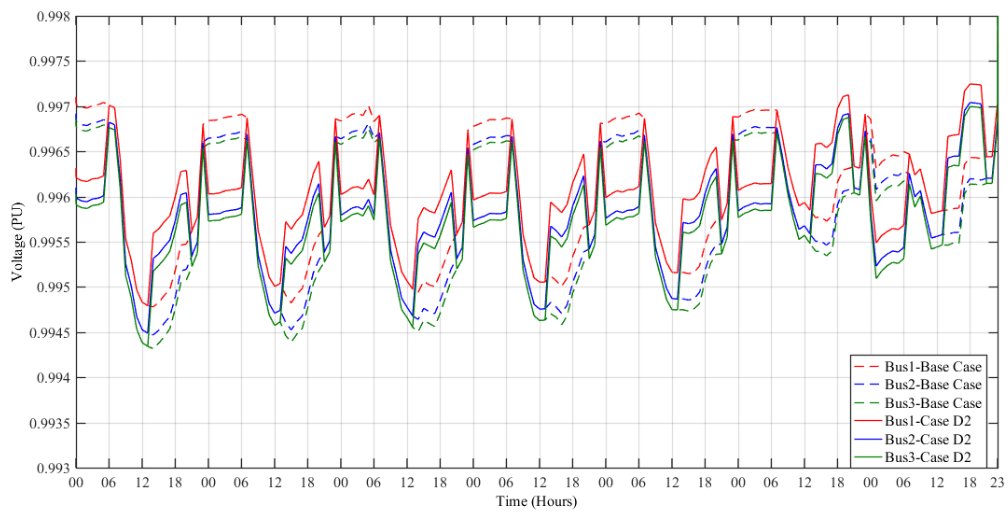

Figure 4.68 voltage profile: base case and Case D2 typical week in summer

ESS discharging has helped reduce current drawn from the grid relieving some of the peak currents load on the distribution line. On the other hand, current gains higher value when the battery is charging, but it does not reach peak value because charging process is done during the off-peak time as shown figures 4.80 and 4.81.

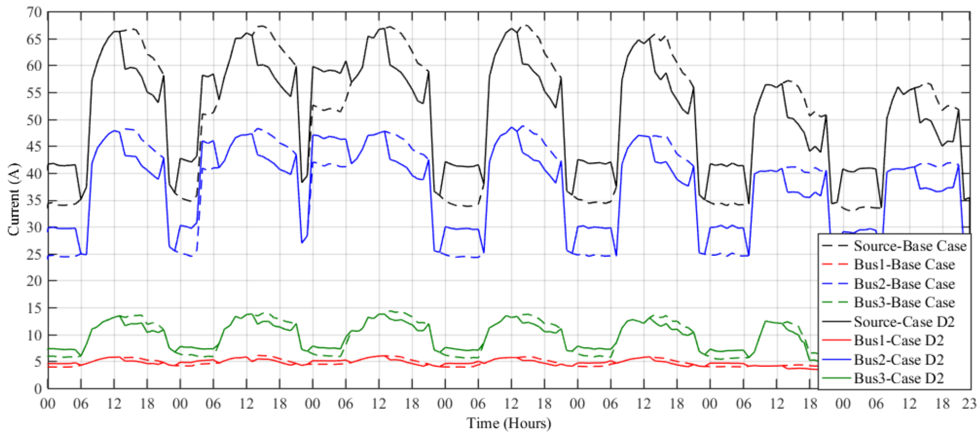

Figure 4.69 current profile: base case and Case D2 typical week in winter

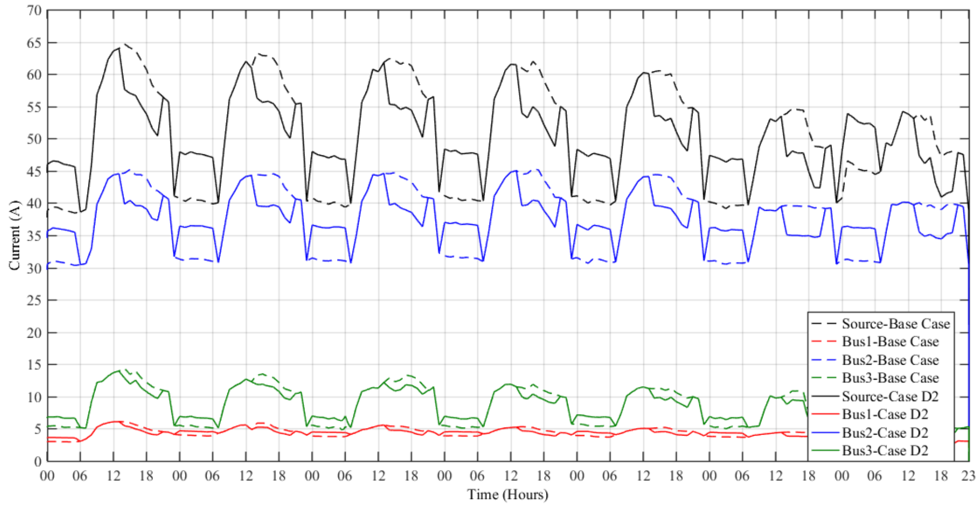

Figure 4.70 current profile: base case and Case D2 typical week in summer

4.9 Comments

Using PV system in the network has shown to give a very good result reducing power consumption from other sources while maintaining voltage profile of the grid intact, which proves the feasibility of using PV on campus.

When it comes to using ESS with PV case A2, Case B2 and, Case C2 results have shown a poor performance in managing the peak load which due to low energy capacity. On the other hand, Case D2 simulation result has better performance managing the peak load, but the issue of long peak period remains an obstacle. By reviewing the results of relying only on ESS to manage peak load it is obvious that large-scale ESS system is required to handle this task. Installing large scale ESS is may not be possible to do on campus due to the limited area available to install large-scale ESS.

As for using ESS along with PV system simulations have shown that the good results obtain in Case C2, yet it still fails to continue the to a close level as the PV.

Case A1and Case B1 simulation results have shown the small impact on peak load reduction specifically when the sun is down and there is no PV generation or with low PV generation.

To sum up, Simulations results of using ingrained PV with ESS for different sizes have shown that Case D system has the best and balanced results.

Chapter 5: **Conclusion and Future Work**

5.1 Conclusion

The aim of the thesis investigated the feasibly of installing PV system to the university network to reduce the amount of power consumed from other sources, monitor how putting PVs in the network would affect the voltages, currents and power factor, then introducing energy storage system to do peak load shaving application this would help shift the peak load from peak hours to off-peak hours, this task required running different simulation scenarios to determine a proper size for the energy storage in a grid-connected PV system. That was accomplished by developing a simulation model in EMTP-RV software for the network and its components, and real data for campus loads and network parameters the model was reflecting real case.

Using EMTP-RV software to build the model and run simulation has the great advantage of getting very fast simulation time and using monitoring devices to plot the results of voltages, currents, power flow and power factor data.

The simulations results presented in this chapter has illustrated the feasibility of using PV to minimize the peak load on campus. Simulations of utilizing the proposed PV system have shown that with almost 30 % PV integration the system stability has not been affected. Reducing energy consumption from the grid by 100 to 150 kW per hour is going to help reduce the carbon tax.

In this thesis, serval scenarios were simulated to get a better understanding how well each configuration would work to reduce peak load. The proposed configuration is Case D1 which has the best performance in shifting the peak load to off-peak hours. In Case D1 integrating PV with ESS to achieve balanced peak load shaving and, maintain the voltage stability.

5.2 Future work

Extended work can be done by including the whole campus network under study by setting PV system around campus. The issue of can be addressed is the poor power factor simulation results have shown that using PV system had affected the poor factor. Future study can make use of the inverters for both ESS and PV to work as leading reactive load which can help improving power factor.

Economic side was not included in this study extension to this work can address economical side in future.

Using different sizes for PV and ES based on each bus needs to get much smoother peak load reduction is an interesting idea to be investigated in further studies.

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