Optimal Scheduled Power Flow for the Distributed Photovoltaic-Wind Turbine-Diesel Generator with Battery Storage System

By

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Declaration

I, Bobongo Bokabo (student number [redacted]) do hereby declare that the dissertation submitted for the degree of Master of Engineering in Electrical Engineering is my own independent work and it complies with the Code of Academic integrity, as well as other relevant policies, procedures, rules and regulations of Central University of Technology and has not been previously submitted to any other institution of higher education for the fulfilment of any qualification.

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B. Bokabo, Date: 25-October-2016

Dedication

I dedicate this work to God, my Lord, my Saviour, my source of inspiration, knowledge, wisdom and understanding.

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First I would like to glorify God for giving me strength, knowledge and understanding to do and complete this work, without Him I would not be able to fulfil this work. Days and nights, He provided me with guidance and away forward to carry out all the necessary research needed to complete this work.

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Abstract

The high cost of the transportation of power from the grid to rural areas is a great concern for most of the countries in the world and the above results in many remote areas not being able to have electricity.

To overcome the challenges of electrification of rural areas, some generate their own energy by continuous or prime power diesel generators (DGs) or by producing energy using different small-scale renewable energy sources (Photovoltaic, Wind, hydroelectric and others).

Despite their advantages of being easy to transport, easy to install and of low initial cost, diesel generators present many disadvantages when they are used as continuous or prime power sources due to the high requirement of fuels and non-linearity of daily load demand profile. Beside the cost, diesel generators are detrimental to the environment and cause global warming.

To overcome the issues of costs and global warming, diesel generators can be used in combination with renewable energy such as photovoltaic as a backup to form a hybrid power generation system.

The stand-alone photovoltaic (PV) and wind turbine (WT) power generators have drawbacks as the power produced depends on the sun and wind, which means that if there is no sun or wind, no electricity can be produced. The non-linearity of solar and wind resources makes the stand-alone photovoltaic and wind operation non-reliable.

The combination of photovoltaic-wind turbine–diesel-battery power generation ensures that the energy produced is reliable and efficient. The diesel generator is used as back up to the system and is used only when the renewable energy sources are insufficient and the battery banks are low.

The PV-WT-Diesel-Battery hybrid power system reduces the consumption of fuel hence minimizes fuel costs. The system also presents the advantage of less pollution to the environment due to the short running time of the generator, a low generator maintenance requirement and long life expectancy of the generator.

As indicated above, the hybrid systems have the advantage of saving costs compare to a standalone diesel generator operation, but the system requires proper control to minimize the operation costs while ensuring optimum power flow considering the intermittent solar and wind resources, the batteries state of charge and the fluctuating load demand.

The aim of this research is to develop two different control strategies to minimize the daily operational cost of hybrid systems involving PV/WT/DG and batteries by finding the optimal schedules for running the diesel generator while in the meantime responding to the power required by the load. The two control strategies developed are “Continuous operational mode” and “ON/OFF” operational mode. The developed mathematical models of the two control strategies are simulated using MatLab functions, with “fmincon solver” for continuous operational mode and “Intlinprog solver” for ON/OFF operational mode.

Keywords:

Optimal operation control, hybrid power generation system, cost minimization, optimization system and optimization algorithm

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Acronyms and abbreviations

AC: Alternative current

ACS: Annualized cost of system

AE: Alternative energy

AGM: Sealed absorbed glass mat

ANN: Article neutral network

BESS: Battery energy storage system

BT: Battery

CO2: Carbone dioxide

DC: Direct current

DG: Diesel generator

DRC: Democratic Republic of Congo

FC: Fuel cost

FLC: Fuzzy logic controller

GA: Genetic algorithm

HOGA: Hybrid optimization by genetic algorithm

HOMER: Hybrid optimization model for energy renewable

HPWH: Heat pump water heaters

HRES: Hybrid renewable energy system

ISE: Integral square error

LCE: Levelized cost of energy

MATLAB: Matrix laboratory

MPP: Maximum power point

PEMFC: Proton exchange membrane fuel cell

PV: Photovoltaic

RBFN: Radial basis function network

RE: Renewable energy

SHEV: Series hybrid electric vehicles

SOC: State of charge

SOFC: Solid oxide fuel cell

TOU: Time-of-use

UC: Ultra-capacitor

WT: Wind turbine

Chapter I: Introduction

1.1. Background

The lack of reliable electrical power supply, the high cost of AC grid extension and rough topography are some of the severe challenges faced in the rural electrification of a good number of developing countries. In most of the cases, loads in those rural areas are powered by small Diesel Generators (DGs) running continuously (Kaabeche A, et al 2014). Compared to other supply options such as renewable energy sources, DGs have low initial capital costs and generate electricity on demand. They are easily transportable, modular, and have a high power-to-weight ratio. DGs can also be integrated with other sources and energy storage in hybrid system configurations, making it an ideal option for standalone power generation. However, due to the long running times and the high non-linearity in the daily load demand profiles, DGs are usually operated inefficiently resulting in the higher cost of energy produced.

Global warming, the ozone layer's depletion and other environmental impacts from using DGs (or other fossil fuels) have led to the use of renewable energy (RE) sources (Mahmoud M. et al 2006).

RE generation is gaining consideration, due to advantages such as low operation and maintenance, and easy deployment to meet growing energy needs (Tazvinga, et al 2014). Solar photovoltaic (PV) and wind turbines (WT) are established clean ways of generating energy and are currently used extensively to supply power in several stand-alone applications (Post HN. et al 1988).

However, except for their high capital costs, the other main disadvantage of PV and WT generation is the fact that their produced powers depends on solar and wind resources which are highly non-linear and vary with the hours of the day and the seasons of the year. Therefore, they cannot always meet the load power demand.

Hybrid solar PV-WT-diesel-battery hybrid systems present a solution to the time correlation of intermittent solar and wind sources as well as load demand fluctuations (Museli M. et al 1999). In this configuration, the DG is used to balance the deficit of the power supply from the renewable sources and the battery system when the load demand is high. This combination enhances the efficiency and the output capability of the entire system.

1.2. Problem statement

Hybrid Renewable Energy Systems have been accepted as a possible means of electrifying rural outlying areas where it is too expensive to extend the grid to supply them. One of the main problems identified with these systems which are not connected to the grid is that the sources themselves are reliant on climatic conditions and therefore inherently intermittent.

In addition to this, the load to be supplied is also fluctuating and therefore it is even more difficult to predict the load and supply together.

As these stand-alone systems run without any grid connection, they must be strategically controlled to be reliable systems with only a small operational cost. In addition to this, as there is generally limited funding for rural areas, the design of such systems must be cost-effective as well.

When the PV-Wind-Diesel-Battery hybrid system is not optimally managed, there is high operational cost mainly related to fuel. The problem that this research deals with is the development of models that can optimally control the use of a diesel generator in the hybrid system to minimize fuel consumption. The high cost of diesel fuel makes the diesel generator operation very expensive when running as a stand-alone power generation system.

The PV-Wind-Diesel-Battery hybrid systems have greater reliability and minimize the fuel cost if strategically controlled.

1.3. Objective of the study

The present work looks at the optimization of the daily operational cost of hybrid Photovoltaic-Wind-Diesel- battery systems from an energy efficiency point of view, as one of the main attributes of energy efficiency is seeking for optimality. Energy efficiency can be defined as the ratio of the output to the input energy and is characterized by the performance efficiency, the operational efficiency, the equipment efficiency, and the technology efficiency as main components (Xia X. et al 2011). Operational efficiency is a system-wide measure, which is assessed by taking into consideration the optimal sizing and matching of all system components, time control and human coordination. Operational efficiency can be enhanced using mathematical optimization and optimal control techniques (Xia X. et al 2011).

Therefore, the present work focuses on the development of two models, namely the “continuous” control strategy and “ON/OFF” control strategy to minimize the operation cost of PV-wind-diesel-battery hybrid systems during a 24-hour period. Considering a short time horizon, the battery, wind and PV’s operation costs are negligible, therefore only the fuel cost of the DG is considered.

1.4. Delimitation of the study

This research will be limited to:

- Development of mathematical models to minimize the operational cost of the proposed system
- Computer simulation of the models through case studies

1.5. Expected outcome of the study

The expected outcome of this research is the development of models for two control strategies involving "CONTINUOUS" and "ON/OFF" operational of the diesel generator in the PV-WT-Diesel-battery hybrid power system to minimize the daily operation cost of the system.

The research results will be documented as part of this master' thesis as well as in publications.

1.6. Project methodology

The following methodology will be used for this research:

- **Literature review**: The literature related to photovoltaic, wind, diesel generator and battery will be reviewed and also previous researches on different control strategies used for photovoltaic-wind-diesel-battery hybrid systems. The review will help one to understand the previous studies in which the diesel generators were used and different control strategies previously applied to optimize the system.

This will also include an in-depth study of all the components involved in the system.

- **System model development**: After reviewing previous studies, the mathematical models of the system will be developed (objective functions and constraints) as well as implementation of the developed model in the MatLab.
- **Simulation of developed models**: The mathematical models developed will be simulated using Matlab tools.
- **Assessment and comparison of the results**: The results of different control strategies will be analysed and the results compared to a diesel generator stand-alone operation. The results will be compared in terms of daily operation cost.

1.7. Hypothesis

- The proposed models will contribute to the reduction of the system's operation cost as the system will help in reducing the prolonged use of the diesel generator, hence reducing the fuel consumption.

1.8. Publications during the study

Paper presented:

B. Bokabo, K. Kusakana "Optimal scheduling of a grid-connected hydrokinetic-battery system under Time of Use tariff". International Conference on Industrial and Commercial Use of Energy (ICUE 2017), pp. 286-291, Cape Town, South Africa August 15 - 17, 2016.

1.9. Dissertation layout

This thesis has been structured in 6 chapters, with chapters IV and V reflecting the main research in which the development, simulations and results are presented.

Chapter I presents the background of the research, the problems of the research and the methodology and approach of the research.

Chapter II reviews previous researches done in hybrid systems and the different control strategies used to control the use of diesel generators in hybrid power systems.

Chapter III presents the components of the proposed hybrid power systems discussed in this research, their stand-alone operations and their operation in hybrid power systems

Chapter IV presents the proposed continuous operation model including a detail algorithm of the optimization. Here the objective function and variables of the model are outlined, the detailed algorithm is presented and simulated in Matlab and the results of the simulation are discussed.

Chapter V presents the proposed on-off operation model including a detailed algorithm of the optimization. Here the objective function and variables of the model are outlined; the detailed algorithm is presented and simulated in Matlab and the results of the simulation are discussed.

Chapter 6 concludes the work and future studies are proposed.

Chapter II: Literature review

2.1 Introduction

A hybrid power system consists of a combination of different renewable energy generation systems. The combination of different renewable sources provides reliability to the output power as the sources complement each other during the fluctuation of climatic conditions and also improve the overall economy of the renewable power generation supplying a given load.
This section reviews the literature related to photovoltaic-wind turbine- diesel generator and battery storage systems, different control strategies and optimal control used for the control of the diesel generators in the hybrid systems.

2.2 Literature related to optimal control of photovoltaic-wind turbine-diesel generator and battery storage system.

Effective operation of a hybrid system can be achieved only by suitable control of the interaction in the operation of different devices (Ani Vincent, 2014).
Several authors have discussed the optimal operation control of hybrid RE-diesel-battery systems for stand-alone power generation.

(Ani Vincent, 2014) presented a supervisory control system that monitors the operation of PV-Wind-Diesel hybrid power generation system with energy storage. The controller was developed in such way that it coordinates when power should be generated by renewable energy (PV panels and wind turbine) and when it should be generated by the diesel generator, and it is intended to maximize the use of a renewable energy system by limiting the use of a diesel generator. Diesel generation is allocated only when the demand cannot be met by the renewable energy sources, including a battery bank. The developed control was used to study the operations of a hybrid PV-Wind-Diesel power system for three hypothetical off-grid remote health clinics at various clinic geographical locations in Nigeria. It was observed that a hybrid controller allocates the sources optimally according to the demand availability. From the control simulation they were able to check the performance of the system over the course of year to see which mode(s) the system spends most time in, the power supplied by each of the energy sources over a year, and the power required by the load during a year.

(Dufo-Lopez et al., 2004) developed the HOGA program (Hybrid Optimization by Genetic Algorithms) used to design a PV-Diesel system (sizing and operation control of a PV-Diesel system). The program has been developed in C++. Two algorithms are used in HOGA. The main algorithm obtains the optimal configuration of the hybrid system, minimizing its Total Net Present Cost. For each vector of the main algorithm, the optimal strategy is obtained (minimizing the non-initial costs, including operation and maintenance costs) by means of the secondary algorithm. In the paper, a PV-Diesel system optimized by HOGA is compared with a stand-alone PV system that has been dimensioned using a classical design method based on the available energy under worst-case conditions. HOGA is also compared with a commercial program for optimization of hybrid systems such as the Hybrid Optimization Model for Energy Renewable (HOMER) and HYBRID2.

In (Dufo-Lopez et al., 2008) presented another study of the influence of mathematical models on the optimal design of PV-Diesel systems. For this purpose, HOGA was used. The mathematical models of some hybrid system elements was improved in comparison to those usually employed in hybrid systems' design programs. Furthermore, a more complete general control strategy was developed, one that also takes into account more characteristics than those usually considered in this kind of design.

(Nafeh A, 2009) developed and applied an operational control technique, based on using the fuzzy logic controller (FLC) and the commonly used ON-OFF controller for a Photovoltaic-Diesel-Battery hybrid energy system. This control technique aims to reliably satisfy the system's load, and at the same time to optimize the battery and diesel operation under all working atmospheric conditions. The proposed hybrid energy system is modelled and simulated using MATLAB/Simulink and FUZZY toolbox.

In (A. Brahma et al., 2000) reviewed the optimization of the instantaneous electrical generation/electrical storage power split in series hybrid electric vehicles (SHEV). Optimal energy management is related to the optimization of the instantaneous generation/storage power split in SHEV. Previously, a power split type solution of the series hybrid energy management problem was attempted using a rule-based approach. Their approach provides a dynamic programming solution of the problem of determining the optimal power split between both sources of energy, with realistic cost calculation for all considered power trajectories for the combined APU/generator, electric machines and battery efficiencies, and a penalty function formulation for the deviation of the ideal state-of-charge to be sustained over the length of time considered. The discrete state formulation of this dynamic programming approach makes computation very efficient. Results are obtained for series hybrids for the FUDS drive cycle.

(Kyoungsoo Ro and S. Rahman, 1998) presented the Two-loop controller for maximizing performance of a grid-connected photovoltaic-fuel cell hybrid power plant. Their focus was to maximize the performance of a grid-connected photovoltaic (PV)-fuel cell hybrid system by using a two-loop controller. One loop is a neural network controller for maximum power point tracking, which extracts maximum available solar power from PV arrays under varying conditions of insolation, temperature, and system load. A real/reactive power controller (RRPC) is the other loop. The RRPC achieves the system's requirements for real and reactive powers by controlling incoming fuel to fuel cell stacks as well as switching control signals to a power conditioning subsystem. Results of time-domain simulations prove not only the effectiveness of the proposed computer models of the two-loop controller but also its applicability for use in the stability analysis of the hybrid power plant.

(S. Hedlund et al., 1999) reviewed method for optimal control of hybrid systems. An inequality of the Bellman type is considered and every solution to this inequality gives a lower bound on the optimal value function. A discretization of this “hybrid Bellman inequality” leads to a convex optimization problem in terms of finite-dimensional linear programming. From the solution of the discretized problem, a value function that preserves the lower bound property can be constructed. An approximation of the optimal feedback control law was given and tried on some examples.

(F. Thanaa et al., 2005) reviewed an energy system comprising three energy sources, namely PV, wind and fuel cells. Each of the three energy sources is controlled so as to deliver energy at optimum efficiency. Fuzzy logic control is employed to achieve maximum power tracking for both PV and wind energies and to deliver this maximum power to a fixed dc voltage bus. The fixed voltage bus supplies the load, while the excess power feeds the water electrolyzer used to generate hydrogen for supplying the fuel cells. A management system is designed to manage the power flow between the system components in order to satisfy the load requirements throughout the whole day. A case study is done using practical data from the El-Hammam site (40 km west of Alexandria, Egypt). The study defines the power generated by the wind and PV systems, the generated hydrogen used and stored in tanks and the power generated by the fuel cells to supply the deficiency in the load demand. Simulation results, done for two seasons, proved the accuracy of the fuzzy logic controllers. In addition, a complete description of the management system was presented.

(R. Chedid et al., 1997) presented a study on the Unit sizing and control of hybrid wind-solar power systems. The aim of the study was to provide the core of a CAD/CAA tool that can help designers determine the optimal design of a hybrid wind-solar power system for either autonomous or grid-linked applications. The proposed analysis employs linear programming techniques to minimize the average production cost of electricity while meeting the load requirements in a reliable manner, and takes environmental factors into consideration both in the design and operation phases. While in autonomous systems, the environmental credit gained as compared to diesel alternatives can be obtained through direct optimization, in grid-linked systems emission is another variable to be minimized so that the use of renewable energy can be justified. A controller that monitors the operation of the autonomous/grid-linked systems is designed. Such a controller determines the energy available from each of the system components and the environmental credit of the system. It then gives details related to cost, unmet and spilled energies, and battery charge and discharge losses.

2.3 Literature related to modelling of a hybrid power system

(Tiryono R. et al., 2003) developed a mathematical model for the operation of a hybrid power system consisting of a solar PV-renewable energy source (photovoltaic PV arrays), a battery bank, an inverter and a generator. They considered the problem of controlling a given hybrid power system in an optimal manner so that the overall operational cost is minimized while the load requirements and various constraints are satisfied. They were interested in determining the optimum running times and levels of operation of the diesel generators over a fixed time period. They assumed that the given generators can operate at a number of different levels of power output. Alternatively, as the generators operate most efficiently at full capacity, they chose the switching times between the various power output levels to optimize the overall system performance. The objective function of their proposed model also contains a term which takes into account the additional mechanical wear on the generators due to short periods of operating in a particular mode. A third consideration in their object function was the cost which can be attributed to the discharge/recharge cycles of the battery bank as deep cycles can significantly shorten the usable lifetime of the battery bank.

In (Woon S.F et al., 2008) reviewed an optimal control approach used by Tiryono R. et al to evaluate the differences in operating strategies and configurations during the design of a PV-diesel-battery model. However, Tiryono R. et al did not capture all realistic aspects of the hybrid power system. In this paper, the optimal control model was analysed and compared with three different simulation and optimization programs. The authors proposed several improvements to the current model to make it more representative to real systems.

(Ashari M. et al., 1999) presented the dispatch strategies for the operation of a PV-diesel–battery hybrid power system using 'set points'. This includes the determination of the optimum set point values for the starting and stopping of the diesel generator in order to minimize the overall system costs. A computer program for a typical dispatch strategy has been developed to predict the long-term energy performance and the life cycle cost of the system. Currently, the development of models for optimal scheduling and energy management of stand-alone or grid connected renewable systems is gaining attention.

In (Tazvinga et al., 2013) developed a hybrid system model incorporating photovoltaic cells and diesel generator in which the daily energy demand fluctuations for different seasonal periods of the year were considered in order to evaluate the equivalent fuel costs as well as the operational efficiency of the system for a 24 hours period. The results show that the developed model can give a more realistic estimate of the fuel costs reflecting fluctuations of power consumption behavior patterns for any given hybrid system.

In (Tazvinga et al., 2009) presented an energy dispatch model that satisfies the load demand, taking into account the intermittent nature of the solar and wind energy sources and variations in load demand was presented for a solar photovoltaic-wind-diesel-battery hybrid power supply system. The emphasis in this work is on the coordinated management of energy flow from the battery, wind, photovoltaic and diesel generators when the system is subject to disturbances. The results show that the advantages of the approach become apparent in its capability to attenuate and its robustness against uncertainties and external disturbances.

(Wu Z. et al., 2015) presented a switching grid connected photovoltaic system for simplifying system installation. An optimal switching control model was proposed to sufficiently utilize the solar energy and to minimize electricity cost under the time-of-use (TOU) program. The results showed that optimal scheduling of the PV system can achieve promising cost savings.

In (Sichilalu S.M et al.2015) developed an optimal control strategy for power dispatch of the grid-tied photovoltaic PV-battery-diesel system to power heat pump water heaters (HPWH). The objective function of the model is to minimize energy and fuel cost while maximizing PV energy trade-off for incentives. The optimal control shows a great potential to realize a practical net zero-energy building and demand side management. The optimal control problem is solved using a mixed integer non-linear program and the results show how TOU affects the power dispatch to the HPWH. The energy and cost savings are presented in this paper.

(Zhou Wei, 2007) presented the simulation and optimum design of a hybrid solar-wind and solar-wind-diesel power generation system. The author developed an optimal sizing method to find the global optimum configuration of stand-alone hybrid (both solar-wing and solar-wing-diesel) power generation systems. By using a genetic algorithm (GA), the optimal sizing method was developed to calculate the system's optimum configuration which offers to guarantee the lowest investment with full use of the PV array, wind turbine and battery bank. For the hybrid solar-wind system, the optimal sizing method is developed based on the loss of power supply probability (LPSP) and the annualized cost of system (ACS) concepts. The optimization procedure aims to find the configuration that yields the best compromise between the two considered objectives: LPSP and ACS. The decision variables, which need to be optimized in the optimization process, are the PV module capacity, battery capacity, PV module slope angle and wind turbine installation height. The hybrid solar-wind-diesel system, minimization of the system is achieved not only by selecting an appropriate system configuration, but also by finding a suitable control strategy (starting and stopping point) of the diesel generator. The optimal sizing method was developed to find the system's optimum configuration and settings that can achieve the custom-required renewable energy fraction (fRE) of the system with minimum annualized cost of system (ACS).

(Besem Idlbi, 2012) presented the dynamic simulation of a PV-Diesel-Battery hybrid plant for off grid electricity supply. The author analysed different control strategies to improve the operation of stand-alone PV-diesel generator-battery plants, and to reduce the operational cost accordingly. Therefore, four control strategies were proposed according to primary and secondary control of frequency. Each control strategy provides different loading patterns of the diesel generators and storage system. Dynamic simulations of the plant operation are performed according to each control strategy. The effects of the control strategy are analysed according to four criteria: the frequency deviations, fuel consumption, lifetime of the batteries and the performance of the diesel generators. Finally, the cost of energy is calculated by considering the difference in fuel consumption according to each control strategy. The simulation results show that the control strategy, which covers the power fluctuations mainly from the battery system, demonstrates more constant output power of diesel generators, lower frequency deviations, less fuel consumption, better performance of diesel generators and less cost of energy, but shorter expected lifetime of the batteries compared to the other analysed control strategies. On the other hand, the control strategy, which covers the power fluctuations from the diesel generators and battery system in parallel, demonstrates higher variation in output power of the diesel generators, higher frequency deviations, higher fuel consumption, less favourable performance of the diesel generators and higher cost of energy, but longer lifetime of the battery compared to the other analysed control strategies.

In 2013 B. Ould Bilal et al presented a paper discussing the study of the influence of load profile variation on the optimal sizing of a stand-alone hybrid PV/WIND/Battery/Diesel system. The paper presented the methodology to size and to optimize a stand-alone hybrid PV/Wind/ Diesel/ Battery bank minimizing the levelised cost of energy (LCE) and the CO_2 emission using a multi-objective genetic algorithm approach. The main objective of the work was to study the influence of the load profile variation on the optimal configuration. The methodology developed was applied using solar radiation, temperature and wind speed collected on the site of Gandon located in North-western Senegal. The results obtained showed that, for the all load profiles, as the LCE increases the CO_2 emission deceases.

(S. K. Kim et al., 2008) presented a paper discussing the dynamic modeling and control of a grid connected hybrid generation system with versatile power transfer. They presented the power control strategies of a grid-connected hybrid generation system with versatile power transfer. Versatile power transfer was defined as a multimode of operation, including normal operation without the use of a battery, power dispatching, and power averaging, which enables grid or user friendly operation. A supervisory control regulates power generation of the individual components so as to enable the hybrid system to operate in the proposed modes of operation. A simple technic using a low-pass filter was introduced for power averaging. A modified hysteresis-control strategy was applied in the battery converter.

(M. Uzunoglo et al., 2008) presented the study on the modelling, control and simulation of a PV/FC/UC based hybrid power generation system for stand-alone applications. The paper focused on the integration of photovoltaic (PV), fuel cell (FC) and ultra-capacitor (UC) systems for sustained power generation. In the proposed system, during adequate insolation, the PV system feeds the electrolyzer to produce hydrogen for future use and transfers energy to the load side if possible. Whenever the PV system cannot completely meet load demands, the FC system provides power to meet the remaining load. If the rate of load demand increases the outside limits of FC capability, the UC bank meets the load demand above that which is provided by PV and FC systems. The main contribution of this work was the hybridization of alternate energy sources with FC systems using long- and short-term storage strategies with appropriate power controllers and control strategies to build an autonomous system, with a pragmatic design and dynamic model proposed for a PV/FC/UC hybrid power generation system. The model was developed and applied in the MATLAB®, Simulink® and SimPowerSystems® environment, based on the mathematical and electrical models developed for the proposed system.

(J.T. Bialasiewicz et al., 1998) presented a modular simulation system developed to study the dynamics and to aid in the design of hybrid power systems with diesel and wind turbine generation. The emphasis was placed on the representation of the dynamics of the elements of a real system and on the control aspects of the modules. Each module represents a component of the hybrid power system, such as the diesel generator, wind turbine generator, village load, etc. Various system configurations with different load and wind resource profiles can be simulated. The tool can be used to study the transient and the steady-state interaction of the various components of a hybrid system. It is especially useful when a new configuration of a power system is to be analysed, a new load or wind speed profile has to be included, additional modules have been installed in an existing power system, or an old control strategy is to be replaced by a new one.

2.4 Literature related to different control strategies used for a hybrid power system.

(Emad M. Natsheh and Alhussein Albarbar, 2013) presented a paper discussing the hybrid power systems' energy controller based on neural network and fuzzy logic. The paper presented a novel adaptive scheme for energy management in stand-alone hybrid power systems. The proposed management system was designed to manage the power flow between the hybrid power system and energy storage elements in order to satisfy the load requirements based on article neural network (ANN) and fuzzy logic controllers. The neural network controller was employed to achieve the maximum power point (MPP) for different types of photo-voltaic (PV) panels. The advance fuzzy logic controller was developed to distribute the power throughout the hybrid system and to manage the charge current flow for performance optimization. The developed management system performance was assessed using a hybrid system comprising PV panels, wind turbines (WT), battery storage and a proton exchange membrane fuel cell (PEMFC). To improve the generating performance of the PEMFC and prolong its life, stack temperature was controlled by a fuzzy logic controller. The dynamic behaviour of the proposed model was examined under different operating conditions. Real-time measured parameters were used as input for the developed system. The proposed model and its control strategy offer a proper tool for optimal hybrid power system performance, such as that used in smart-house applications.

(S.R. Vosen and J.O. Keller, 1999) presented a study discussing the hybrid energy storage systems for the stand-alone electric power systems: optimization of system performance and cost through control strategies. A time-dependent model of a stand-alone, solar powered, battery-hydrogen hybrid energy storage system was developed to investigate energy storage options for cases where supply and demand of energy are not well matched daily or seasonally. Simulations were performed for residential use with measure solar fluxes and simulated hourly loads for a site at Yuma, Arizona, USA, with a desert climate at 32.7 N latitude. Renewable-based power not needed to satisfy the load was stored for later user. Two hybrid energy storage algorithms were considered. The first was a conventional state-of-charge control system that uses the current state of charge of the storage system control. The second control system presumes knowledge of future demand through a feed-forward, neural- net or other intelligent control systems.

Both algorithms use battery storage to provide much of the daily energy shifting and hydrogen to provide seasonal energy shifting, thus using each storage technology to its best advantage. The cost of storing energy with a hybrid energy-storage scheme was found to be much less expensive than either single storage method, with a hybrid system storage costing 48% of the cost of a hydrogen-only system and only 9% of the cost of a conventional, battery-only system. In addition, the neural-net control system was compared to a standard battery state-of-charge control scheme, and it was shown that neural-net control systems better utilize expensive components and result in less expensive electric power than state-of-charge control systems.

(G.C Seeling-Hochmuth, 1997) presented a combined optimization concept for the design and operation strategy of hybrid-PV energy systems. The paper presented a method to jointly determine the sizing and operation control of hybrid-PV systems. The outlined approach finds an optimum operation strategy for a hybrid system by carrying out a search through possible options for the system operation control. The search was conducted over a period using estimated weather and demand data and long-term system component characteristics. The costing of the operating strategies was evaluated and component sizes were changed by the designed algorithm according to optimum search rules. As a result, an optimum system configuration was chosen by the algorithm together with an optimum operation strategy for a given site and application requirement.

(C. Dennis Barley and C. Byron Winn, 1996) presented the optimal strategy in remote hybrid power systems. In this study, dispatch strategies were compared using (1) an analysis of cost trade-offs, (2) a simple, quasi-steady-state time-series model, and finally (3) HYBRID2, a more sophisticated stochastic time-series model. An idealized predictive dispatch strategy, based on assumed perfect knowledge of future load and wind conditions was developed and used as a benchmark in evaluating simple, non-predictive strategies. The results illustrate the nature of the optimal strategy and indicate that one of two simple diesel dispatch strategies-either load-following or full power for a minimum run time-can, in conjunction with the frugal use of stored energy (the Frugal discharge strategy), be virtually as cost-effective as the Ideal Predictive Strategy. The optimal choice of these two simple charging strategies is correlated to three dimensionless parameters, yielding a generalized dispatch design chart for an important class of systems.

(T.S. Bhatti et al., 1997) presented a paper discussing the load frequency control of isolated wind diesel hybrid power systems. In the study, a load frequency controller was designed for isolated wind diesel hybrid power systems, and its effect on the transient performance of the system is evaluated. The modelling of the system, consisting of a wind turbine induction generator unit and a diesel engine synchronous alternator unit, is presented along with the controller, both for continuous and discrete control cases. Optimum parameter values were obtained for different hybrid power system examples with continuous and discrete load frequency control and with and without blade pitch controllers, using the integral square error criterion (ISE). It was shown that wind diesel or multi-wind diesel hybrid power systems, with blade pitch control mechanism and with continuous load frequency control, have better dynamic performance than any other configuration of the isolated wind diesel hybrid systems. Finally, some of the transient responses of the systems were shown for optimum gain settings.

(K. Yoshimoto et al., 2006) developed the New Control Method for Regulating State-of-Charge of a Battery in Hybrid Wind Power/Battery Energy Storage System. As an approach for the output fluctuation, authors have done a research in smoothing out a short-term fluctuation using a hybrid system of a battery energy storage system and a wind farm. In order to operate the hybrid system, the charging level of the battery has to be regulated not to exceed its operable range. The paper presented a control system called as "state-of-charge feedback control" to keep the charging level of the battery within its proper range, while the battery energy storage system smoothes out output fluctuation of a wind farm. Furthermore, the paper clarifies fundamental characteristics of the control to show its effectiveness through a theoretical study and numerical simulations.

(W.M. Lin et al, 2011) presented a paper discussing the Neural-Network-Based MPPT Control of a Stand-Alone Hybrid Power Generation System. A stand-alone hybrid power system was proposed in the paper. The system consists of solar power, wind power, diesel engine, and an intelligent power controller. MATLAB/Simulink was used to build the dynamic model and simulate the system. To achieve a fast and stable response for the real power control, the intelligent controller consists of a radial basis function network (RBFN) and an improved Elman neural network (ENN) for maximum power point tracking (MPPT). The pitch angle of the wind turbine is controlled by the ENN, and the solar system uses RBFN, where the output signal is used to control the dc/dc boost converters to achieve the MPPT.

(Phatiphat Thounthong et al., 2005) examined the Control strategy of fuel cell/supercapacitors hybrid power sources for an electric vehicle. They presented a control principle for utilizing a PEM fuel cell as main power source and supercapacitors as auxiliary power sources for electric vehicle applications. The strategy was based on dc link voltage regulation, and the fuel cell is simply operating in almost steady state conditions in order to minimize its mechanical stresses and to ensure a good synchronization between fuel flow and fuel cell current. Supercapacitors are functioning during transient energy delivery or transient energy recovery. To authenticate control algorithms, the system structure is realized by analogical current loops and digital voltage loops (dSPACE). The experimental results with a 500 W PEM fuel cell point out the fuel cell starvation problem when operating with a dynamic load, and also confirm that the supercapacitor can improve system performance for hybrid power sources.

(M.H. Nehrir et al., 2011) reviewed the Hybrid Renewable/Alternative Energy Systems for Electric Power Generation systems focusing on energy sustainability. They highlighted some important issues and challenges in the design and energy management of hybrid RE/AE systems. System configurations, generation unit sizing, storage needs, and energy management and control are addressed. Statistics on the current status and future trend of renewable power generation, as well as some critical challenges facing the widespread deployment of RE/AE power generation technologies and vision for future research in this area, are also presented.

In (F. Valenciaga et al., 2001) presented power control of a photovoltaic array in a hybrid electric generation system using sliding mode techniques. The system comprises photovoltaic and wind generation, a storage battery bank and a variable monophasic load. The control law admits two modes of operation. The first takes place when the insolation regime is sufficient to satisfy the power demand. The second mode of operation takes place under insufficient insolation regimes. The latter leads the system operation at the maximum power operation point to save as much stored energy as possible. A new method based on the IncCond algorithm was developed. Sliding mode control techniques are used to design the control law. These techniques provide a simple control law design framework and contribute with their well-known robust properties. Finally, guidelines based on chattering considerations are given for the design of the practical system

In (F. Valenciaga et al., 2005) developed the supervisor control for a stand-alone hybrid generation system using wind and photovoltaic energy. The objectives of the supervisor control were, primarily, to satisfy the load power demand and, second, to maintain the state of charge of the battery bank to prevent blackout and to extend the life of the batteries. For these purposes, the supervisor controller determines online the operational mode of both generation subsystems, switching from power regulation to maximum power conversion. Decision criteria for the supervisor based on measurable system variables are presented. Finally, the performance of the supervisor controller is extensively assessed through computer simulation using a comprehensive nonlinear model of the plant.

(A. M. O. Haruni et al., 2010) presented the dynamic operation and control strategies of a hybrid wind-diesel-battery energy storage based power supply system for isolated communities. Control strategies for voltage and frequency stabilization and efficient power flow among the hybrid system components were developed. The voltage and frequency of the hybrid wind-diesel system is controlled either by a load side inverter or by diesel generation depending on the wind conditions. During high penetration of wind, the wind turbine supplies the required power to the load. A battery energy storage system is connected to the dc-link to balance the power generated from the wind turbine and the power demanded by the load. Under low wind conditions, a diesel generator is used with a wind energy conversion system to generate the required power to the load. A power sharing technique has been developed to allocate power generation for diesel generator in low wind conditions. Results show that the control strategies work very well under dynamic and steady state conditions to supply power to the load.

In (T. Zhou et al., 2010) presented the studies on the Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration. A dc-coupled wind/hydrogen/supercapacitor hybrid power system was studied. The purpose of the control system was to coordinate these different sources, particularly their power exchange, in order to control the generated power. As a result, an active wind generator can be built to provide some ancillary services to the grid. The control system should be adapted to integrate the power management strategies. Two power management strategies are presented and compared experimentally. It was found that the “source-following” strategy has a better performance on the grid power regulation than the “grid-following” strategy.

(M. Datta et al., 2009) reviewed a Frequency-Control Approach by Photovoltaic Generator in a PV–Diesel Hybrid Power System. A simple fuzzy-based frequency-control method was proposed for the PV generator in a PV-diesel hybrid system without the smoothing of PV output power fluctuations. By means of the proposed method, output power control of a PV generator considering the conditions of power utilities and the maximizing of energy capture, are achieved. Fuzzy control was used to generate the PV output power command. This fuzzy control has average insolation, change of insolation, and frequency deviation as inputs. The proposed method was compared with a maximum power point tracking control-based method and with an ESS-based conventional control method. The numerical simulation results showed that the proposed method is effective in providing frequency control and also delivers power near the maximum PV power level.

N.J. Schouten et al developed a fuzzy logic controller for hybrid vehicles with parallel configuration. Using the driver command, the state of charge of the energy storage, and the motor/generator speed, a set of rules has been developed, in a fuzzy controller, to effectively determine the split between the two power plants: electric motor and internal combustion engine. The underlying theme of the fuzzy rules is to optimize the operational efficiency of all components, considered as one system. Simulation results were used to assess the performance of the controller. A forward-looking hybrid vehicle model was used for implementation and simulation of the controller. Potential fuel economy improvement is shown by using fuzzy logic, relative to other controllers, which maximize only the efficiency of the engine.

In (Amin Hajizadeh et al., 2007) presented the intelligent power management strategy of a hybrid distributed generation system. The study describes a novel control strategy for active power flow in a hybrid fuel cell/battery distributed generation system. The method introduces an on-line power management by a hierarchical hybrid controller between dual energy sources that consist of a battery bank and a solid oxide fuel cell (SOFC). The proposed method includes an advance supervisory controller in the first layer which captures all of the possible operation modes. This layer has been developed by a state flow toolbox and prepares a proper supervisory environment for this complex structure. In the second layer, an advanced fuzzy controller has been developed for power splitting between battery and fuel cell. With regards to the operation modes, the upper layer makes a decision to choose the switching chain rules and corresponding controller in the second layer. Finally, in the third layer, there are local controllers to regulate the set points of each subsystem to reach the best performance and acceptable operational indexes. Simulation results of a test system illustrate improvement in the operational efficiency of the hybrid system and the battery state-of-charge has been maintained at a reasonable level.

(C. Wang et al., 2008) proposed an AC-linked hybrid wind/photovoltaic (PV)/fuel cell (FC) alternative energy system for stand-alone applications. Wind and PV were the primary power sources of the system, and an FC-electrolyzer combination was used as a backup and a long-term storage system. An overall power management strategy was designed for the proposed system to manage power flows among the different energy sources and the storage unit in the system. A simulation model for the hybrid energy system has been developed using MATLAB/Simulink. The system's performance under different scenarios was verified by carrying out simulation studies using a practical load demand profile and real weather data.

In (Jose L. Bernal-Augustin et al., 2008) presented the application of the strength Pareto evolutionary algorithm to the multi-objective design of isolated hybrid systems, minimizing both the total cost throughout the useful life of the installation and the unmet load. For this task, a multi-objective evolutionary algorithm (MOEA) and a genetic algorithm (GA) have been used in order to find the best combinations of components for the hybrid system and control strategy. Also, a novel control strategy has been developed and it was expounded in the article. As an example of application, a PV–wind–diesel system has been designed, obtaining a set of possible solutions (Pareto set) from which the designer can choose those which he/she prefers considering the costs and unmet load of each.

In (Erkan Dursun et al., 2011) presented the different power management strategies of a stand-alone hybrid power system. The system consisted of three power generation systems, photovoltaic (PV) panels, a wind turbine and a proton exchange membrane fuel cell (PEMFC). PV and wind turbine provide the main supply for the system, and the fuel cell performs as a backup power source. Therefore, continuous energy supply needs energy storing devices. In the proposed hybrid system, gel batteries were used. The state-of-charge (*SOC*), charge-discharge currents were affecting the battery energy efficiency. The battery energy efficiency was evaluated with three different power management strategies. The control algorithm was using Matlab-Simulink.

In (T. Hirose et al., 2011) proposed a unique stand-alone hybrid power generation system, applying advanced power control techniques, fed by four power sources: wind power, solar power, storage battery, and diesel engine generator. Considerable effort was put into the development of active-reactive power and dump power controls. The results of laboratory experiments revealed that amplitudes and phases of ac output voltage were well regulated in the proposed hybrid system. Different power sources can be interconnected anywhere on the same power line, leading to flexible system expansion. It is anticipated that this hybrid power generation system, into which natural energy is incorporated, will contribute to global environmental protection on isolated islands and in rural locations without any dependence on commercial power systems.

(Y. Rifonneau et al., 2011) presented an optimal power management mechanism for grid connected photovoltaic (PV) systems with storage. The objective was to help intensive penetration of PV production into the grid by proposing peak shaving service at the lowest cost. The structure of a power supervisor based on an optimal predictive power scheduling algorithm is proposed. Optimization was performed using Dynamic Programming and was compared with a simple ruled-based management. The particularity of this study remains firstly in the consideration of batteries ageing into the optimization process and secondly in the "day-ahead" approach of power management. Simulations and real conditions application are carried out over one exemplary day. In simulation, it points out that peak shaving is realized with the minimal cost, but especially that power fluctuations on the grid are reduced which fits in with the initial objective of helping PV penetration into the grid. In real conditions, efficiency of the predictive schedule depends on accuracy of the forecasts, which leads to future inputs about optimal reactive power management.

In (Nabil A et al, 2008) reviewed the power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems. A hybrid energy system combining variable speed wind turbine, solar photovoltaic and fuel cell generation systems was presented to supply continuous power to residential power applications as stand-alone loads. The wind and photovoltaic systems are used as main energy sources while the fuel cell was used as secondary or back-up energy source. Three individual dc–dc boost converters were used to control the power flow to the load. A simple and cost effective control with dc–dc converters was used for maximum power point tracking and hence maximum power extracting from the wind turbine and the solar photovoltaic systems. The hybrid system was sized to power a typical 2 kW/150 V dc load such as telecommunication power plants or ac residential power applications in isolated islands, continuously throughout the year.

The results show that even when the sun and wind are not available, the system is reliable and available and it can supply high-quality power to the load. The simulation results which proved the accuracy of the proposed controllers are given to demonstrate the availability of the proposed system in this paper. Also, a complete description of the management and control system is presented.

2.5 Summary

This chapter reviewed the previous works developed for the optimal operational control of hybrid systems. Literature related to hybrid systems involving photovoltaic, wind turbine, diesel generators and battery systems have been reviewed, including the different control strategies used to control the use of diesel generators in the hybrid systems.

Chapter III: Proposed hybrid system description

3.1. Introduction

This chapter describes the different components of the proposed hybrid system and their utilization in the hybrid power systems. The proposed hybrid system model consists of a combination of photovoltaic, wind turbine, diesel generator and battery system. In this chapter all the components of the system will be described and their stand-alone operation and their operation in a hybrid system will be elaborated on and the collected data for the specific household used for the case study will be presented.

3.2. Photovoltaic system

3.2.1. Description of photovoltaic system

A solar panel consists of number of photovoltaic (PV) solar cells connected in series and parallel. These cells are made up of at least two layers of semiconductor material (usually pure silicon infused with boron and phosphorous). One layer has a positive charge; the other has a negative charge. When sunlight strikes the solar panel, photons from the light are absorbed by the semiconductor atoms, which then release electrons. The electrons, flowing from the negative layer (n-type) of semiconductor, flow to the positive layer producing an electrical current. Since the electric current flows in one direction (like a battery), the electricity generated is DC (Shaika Tamanna et al., 2010).

The solar cell is the basic unit of a PV system. An individual solar cell produces direct current and power typically between 1 and 2W, hardly enough to power most applications. For actual usage, the solar cells are interconnected in series/parallel combinations to form a PV module.

In the outdoor environment the magnitude of the current output from a PV module directly depends on the solar irradiance and can be increased by connecting solar cells in parallel. The voltage of a solar cell does not depend largely on solar irradiance, but depends primarily on the cell temperature. PV modules can be designed to operate at different voltages by connecting solar cells in series. Electrical parameters of a PV system are determined at standard test conditions, i.e. 1000 W/m^2 solar irradiance, 25°C cell temperature and AM1.5 solar radiation (Miro Zeman, 2014).

The power output (P_{PV}) of the PV module can be expressed as follows (Francisco Jose Contreras Cordero, 2015):

$$P_{PV} = A_{PV} \times \eta_{PV} \times I_{PV} \tag{3.1}$$

Where: A_{PV} is the total area of the photovoltaic generator (m^2);

η_{PV} is the module efficiency;

I_{PV} is the hourly irradiance (kWh/m^2).

The rated power of the PV is the maximum power that the panel can produce with 1,000 watts of sunlight per square metre at a module temperature of 25°C and air mass AM1.5. Actual conditions will rarely match rated conditions and so actual power output will almost always be less. PV modules with higher efficiency will have a higher ratio of watts to area. The higher the efficiency, the smaller the area (i.e. fewer modules) will be required to achieve the same power output of an array. Installation and racking costs will be less with more efficient modules, but this must be weighed against the higher cost of the modules (Miro Zeman, 2014).

3.2.2. Advantages of a photovoltaic power system

Photovoltaic presents distinct advantages such as zero pollution and the absence of the need to transport fuel to the generating site, makes it attractive in many applications. Photovoltaic facilities maybe located at the point of power consumption and do not require the purchase of fuel, so this makes them economically feasible for remote applications because constructing expensive distribution lines and high losses sustained by transmission of conventional power do not apply (Tom Penick and Bill Louk, 1998).

PV systems that are well designed and properly installed require minimum maintenance and have long service lifetimes (Gabrovska et al., 2004).

An important characteristic of photovoltaic power generation is that it does not require a large scale installation to operate, as to conventional power generation stations. Power can be installed in a distributed fashion, on each house or business, or school, using area that is already developed, and allowing individual users to generate their own power quietly and safely (Zhou Wei, 2007).

3.2.3. Disadvantages of a photovoltaic power system

The high cost of a photovoltaic power system makes it difficult to replace conventional power generation. The stand-alone photovoltaic power system is not always reliable as the energy produced depends on solar irradiation and requires the use of batteries or other storage.

3.2.4. Types of PV systems

a) Stand-alone PV systems

Stand-alone systems rely on PV power only. These systems can comprise only PV modules and a load or can include batteries for energy storage. PV system energy production depends on the sun and if sun is not available no energy can be produced. When the PV system is designed to supply a night load, the system needs to be combined with battery storage to store the energy produced by the PV during the day for use at night or during cloudy weather. When using batteries charge regulators are included, which switch off the PV modules when batteries are fully charged, and switch off the load in case batteries become discharged below a certain limit. The batteries must have enough capacity to store the energy produced during the day to be used at night and during periods of poor weather.

The stand-alone PV systems are commonly used in rural areas where there is no grid or other power stations and where the reliability of power is not a concern.

b) Grid-connected PV systems

Grid connected PV systems do not require batteries for storage, as the energy generated by the PV systems is coupled to the grid by using inverters to convert the DC energy generated by the PV to AC energy for compatibility with grid energy. The grid-connected PV systems have advantages of eliminating the need of energy storage and the cost associated to the substituting and recycling of batteries for individual clients.

c) Hybrid operation of PV systems

The PV system can be combined with other sources of energy to form a hybrid power configuration. Hybrid power systems have greater flexibility, high efficiency and lower cost for the same quantity of energy production (M. Ashiri, 2001).

Hybrid systems consist of a combination of PV modules and a complementary means of electricity generation such as a diesel, gas or wind generator. In order to optimize the operations of the two generators, hybrid systems typically require more sophisticated controls than stand-alone PV systems. For example, in the case of PV/diesel systems, the diesel engine must be started when the battery reaches a given discharge level, and stopped again when the battery reaches an adequate state of charge. The back-up generator can be used to recharge batteries only or to supply the load as well.

A common problem with hybrid PV/diesel generators is inadequate control of the diesel generator. If the batteries are maintained at too high a state-of-charge by the diesel generator, then energy which could be produced by the PV generator is wasted. Conversely, if the batteries are inadequately charged, then their operational life will be reduced. Such problems must be expected if a PV generator is added to an existing diesel engine without installing an automatic system for starting the engine and controlling its output (Miro Zeman et al., 2014).

3.3. Wind energy system

3.3.1. Description of a wind energy system

A wind turbine is a machine for converting the kinetic energy in wind into mechanical energy, which the mechanical energy produced from the wind is then converted to electric energy via a generator. Wind turbines can be separated into two basic types based on the axis around which the turbine rotates. Turbines that rotate around a horizontal axis are more common. Vertical-axis turbines are less frequently used. Wind turbines can also be classified by the location in which they are used such as onshore, offshore, and aerial wind turbines (I.A. Adejumobi et al., 2011).

The power produced by the wind generators has AC voltage but has variable amplitude and frequency. To maintain the frequency, the AC is converted to DC, stored in battery and then converted back to AC.

The extractable power from the wind is given by:

$$P_{WT} = \frac{1}{2} \times \rho_a \times A_{WT} \times C_{p,WT} \times v^3 \tag{3.2}$$

Where: P_{WT} is the output power of the wind turbine

ρ_a is the density of air (kg/m^3);

C_{pWT} is the coefficient of the wind turbine performance;

A is the wind turbine area (m^2);

v is the wind velocity (m/s);

The amount of power transferred to a wind turbine is directly proportional to the area swept out by the rotor, to the density of the air, and the cube of the wind speed

The limitations on the extraction of energy from the wind include the practical size of wind machines, their density, friction losses in the rotating machinery and efficiency of conversion from rotational energy to electrical energy (Gagari deb et al., 2012).

A German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. To this day, this is known as the Betz Limit or Betz' Law. The theoretical maximum power efficiency of any design of wind turbine is 0.59 (Mohit Sigh and Surya Santoso, 2008)

3.3.2. Operation of wind turbine in a hybrid system

As seen in the section above, standalone wind energy systems generate highly fluctuating and therefore unreliable energy due to the constant fluctuating wind speed. If the wind turbine is used in combination with other sources in hybrid system configurations, the produced energy can become more stable, increasing the system's performance while reducing the size and the overall cost of the system (K. Kusakana, 2014).

3.4. Diesel generator

3.4.1. Description of a diesel generator

A DG is a normal diesel engine coupled to an electrical generator. DGs are usually designed in such a way that they always operate close to their power rating to achieve high efficiency;

this condition can be used later as an operational constraint. With this operation strategy as well as operational constraint, the DG is expected to run at high load factors, which will result a decrease of the fuel consumption, a small carbon footprint and an increase in the DG lifespan.

The fuel cost (FC) calculated for a day is given by the quadratic non-linear function below:

$$C_f \sum_{j=1}^{N} (aP_{DG(j)}^2 + bP_{DG(j)} + c) \tag{3.3}$$

Where: a, b and c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_f is the price of one liter of diesel fuel; $P_{DG(j)}$ is the output power or control variable from the DG in any sampling interval. It has to be highlighted that different DGs of different sizes as well as from different manufacturers present different fuel consumption curves and parameters.

3.4.2. Stand-alone Operation of diesel generator system

Electric power generators can be classified in one of three ways depending on their mode of operation: continuous, prime, or standby. Continuous and prime power generators are very similar as they function as the main source of power and are designed to operate continuously or for extended periods of time. The major difference between the two is that continuous generator sets are designed to operate continuously with a consistent load while prime generators are designed to operate for long durations at variable load. The other type of generator – standby/emergency – is to be run only when there is an outage to the utility grid or the main source of power in a back-up situation. Continuous and prime generators are primarily used in remote locations where there is no access to the grid to supply electric power. These are also used when the amount of electric power that can be drawn from the grid is limited. On the other hand, the need for standby power arises when there is a temporary disruption to the primary supply of electrical power, such as when the main grid is off.

Diesel generation power systems are the simplest generators that anyone can use to generate energy in any location depending on the need. The system presents some advantages like: low initial cost, easy to install, high power to weight ratio. However diesel generators, when used as stand-alone, do present some disadvantages such as:

High operational and maintenance costs, pollution of the environment, noise pollution and also the availability of fuels; if there is no fuel around no power can be produced.

3.4.3. Operation of diesel generator in a hybrid system

A diesel generator is used in a hybrid system as a back-up system to supply the deficit of energy from other sources required by the load. The diesel generator is kept off and can only run when the other sources are not able to produce energy at all or cannot produce enough energy to satisfy the requirement of the load. The utilization of a diesel generator in the hybrid systems increases the reliability of the energy system and minimizes the fuel consumption and hence reduces the running cost of the diesel generation power system.

3.5. Battery storage system

3.5.1. Description of a battery storage system

Battery energy storage systems (BESS) are the most common type of energy storage in micro grids and are essential for efficiently utilizing the energy produced by intermittent energy sources such as PV. Batteries convert electrical energy into chemical energy which is stored and converted back into electrical energy when needed. There is currently a significant development occurring in battery technology, but deep-cycle lead-acid batteries are still the most common due to their low cost and high efficiency. A bidirectional DC-DC charge controller controls the power flow to and from the battery. While deep-cycle batteries are designed for deep discharges, the maximum discharge should still not exceed 75 % to avoid damaging the batteries (Marte Wiig Lotveit, 2014).

3.5.2. Advantages and disadvantages of batteries in renewable energy

Advantages are:

- Capability to provide energy for sunless or windless periods
- Capability to meet momentary peak power demands
- A stable voltage for the system
- Capability to store energy produced by the PV or WT in excess of the instantaneous demand, thereby reducing energy loss

One recent study showed that systems without batteries deliver an average of 2.5 hours per day of rated output, whereas systems with batteries deliver 4.5 hours. Because batteries and the associated charge-rate regulator add to the number of parts in the system, certain disadvantages accrue.

- Batteries add to the system complexity;
- Increase activity and maintenance costs for the system;
- And frequently reduce the system's reliability.

Despite these disadvantages, batteries are frequently worth including in the design, so understanding their operation is important (H.L Macomber et al., 1981).

3.5.3. Types of batteries commonly used in renewable energy systems

Lead-Acid Batteries – Lead-acid batteries are most common in PV systems in general, and sealed lead-acid batteries are most commonly used in grid-connected systems.
Sealed batteries are spill-proof and do not require periodic maintenance. Flooded lead-acid batteries are usually the least expensive but require adding distilled water at least monthly to replenish water lost during the normal charging process.
There are two types of sealed lead-acid batteries: sealed absorbent glass mat (AGM) and gel cell. AGM lead-acid batteries have become the industry standard, as they are maintenance free and particularly suited for grid-tied systems where batteries are typically kept at a full state-of-charge. Gel-cell batteries, designed for freeze-resistance, are generally a poor choice because any overcharging will permanently damage the battery.

Alkaline Batteries – Because of their relatively high cost, alkaline batteries are only recommended where extremely cold temperatures (-50oF or less) are anticipated or for certain commercial or industrial applications requiring their advantages over lead-acid batteries. These advantages include tolerance of freezing or high temperatures, low maintenance requirements, and the ability to be fully discharged or overcharged without harm (Carolyn Roos, 2005).

The number of batteries in series is dictated by the nominal voltage of the DC bus, which is a constant. The instantaneous output power from the whole battery bank depends on variables such as the type and the size of the battery used, and the number of battery strings in parallel n_B.

The dynamics of the battery state of charge SOC can be expressed in discrete-time domain by a first order difference equation as follows (K Kusakana, 2014). The battery dynamic equation can be expressed as:

$$SOC_{(j)} = SOC_{(0)} - t_s \frac{\eta_{Bat}}{E_{nom}} \sum_{i=1}^{j} P_{Bat}(i) \tag{3.4}$$

Where: SOC is the state of charge of the battery; η_{Bat} is the battery charging or discharging efficiency; t_s is the sampling time (interval); E_{nom} is the battery system nominal energy, and P_{Bat} is the power flowing from the battery system.

The lifespan of the battery depends on many parameters related to the way it is operated and to external conditions, in particular the ambient temperature. For instance, typical lead-acid batteries designed for solar energy applications will lose between 15% to 20% of their lifespan (the number of charge/discharge cycles they can perform) for each 5^{o}C above the standard temperature of 25^{o}C. In addition, the deeper the battery is discharged at each cycle (depth of discharge), the shorter its lifespan. This implies that to reach an optimal battery lifespan, a large enough battery needs to be installed to achieve a suitable depth of discharge (IEA-PVS T9-13: 2013).

3.5.4. Operation of battery storage system in hybrid systems

The battery storage system facilitates the storage of the energy generated by the renewable sources during low peak periods and use the stored energy during peak demand periods. The excess of energy generated by different sources not used by the load' instead of being wasted, is stored in the battery storage system. The battery storage system creates more reliability when used in combination with renewable energy sources. Renewable energy system power generations depend on the natural resources such as sunlight and wind, and if these resources are not available no energy can be produced. The battery storage system facilitates the continuity of power supply to the loads during these intermittent periods.

The utilization of batteries in the hybrid system extends the life span of the batteries as they are not used permanently to supply the loads. The batteries operate only when the other sources are not generating at all or are not generating sufficient energy as required by the load.

3.6. Inverters and rectifiers

3.6.1. Description of inverters and rectifiers

Most of the energy produced by different renewable energy sources requires transformation before it can be utilized by the loads.

Inverters and rectifiers are used in cases above to convert energy from one type to a different type depending on the load requirement.

Inverters are used to transform DC current to AC current, while rectifiers convert AC current to DC current for load use or battery charging.

3.6.2. Types of inverters

The inverters can be classified into three categories:

- Stand-alone inverters and
- Grid-tied inverters
- Hybrid inverter

a) Stand-alone inverters

These inverters are meant to operate isolated from the electrical distribution networks and require batteries for proper operation. The batteries provide constant voltage sources at the DC input of the inverters.

b) Grid-tied inverters

Grid-tied inverters operate coupled to the electric distribution network and therefore must be able to produce almost pert sinusoidal voltages and currents.

b) Hybrid inverters (Grid-interactive)

A hybrid inverter is just one type of solar inverter used in a solar electricity system. Also known as an on-grid solar with a battery storage system, this type of system combines a power inverter with a battery. In a traditional solar power system, homeowners have to use the power as the inverters convert it to usable electricity. Since many people work during the day away from the home, they cannot use their solar power to the fullest extent. A hybrid inverter collects the power and stores it in the battery so that people can take advantage of it at a later time.

3.7 Loads

The power demand of a household depends on the appliances in the relevant household and the utilization and diversity factors. In most of rural households, the loads are:

- Fluorescent and incandescent light,
- Television sets,
- Fridges,
- Irons,
- Stoves,

The power sources have to be designed to withstand the total power required by the load at any given time and period.

3.8 Stand-alone hybrid power system

The combination of diesel generators with renewable energy and a battery storage system presents the advantage of reliability of power generation when compared to stand-alone renewable energy sources and also presents a reduction of fuel consumption, as a stand-alone diesel generator has to run continuously to supply a given load. The combination helps the different sources integrated to compensate or supplement each other in case of non-generation of any of the sources.

Renewable energy (RES) such as solar and wind provide sustainable and environmentally friendly alternatives for power generation, however, some technical and economic challenges have to be resolved before these sources can substitute the current power generation resources. Firstly these renewable energies are intermittent, unpredictable, and uncontrollable. This means they cannot be safely used to supply the load demand in reliable manner. In addition, renewable energy generation technologies are generally more expensive than conventional generators of comparable sizes, especially if used in conjunction of with battery storage devices to enhance their reliability. As a result, they cannot supply energy at a competitive price. Lastly their distribution nature and locational dependency cause difficulties with respect to their integration into the centralized architecture of contemporary power generation and delivery systems (Ahmed Saif, 2011).

3.10. Summary

In this chapter, the different components of the proposed hybrid system involving PV-WT-DG and battery storage systems have been described, as well as their stand-alone operations and their operation in hybrid systems.

Chapter IV: Proposed optimization using a continuous operation mode

4.1. Introduction

In this chapter the proposed continuous operation model is presented including a detailed algorithm of the optimization. Here the objective function and variables of the model are to be outlined, the detailed algorithm to be presented and simulated in Matlab and the results of the simulation to be discussed.

4.2. Model development

4.2.1. Power flow layout and operation sequence

From figure 4.1 the following variable can be defined:

P_1 is the control variable representing power flow from the PV to the load at any sampling interval (j) (kW);

P_2 is the control variable representing power flow from the WT to the load at any sampling interval (j) (kW);

P_4 is the control variable representing power flow from the DG to the load at any sampling interval (j) (kW);

P_3 is the control variable representing power flow from the battery to the load at any sampling interval (j) (kW), and

P_5 is the control variable representing power flow from the PV to the Battery at any sampling interval (j) (kW);

P_6 is the control variable representing power flow from the WT to the Battery at any sampling interval (j) (kW);

P_7 is the control variable representing power flow from the DG to the Battery at any sampling interval (j) (kW);

P_L is the load demand at any sampling interval (j) (kW).

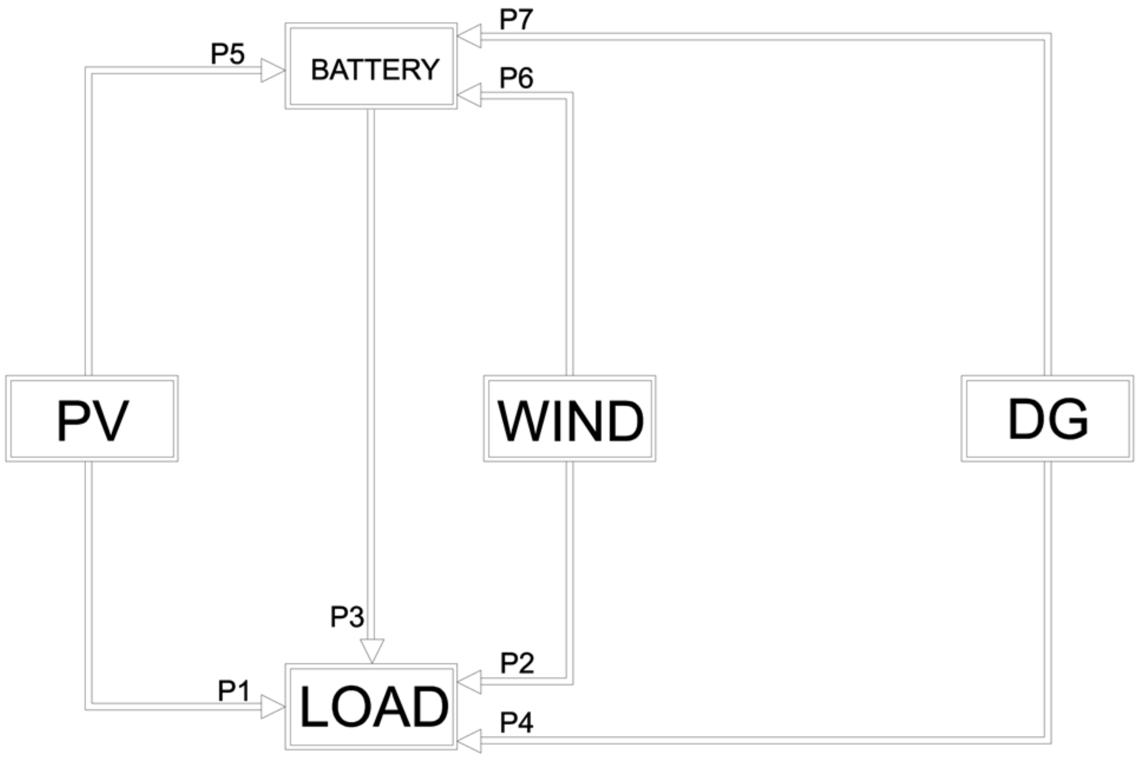

Figure 4.1: Continuous model power flow layout

The model proposed consists of the integration of different power sources. The model includes: photovoltaic, wind turbine, diesel generator and battery storage system as shown in figure 4.1 below. The load demand in the model is primarily met by the sum of the power from photovoltaic (P_1) and wind turbine (P_2) and the battery (P_3) starts discharging within its operating limits as soon as the (P_1) and (P_2) do not meet the demand. If the sum of the power from the PV and WT is above the load demand, the excess power is used to recharge the battery (P_5 & P_6) (a dump load can be used to dissipate this power in a case in which the RE generation is more than the load and the required power to recharge the battery). Power from the DG (P_4) is used when the sum of P_1, P_2 and P_3 cannot respond to the load requirements. The deficit of power from the DG (P_7) can be used to recharge the battery.

4.2.2. System modeling

The proposed optimization problem is to be simulated in a 24-hour period divided into equal intervals "**N**" with sampling interval "Δ***t***".

The number of sampling intervals are to be limited to "**N=2**" for modelling purposes, then the expression of the objective function and of the different constraints of the system can be summarized into canonical forms required by the solver.

The variable "***x***" will be the only variable in the MatLab code to be developed. Therefore, the output powers from different sources of the system have to be expressed in functions of the variable "***x***".

The following allocations on variable "***x***" have been made:

$$P_1 = x(1:N) = [x_1, x_2] \tag{4.1}$$

$$P_2 = x(N+1:2N) = [x_3, x_4] \tag{4.2}$$

$$P_3 = x(2N+1:3N) = [x_5, x_6] \tag{4.3}$$

$$P_4 = x(3N+1:4N) = [x_7, x_8] \tag{4.4}$$

$$P_5 = x(4N+1:5N) = [x_9, x_{10}] \tag{4.5}$$

$$P_6 = x(5N+1:6N) = [x_{11}, x_{12}] \tag{4.6}$$

$$P_7 = x(6N+1:7N) = [x_{13}, x_{14}] \tag{4.7}$$

4.2.3. Objective function of the system

The objective function of this mode of operation is to minimize the fuel consumption cost of the diesel generator from the system during operation time, while in the meantime responding to the power requirement of the load.

In the continuous operational mode, the DG is ON most of the time and its output power is continuously controlled, depending on the demand, to minimize the fuel consumption, resulting in operational cost. The DG is used as back-up to the system to supply the deficit of power from other sources needed by the load.

The objective function is expressed as:

$$\min C_f \sum_{j=1}^{N} \{(aP_{4(j)}^2 + bP_{4(j)} + c) + (aP_{7(j)}^2 + bP_{7(j)} + c)\} \tag{4.8}$$

Where: a, b, c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_f is the price of one litre of diesel fuel; $(P_{4(j)}$ & $P_{7(j)})$ are the output power from the DG in any sampling interval (j).

The parameters of the DG differ as per the size and manufacturers.

4.2.4. Constraints

The different constraints on the operation are as follows:

- Power balance

At any sampling interval j, the sum of the supplied powers (control variables) P_1, P_2, P_3, and P_4 from different power sources must be equal to the power required by the load.

This can be expressed as:

$$P_{1(j)} + P_{2(j)} + P_{3(j)} + P_{4(j)} = P_{L(j)} \tag{4.9}$$

- Control Variable limits

The P_1 & P_5 from Photovoltaic and P_2 & P_6 from Wind Turbine are modelled as control variable power sources controllable in the range of zero to their maximum available power in the specific sampling interval power, and P_4 & P_7 from DG and P_3 from the Battery are modelled as a control variable controllable in the range of zero or minimum to their rated power for the 24-hour period. Therefore, the variable limits are the output limits of these different power sources as well as of the battery storage system at any sampling interval (j). These constraints depend on the characteristics of each power source and can be expressed as:

$$0 \le P_{1(j)} \le P_1^{\max} \quad (1 \le j \le N) \tag{4.10}$$

$$0 \le P_{2(j)} \le P_5^{\max} \quad (1 \le j \le N) \tag{4.11}$$

$$0 \le P_{3(j)} \le P_2^{rated} \quad (1 \le j \le N) \tag{4.12}$$

$$0 \le P_{4(j)} \le P_6^{rated} \quad (1 \le j \le N) \tag{4.13}$$

$$0 \le P_{5(j)} \le P_5^{\max} \quad (1 \le j \le N) \qquad (4.14$$

$$0 \le P_{6(j)} \le P_6^{\max} \quad (1 \le j \le N) \tag{4.15}$$

$$0 \le P_{7(j)} \le P_7^{rated} \quad (1 \le j \le N) \tag{4.16}$$

Where: $P_1^{\max}, P_2^{\max}, P_5^{\max}$ & $P_6^{\max}$ is the maximum value of a given renewable power source at any sampling interval (j) and

P_4^{rated} & P_7^{rated} and P_3^{rated} are the rated power of the DG and the battery system respectively.

- Battery state-of-charge

The available battery state-of-charge in any sampling internal (j) must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state-of-charge. This can be expressed as:

$$SOC^{\min} \leq SOC_{(j)} \leq SOC^{\max} \tag{4.17}$$

$$SOC_{(j)} = SOC_{(0)} + \frac{\eta_C \times \Delta t}{E_{nom}} \sum_{j=1}^{N} (P_{5(j)} + P_{6(j)} + P_{7(j)}) - \sum_{j=1}^{N} P_{3(j)} \times \frac{\Delta t}{\eta_D \times E_{nom}} \tag{4.18}$$

Where: $SOC^{\min}$ and $SOC^{\max}$ are respectively, the minimum and maximum of the battery state of charge; η_C is the battery charging efficiency; η_D is the battery discharging efficiency; E_{nom} is the battery system nominal energy, and Δt is the sampling time interval.

4.2.5. Proposed optimization solver and algorithm

The developed problem has a non-linear objective function and linear constraints and can be solved using "fmincon" (AS Kumar et al 2014).

Fmincon solves problems in the form:

$$\min_{x} \ f(x) \text{ Subject to: } \begin{cases} c(x) \le 0 \\ c_{eq}(x) \le 0 \\ A.x \le b \\ A_{eq}.x \le b_{eq} \\ l_b \le x \le u_b \end{cases} \tag{4.19}$$

Where x, b, b_{eq}, l_b and u_b are vectors; A and A_{eq} are matrices; $c(x)$ and $c_{eq}(x)$ are functions that return vectors; and $f(x)$ is a function that returns a scalar, $f(x)$, $c(x)$, and $c_{eq}(x)$ are non-linear functions.

4.2.6. Objective function definition in fmincon syntax

The objective function is to minimize the fuel consumption costs of the DG during operational time, and this can be expressed as follows:

$$\min \ FC = \Delta t(aP_4^2 + bP_4 + c) + \Delta t(aP_7^2 + bP_7 + c) + ... + \Delta t(aP_{DGN}^2 + bP_{DGN} + c) \tag{4.20}$$

$$\min \ FC = \Delta t \sum_{j=1}^{N} \{(aP_{4(j)}^2 + bP_{4(j)} + c) + (aP_{7(j)}^2 + bP_{7(j)} + c) \tag{4.21}$$

$$\begin{aligned} &\min \ \Delta t \sum_{j=1}^{N} [(a * x(3*N+1:4*N)^2 + b * x(3*N+1:4*N) + c) \\ &+ (a * x(3*N+1:4*N)^2 + b * x(3*N+1:4*N) + c)] \end{aligned} \tag{4.22}$$

Where: j is the sampling interval.

4.2.7. Constraints definition in fmincon syntax

- Power balance

The power balance at any j^{th} sampling interval can be expressed as:

$$P_{1(j)} + P_{2(j)} + P_{3(j)} + P_{4(j)} = P_{L(j)} \tag{4.23}$$

As $N = 2$, the power balance can be developed for these two sampling intervals as:

For $j = 1 \rightarrow x_1 + x_3 + x_5 + x_7 = P_{L1}$ (4.24)

$j = 2 \rightarrow x_2 + x_4 + x_6 + x_8 = P_{L2}$ (4.25)

Taking the coefficient of the equations, the system can be rewritten in a matrix form as:

$$\begin{pmatrix} 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_{14} \end{pmatrix} = \begin{pmatrix} P_{L1} \\ P_{L2} \end{pmatrix} \tag{4.26}$$

Using the canonical formulation of the linear equality constraints in fmincon, the power balance can be finally expressed as:

$$Aeq = [eye(N,N), eye(N,N), eye(N,N), eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N)] \tag{4.27}$$

$$b_{eq} = P_L(1:N) \tag{4.28}$$

- Linear inequality

❖ Linear inequality for battery bank

The available battery bank state-of-charge in any sampling internal must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state-of-charge. This can be expressed as

$$SOC^{\min} \leq SOC_{(j)} \leq SOC^{\max} \tag{4.29}$$

$$SOC^{\min} \leq SOC_{(0)} + \frac{\eta_C \times \Delta t}{E_{nom}} \sum_{j=1}^{N} (P_{5(j)} + P_{6(j)} + P_{7(j)}) - \sum_{j=1}^{N} P_{3(j)} \times \frac{\Delta t}{\eta_D \times E_{nom}} \leq SOC^{\max} \tag{4.30}$$

Where E_{nom} is the nominal energy from the battery system, and η_C and η_D are the efficiencies of the battery system (during charging and discharging).

This expression can be re-written as:

$$SOC^{\min} \leq SOC_{(0)} + d \sum_{j=1}^{N} (P_{5(j)} + P_{6(j)} + P_{7(j)} - \sum_{j=1}^{N} P_{3(j)} \times e \leq SOC^{\max} \tag{4.31}$$

Where:

$$d = \frac{\eta_C \times \Delta t}{E_{nom}} \tag{4.32}$$

$$e = \frac{\Delta t}{\eta_D \times E_{nom}} \tag{4.33}$$

- Dealing with maximum inequality $(SOC^{\max})$

For $j = 1$

$$SOC_{(0)} + d(x_9 + x_{11} + x_{13}) - ex_5 \leq SOC^{\max} \tag{4.34}$$

For $j = 2$

$$SOC_{(0)} + d(x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14}) - ex_5 - ex_6 \leq SOC^{\max} \tag{4.35}$$

Then

$$dx_9 + dx_{11} + dx_{13} - ex_5 \leq SOC^{\max} + SOC_{(0)} \tag{4.36}$$

$$dx_9 + dx_{10} + dx_{11} + dx_{12} + dx_{13} + dx_{14}) - ex_5 - ex_6 \leq SOC^{\max} + SOC_{(0)} \tag{4.37}$$

- Dealing with minimum inequality $(SOC^{\min})$

For $j = 1$

$$SOC^{\min} \leq SOC_{(0)} + d(x_9 + x_{11} + x_{13}) - ex_5 \tag{4.38}$$

The above expression can also be written as:

$$-dx_9 - dx_{11} - dx_{13} + ex_5 \leq SOC_{(0)} - SOC^{\min} \tag{4.39}$$

For $j = 2$

$$SOC^{\min} \leq SOC_{(0)} + d(x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14}) - ex_5 - ex_6 \tag{4.40}$$

The above expression can also be written as:

$$-dx_9 - dx_{10} - dx_{11} - dx_{12} - dx_{13} - dx_{14} + ex_5 + ex_6 \leq SOC_{(0)} - SOC^{\min} \tag{4.41}$$

- Linear inequality for PV

$$P_{1(j)} + P_{5(j)} \leq P_{PV}{}^{\max} \tag{4.42}$$

For $j = 1$

$$x_1 + x_9 \leq P_{PV1}{}^{\max} \tag{4.43}$$

For $j = 2$

$$x_2 + x_{10} \leq P_{PV2}{}^{\max} \tag{4.44}$$

- Linear inequality for WT

$$P_{2(j)} + P_{6(j)} \leq P_{WT}{}^{\max} \tag{4.45}$$

For $j = 1$

$$x_3 + x_{11} \leq P_{WT1}^{\max} \tag{4.46}$$

For $j = 2$

$$x_4 + x_{12} \leq P_{WT2}^{\max} \tag{4.47}$$

- Linear inequality for DG

$$P_{4(j)} + P_{7(j)} \leq P_{DG}^{rated} \tag{4.48}$$

For $j = 1$

$$x_7 + x_{13} \leq P_{DG}^{rated} \tag{4.49}$$

For $j = 2$

$$x_8 + x_{14} \leq P_{DG}^{rated} \tag{4.50}$$

Taking the coefficient of the equations (4.36), (4.37), (4.39), (4.41), (4.43), (4.44), (4.47), (4.48), (4.49) and (4.50) the system can be rewritten in a matrix form as:

$$\begin{pmatrix} 0 & 0 & 0 & 0 & -e & 0 & 0 & 0 & d & 0 & d & 0 & d & 0 \\ 0 & 0 & 0 & 0 & -e & -e & 0 & 0 & d & d & d & d & d & d \\ 0 & 0 & 0 & 0 & e & 0 & 0 & 0 & -d & 0 & -d & 0 & -d & 0 \\ 0 & 0 & 0 & 0 & e & e & 0 & 0 & -d & -d & d & d & d & d \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2. \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \\ x_{13} \\ x_{14} \end{pmatrix} \leq \begin{pmatrix} SOC^{\max} - SOC_0 \\ SOC^{\max} - SOC_0 \\ SOC^{\min} - SOC_0 \\ SOC^{\min} - SOC_0 \\ P_{PV1}{}^{\max} \\ P_{PV2}{}^{\max} \\ P_{WT1}{}^{\max} \\ P_{WT2}{}^{\max} \\ P_{DG}{}^{rated} \\ P_{DG}{}^{rated} \end{pmatrix} \tag{4.51}$$

Using the canonical formulation of the linear inequality constraints in fmincon, this can be finally expressed as:

$$A_1 = \begin{bmatrix} zeros(N,N), zeros(N,N), -e * tril(ones(N,N)), zeros(N,N), d * tril(ones(N,N)), \\ d * tril(ones(N,N)), d * tril(ones(N,N)) \end{bmatrix} \tag{4.52}$$

$$A_2 = -A_1 \tag{4.53}$$

$$A_3 = [eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N)] \tag{4.54}$$

$$A_4 = [zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N)] \tag{4.55}$$

$$A_5 = [zeros(N,N), zeros(N,N), zeros(N,N), .eye(N,N), zeros(N,N), zeros(N,N), eye(N,N)] \tag{4.56}$$

$$A = [A_1; A_2; A_3; A_4; A_5] \tag{4.57}$$

$$b_1 = (SOC^{\max} - SOC_0) * ones(N,1) \tag{4.58}$$

$$b_2 = (SOC_0 - SOC^{\min}) * ones(N,1) \tag{4.59}$$

$$b_3 = P_{PV}{}^{\max}(1:N) \tag{4.60}$$

$$b_4 = P_{WT}{}^{\max}(1:N) \tag{4.61}$$

$$b_5 = P_{DG}{}^{rated} * ones(N:1) \tag{4.62}$$

$$b = [b_1; b_2; b_3; b_4; b_5] \tag{4.63}$$

- Variable boundaries

These boundaries represent the upper and lower limits of outputs from each power source as well as of the battery storage system for each j^{th} sampling time.

$$lb \le x \le ub \tag{4.64}$$

With: lb : lower boundaries and ub : upper boundaries

These can be expressed for each j^{th} sampling interval as:

$$0 \leq P_{1(j)} \leq P_1^{\max} \tag{4.65}$$

$$0 \leq P_{2(j)} \leq P_2^{rated} \tag{4.66}$$

$$-P_3^{\min} \leq P_{3(j)} \leq P_3^{\max} \tag{4.67}$$

$$0 \leq P_{4(j)} \leq P_4^{rated} \tag{4.68}$$

$$0 \leq P_{5(j)} \leq P_5^{\max} \tag{4.69}$$

$$0 \leq P_{6(j)} \leq P_6^{\max} \tag{4.70}$$

$$0 \leq P_{7(j)} \leq P_7^{rated} \tag{4.71}$$

- Lower boundaries

The change of minimum values that each power source can produce in different time intervals is “zero”; however, for the specific case of the battery system, this value “$-P_3^{rated}$” is the maximum power entering the battery while charging. The system’s lower boundaries change can be expressed in vector forms as follows:

$$lb_1 = P_1^{\min} * ones(N,1) \tag{4.72}$$

$$lb_2 = P_2^{\min} * ones(N,1) \tag{4.73}$$

$$lb_3 = -P_3^{\max} * ones(N,1) \tag{4.74}$$

$$lb_4 = P_4^{\min} * ones(N,1) \tag{4.75}$$

$$lb_5 = P_5^{\min} * ones(N,1) \tag{4.76}$$

$$lb_6 = P_6^{\min} * ones(N,1) \tag{4.77}$$

$$lb_7 = P_7^{\min} * ones(N,1) \tag{4.78}$$

$$lb = [lb_1; lb_2; lb_3; lb_4; lb_5; lb_6; lb_7] \qquad (4.79$$

❖ Upper boundaries

The change of maximum values that each renewable source can produce in different time intervals is "$P_{i(j)}^{\max}$", which depends on the availability of the renewable resources. However, for the specific case of the DG and the battery system, these values are their maximum rated values “ P_4^{rated}, P_7^{rated},” and “ P_3^{rated} ” respectively. The system’s lower bounds change can be expressed in vector forms as follows:

$$ub_1 = P_1^{\max}(1:N) \tag{4.80}$$

$$ub_2 = P_2^{\max}(1:N) \tag{4.81}$$

$$ub_3 = P_3^{\max} * ones(N:1) \tag{4.82}$$

$$ub_4 = P_4^{\max} * ones(N:1) \tag{4.83}$$

$$ub_5 = P_5^{\max}(1:N) \tag{4.84}$$

$$ub_6 = P_6^{\max}(1:N) \tag{4.85}$$

$$ub_7 = P_7^{\max} * ones(N:1) \tag{4.86}$$

$$ub = [ub_1; ub_2; ub_3; ub_4; ub_5; ub_6; ub_7] \tag{4.87}$$

4.2.8. Final model of continuous operation mode

The final model of the continuous operation of the system will be a MatLab code that any user can use by changing the technical input data. The user will be able to introduce his own load profiles, the capacity of the diesel generator, the battery state of charge, and the profile of photovoltaic and wind turbine. The final model developed will be able to optimize the operation of the system by minimizing the consumption of the diesel generator, therefore minimizing the cost.

4.3. Simulation results and discussions

4.3.1. General description

Here the continuous operation is simulated using MatLab function and the simulation results are discussed. As indicated under the objective function, the aim of the simulation is to show how the diesel's generator fuel consumption can be minimized using the continuous control strategy developed.

In this case the diesel generator is on most of the time and its output is continuously controlled to minimize fuel consumption, while in the meantime responding to requirement of the load. The simulation of the household is carried out during summer and winter to indicate how climate change can influence the load demand, RE primary resources, and as result influence the operation and cost of the hybrid systems.

4.3.2. Data presentation

The solar radiation data used in this study are calculated from stochastically generated values of hourly global and diffuse irradiation using the simplified tilted-plane mode. This is calculated for a South African rural area close to Bloemfontein. Wind speed data measured at 10m height at the site over a period of two years is used in this work. Two typical summer and winter load demand profiles for institutional applications based on an energy demand survey carried out in rural communities in South Africa, are used.

The load and RE data for the selected summer and winter days are as shown in Table 6.1. The two daily load profiles are used to analyse the benefit of the hybrid system operating under the two control strategies compared with the DG used as stand-alone.

4.3.3. Resources and load data of the household

The Table 6.1 below indicates the detailed load profile taken from typical household for a 24-hour simulation period during summer and winter. The household has low consumption appliances, such as TV, lights, kettle, iron, toaster, laptop, etc. The Table also indicates the hourly profiles of solar irradiation and wind speed during summer and winter.

Table 4.1: Household Resources & Load Data

Time	Summer			Winter		
(h)	Global Solar (kW/m^2)	Wind speed at rotor hub (m/s)	Load (kW)	Global Solar (kW/m^2)	Wind speed at rotor hub (m/s)	Load (kW)
00:00	0.000	0.821	0.3	0.000	0.871	0.3
01:00	0.000	1.665	0.2	0.000	0.381	0.2
02:00	0.000	0.998	0.1	0.000	0.947	0.1
03:00	0.000	0.956	0.0	0.000	1.425	0.0
04:00	0.000	2.549	0.3	0.000	1.575	0.3
05:00	0.000	2.558	0.0	0.000	1.463	0.0
06:00	0.000	2.775	2.4	0.000	0.932	3.0
07:00	0.002	3.754	0.6	0.000	1.560	0.7
08:00	0.141	2.948	4.3	0.145	1.337	8.0
09:00	0.417	2.828	5.6	0.244	1.761	5.6
10:00	0.687	2.870	3.2	0.306	2.611	2.6
11:00	0.940	2.522	1.6	0.512	3.542	3.0
12:00	1.062	1.766	0.3	0.611	3.956	0.5
13:00	1.061	2.576	2.0	0.614	4.698	3.4
14:00	0.978	2.017	0.4	0.568	4.898	0.7
15:00	0.846	2.282	0.8	0.428	4.089	1.3
16:00	0.679	3.116	3.9	0.460	5.544	1.4
17:00	0.464	2.626	1.8	0.266	4.404	1.5
18:00	0.208	3.427	1.7	0.000	4.547	3.8

19:00	0.043	2.972	1.9	0.000	4.711	4.6
20:00	0.000	2.543	2.2	0.000	3.881	5.9
21:00	0.000	2.336	0.9	0.000	4.610	2.1
22:00	0.000	1.863	0.7	0.000	2.537	0.8
23:00	0.000	1.231	0.3	0.000	2.370	0.3

4.3.4. Components sizes & model parameters

The hybrid system is designed so that the load power demand is met at any given time. The sizes of different components of the system have already been discussed in chapter 3. This chapter focuses more on the simulation and discussion of the results.

This study also emphasizes mainly the optimal energy management of the given hybrid system. The different parameters used in the simulations are given in Table 6.2.

(K Kusakana, 2015)

Table 4.2: Simulation Parameters

Item	Figure
Sampling time	30min
Battery nominal capacity	5.6kWh
Battery maximum SOC	95%
Battery minimum SOC	40%
Battery charging efficiency	85%
Battery discharging efficiency	100%

Diesel fuel price	1.4$/l
a	0.246
b	0.815
c	0.4333

4.3.5. Simulation and discussion results during winter

a) 24-Hour load Supplied by the hybrid system during winter

- Load profile

Figure 4.1 indicates the load profile of the household during winter. From the figure it can be seen that from 22:00 to 6:00 in the morning, the load demand is very minimum. The load starts picking up after 6h in the morning and reaches its maximum demand between 8:00 and 9h, after 9h it starts decreasing up to 17:00 in the evening. The load is high again around 22:00.

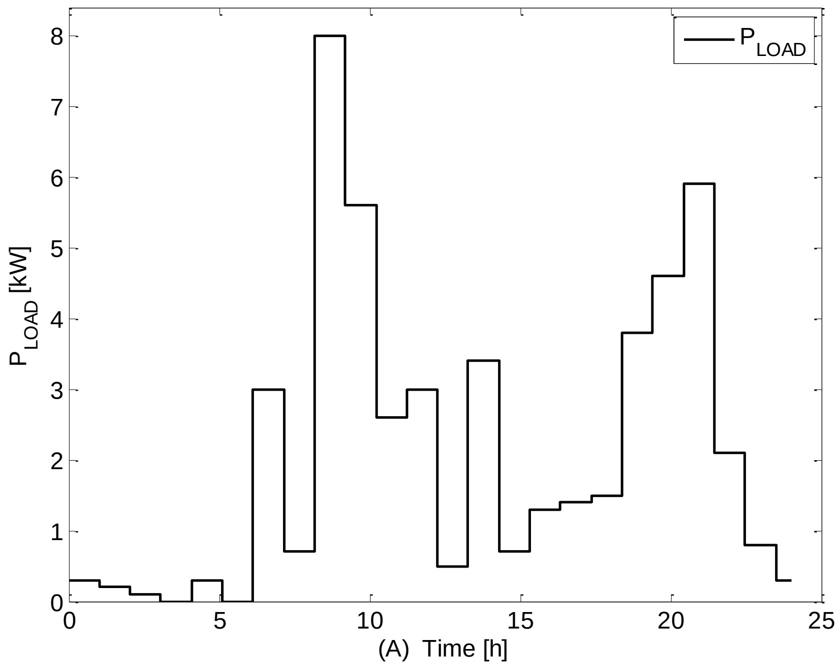

Figure 4.2: Household 24-hr load profile during winter

- Power from different sources to the load

Figures 4.2 to 4.5 indicate the power flow from different power sources to the loads During the midnight and early in the morning, the power requirement of the household is very low, only the battery is used to respond to the load demand, and the diesel generator is off. The renewable energy output powers are zeros as they are not able to generate at that time.

After 6:00, the load starts picking up as shown in figure 4.1 and in the meantime the renewable energy sources start to generate and the household power requirement is met by the combinations of output power from PV, WT and battery while the DG is still off.

From 8:00 to 9:00 in the morning, the load reaches its peak demand and the sum of the outputs power from PV, WT and battery is able to respond to the high load demand, and the DG is still off. The renewable energy sources generate more at energy this time and there is no need for the DG to run.

From 9:00 to 10:00, the household load demand starts dropping, the PV power generation increases, and the load requirement is met by the sum of the output power from PV, WT and battery and there is no need to run the DG.

From 10:00 to 17:00, the load demand is low while the PV generates a lot of power. The power generated is used to supply the load and the excess power is used to recharge the battery. Between 17:00 and 20:00, the load demand starts picking up and the WT starts generating again, but the sum of the out power from PV, WT and battery is not sufficient to respond to the load requirement, so the diesel generator is switched on to back up the system.

Between 20:00 and 21:00, the household load demand again reaches its peak, and at this time the renewable energy sources (PV and WT) are no longer generating any power, and the battery itself also cannot respond to the requirement of the load, therefore the diesel generator is kept on to back up the system. The DG is continuously controlled to meet the deficit of power from other sources required by the load.

Between 21:00 and midnight the renewable energy sources are no longer generating and the load demand is met by the output power from the battery and the diesel generator.

From the simulation results, it can be noticed that the PV is the main component of the system and is the one that mostly influences the running cost of the system. The PV also contributes more in recharging the battery as during the day when the PV produces more output power, the load demand is very minimum and the excess power produced is accumulated in the battery.

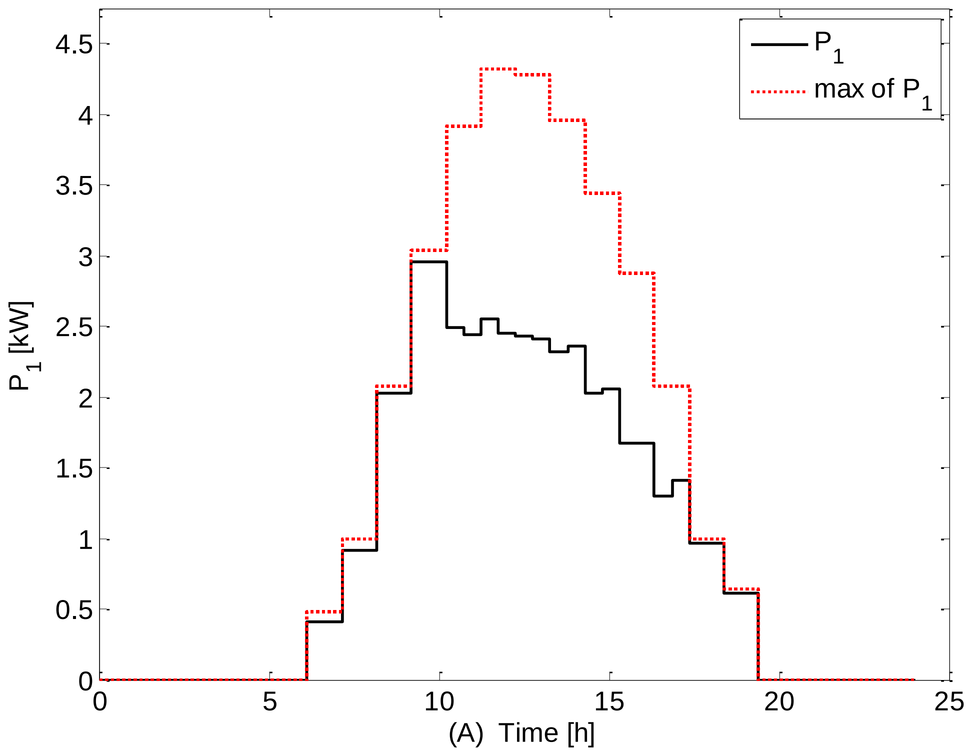

Figure 4.3: Photovoltaic output power & power supplied to the load during winter

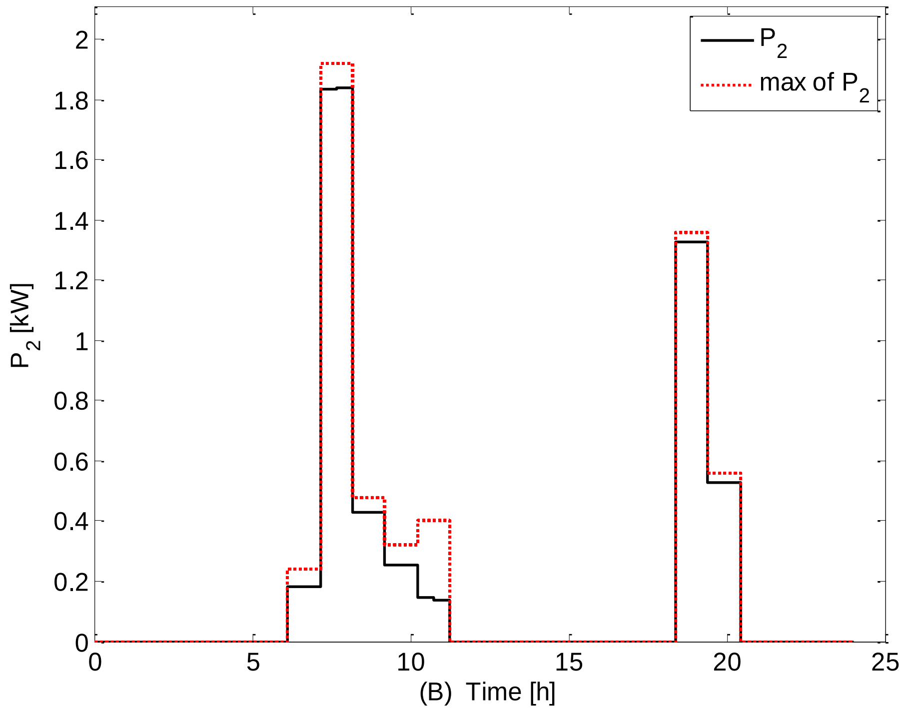

Figure 4.4: Wind turbine output power & power supplied to the load during winter

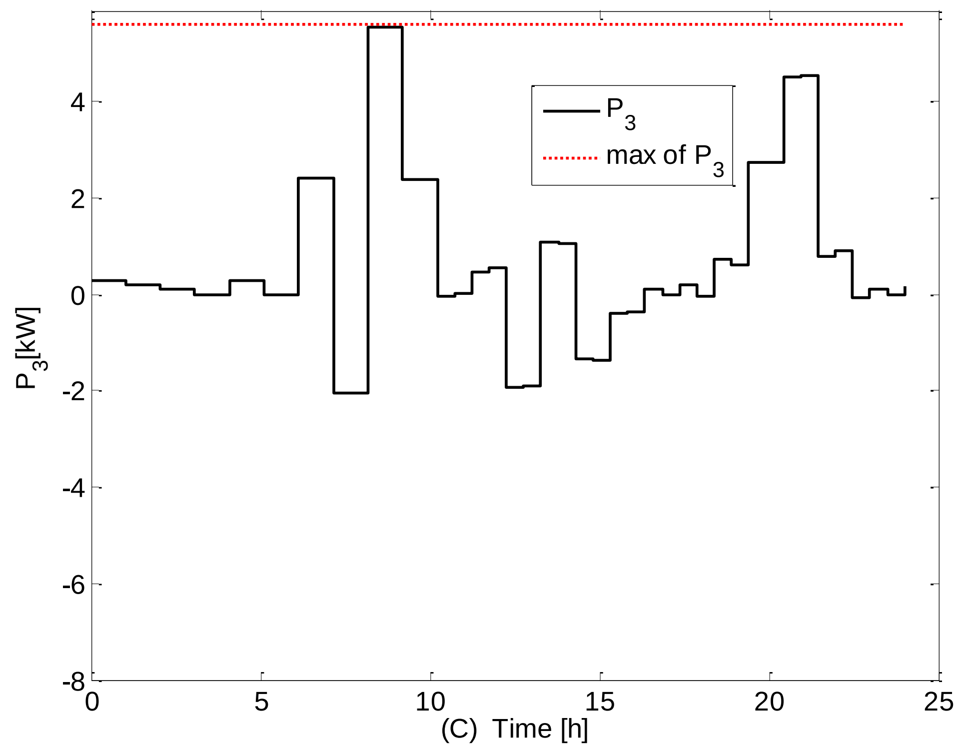

Figure 4.5: Battery output power & power supplied to the load during winter

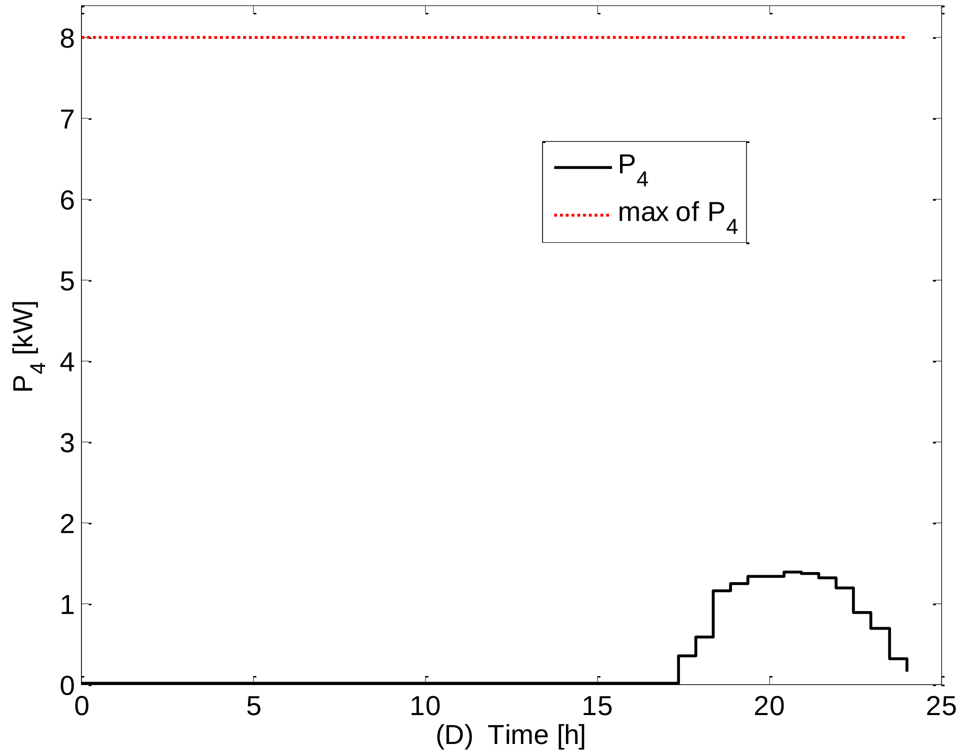

Figure 4.6: Diesel generator output power & power supplied to the load during winter

- Power from different sources to the battery system

Figures 4.6 to 4.8 indicate the power from PV, DG and WT used to recharge the battery system.

From Figures 4.6 and 4.7, it can be seen that when power produced by the renewable energy sources is more than the power required by the load, the excess is used to recharge the battery.

From Figure 4.6, it can be noticed that the PV is the source that contributes more to recharging the battery than WT. As indicated in the figure 4.7, the WT contributes very little to the recharging of the battery.

Figure 4.8 below indicates that for a continuous operation mode, the diesel generator output power is not used to recharge the battery as its output is controlled to supply only the deficit of power from other power sources required by the load.

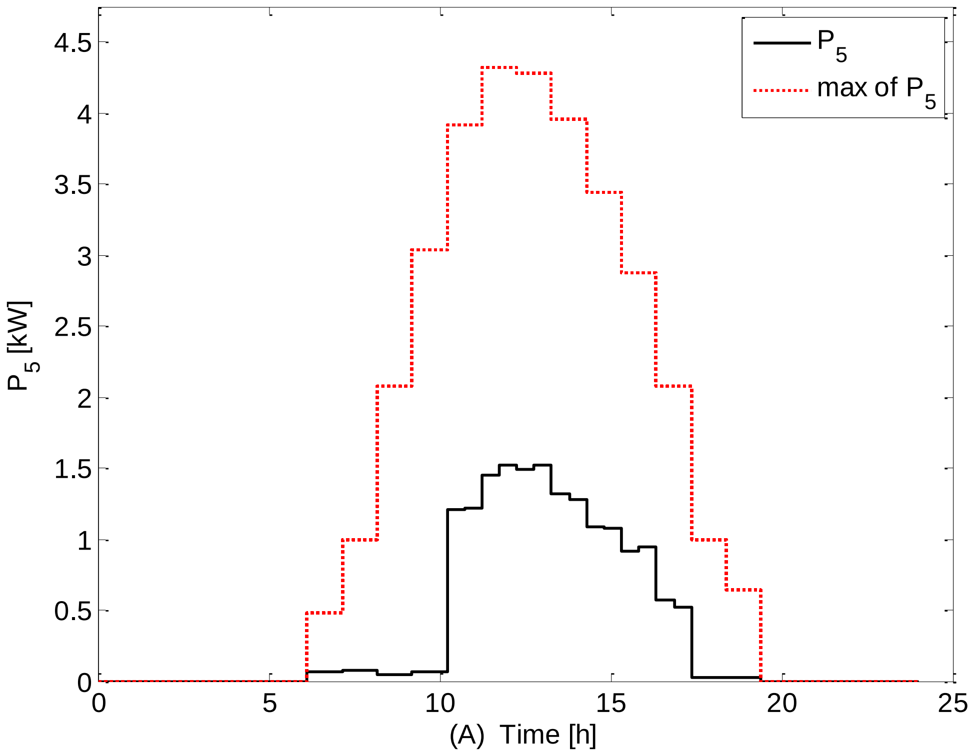

Figure 4.7: Photovoltaic output power & power supplied to the battery during winter

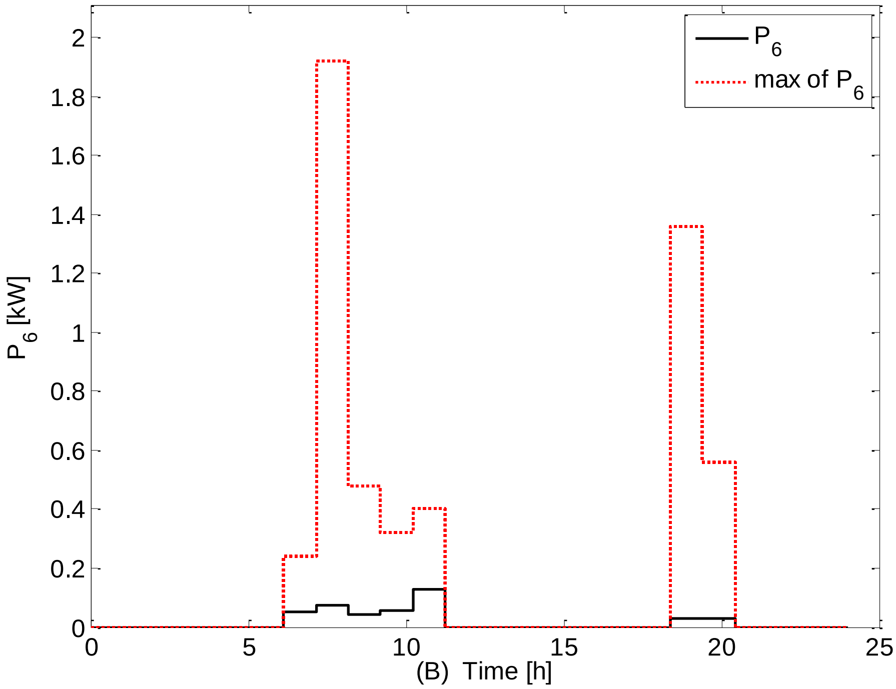

Figure 4.8: Wind turbine output power & power supplied to the battery during winter

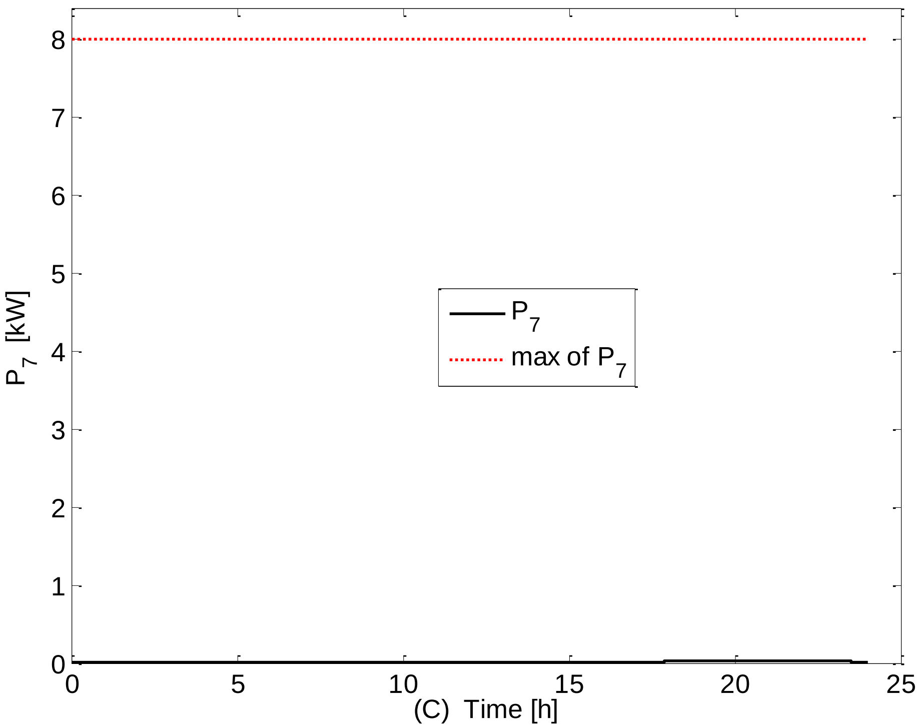

Figure 4.9: Diesel generator output power & power supplied to the battery during winter

- Battery SOC dynamic

Figure 4.9 below shows that the battery state-of-charge operates within acceptable boundaries with the minimum being 40% and the maximum being 95%.

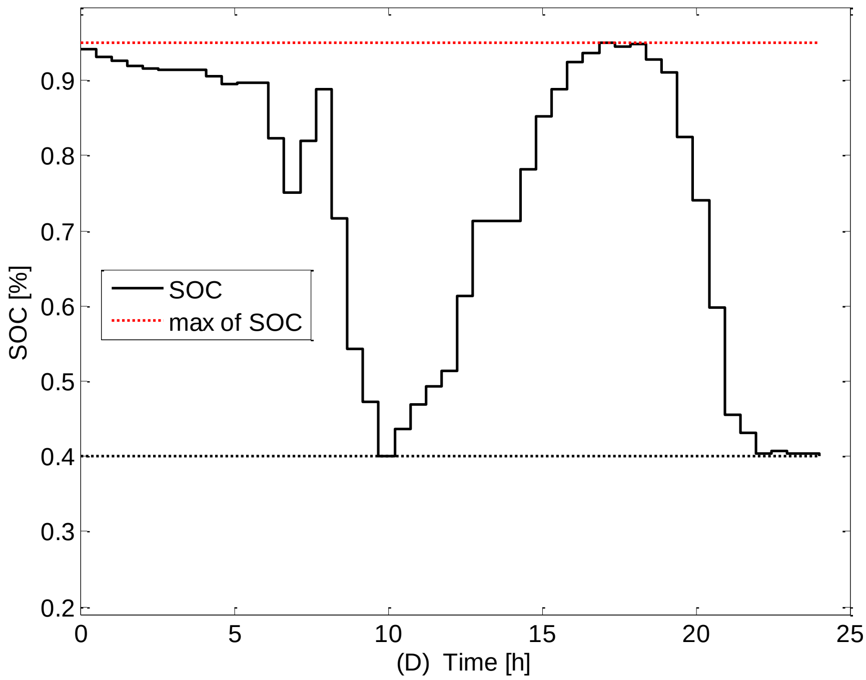

Figure 4.10: Battery SOC dynamic

The simulation results show that during the winter the diesel generator runs for 7 hours and the highest output power that it supplies to the load does not exceed 30% of its rated capacity, therefore its fuel consumption is minimized.

b) 24 Hourly load supplied by a stand-alone diesel generator only (Winter)

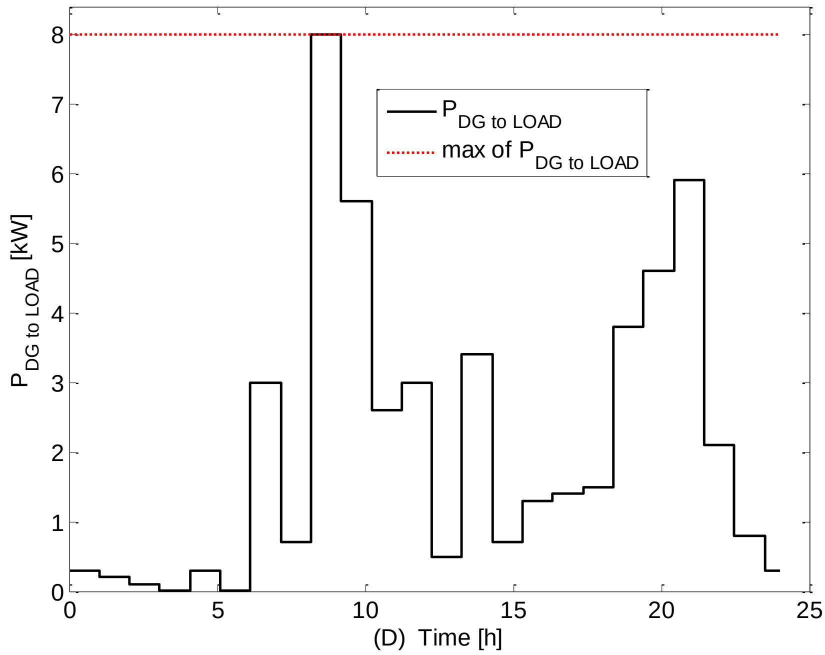

Figure 4.11: Standalone diesel generator output power supplied to load during winter

The Figure 4.10 above illustrates the output power supplied by the DG when used as a stand-alone to supply the full load of the household during a 24-hour period. It can be seen that the DG works almost 24 hours and during peak times, it has to generate the highest power load required. This illustration of running the DG alone to supply the full load required by a household will help in determining the cost required for such a household and this can be compared with a case which the DG is used in combination with renewable sources.

c) Daily operational cost summary of the continuous operation mode

The table below reflects a comparison of costs of running a household with a stand-alone diesel generator and running the same household with a hybrid power system in which the diesel generator is used as back-up to the system and controlled using a continuous operation strategy. The actual daily fuel expense can be determined by multiplying the diesel price ($/L) by the amount of fuel used (L/day). The table below demonstrates that the fuel consumption is directly proportional to the power supplied by the diesel generator and the running time of this generator. The table indicates that more fuel can be saved by introducing a hybrid system instead of running a stand-alone diesel generator to supply the load.

Table 4.1 below also indicates that more fuel is consumed during winter than summer; this is due to the household's summer power requirement being less than that required during winter.

Table 4.3: Continuous mode fuel savings

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	28.26L	22.6$	19.23L	15.39$
Hybrid system	3.55L	2.84$	0.36L	0.29$
Savings	24.71L	19.78$	18.87L	15$
Savings %	87.5%	87.5%	98%	98%

4.4. Summary

In this chapter, the mathematical models of continuous operation mode have been developed and presented. The developed model has been simulated using fmicon syntax in Matlab. The simulated results have been presented and discussed. The simulation results have indicated how the cost can be minimized by controlling the use of the diesel generator in the hybrid systems using continuous operation mode.

Chapter V: Proposed optimization using ON/OFF operation mode

5.1. Introduction

In this chapter the proposed ON/OFF operation model is presented including a detailed algorithm of the optimization. Here the objective function and variables of the model will be outlined, the detailed algorithm will be presented and simulated in Matlab, and the results of the simulation will be discussed.

5.2. Model development

5.2.1. Power flow layout

From figure 5.1 the following variables can be explained:

$\mathbf{P_1}$ is the control variable representing power flow from the PV to the load at any sampling interval (j) (kW);

$\mathbf{P_2}$ is the control variable representing power flow from the WT to the load at any sampling interval (j) (kW);

$\mathbf{P_3}$ is the control variable representing power flow from the battery to the load at any sampling interval (j) (kW);

$\mathbf{P_4}$ is the control variable representing power flow from the PV to the Bat at any sampling interval (j) (kW);

P_5 is the control variable representing power flow from the WT to the Bat at any sampling interval (j) (kW);

S is the control variable representing the switch that controls the state of the diesel generator; **S** can take two values either “0” or “1”;

P_{DGmax} is the rated power from the DG to the load or battery that depends on the state of the switch;

P_L is the load demand at any sampling interval (j) (kW).

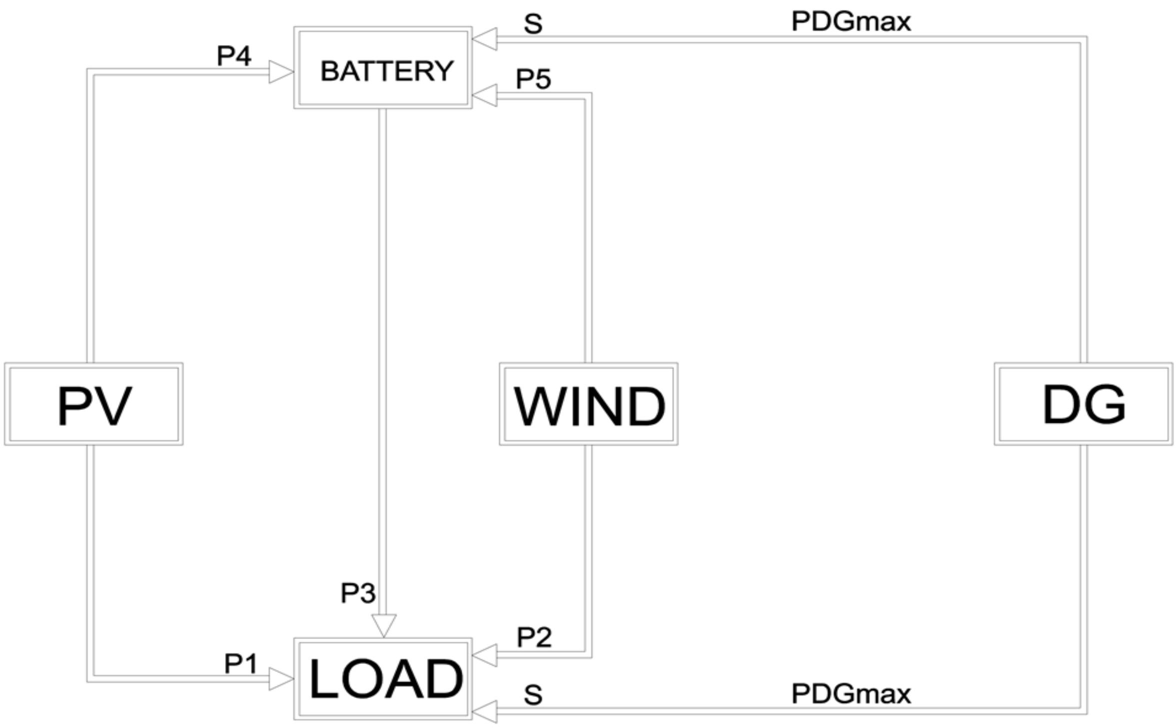

Figure 5.1: System model power flow

The model proposed consists of the integration of different power sources. The model includes: photovoltaic, wind turbine, diesel generator and battery storage systems as shown in figure 5.1. The load demand in the model is primarily met by the sum of the power from photovoltaic (P_1) and wind turbine (P_2) and the battery (P_3) starts discharging within its operating limits as soon as the (P_1) and (P_2) do not meet the demand. If the sum of the power from the PV and WT is above the load demand, the excess of power is used to recharge the battery (P_4 & P_5) (a dump load can be used to dissipate this power in the case where the RE generation exceeds the load and the required power to recharge the battery). When the sum of the power from PV, WT and battery (P_1, P_2 & P_3) cannot respond to the requirement of the load, the generator is switched on and, when sum of P_1, P_2 and P_3 is above the P_L, the generator is switched off. When the DG is on, it runs at its rated power and the excess power is used to recharge the battery. The power of the DG can only take two values, either zero or rated power. The switch "S" dictates the state of the DG that can be either on or off.

5.2.2. System modeling

The proposed optimization problem will be simulated in a 24-hour period divided into equal intervals "**N**" with sampling interval "Δ***t*"**.

The number of sampling interval will be limited to "**N=2**" for modelling purposes, then the expression of the objective function and of the different constraints of the system can be summarized into canonical forms required by the solver.

The variable "***x***" will be the only variable in the MatLab code to be developed. Therefore, the output power from different sources of the system have to be expressed in functions of the variable "***x***".

The following allocations have been made:

$$S = x(1:N) = [x_1, x_2] \tag{5.1}$$

$$P_1 = x(N+1:2N) = [x_3, x_4] \tag{5.2}$$

$$P_2 = x(2N+1:3N) = [x_5, x_6] \tag{5.3}$$

$$P_3 = x(3N+1:4N) = [x_7, x_8] \tag{5.4}$$

$$P_4 = x(4N+1:5N) = [x_9, x_{10}] \tag{5.5}$$

$$P_5 = x(5N+1:6N) = [x_{11}, x_{12}] \tag{5.6}$$

5.2.3. Objective function of the system

The object function of this mode of operation is to minimize the fuel consumption cost of the diesel generator from the system during operational time, in the meantime responding to the power requirement of the load.

In the ON/OFF operation mode, the DG is still used as a back-up to the system as a continuous operation mode to supply the deficit of power from other sources required by the load. In this case, the DG is forced to run at its rated capacity to back up the system and the excess power can be used to recharge the battery contrary to continuous mode. Here the DG can be either on or off. The main aim here is to establish the right time to switch DG either on or off, without compromising the load requirement so that fuel consumption can be minimized.

The objective function is expressed as:

$$\min C_f \sum_{j=1}^{N} (aP^2{}_{DG\max} + bP_{DG\max} + c) \times S_{(j)} \tag{5.7}$$

Where: a, b, c are the parameters related to any DG's fuel consumption curve (available from the manufacturer); C_f is the price of one litre of diesel fuel; $P_{DG\max}$ is the rated power from the DG, and $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1. $S_{(j)} = 0$ means that the DG is switched off during the j^{th} sampling interval, while $S_{(j)} = 1$ means that the DG is switched on. The output power of the DG is therefore constant.

5.2.4. Constraints

The different constraints on the operation are as follows:

- Power balance

At any sampling interval "j", the sum of the supplied power (control variables) P_1, P_2, P_3 and $P_{DG\max} \times S_{(j)}$ from different power sources must be equal to the power required by the load. This can be expressed as:

$$P_{DG\max} S_{(j)} + P_{1(j)} + P_{2(j)} + P_{3(j)} = P_{L(j)} \tag{5.8}$$

- Control Variable limits

The $P_{1(j)}$ & $P_{4(j)}$ from Photovoltaic and $P_{2(j)}$ & $P_{5(j)}$ from Wind Turbine are modelled as control variable power sources controllable in the range of zero to their maximum power, and $S_{(j)}$ is a discrete-switching function that takes the value of either 0 or 1 and $P_{3(j)}$ from the battery is modelled as control variable controllable in the range of zero or minimum to its rated power for the 24-hour period. Therefore, the variable limits are the output limits of these different power sources as well as of the battery storage system at any sampling interval (j) . These constraints depend on the characteristics of each power source and can be expressed as:

$$0 \leq P_{1(j)} \leq P_1^{\max} \quad (1 \leq j \leq N) \tag{5.9}$$

$$0 \leq P_{2(j)} \leq P_2^{rated} \quad (1 \leq j \leq N) \tag{5.10}$$

$$0 \leq P_{3(j)} \leq P_3^{rated} \quad (1 \leq j \leq N) \tag{5.11}$$

$$0 \leq P_{4(j)} \leq P_4^{\max} \quad (1 \leq j \leq N) \tag{5.12}$$

$$0 \leq P_{5(j)} \leq P_5^{\max} \quad (1 \leq j \leq N) \tag{5.13}$$

Where: $P_1^{\max}, P_2^{\max}, P_4^{\max}$ & $P_5^{\max}$ is the maximum value of a given renewable power source at any sampling interval (j) and

P_3^{rated} is the rated power of the battery system.

- Battery state of charge

The available battery state-of-charge in any sampling internal (j) must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state-of-charge. This can be expressed as:

$$SOC^{\min} \leq SOC_{(j)} \leq SOC^{\max} \tag{5.14}$$

$$SOC_{(j)} = SOC_{(0)} + \frac{\eta_C \times \Delta t}{E_{nom}} \sum_{j=1}^{N} (P_{4(j)} + P_{5(j)} + P_{DG\max} S_{(j)}) - \sum_{j=1}^{N} P_{3(j)} \times \frac{\Delta t}{\eta_D \times E_{nom}} \tag{5.15}$$

Where: $SOC^{\min}$ and $SOC^{\max}$ are respectively, the minimum and maximum of the battery state of charge.

5.2.5. Proposed optimization solver and algorithm

The objective function has to be modelled as a function of the switch controlling the DG and the variable battery output power. This mixed-integer optimization problem can be solved using the “Intlinprog” function from MatLab Optimization toolbox.

$$\min_{x} \ f^T(x) \text{ Subject to: } \begin{cases} x(intcon) \\ A.x \le b \\ A_{eq}.x = b_{eq} \\ l_b \le x \le ub \end{cases} \tag{5.16}$$

Where f, x, intcon, b, b_{eq}, l_b and u_b are vectors; A and A_{eq} are matrices.

5.2.6. Objective function definition in Intlinprog syntax

The objective function is to minimize the fuel consumption cost of the DG during operational time, and this can be expressed as follows:

$$\min \ FC = \Delta t \times \sum_{j=1}^{N} \{(aP_{DG\max}^2 + bP_{DG\max} + c) \times S_{(j)} \tag{5.17}$$

$$\min \ \Delta t \sum_{j=1}^{N} [(a * P_{DG\max}^2 + b * P_{DG\max} + c) * x(1:N)] \tag{5.18}$$

$$\min \ \Delta t \sum_{j=1}^{N} [k * x(1:N)] \tag{5.19}$$

Where $k = a * P^2{}_{DG\max} + b * P_{DG\max} + c$ (5.20)

Where: j is the sampling interval.

5.2.7. Constraints definition in Intlinprog syntax

- Power balance

The power balance at any j^{th} sampling interval can be expressed as:

$$P_{DG\max} S_{(j)} + P_{1(j)} + P_{2(j)} + P_{3(j)} = P_{L(j)} \tag{5.21}$$

As $N = 2$, the power balance can be developed for these two sampling intervals as:

For:

$$j = 1 \rightarrow P_{DG\max} x_1 + x_3 + x_5 + x_7 = P_{L1} \tag{5.22}$$

$$j = 2 \rightarrow P_{DG\max} x_2 + x_4 + x_6 + x_8 = P_{L2} \tag{5.23}$$

Taking the coefficient of the equations, the system can be rewritten in a matrix form as:

$$\begin{pmatrix} P_{DG\max} & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & P_{DG\max} & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ . \\ . \\ . \\ x_{12} \end{pmatrix} = \begin{pmatrix} P_{L1} \\ P_{L2} \end{pmatrix} \tag{5.24}$$

Using the canonical formulation of the linear equality constraints in Intlinprog, the power balance can be finally expressed as:

$$Aeq = [P_{DG\max} * eye(N,N), eye(N,N), eye(N,N), eye(N,N), zeros(N,N), zeros(N,N)] \tag{5.25}$$

$$b_{eq} = P_L(1:N) \tag{5.26}$$

- Linear inequality

❖ Linear inequality for battery bank

The available battery bank state-of-charge in any sampling internal must not be less than the minimum allowable state-of-charge and must not be higher than the maximum allowable state-of-charge. This can be expressed as

$$SOC^{\min} \le SOC_{(j)} \le SOC^{\max} \tag{5.27}$$

$$SOC^{\min} \le SOC_{(0)} + \frac{\eta_C \times \Delta t}{E_{nom}} \sum_{j=1}^{N} (P_{DG\max} S_{(j)} + P_{4(j)} + P_{5(j)}) - \sum_{j=1}^{N} P_{3(j)} \times \frac{\Delta t}{\eta_D \times E_{nom}} \le SOC^{\max} \tag{5.28}$$

Where E_{nom} is the nominal energy from the battery system, and $\eta_C \,\&\, \eta_D$ the efficiencies of the battery system (during charging and discharging).

This expression can be rewritten as:

$$SOC^{\min} \le SOC_{(0)} + d \sum_{j=1}^{N} (P_{DG\max}\ S_{(j)} + P_{4(j)} + P_{5(j)}) - \sum_{j=1}^{N} P_{3(j)} \times e \le SOC^{\max} \tag{5.29}$$

Where:

$$d = \frac{\eta_C \times \Delta t}{E_{nom}} \tag{5.30}$$

$$e = \frac{\Delta t}{\eta_D \times E_{nom}} \tag{5.31}$$

- Dealing with maximum inequality $(SOC^{\max})$

For $j = 1$

$$SOC_{(0)} + d(P_{DG\max} x_1 + x_9 + x_{11}) - ex_7 \le SOC^{\max} \tag{5.32}$$

For $j = 2$

$$SOC_{(0)} + d(P_{DG\max} x_1 + P_{DG\max} x_2 + x_9 + x_{10} + x_{11} + x_{12}) - ex_7 - ex_8 \le SOC^{\max} \tag{5.33}$$

Then

$$dP_{DG\max} x_1 + dx_9 + dx_{11} - ex_7 \le SOC^{\max} - SOC_{(0)} \tag{5.34}$$

$$P_{DG\max} dx_1 + P_{DG\max} dx_2 + dx_9 + dx_{10} + dx_{11} + dx_{12} - ex_7 - ex_8 \le SOC^{\max} - SOC_{(0)} \tag{5.35}$$

- Dealing with minimum inequality $(SOC^{\min})$

For $j = 1$

$$SOC^{\min} \leq SOC_{(0)} + d(P_{DG\max} x_1 + x_9 \ + x_{11} \ ) - ex_7 \tag{5.36}$$

The above expression can also be written as:

$$-dP_{DG\max} x_1 - dx_9 \ - dx_{11} \ + ex_7 \leq SOC_{(0)} - SOC^{\min} \tag{5.37}$$

For $j = 2$

$$SOC^{\min} \leq SOC_{(0)} + d(P_{DG\max} x_1 + P_{DG\max} x_2 + x_9 + x_{10} \ + x_{11} + x_{12} \ ) - ex_7 - ex_8 \tag{5.38}$$

The above expression can also be written as:

$$-P_{DG\max} dx_1 - P_{DG\max} dx_2 - dx_9 \ - dx_{10} - dx_{11} - dx_{12} \ + ex_7 + ex_8 \leq SOC_{(0)} - SOC^{\min} \tag{5.39}$$

- Linear inequality for PV

$$P_{1(j)} + P_{4(j)} \leq P_{PV}{}^{\max} \tag{5.40}$$

For $j = 1$

$$x_3 + x_9 \leq P_{PV1}{}^{\max} \tag{5.41}$$

For $j = 2$

$$x_4 + x_{10} \le P_{PV2}^{\max} \tag{5.42}$$

- ❖ Linear inequality for WT

$$P_{5(j)} + P_{11(j)} \le P_{WT}^{\max} \tag{5.43}$$

For $j = 1$

$$x_6 + x_{12} \le P_{WT1}^{\max} \tag{5.44}$$

For $j = 2$

$$x_4 + x_{12} \le P_{WT2}^{\max} \tag{5.45}$$

Taking the coefficient of the equations, the system can be rewritten in a matrix form as:

$$\begin{pmatrix} dP_{DG\max} & 0 & 0 & 0 & 0 & 0 & -e & 0 & d & 0 & d & 0 \\ dP_{DG\max} & dP_{DG\max} & 0 & 0 & 0 & 0 & -e & -e & d & d & d & d \\ -dP_{DG\max} & 0 & 0 & 0 & 0 & 0 & e & 0 & -d & 0 & -d & 0 \\ -dP_{DG\max} & -dP_{DG\max} & 0 & 0 & 0 & 0 & e & e & -d & -d & -d & -d \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \\ x_{11} \\ x_{12} \end{pmatrix} \le \begin{pmatrix} SOC^{\max} - SOC_0 \\ SOC^{\max} - SOC_0 \\ SOC_0 - SOC^{\min} \\ SOC_0 - SOC^{\min} \\ P_{PV1}^{\max} \\ P_{PV2}^{\max} \\ P_{WT1}^{\max} \\ P_{WT2}^{\max} \end{pmatrix} \tag{5.46}$$

Using the canonical formulation of the linear inequality constraints in Intlingprog, this can be finally expressed as:

$$A_1 = \begin{bmatrix} d * P_{DG\max} * tril(ones(N,N)), zeros(N,N), zeros(N,N), -e * tril(ones(N,N)), \\ d * tril(ones(N,N)), d * tril(ones(N,N)) \end{bmatrix} \tag{5.47}$$

$$A_2 = -A_1 \tag{5.48}$$

$$A_3 = [zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N)] \tag{5.49}$$

$$A_4 = [zeros(N,N), zeros(N,N), eye(N,N), zeros(N,N), zeros(N,N), eye(N,N)] \tag{5.50}$$

$$A = [A_1; A_2; A_3; A_4] \tag{5.51}$$

$$b_1 = (SOC^{\max} - SOC_0) * ones(N,1) \tag{5.52}$$

$$b_2 = (SOC_0 - SOC^{\min}) * ones(N,1) \tag{5.53}$$

$$b_3 = P_{PV}{}^{\max}(1:N) \tag{5.54}$$

$$b_4 = P_{WT}{}^{\max}(1:N) \tag{5.55}$$

$$b = [b_1; b_2; b_3; b_4] \tag{5.56}$$

- Variable boundaries

These boundaries represent the upper and lower limits of outputs from each power source as well as of the battery storage system for each j^{th} sampling time.

$$lb \le x \le ub \quad (5.57)$$

These can be expressed for each j^{th} sampling interval as:

$$0 \le P_{1(j)} \le P_1^{\max} \quad (5.58)$$

$$0 \le P_{2(j)} \le P_2^{rated} \quad (5.59)$$

$$-P_3^{\min} \le P_{3(j)} \le P_3^{\max} \quad (5.60)$$

$$0 \le P_{4(j)} \le P_4^{rated} \quad (5.61)$$

$$0 \le P_{5(j)} \le P_5^{\max} \quad (5.62)$$

❖ Lower boundaries

The change of minimum values that each power source can produce different time intervals is "zero"; however, for the specific case of the battery system, this value "$-P_3^{rated}$" is the maximum power entering the battery while charging. The system's lower boundaries change can be expressed in vector forms as follows:

$$lb_1 = P_1^{\min} * ones(N,1) \tag{5.63}$$

$$lb_2 = P_2^{\min} * ones(N,1) \tag{5.64}$$

$$lb_3 = -P_3^{\max} * ones(N,1) \tag{5.65}$$

$$lb_4 = P_4^{\min} * ones(N,1) \tag{5.66}$$

$$lb_5 = P_5^{\min} * ones(N,1) \tag{5.67}$$

$$lb = [lb_1; lb_2; lb_3; lb_4; lb_5] \tag{5.68}$$

- ❖ Upper boundaries

The change of maximum values that each renewable source can produce different time intervals is "$P_{i(j)}^{\max}$", which depends on the availability of the renewable resources. However, for the specific case of the battery system, this value is its maximum rated value "P_3^{rated}". The system's upper boundaries change can be expressed in vector forms as follows:

$$ub_1 = P_1^{\max}(1:N) \tag{5.69}$$

$$ub_2 = P_2^{\max}(1:N) \tag{5.70}$$

$$ub_3 = P_3^{\max} * ones(N:1) \tag{5.71}$$

$$ub_4 = P_4^{\max}(1:N) \tag{5.72}$$

$$ub_5 = P_5^{\max}(1:N) \tag{5.73}$$

$$ub = [ub_1; ub_2; ub_3; ub_4; ub_5] \tag{5.74}$$

5.2.8. Final model of ON/OFF operation mode

The final model of the ON/OFF operation of the system will be a MatLab code that any user can use by changing the technical input data. The user will be able to introduce his own load profiles, the capacity of the diesel generator, the battery state-of-charge, the profile of the photovoltaic and wind turbine. The final model developed will be able to optimize the operation of the system by minimizing the consumption of the diesel generator, therefore minimizing the cost.

5.3. Simulation results and discussions

5.3.1. General description

At this point, the ON/OFF operation mode is simulated using MatLab function and the simulation results are discussed. As indicated under the objective function, the aim of the simulation is to show how the diesel generator's fuel consumption can be minimized using the ON/OFF control strategy developed.

5.3.2. Simulation and discussion results during winter

a) 24 Hour Load Supplied by the Hybrid System during winter

- Load profile

Figure 5.2 indicates the load profile of the household during winter. From the figure it can be seen that from 22:00 to 6:00 in the morning, the load demand is minimum. The load starts picking up after 6:00 in the morning and reaches its maximum demand between 8:00 and 9:00, after 9:00 it starts decreasing up to 17:00 in the evening. The load is high again around 22h at night.

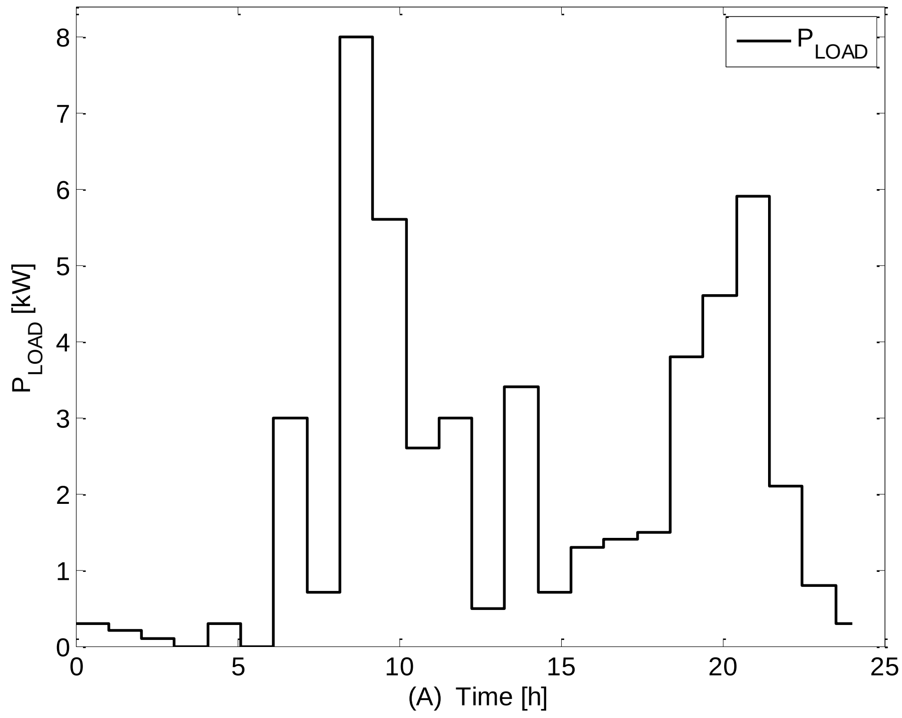

Figure 5.2: Household 24-hr load profile during winter

- Power from different sources to the load

Figures 5.3 to 5.5 indicate the power flow from different power sources to the loads

At midnight and early in the morning, the power requirement of the household is very low, so only the battery is used to respond to the load demand, and the diesel generator is off. The renewable energy output power figures are zeros as they are not able to generate at that time.

After 6:00, the load starts picking up as shown in figure 4.1, and in the meantime the renewable energy sources start to generate and the household power requirement is met by the combinations of output power from PV, WT and battery while the DG still off.

From 8:00 to 9:00 in the morning, the load reaches its peak demand and the sum of the outputs power from PV, WT and battery is able to respond to the high load demand, while the DG is still off. The renewable energy sources generate more energy at this time and there is no need for the DG to run.

From 9:00 to 10:00, the household load demand starts dropping, the PV power generation increases, and the load requirement is met by the sum of the output power from PV, WT and battery and there is no need to run the DG.

From 10:00 to 18:00, the load demand is low while the PV generates a lot of power. The power generated is used to supply the load and the excess power is used to recharge the battery. Between 18:00 and 20:00, the load demand starts picking up as it is likely that the WT starts generating again. The sum of the output power from PV, WT and battery is sufficient to respond to the load demand.

Between 20:00 and 21:00, the household load demand again reaches again its peak, and at this time the renewable energy sources (PV and WT) are no longer generating any power, and as the battery itself also cannot respond to the requirement of the high load demand, the generator is switched on to back up the system. The DG is run at its rated power to supply the load and the excess power from DG is used to recharge the battery.

Between 21:00 and midnight the load demand is low again, the renewable energy sources are no longer generating power and the load demand is met by the output power from the battery only and the diesel generator is switched off.

From the simulation results, it can be noticed that the PV is the main component of the system and is the one that most influences the running costs of the system. The PV also contributes more to recharging the battery as during the day when the PV produces more output power, the load demand is at a minimum and the excess power produced is accumulated in the battery.

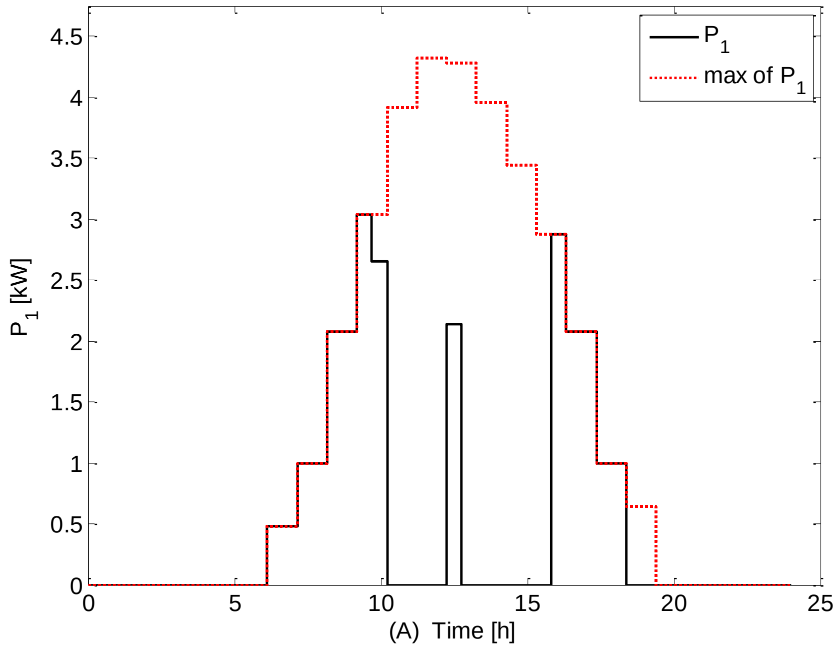

Figure 5.3: PV output power & power supplied to the load during winter

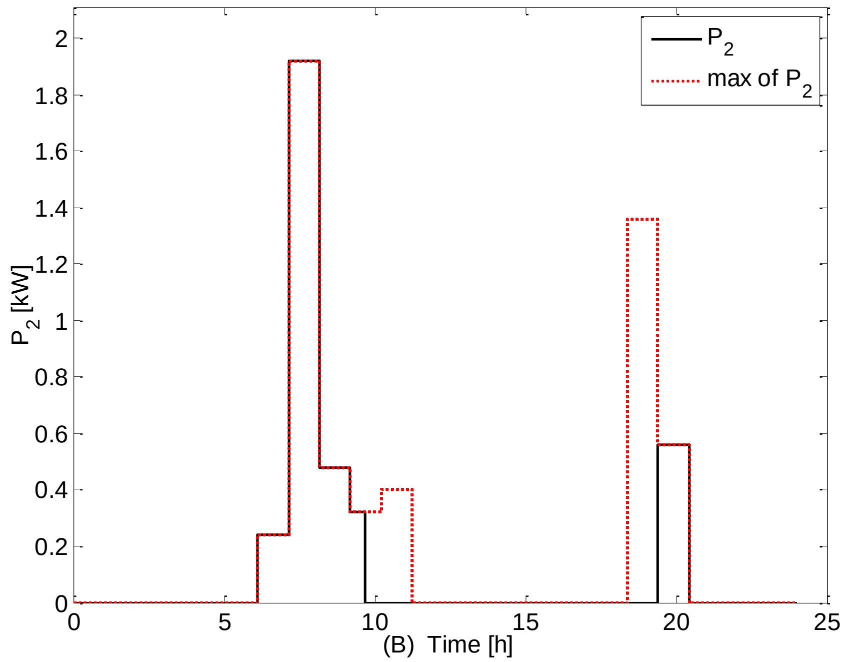

Figure 5.4: Wind turbine output power & power supplied to the load during winter

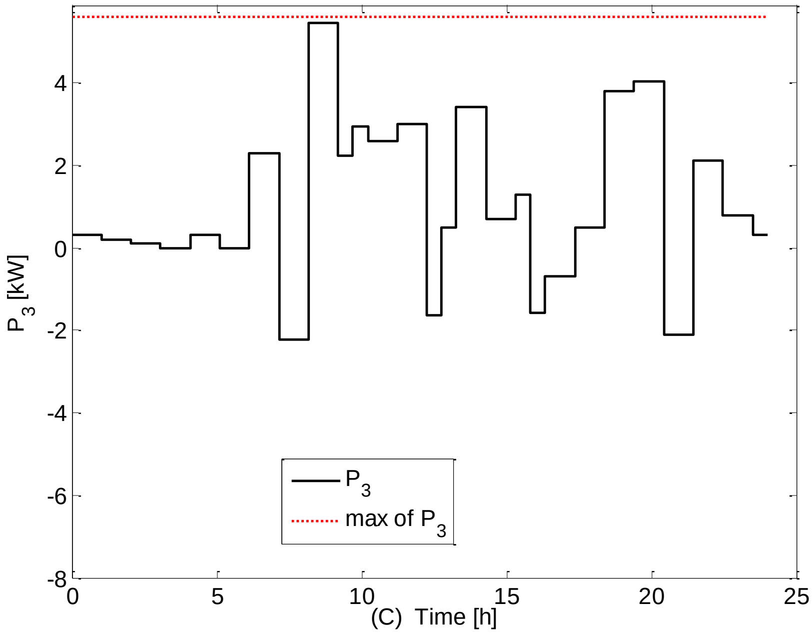

Figure 5.5: Battery output power & power supplied to the load during winter

- DG ON/OFF state

The Figure 5.6 below indicates the ON/OFF state of the DG during a 24hr period. From the figure, it can be noticed that, the generator is off most of the time and it runs only for one hour (between 20:00 and 21:00), when the PV and WT cannot generate any longer and the battery is low. However, when the generator runs, it is forced to run at its rated capacity to respond to the high requirement of the load.

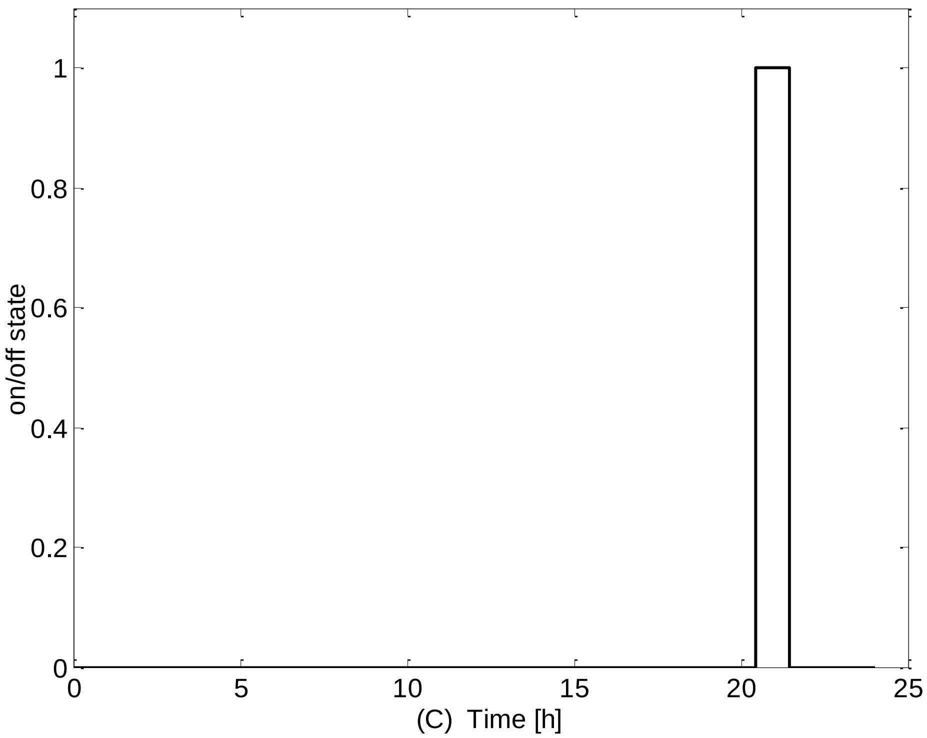

Figure 5.6: ON/OFF state of DG during winter

- Power from different sources to the battery system

Figures 5.7 and 5.8 indicate the power from the PV and WT used to recharge the battery system. From Figures 5.7 and 5.8, it can be seen that when power produced by the renewable energy sources is more than the power required by the load, the excess is used to recharge the battery. From Figure 5.7, it can be noticed that the PV contributes more recharging the battery than the WT. As indicated in the figure 5.8, the WT contribute very little to the recharging of the battery.

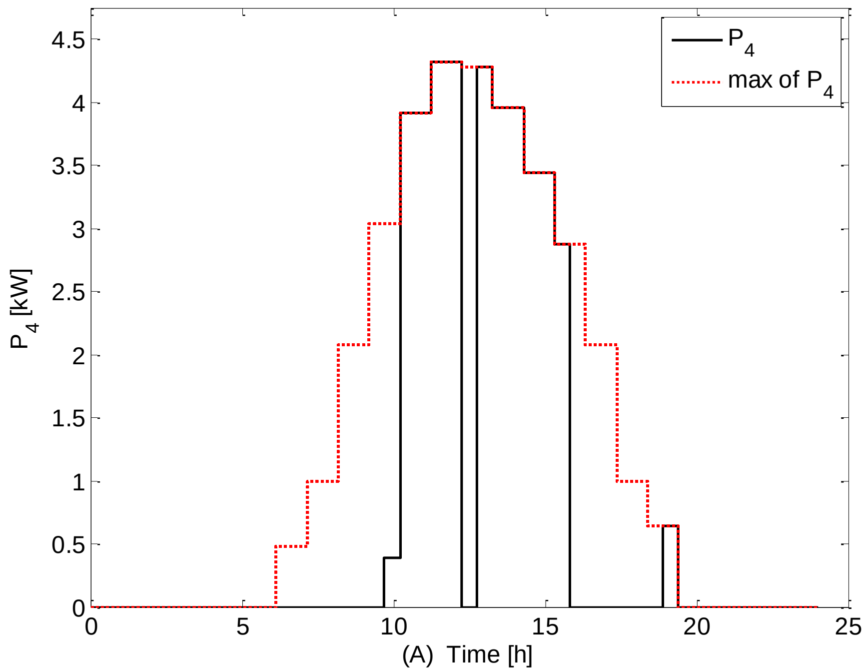

Figure 5.7: PV output power & power supplied to the battery during winter

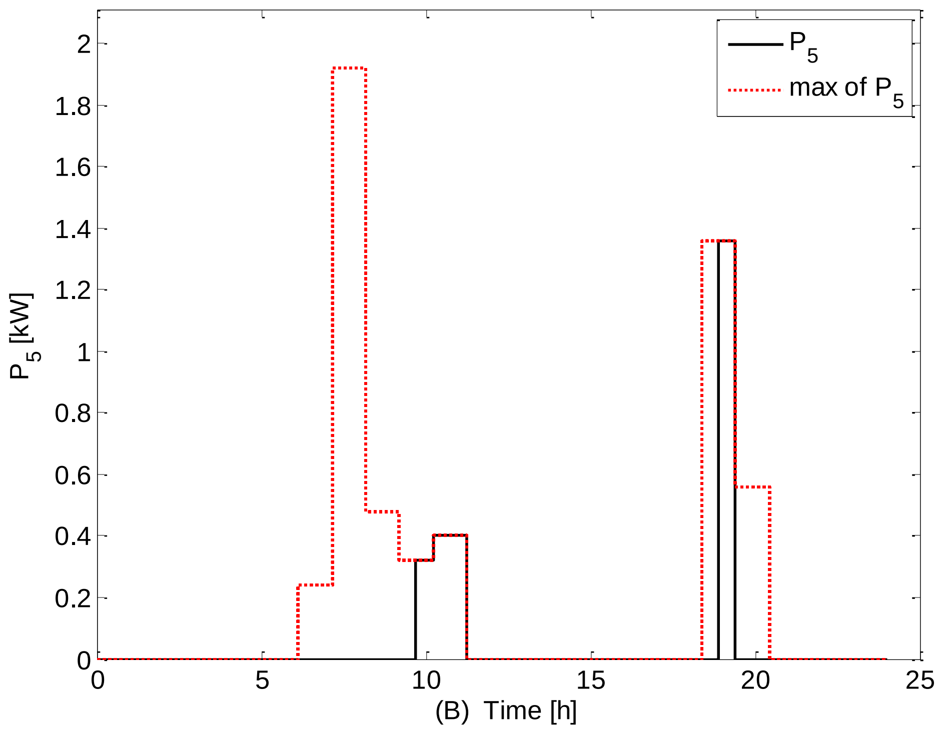

Figure 5.8: WT output power & power supplied to the battery during winter

* Battery SOC dynamic

The Figure 5.9 below shows that the battery state-of-charge operates within the acceptable boundaries, with the minimum being 40% and the maximum being 95%. It can also be noticed that, between 20:00 and 21:00, the SOC is very high, which indicates that the excess power from the DG is used to recharge the battery. At this time, the battery is not generating but is accumulating excess power from the DG.

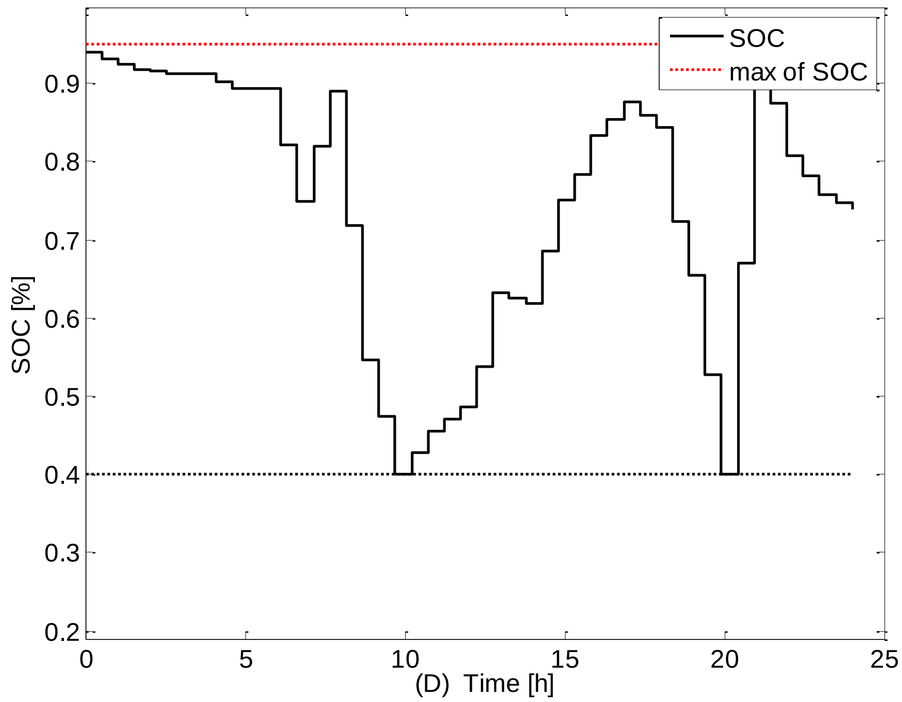

Figure 5.9: Battery SOC dynamic

b) Daily operation cost summary of ON/OFF operation mode

The table below indicates the comparative cost between running a household with a stand-alone diesel generator and running the same household with hybrid power system where in the diesel generator is used as back-up to the system and controlled using ON/OFF operational strategy. The actual daily fuel expense can be determined by multiplying the diesel price ($/L) by the litres of fuel used (L/day). The table below demonstrates that the fuel consumption is directly proportional to the power supplied by the generator and the running time of the diesel generator. The table indicates that more fuel can be saved by introducing hybrid in the system instead of running a stand-alone diesel generator to supply the load.

Table 5.1 below also indicates that more fuel is consumed during winter than in summer, which is due to the household's summer power requirement being less than that required during winter.

Table 5.1: ON/OFF mode daily fuel cost savings

	Winter		Summer	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	28.26L	22.6$	19.23L	15.39$
Hybrid system	5.01L	4$	2.5L	2$
Savings	23.25L	18.6$	16.73L	13.35$
Savings %	82.2%	82.2%	87%	87%

c) Daily operational cost summary of continuous and ON/OFF operation modes

The two tables below highlight the comparison between the two control strategies developed (continuous operation mode and ON/OFF operation mode) during winter and summer. The table indicates which one of the control strategies provides more cost savings regarding the use of the diesel generator in hybrid systems. The table indicates that during the continuous operation mode, the diesel generator runs for a longer time but its output is very limited, hence less fuel is used as the fuel consumption of the diesel generator is directly proportional to the output power it generates. The tables below also indicate that there are more cost savings in summer than in winter. By using a continuous operation mode during summer one can save 11% more than when using an ON/OFF operation mode and there are savings of 5.3% when using a continuous operation mode instead of an ON/OFF operation mode.

During ON/OFF operation mode, the diesel generator runs for fewer hours than in continuous mode but more fuel is used as the DG runs at the rated power.

Table 5.2: Daily fuel cost savings in winter using different control strategies

	Continuous		ON/OFF	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	28.26L	22.6$	28.26L	22.6$
Hybrid system	3.55L	2.84$	5.01L	4$
Savings	24.71L	19.78$	23.25L	18.6$
Savings %	87.5%	87.5%	82.2%	82.2%

Table 5.3: Daily fuel cost savings in summer using different control strategies

	Continuous		ON/OFF	
	Consumption (L)	Cost ($)	Consumption (L)	Cost ($)
DG only	19.23L	15.4$	19.23L	15.4$
Hybrid system	0.36L	0.29$	2.5L	2$
Savings	18.87L	15.1$	16.73L	13.4$
Savings %	98%	98%	87%	87%

5.4. Summary

In this chapter, the mathematical models of ON/OFF operation mode have been developed and presented. The developed model has been simulated using Intlinprog syntax in Matlab. The simulated results have been presented and discussed. The results indicate how costs can be minimized by controlling the use of the diesel generator in hybrid systems using an ON/OFF operation mode to respond to the requirement of the load.

Chapter VI: Conclusion and recommendations

6.1 Conclusion

This chapter concludes the research done on the optimal control of hybrid power systems using a photovoltaic system, wind turbine system, diesel generator system and battery storage system.

There are high operational costs involved when running a diesel generator to supply a specific load due to the high quantity of fuel required and operation issues due to long running time.

To overcome the operational costs, the renewable energy can be introduced to a standalone diesel generator to form a hybrid power generation system. However the complications caused by the use of the diesel generator in the system, require careful control to ensure that there is a benefit in combining the diesel generator with other systems of power generations. The above issue of optimal operational control was the basis of this research aimed by developing control strategies that can be utilized to control the use of diesel generators in hybrid systems to achieve optimal operation of such systems by minimizing the fuel consumption of the diesel generator hence minimizing the operational costs of the systems.

To achieve the aim of this study, the different components involved in the system developed were described in chapter III to provide a background regarding their stand-alone use and their operations when combined with various other sources of energy to form hybrid power generation systems. Also in the same chapter, the data collected for the simulation of the system were presented.

In chapter IV, the continuous operation mode, which is one of the control strategies of the procedure, was developed. The layout and mathematical approaches of the system were developed. The objective function of the system was clearly presented and also all the constraints and variables. The aim of this control strategy is to control the use of the diesel generator in the hybrid system to minimize its fuel consumption and minimize the costs of the operation for the system to be affordable for rural applications. A detailed algorithm of the model was presented and simulated using a Fmincon Matlab solver. The results of the simulations were presented and analysed as well. In chapter V, the second proposed control strategy an ON/OFF operation mode was developed from mathematical to detailed algorithms with its objective function, constraints and different variables. The aim of these control strategies is similar to that of the continuous mode, in that optimal schedules for running the diesel generator without compromising the requirements of the loads that would minimize the fuel consumption and minimize the operational cost of the system were developed.

The results of the two control strategies were compared to the case in which a stand-alone diesel generator is used to supply the same load, and in addition the two control strategies were also compared to see which one of the two strategies produces highest cost savings.

The comparative tables showed that, by introducing hybrid system to a standalone diesel generator, a household could save up to 98% on the operational cost. The table also indicated that there is more cost saving when the system is controlled by using a continuous strategy rather than ON/OFF strategies. The simulation results obtained indicate that more fuel is used during winter than summer, due to the load requirement being higher in winter.

Only winter case results have been included in chapters IV and V. Results concerning summer in respect of both strategies have been included in appendixes and also in the tables indicating the power flows of the different power sources and different control strategies.

6.2 Recommendations

This research was focused on developing control strategies that can be used to implement the control of diesel generators in hybrid systems by focusing on the optimal control aspect of the system and not detailed designs of the physical components and all other aspects. To ensure proper implementation of the system, optimal design of the system needs to be considered for the full system to be optimal from the design to the operation.

The model developed in this dissertation includes only photovoltaic and wind turbine as renewable sources. Further studies should be conducted to include different additional sources to those in this research to achieve more cost savings and to minimize the use of the diesel generator almost to zero.

The aspect of running the diesel generator at loads of less than 50% of its rated capacity should be investigated for continuous control strategies, as running the diesel generator ineffectively can cause problems and reduce its lifespan.

For further research, the impacts of long running times as well as the impact of several starts and stops of the diesel generator should be investigated to find out which of the two control strategies will achieve the lowest lifecycle costs of hybrid systems.

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Appendixes

Appendix A: Selected optimal operation control program using fmicon

a) Main Code

```
deltaT=30;
hours=24;
N=hours*60/deltaT;
soc_max=0.95;
Soc_min=0.40;
soc0=0.95;
Eff_c=0.85;
Eff_d=0.95;
En=1000;
d=(deltaT*Eff_c)/En;
e=deltaT/(En*Eff_d);

PPV_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),
0*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.9
2*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),
2.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*
ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';
```

PWT_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24), 0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24), 0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';

PL=[0.3*ones(1,N/24), 0.2*ones(1,N/24), 0.1*ones(1,N/24), 0.0*ones(1,N/24), 0.3*ones(1,N/24), 0.0*ones(1,N/24), 3*ones(1,N/24), 0.7*ones(1,N/24), 8*ones(1,N/24), 5.6*ones(1,N/24), 2.6*ones(1,N/24), 3*ones(1,N/24), 0.5*ones(1,N/24), 3.4*ones(1,N/24), 0.7*ones(1,N/24), 1.3*ones(1,N/24), 1.4*ones(1,N/24), 1.5*ones(1,N/24), 3.8*ones(1,N/24), 4.6*ones(1,N/24), 5.9*ones(1,N/24), 2.1*ones(1,N/24), 0.8*ones(1,N/24), 0.3 *ones(1,N/24)];

PDG_max=8;

P1_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.92*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),2.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';

P2_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24), 0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24), 0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';

```
P3_max=5.6; P4_max=8;
P5_max=[0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0
*ones(1,N/24),0.48*ones(1,N/24),1*ones(1,N/24),2.08*ones(1,N/24),3.04*ones(1,N/24),3.92
*ones(1,N/24),4.32*ones(1,N/24),4.28*ones(1,N/24),3.96*ones(1,N/24),3.44*ones(1,N/24),2
.88*ones(1,N/24),2.08*ones(1,N/24),1*ones(1,N/24),0.64*ones(1,N/24),0*ones(1,N/24),0*o
nes(1,N/24),0*ones(1,N/24),0*ones(1,N/24),0*ones(1,N/24)]';

P6_max=8*[0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0.03*ones(1,N/24), 0.24*ones(1,N/24), 0.06*ones(1,N/24),
0.04*ones(1,N/24), 0.05*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24),
0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0.17*ones(1,N/24),
0.07*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24), 0*ones(1,N/24)]';
P7_max=8;
P1_min=0; P2_min=0; P3_min=-P3_max; P4_min=0;P5_min=0;P6_min=0;P7_min=0;

A1=[zeros(N,N),zeros(N,N),-
e*tril(ones(N,N)),zeros(N,N),d*tril(ones(N,N)),d*tril(ones(N,N)),d*tril(ones(N,N))];
A2=-A1;
A3= [eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N)];
A4= [zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N),eye(N,N),zeros(N,N)];
A5= [zeros(N,N),zeros(N,N),zeros(N,N),eye(N,N),zeros(N,N),zeros(N,N),eye(N,N)];
A=[A1;A2;A3;A4;A5];
b=[(soc_max-soc0)*ones(N,1);(soc0-
Soc_min)*ones(N,1);PPV_max(1:N);PWT_max(1:N);PDG_max*ones(N,1)];
```

```
Aeq =[eye(N,N),eye(N,N),eye(N,N),eye(N,N),zeros(N,N),zeros(N,N),zeros(N,N)];
beq=PL(1:N);
lb=[P1_min*ones(N,1);P2_min*ones(N,1);P3_min*ones(N,1);P4_min*ones(N,1);P5_min*o
nes(N,1);P6_min*ones(N,1);P7_min*ones(N,1)];
ub=[P1_max(1:N);P2_max(1:N);P3_max*ones(N,1);P4_max*ones(N,1);P5_max(1:N);P6_m
ax(1:N);P7_max*ones(N,1)];
x0=ub;

options=optimset('Algorithm','interior-point');
 optnew=optimset(options,'MaxFunEvals',90000,'Tolx',1e-8);

[x,fuel] = fmincon(@obj_moriceWinterX,x0,A,b,Aeq,beq,lb,ub,[],optnew);
%exctract different variable vectors

P_1=x(1:N);
P_2=x(N+1:2*N);
P_3=x(2*N+1:3*N);
P_4=x(3*N+1:4*N);
P_5=x(4*N+1:5*N);
P_6=x(5*N+1:6*N);
P_7=x(6*N+1:7*N);

for i=1:N
 soc(i)=soc0+d*(P_5(i)+P_6(i)+P_7(i))-e*(P_3(i));
```

```
 soc0=soc(i);
end
soc1=soc(1:N);

figure (1)
stairs(linspace(0,hours,N),PL(1:N),'k','linewidth',1.5)
ylabel('P_L_O_A_D [kW]')
axis([0 hours+1 0 1.05*max(PL)]);
xlabel('(A)  Time [h]')
legend('P_L_O_A_D')

figure (2)
stairs(linspace(0,hours,N),P_1(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),PPV_max*ones(1,N),':r','linewidth',1.5)
ylabel('P_1 [kW]')
xlabel('(A)  Time [h]')
legend('P_1,'max of P_1')
axis([0 hours+1 0 1.1*max(P1_max)]);

figure (3)
stairs(linspace(0,hours,N),P_2(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),PWT_max*ones(1,N),':r','linewidth',1.5)
```

```
ylabel('P_2 [kW]')

xlabel('(B)  Time [h]')

legend('P_2','max of P_2')

axis([0 hours+1 0 1.1*max(P2_max)]);


figure (4)

stairs(linspace(0,hours,N),P_3(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P3_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_3 [kW]')

xlabel('(C)  Time [h]')

legend('P_3','max of P_3')

axis([0 hours+1 -8 1.05*max(P3_max)]);


figure (5)

stairs(linspace(0,hours,N),P_4(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P4_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_4 [kW]')

xlabel('(D)  Time [h]')

legend('P_4','max of P_4')

axis([0 hours+1 0 1.05*max(P4_max)]);

  figure (6)

stairs(linspace(0,hours,N),P_5(1:N),'k','linewidth',1.5)
```

```
hold on

stairs(linspace(0,hours,N),PPV_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_5 [kW]')

xlabel('(A)  Time [h]')

legend('P_5','max of P_P_5')

axis([0 hours+1 0 1.1*max(P5_max)]);


figure (7)

stairs(linspace(0,hours,N),P_6(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),PWT_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_6 [kW]')

xlabel('(B)  Time [h]')

legend('P_6','max of P_6')

axis([0 hours+1 0 1.1*max(P6_max)]);


figure (8)

stairs(linspace(0,hours,N),P_7(1:N),'k','linewidth',1.5)

hold on

stairs(linspace(0,hours,N),P7_max*ones(1,N),':r','linewidth',1.5)

ylabel('P_7  [kW]')

xlabel('(C)  Time [h]')

legend('P_7','max of P_7')

axis([0 hours+1 0 1.05*max(P7_max)]);
```

```
figure (9)
stairs(linspace(0,hours,N),soc1(1:N),'k','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),soc_max*ones(1,N),':r','linewidth',1.5)
hold on
stairs(linspace(0,hours,N),Soc_min*ones(1,N),':k','linewidth',1.5)
ylabel('SOC [%]')
axis([0 hours+1 0.19 1.05*max(soc_max)]);
xlabel('(D)  Time [h]')
legend('SOC','max of SOC')
```

b) Objective function

```
function f=obj_moriceWinterX(x)
deltaT=30; %sampling time in minute
hours=24;
N=hours*60/deltaT;
fc=14;
a=0.008415;
b=0.246;
f=
sum((a*(x(3*N+1:4*N).^2)+b*x(3*N+1:4*N))+(a*(x(6*N+1:7*N).^2)+b*x(6*N+1:7*N)));
end
```

Appendix B: Continuous mode simulation results (summer)

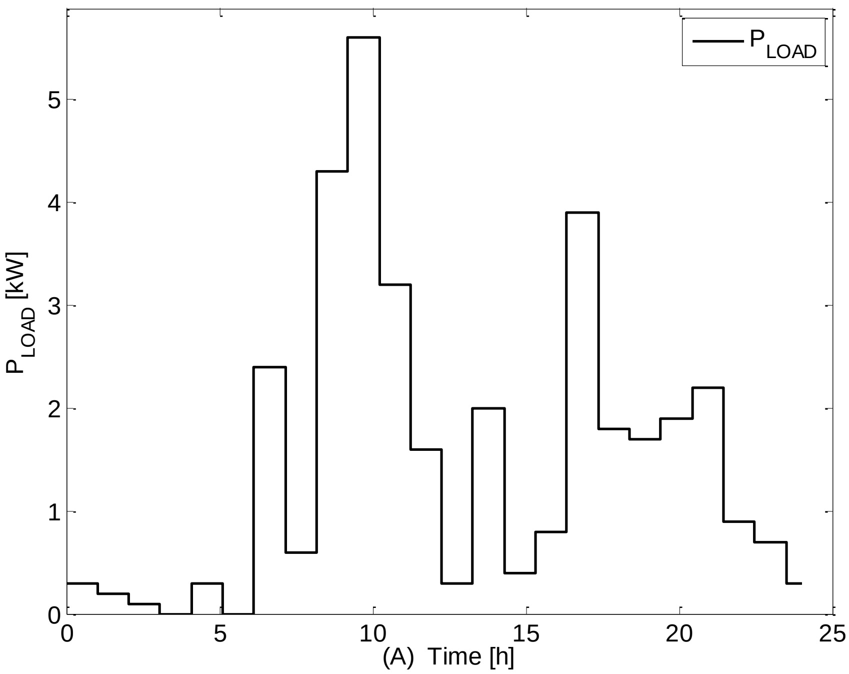

Figure B1: Load profile during summer

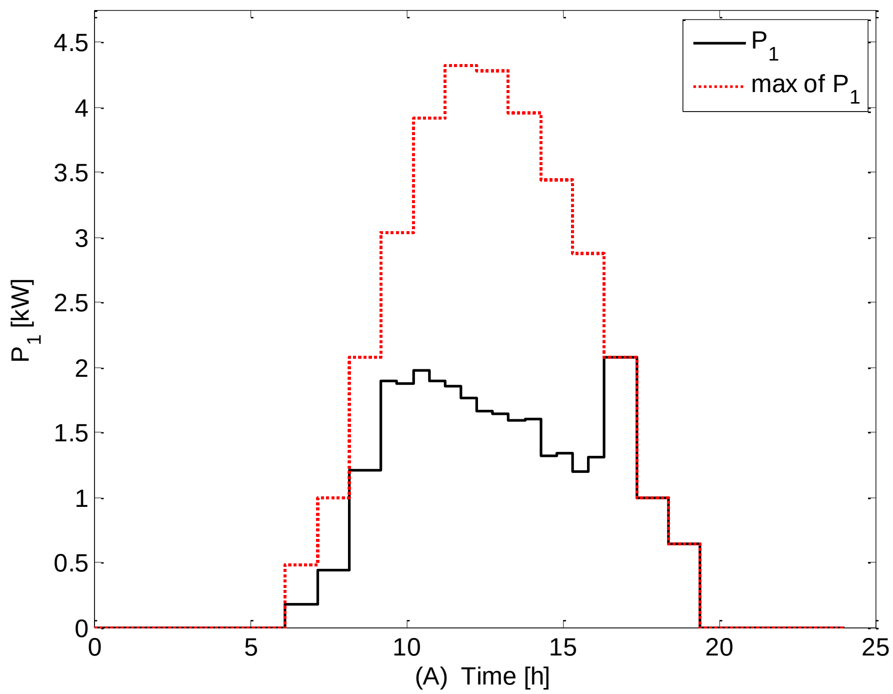

Figure B2: PV output power and power supplied to the load during summer

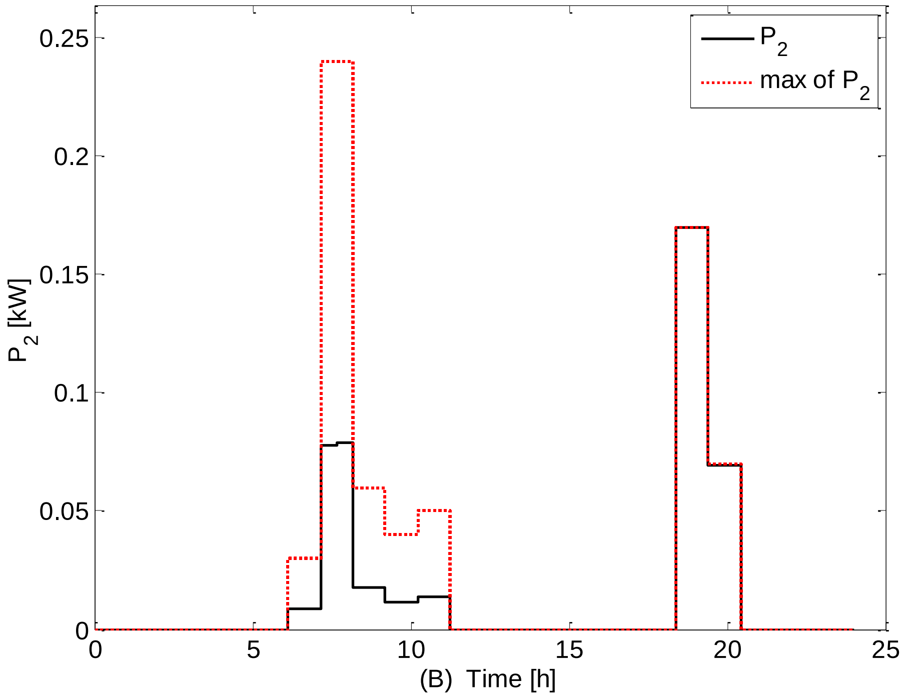

Figure B3: WT output power and power supplied to the load during summer

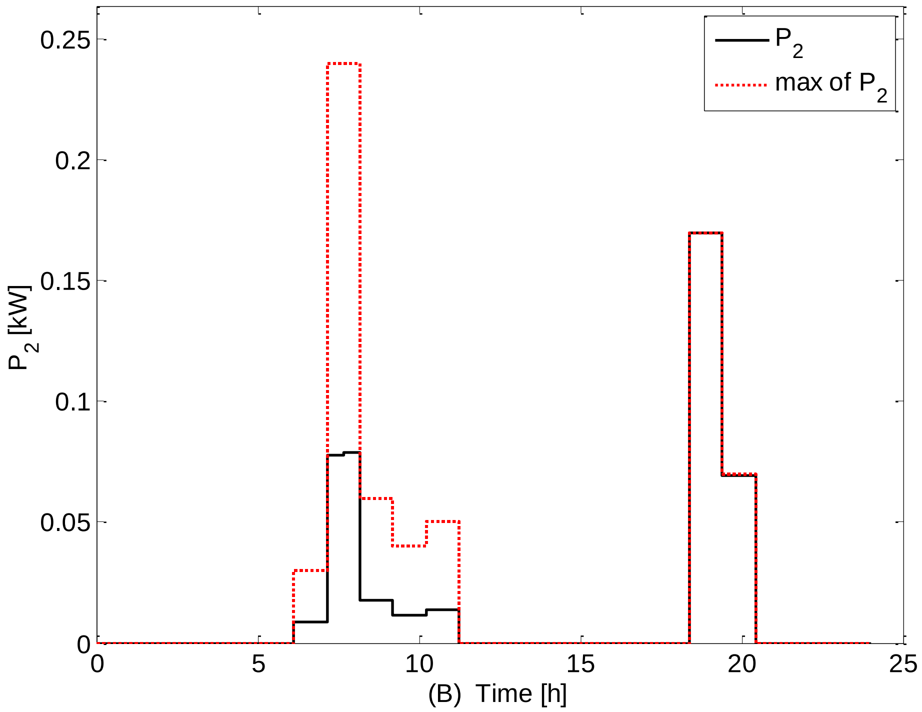

Figure B4: Battery output power and power supplied to the load during summer

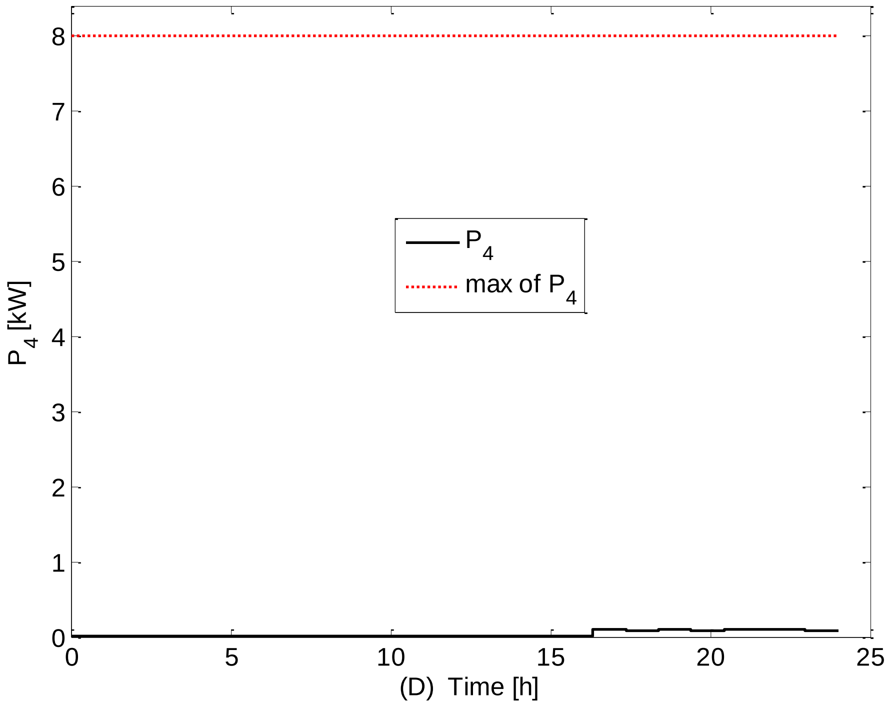

Figure B5: DG output power and power supplied to the load during summer

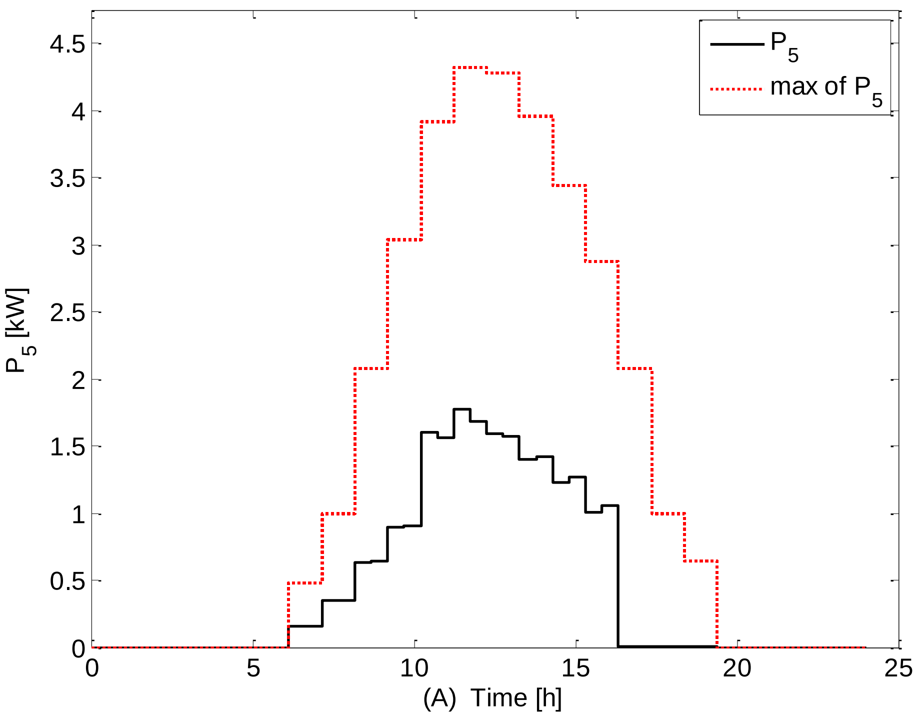

Figure B6: PV output power and power supplied to the load Battery during summer

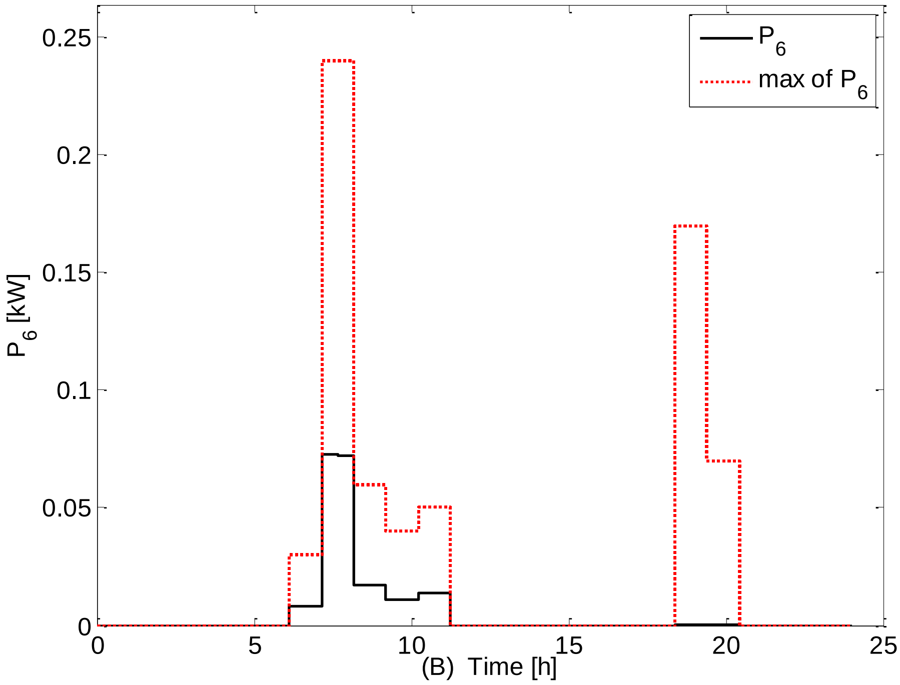

Figure B7: WT output power and power supplied to the load battery during summer

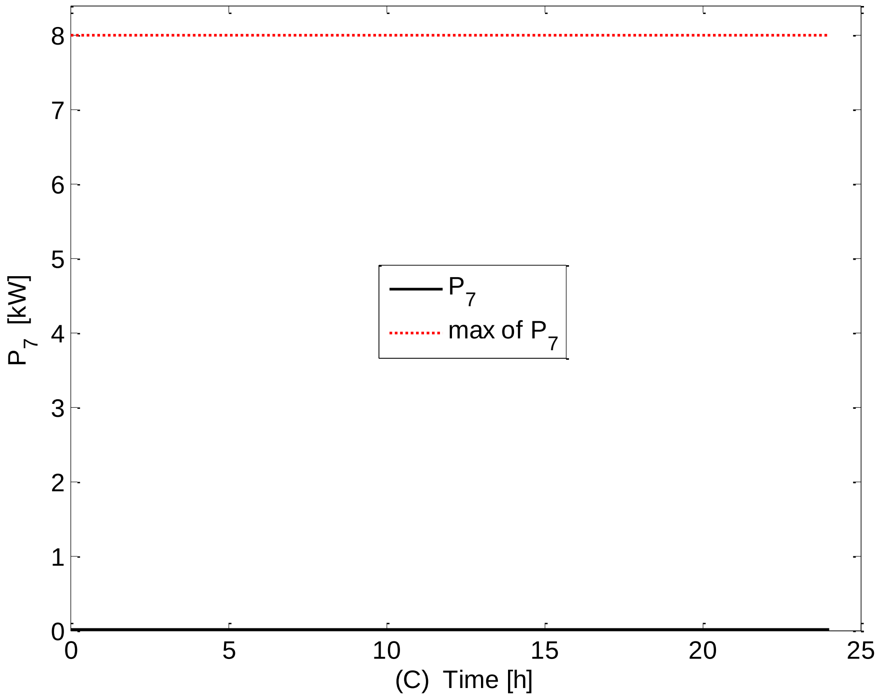

Figure B8: DG output power and power supplied to the load battery during summer

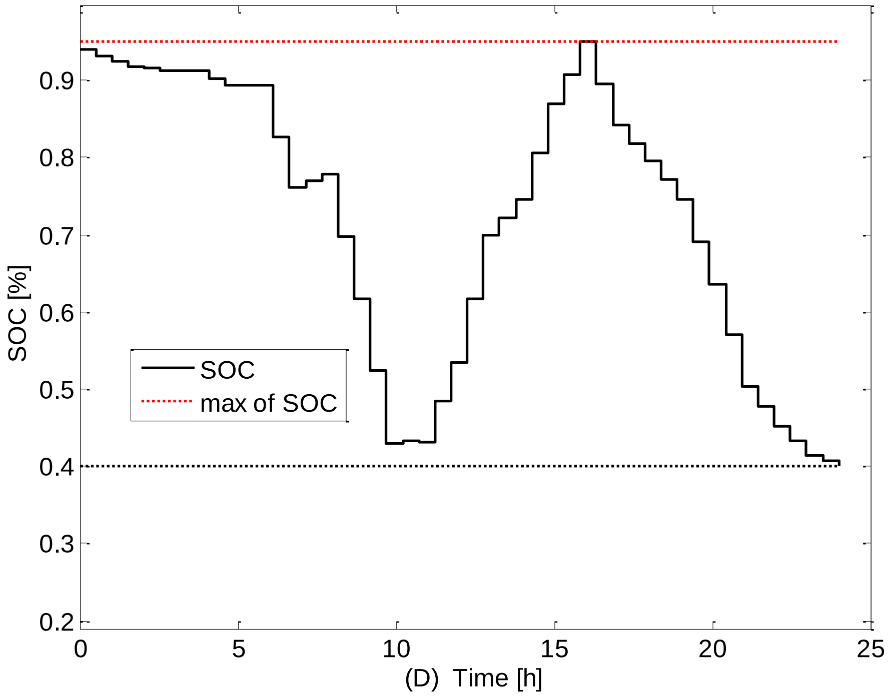

Figure B9: Battery state charge during summer

Appendix C: ON/OFF mode simulation results (summer)

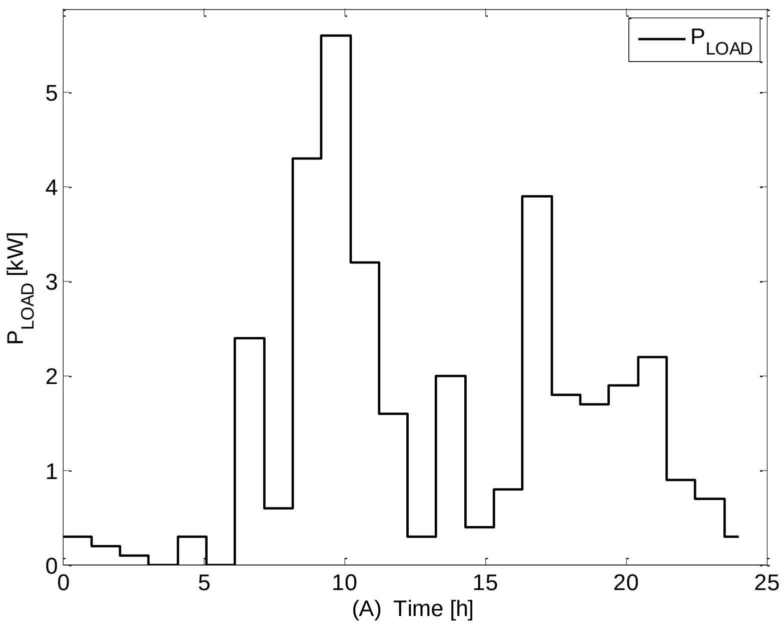

Figure C1: Load profile during summer

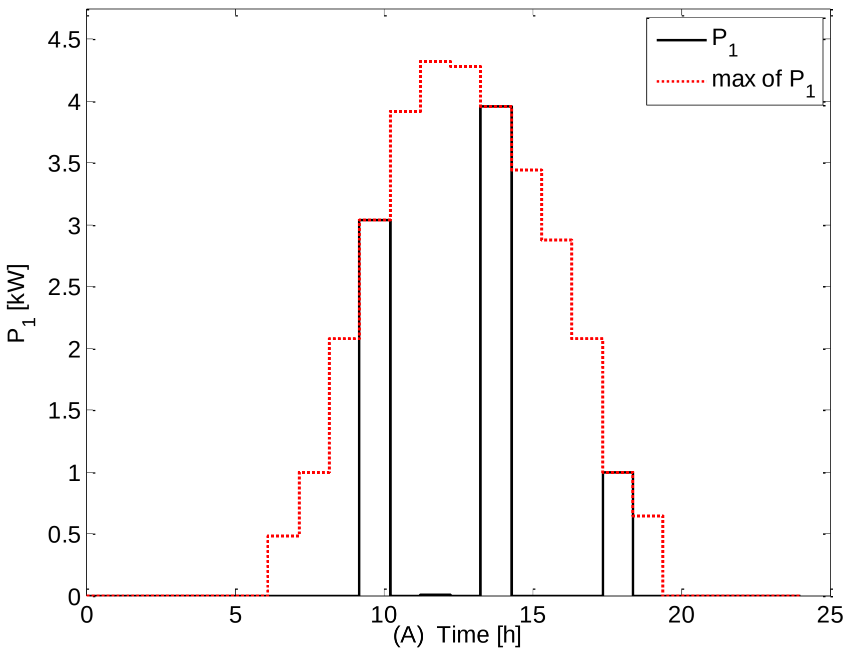

Figure C2: PV output power and power supplied to the load during summer

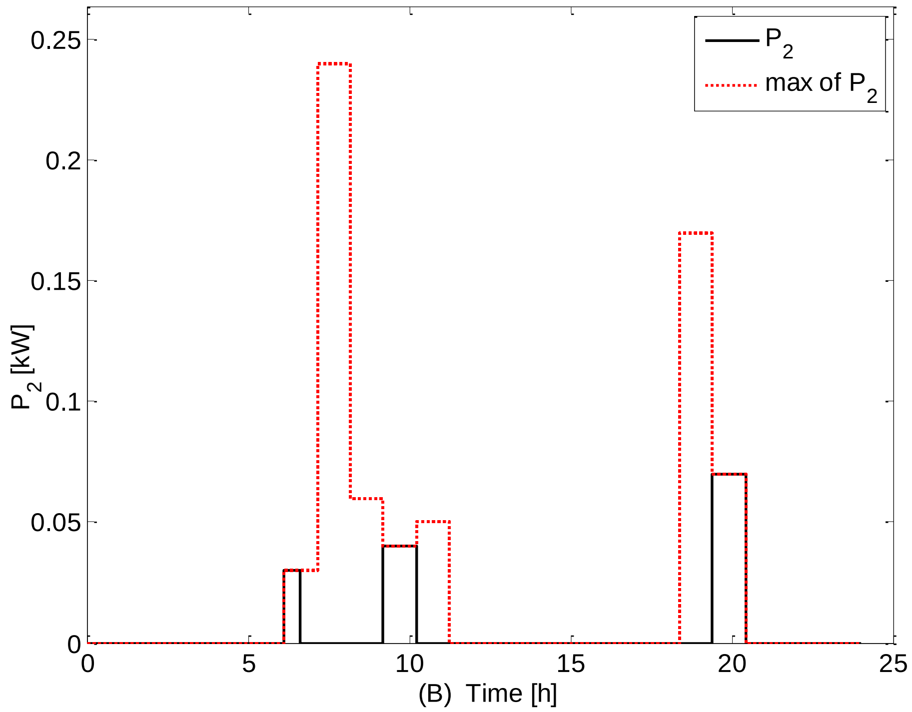

Figure C3: WT output power and power supplied to the load during summer

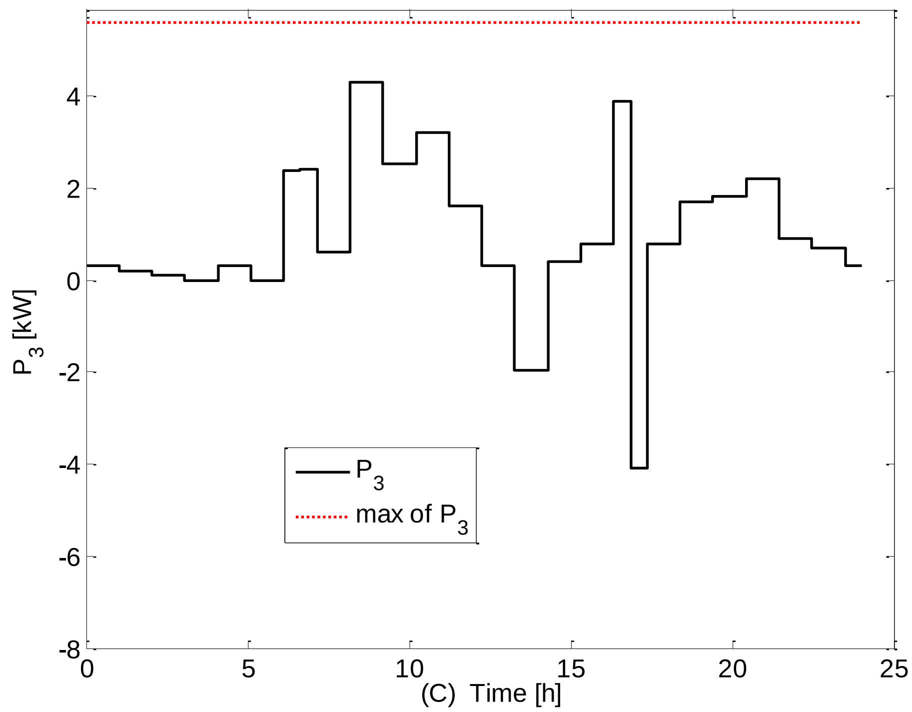

Figure C4: Battery output power and power supplied to the load during summer

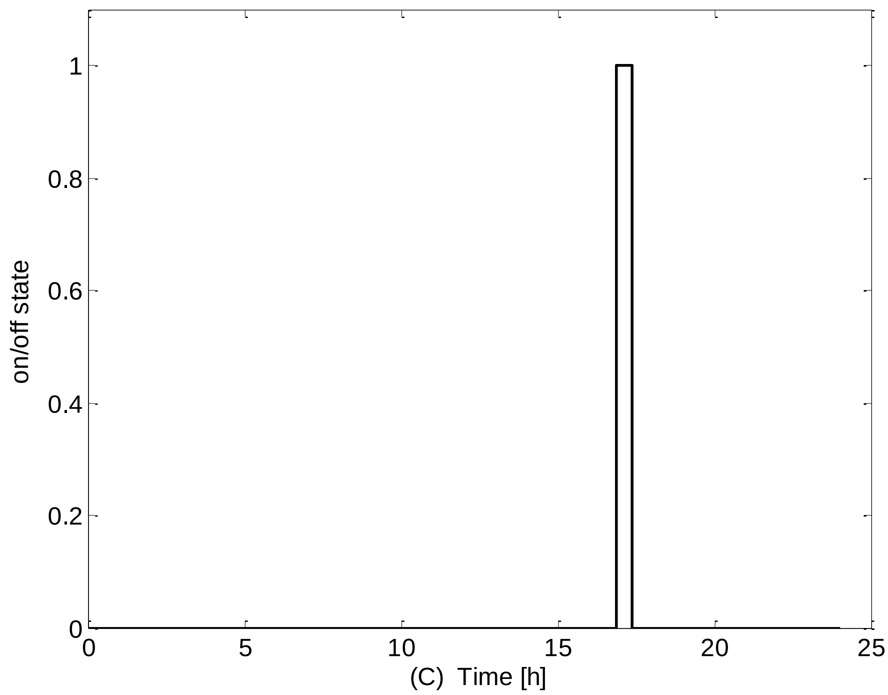

Figure C5: On-Off state during summer

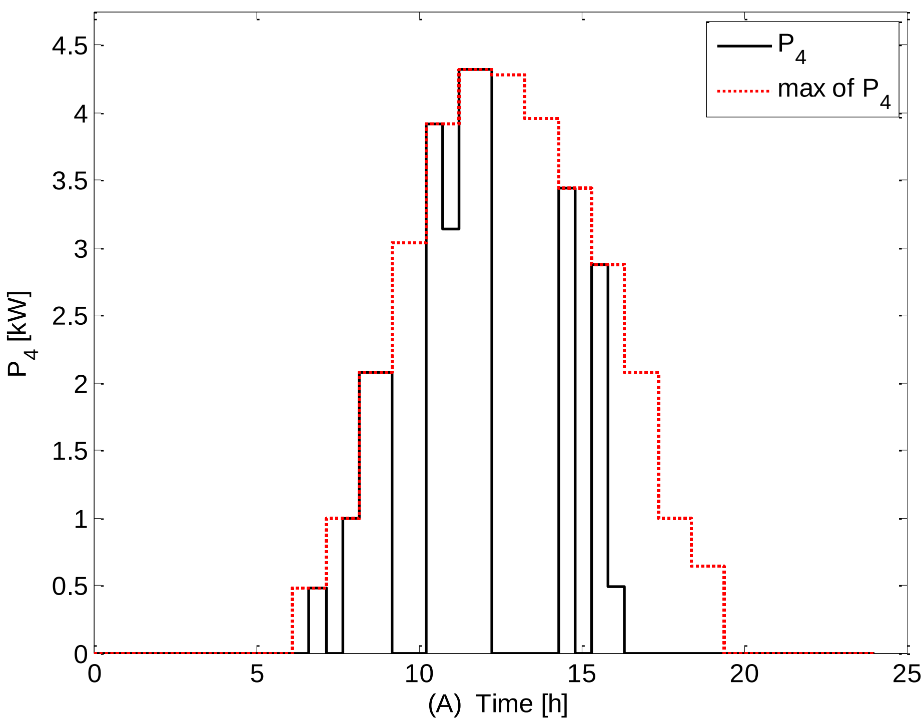

Figure C6: PV output power and power supplied to the battery during summer

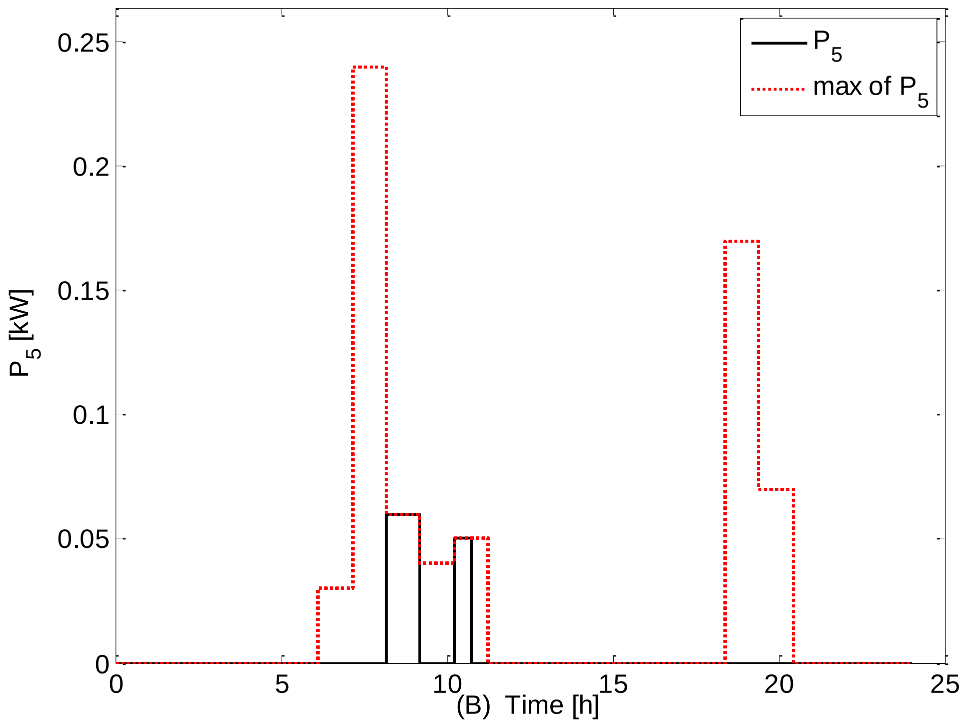

Figure C7: WT output power and power supplied to the battery during summer

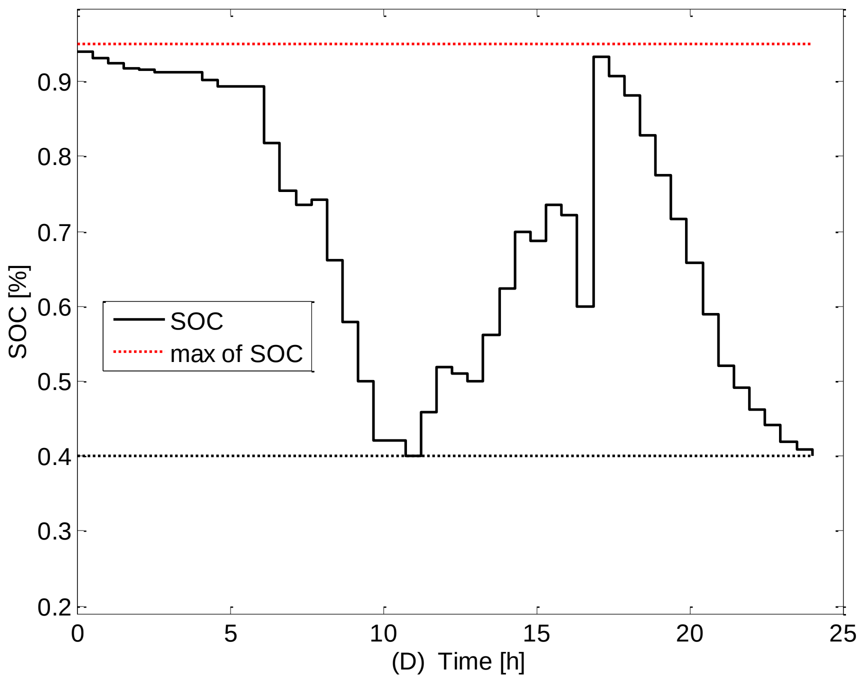

Figure C8: Battery state of charge during summer

Appendix D: Optimal power flow results

Table D1: Continuous operation mode winter case power flow

N	P_1	P_2	P_3	P_4	P_5	P_6	P_7	PL
1	0	0	0.2948	0.0052	0	0	0.0047	0.3000
2	0	0	0.2947	0.0053	0	0	0.0047	0.3000
3	0	0	0.1947	0.0053	0	0	0.0048	0.2000
4	0	0	0.1946	0.0054	0	0	0.0048	0.2000
5	0	0	0.0739	0.0054	0	0	0.0048	0.1000
6	0	0	0.0946	0.0054	0	0	0.0048	0.1000
7	0	0	-0.0055	0.0055	0	0	0.0048	0
8	0	0	-0.0055	0.0055	0	0	0.0048	0
9	0	0	0.2945	0.0055	0	0	0.0049	0.3000
10	0	0	0.2945	0.0055	0	0	0.0049	0.3000
11	0	0	-0.0055	0.0055	0	0	0.0049	0
12	0	0	-0.0055	0.0055	0	0	0.0049	0
13	0.4076	0.1815	2.4053	0.0056	0.0638	0.0500	0.0049	3.0000
14	0.4076	0.1815	2.4053	0.0056	0.0638	0.0500	0.0049	3.0000
15	0.9154	1.8365	-2.0575	0.0056	0.0760	0.0749	0.0049	0.7000
16	0.9162	1.8380	-2.0597	0.0056	0.0753	0.0735	0.0049	0.7000
17	2.0277	0.4305	5.5357	0.0061	0.0444	0.0416	0.0049	8.0000
18	2.0273	0.4304	5.5362	0.0061	0.0448	0.0417	0.0049	8.0000

19	2.9613	0.2544	2.3787	0.0056	0.0702	0.0572	0.0049	5.6000
20	2.9617	0.2546	2.3781	0.0056	0.0698	0.0569	0.0049	5.6000
21	2.4949	0.1440	-0.0422	0.0033	1.2064	0.1297	0.0033	2.6000
22	2.4446	0.1385	0.0136	0.0033	1.2160	0.1270	0.0033	2.6000
23	2.5498	0	0.4470	0.0033	1.4508	0	0.0033	3.0000
24	2.4567	0	0.5400	0.0033	1.5176	0	0.0033	3.0000
25	2.4363	0	-1.9395	0.0033	1.4933	0	0.0033	0.5000
26	2.4108	0	-1.9140	0.0033	1.5176	0	0.0033	0.5000
27	2.3184	0	1.0783	0.0033	1.3147	0	0.0033	3.4000
28	2.3598	0	1.0369	0.0033	1.2775	0	0.0033	3.4000
29	2.0285	0	-1.3318	0.0033	1.0894	0	0.0033	0.7000
30	2.0539	0	-1.3572	0.0033	1.0732	0	0.0033	0.7000
31	1.6779	0	-0.3812	0.0033	0.9180	0	0.0033	1.3000
32	1.6753	0	-0.3786	0.0033	0.9410	0	0.0033	1.3000
33	1.3015	0	0.0952	0.0033	0.5757	0	0.0033	1.4000
34	1.4120	0	-0.0154	0.0033	0.5227	0	0.0033	1.4000
35	0.9663	0	0.1937	0.3400	0.0302	0	0.0174	1.5000
36	0.9663	0	-0.0524	0.5861	0.0303	0	0.0196	1.5000
37	0.6079	1.3277	0.7151	1.1493	0.0288	0.0290	0.0249	3.8000
38	0.6082	1.3279	0.6166	1.2472	0.0285	0.0288	0.0257	3.8000
39	0	0.5290	2.7444	1.3266	0	0.0277	0.0262	4.6000
40	0	0.5291	2.7329	1.3380	0	0.0277	0.0263	4.6000
41	0	0	4.5089	1.3911	0	0	0.0261	5.9000

42	0	0	4.5301	1.3699	0	0	0.0260	5.9000
43	0	0	0.7946	1.3054	0	0	0.0260	2.1000
44	0	0	0.9030	1.1970	0	0	0.0256	2.1000
45	0	0	-0.0832	0.8832	0	0	0.0218	0.8000
46	0	0	0.1159	0.6841	0	0	0.0200	0.8000
47	0	0	-0.0217	0.3217	0	0	0.0175	0.3000
48	0	0	0.1560	0.1440	0	0	0.0160	0.3000

Table D2: Continuous operation mode summer case power flow

N	**P_1**	**P_2**	**P_3**	**P_4**	**P_5**	**P_6**	**P_7**	**PL**
1	0	0	0.3000	0.0000	0	0	0.0000	0.3000
2	0	0	0.3000	0.0000	0	0	0.0000	0.3000
3	0	0	0.2000	0.0000	0	0	0.0000	0.2000
4	0	0	0.2000	0.0000	0	0	0.0000	0.2000
5	0	0	0.1000	0.0000	0	0	0.0000	0.1000
6	0	0	0.1000	0.0000	0	0	0.0000	0.1000
7	0	0	-0.0000	0.0000	0	0	0.0000	0
0.8	0	0	-0.0000	0.0000	0	0	0.0000	0
9	0	0	0.3000	0.0000	0	0	0.0000	0.3000
10	0	0	0.3000	0.0000	0	0	0.0000	0.3000
11	0	0	-0.0000	0.0000	0	0	0.0000	0

12	0	0	-0.0000	0.0000	0	0	0.0000	0
13	0.1748	0.0086	2.2166	0.0000	0.1559	0.0083	0.0000	2.4000
14	0.1764	0.0086	2.2150	0.0000	0.1553	0.0083	0.0000	2.4000
15	0.4373	0.0779	0.0847	0.0000	0.3470	0.0726	0.0000	0.6000
16	0.4421	0.0789	0.0789	0.0000	0.3463	0.0724	0.0000	0.6000
17	1.2131	0.0178	3.0691	0.0000	0.6327	0.0169	0.0000	4.3000
18	1.2082	0.0178	3.0740	0.0000	0.6392	0.0169	0.0000	4.3000
19	1.8914	0.0115	3.6971	0.0000	0.8972	0.0112	0.0000	5.6000
20	1.8777	0.0115	3.7108	0.0000	0.8999	0.0112	0.0000	5.6000
21	1.9739	0.0140	1.2121	0.0000	1.6005	0.0140	0.0000	3.2000
22	1.8947	0.0139	1.2914	0.0000	1.5665	0.0139	0.0000	3.2000
23	1.8576	0	-0.2576	0.0000	1.7774	0	0.0000	1.6000
24	1.7666	0	-0.1667	0.0000	1.6847	0	0.0000	1.6000
25	1.6590	0	-1.3590	0.0000	1.5960	0	0.0000	0.3000
26	1.6469	0	-1.3470	0.0000	1.5683	0	0.0000	0.3000
27	1.5875	0	0.4125	0.0000	1.4019	0	0.0000	2.0000
28	1.6010	0	0.3989	0.0000	1.4159	0	0.0000	2.0000
29	1.3199	0	-0.9199	0.0000	1.2299	0	0.0000	0.4000
30	1.3426	0	-0.9426	0.0000	1.2716	0	0.0000	0.4000
31	1.2031	0	-0.4031	0.0000	1.0032	0	0.0000	0.8000
32	1.3119	0	-0.5119	0.0000	1.0535	0	0.0000	0.8000
33	2.0796	0	1.7220	0.0984	0.0003	0	0.0001	3.9000
34	2.0796	0	1.7231	0.0972	0.0003	0	0.0001	3.9000

35	0.9996	0	0.7117	0.0887	0.0003	0	0.0001	1.8000
36	0.9996	0	0.7112	0.0892	0.0003	0	0.0001	1.8000
37	0.6396	0.1696	0.7936	0.0972	0.0003	0.0003	0.0001	1.7000
38	0.6396	0.1696	0.7934	0.0973	0.0003	0.0003	0.0001	1.7000
39	0	0.0696	1.7418	0.0886	0	0.0003	0.0001	1.9000
40	0	0.0696	1.7417	0.0887	0	0.0003	0.0001	1.9000
41	0	0	2.1064	0.0936	0	0	0.0001	2.2000
42	0	0	2.1066	0.0934	0	0	0.0001	2.2000
43	0	0	0.8067	0.0933	0	0	0.0001	0.9000
44	0	0	0.8079	0.0921	0	0	0.0001	0.9000
45	0	0	0.6098	0.0902	0	0	0.0001	0.7000
46	0	0	0.6126	0.0874	0	0	0.0001	0.7000
47	0	0	0.2166	0.0834	0	0	0.0001	0.3000
48	0	0	0.2164	0.0836	0	0	0.0001	0.3000

Table D3: On-Off operation mode winter case power flow

N	**S**	**P_1**	**P_2**	**P_3**	**P_4**	**P_5**	**PL**
1	0	0	0	0.3000	0	0	0.3000
2	0	0	0	0.3000	0	0	0.3000
3	0	0	0	0.2000	0	0	0.2000
4	0	0	0	0.2000	0	0	0.2000
5	0	0	0	0.1000	0	0	0.1000

6	0	0	0	0.1000	0	0	0.1000
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0.3000	0	0	0.3000
10	0	0	0	0.3000	0	0	0.3000
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0.4800	0.2400	2.2800	0	0	3.0000
14	0	0.4800	0.2400	2.2800	0	0	3.0000
15	0	1.0000	1.9200	-2.2200	0	0	0.7000
16	0	1.0000	1.9200	-2.2200	0	0	0.7000
17	0	2.0800	0.4800	5.4400	0	0	8.0000
18	0	2.0800	0.4800	5.4400	0	0	8.0000
19	0	3.0400	0.3200	2.2400	0	0	5.6000
20	0	2.6500	0	2.9500	0.3900	0.3200	5.6000
21	0	0	0	2.6000	3.9200	0.4000	2.6000
22	0	0	0	2.6000	3.9200	0.4000	2.6000
23	0	0	0	3.0000	4.3200	0	3.0000
24	0	0	0	3.0000	4.3200	0	3.0000
25	0	2.1387	0	-1.6387	0	0	0.5000
26	0	0	0	0.5000	4.2800	0	0.5000
27	0	0	0	3.4000	3.9600	0	3.4000
28	0	0	0	3.4000	3.9600	0	3.4000

29	0	0	0	0.7000	3.4400	0	0.7000
30	0	0	0	0.7000	3.4400	0	0.7000
31	0	0	0	1.3000	2.8800	0	1.3000
32	0	2.8800	0	-1.5800	0	0	1.3000
33	0	2.0800	0	-0.6800	0	0	1.4000
34	0	2.0800	0	-0.6800	0	0	1.4000
35	0	1.0000	0	0.5000	0	0	1.5000
36	0	1.0000	0	0.5000	0	0	1.5000
37	0	0	0	3.8000	0	0	3.8000
38	0	0	0	3.8000	0.6400	1.3600	3.8000
39	0	0	0.5600	4.0400	0	0	4.6000
40	0	0	0.5600	4.0400	0	0	4.6000
41	1	0	0	-2.1000	0	0	5.9000
42	1	0	0	-2.1000	0	0	5.9000
43	0	0	0	2.1000	0	0	2.1000
44	0	0	0	2.1000	0	0	2.1000
45	0	0	0	0.8000	0	0	0.8000
46	0	0	0	0.8000	0	0	0.8000
47	0	0	0	0.3000	0	0	0.3000
48	0	0	0	0.3000	0	0	0.3000

Table D4: On-Off operation mode summer case power flow

N	S	P_1	P_2	P_3	P_4	P_5	PL
1	0	0	0	0.3000	0	0	0.3000
2	0	0	0	0.3000	0	0	0.3000
3	0	0	0	0.2000	0	0	0.2000
4	0	0	0	0.2000	0	0	0.2000
5	0	0	0	0.1000	0	0	0.1000
6	0	0	0	0.1000	0	0	0.1000
7	0	0	0	0	0	0	0
0.8	0	0	0	0	0	0	0
9	0	0	0	0.3000	0	0	0.3000
10	0	0	0	0.3000	0	0	0.3000
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
13	0	0	0.0300	2.3700	0	0	2.4000
14	0	0	0	2.4000	0.4800	0	2.4000
15	0	0	0	0.6000	0	0	0.6000
16	0	0	0	0.6000	1.0000	0	0.6000
17	0	0	0	4.3000	2.0800	0.0600	4.3000
18	0	0	0	4.3000	2.0800	0.0600	4.3000
19	0	3.0400	0.0400	2.5200	0	0	5.6000
20	0	3.0400	0.0400	2.5200	0	0	5.6000
21	0	0	0	3.2000	3.9200	0.0500	3.2000

22	0	0	0	3.2000	3.1410	0	3.2000
23	0	0.0000	0	1.6000	4.3200	0	1.6000
24	0	0.0000	0	1.6000	4.3200	0	1.6000
25	0	0.0000	0	0.3000	0	0	0.3000
26	0	0.0000	0	0.3000	0	0	0.3000
27	0	3.9600	0	-1.9600	0	0	2.0000
28	0	3.9600	0	-1.9600	0	0	2.0000
29	0	0	0	0.4000	3.4400	0	0.4000
30	0	0	0	0.4000	0	0	0.4000
31	0	0.0000	0	0.8000	2.8800	0	0.8000
32	0	0.0000	0	0.8000	0.4951	0	0.8000
33	0	0	0	3.9000	0	0	3.9000
34	1.0000	0	0	-4.1000	0	0	3.9000
35	0	1.0000	0	0.8000	0	0	1.8000
36	0	1.0000	0	0.8000	0	0	1.8000
37	0	0	0	1.7000	0	0	1.7000
38	0	0	0	1.7000	0	0	1.7000
39	0	0	0.0700	1.8300	0	0	1.9000
40	0	0	0.0700	1.8300	0	0	1.9000
41	0	0	0	2.2000	0	0	2.2000
42	0	0	0	2.2000	0	0	2.2000
43	0	0	0	0.9000	0	0	0.9000
44	0	0	0	0.9000	0	0	0.9000

45	0	0	0	0.7000	0	0	0.7000
46	0	0	0	0.7000	0	0	0.7000
47	0	0	0	0.3000	0	0	0.3000
48	0	0	0	0.3000	0	0	0.3000