OPTIMAL LOCATION AND SIZING OF PHOTOVOLTAIC AND BATTERY STORAGE IN DISTRIBUTION SYSTEM CONSIDERING TIME-VARYING LOAD DATA

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DEDICATION

This thesis is dedicated to

My dearest parents

Pn. Nolia Adam, and En. Jamahori Shaharuddin

for their endless love, prayers, and support

My lovely family,

for their motivation and encouragement

Specially dedicated to my beloved son

Adam Haydaan ♡

Blessings from Allah SWT

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ABSTRACT

The integration of distributed renewable energy generation, especially in Photovoltaic (PV) planning studies, has increased over the past years due to its great benefit in distribution systems. However, the energy generated from PV is highly unpredictable and inconsistent as the generation depends on weather conditions. The rising issues associated with the variability and intermittency of PV sources could be overcome by integrating PV with battery storage systems (PV-BSS). Many studies on PV integration with batteries have been proposed; nevertheless, previous work only considers a constant load model and dispatchable generation unit. In addition, the battery is normally charged when PV output exceeds load demand. The impact of the battery on the technical benefits of the distribution system and the method to size the battery based on PV availability and load demand requirements are disregarded. Therefore, proper PV and battery sizing methods are necessary to supply the loads and avoid mismatches between PV and battery generation. This research proposed the optimization model of the PV-BSS integration to supply load during peak times to reduce power losses in the distribution system. In addition, the proposed model also aimed to reduce high-cost maximum demand charges from utility providers considering the latest Time of Use (ToU) tariffs, weather-dependent PV generation, and time-varying loads. To maximize the technical and economic benefits from PV-BSS integration over the total maximum demand reduction, Particle Swarm Optimization (PSO) is employed to find the optimal location and size of PV and battery by utilizing 13 years of historical solar irradiance data with different time-varying load models. The findings are evaluated based on the comparative analysis of total active and reactive power losses, bus voltage improvement, PV penetration level, and different impact indices, namely, active power loss index (PLI), reactive power loss index (QLI), and voltage deviation index (VDI). The research has been performed on IEEE 33-bus and IEEE 69-bus test distribution systems. Findings revealed that the proposed optimization model effectively determines the optimal location and size of PV and battery with a significant reduction of power losses and improvement in bus voltages. The power loss reduction with PV integration varies between 13.84% to 32.71%. The combination of batteries in PV-BSS helped further reduce power loss by between 34.72% to 62.22% and achieved high maximum demand reduction, which yielded to 27.85% and 24.18% annual energy savings for commercial and industrial consumers, respectively. In addition, the improvement in other performance indices is also significant. The optimization results using PSO have been validated using a Genetic Algorithm (GA), with negligible differences between both techniques. Overall, this thesis contributed to an optimization method to size and locate PV and battery considering time-varying load models to maximize the technical performances of the distribution network and electricity bill savings to the consumer for efficient power use during peak hours.

ABSTRAK

Penyepaduan penjanaan tenaga boleh diperbaharui teragih, terutamanya dalam kajian perancangan Fotovoltaik (PV), telah meningkat sejak beberapa tahun lalu kerana manfaatnya yang besar dalam sistem pengagihan. Walau bagaimanapun, tenaga yang dijana daripada PV tidak dapat diramalkan dan tidak konsisten kerana penjanaan tenaga bergantung kepada keadaan cuaca. Isu sumber PV yang berubah-ubah dan terputus-putus boleh diatasi dengan menyepadukan PV dengan sistem storan bateri (PV-BSS). Banyak kajian mengenai penyepaduan PV dengan bateri telah dibentangkan; namun begitu, perancangan PV-BSS hanya mempertimbangkan model beban malar dan unit penjanaan boleh dihantar. Di samping itu, bateri biasanya dicas apabila keluaran PV melebihi permintaan beban. Kesan bateri ke atas faedah teknikal sistem pengagihan dan kaedah untuk saiz bateri berdasarkan kebolehsediaan PV dan keperluan permintaan beban telah diabaikan. Oleh itu, kaedah pensaizan PV dan bateri yang optimum adalah perlu untuk mengelakkan ketidakpadanan antara penjanaan PV dan bateri untuk membekalkan tenaga kepada beban. Penyelidikan ini mencadangkan integrasi model PV-BSS untuk membekalkan beban semasa waktu puncak bagi mengurangkan kehilangan kuasa dalam sistem pengagihan. Di samping itu, model yang dicadangkan juga bertujuan untuk mengurangkan caj permintaan maksimum yang tinggi daripada pembekal utiliti dengan mengambil kira tarif Masa Penggunaan (ToU), penjanaan PV yang bergantung kepada cuaca dan permintaan beban yang berubah dengan masa. Untuk memaksimumkan faedah teknikal dan ekonomi daripada penyepaduan PV-BSS demi mengurangkan permintaan beban maksimum, Pengoptimuman Kawanan Zarah (PSO) digunakan untuk mencari lokasi dan saiz yang optimum bagi PV dan bateri dengan menggunakan 13 tahun sejarah data penyinaran suria dengan model beban berubah masa. Penemuan kajian ini dinilai berdasarkan analisis perbandingan jumlah kehilangan kuasa aktif dan reaktif, peningkatan voltan bas, tahap penembusan PV, dan impak indeks yang berbeza, iaitu indeks kehilangan kuasa aktif (PLI), indeks kehilangan kuasa reaktif (QLI), dan indeks sisihan voltan (VDI). Penyelidikan telah diuji pada bas ujian sistem pengagihan IEEE 33-bas dan IEEE 69-bas. Keputusan menunjukkan bahawa model yang dicadangkan berkesan dalam menentukan lokasi dan saiz yang optimum bagi PV dan bateri dengan pengurangan kehilangan kuasa dan peningkatan voltan bas yang ketara. Pengurangan kehilangan kuasa dengan penyepaduan PV berbeza antara 13.84% hingga 32.71%. Gabungan bateri dalam model PV-BSS membantu mengurangkan lagi kehilangan kuasa antara 34.72% hingga 62.22% dan mencapai pengurangan permintaan maksimum yang tinggi, menghasilkan 27.85% dan 24.18% penjimatan tenaga tahunan untuk pelanggan komersial dan industri. Di samping itu, peningkatan dalam indeks prestasi lain juga adalah ketara. Keputusan yang diperoleh dari PSO telah disahkan menggunakan Algoritma Genetik (GA), dengan perbezaan yang tidak ketara antara kedua-dua teknik. Secara keseluruhannya, tesis ini menyumbang kepada kaedah pengoptimuman lokasi, saiz PV dan bateri dengan menggunakan beban yang berubah dengan masa untuk memaksimumkan prestasi teknikal rangkaian pengagihan dan penjimatan bil elektrik kepada pengguna untuk penggunaan kuasa yang cekap pada waktu puncak.

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LIST OF ABBREVIATIONS

BSS	-	Battery Storage System
C2	-	Category for a commercial user
DG	-	Distributed Generation
DOD	-	Depth of discharge
DREG	-	Distributed Renewable Energy Generation
DSM	-	Demand Side Management
E2	-	Category for an industrial user
GA	-	Genetic Algorithm
GW	-	Giga Watt
HV	-	High Voltage
kV	-	Kilo Volt
kVAr	-	Kilovolt-Ampere Reactive
kW	-	Kilo Watt
kWh	-	Kilo Watt Hour
Li-on	-	Lithium-ion
MD	-	Maximum Demand
MPPT	-	Maximum Power Point Tracking
MV	-	Medium Voltage
MW	-	Mega Watt
MWh	-	Mega Watt Hour
MWp	-	Mega Watt Peak
PDF	-	Probability Density Function
PLI	-	Active Power Loss Index
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
PV-BSS	-	Photovoltaic-Battery Storage System
QLI	-	Reactive Power Loss Index
RDS	-	Radial Distribution System
RE	-	Renewable Energy
RM	-	Ringgit Malaysia

SOC	-	State of Charge
TNB	-	Tenaga Nasional Berhad
ToU	-	Time of Use
TPLI	-	Total Power Loss Index
TW	-	Tera Watt
VDI	-	Voltage Deviation index

LIST OF SYMBOLS

$\mathrm{AMD}_{\mathrm{PVBSS}}$	-	Allowable Maximum Demand with PV-BSS
$\mathrm{C}_{\mathrm{Load\_net}}$	-	Energy Consumption Charge (RM/kWh)
C_{MD}	-	Maximum Demand charge (RM/kW)
$\mathrm{C}_{\mathrm{Saving}}$	-	Energy consumption savings (kWh)
$\mathrm{C}_{\mathrm{Total}}$	-	Total electricity bill (RM)
$\mathrm{N}_{\mathrm{bus}}$	-	Number of buses
$\mathrm{P}_{\mathrm{BSS}}$	-	Power stored in the battery
$\mathrm{P}_{\mathrm{BSS}}^{\mathrm{CH}}$	-	Charging power of the battery
$\mathrm{P}_{\mathrm{BSS}}^{\mathrm{DCH}}$	-	Discharging power of the battery
$\mathrm{P}_{\mathrm{D(total)}}$	-	Reactive load demand
P_{Di}	-	Actual active load power
$\mathrm{P}_{\mathrm{Dnew}}$	-	New active power demand
$\mathrm{P}_{\mathrm{Load\_net}}$	-	Energy Consumption (kWh)
$\mathrm{P}_{\mathrm{Loss(i)}}$	-	Active power loss at i branch
$\mathrm{P}_{\mathrm{Loss,PV(i)}}$	-	Active power loss at i branch with PV
$\mathrm{P}_{\mathrm{Loss,PVBSS(i)}}$	-	Active power loss at i branch with PV-BSS
$\mathrm{P}_{\mathrm{PV(rated)}}$	-	DC output power of the expected PV array
P_{ss}, Q_{ss}	-	Substation active and reactive power supplies
$\mathrm{PV}_{\mathrm{NET}}$	-	Photovoltaic output power
$\mathrm{PV}_{\mathrm{out}}$	-	Total expected PV output power
$\mathrm{PV}_{\mathrm{out(kWp)}}$	-	AC output power of the expected PV array
$\mathrm{PV}_{\mathrm{size}}$	-	Size of PV
$\mathrm{Q}_{\mathrm{D(total)}}$	-	Reactive load demand
Q_{Di}	-	Actual reactive load power
$\mathrm{Q}_{\mathrm{Dnew}}$	-	New reactive power demand
$\mathrm{Q}_{\mathrm{Loss(i)}}$	-	Reactive power loss at i branch
$\mathrm{Q}_{\mathrm{Loss,PV(i)}}$	-	Reactive power loss at i branch with PV
$\mathrm{Q}_{\mathrm{Loss,PVBSS(i)}}$	-	Reactive power loss at i branch with PV-BSS

$TP_{Loss,PV\ (i)}$	-	Active power losses for individual buses with PV
$TP_{Loss,PVBSS\ (i)}$	-	Active power losses for individual buses with PV-BSS
$TP_{Loss(i)}$	-	Active power losses for individual buses
V_i	-	Voltage magnitude
V_{min}	-	Lower limit of the bus voltage
V_{max}	-	Upper limit of the bus voltage
$v_i{}^k$	-	Initial velocity of a particle i at iteration k
$v_i{}^{k+1}$	-	New modified velocity of a particle i at iteration k
$x_i{}^k$	-	Current position of a particle i at iteration k
$x_i{}^{k+1}$	-	New modified position of a particle i at iteration k
η_{ch}	-	Efficiency of battery during charging
η_{dch}	-	Efficiency of battery during discharging
η_{inv}	-	Round-trip efficiency
c_1, c_2	-	Accelerations constraints
g_{best}	-	Best global solution
p_{best}	-	Current best fitness solution
r_1, r_2	-	Random number
μ	-	Standard deviation
Beta(s)	-	Beta probability density function
f	-	Objective function
s	-	Random variable for solar irradiance
α	-	Parameters of Beta (s)
β	-	Parameters of Beta (s)
Γ	-	Gamma function
ρ(s)	-	Probability of solar irradiance
σ	-	Mean
ω	-	Weighting inertia
vp, vq	-	Active and reactive load voltage coefficients

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CHAPTER 1

INTRODUCTION

1.1 Background

In recent years, the integration of distributed generation (DG) in distribution networks has gained more attention, especially in developing countries, due to the global increase in fossil fuel prices [1, 2]. This concern has encouraged using renewable energy (RE) sources to replace traditional diesel generators, which have long been regarded as the most reliable and cost-effective DG source for power generation. The RE-based DG types, known as distributed renewable energy generation (DREG), include solar Photovoltaic (PV), wind turbines, biomass, tidal, and hydropower [3]. The availability of RE in various countries worldwide and adequate energy resources have contributed to its growing interest due to the abundance of the fuel itself and its self-sustaining in replenishing its sources. This ever-increasing interest is also related to several substantial reasons: huge potentials and advantages of DREG, increased electrical load demands, technical and economic boundaries to construct new power plants and transmission lines, and also their ability to improve the performance of distribution networks without contributing to carbon footprints and greenhouse emissions [4, 5].

Among all RE technologies available, solar PV energy has evolved rapidly with some unprecedented developments in the recent past. The integration of solar PV into the distribution system is gaining more attention worldwide and is being utilized as an alternative to conventional power generation using fossil fuels. The advantage of using a PV system as a renewable energy source is that the supply is derived from abundant natural resources. PV offers low maintenance and operational expenses because it does not involve mechanical moving parts to generate power [6], making this technology more favourable than other RE sources [7, 8]. The global solar market is growing as solar PV remains the most rapidly expanding renewable energy source, accounting for more than half of the 302 GW renewable capacity installed globally in 2021. Global solar capacity expanded from 100 GW in 2012 to 1 TW in 10 years [9]. Despite its benefits and potential, the drawbacks associated with solar PV are that the energy supply is highly unpredictable and inconsistent. Since the current energy is based on the grid system, integrating PV poses extra challenges, especially in the power quality [10]. These problems arise due to PV's nature, which depends on weather and geographical factors. The rapid penetration of intermittent PV will affect network stability and reliability of the energy generation and load balance. Furthermore, sudden changes from weather-dependent PV will create fluctuations in the output power and thus might result in either less or over electricity being generated at a time [11].

Great efforts have been made to mitigate the intermittency-related issues of the PV systems, such as integration with the energy storage system, interconnection with external grids, and load shifting through demand control. Among these, energy storage is recognized as the most promising approach capable of enhancing grid integration while preserving the stability and safety of the system. A battery storage system (BSS) is widely chosen among other types of energy storage. The battery can store the excess energy from PV during the day and be used later at night. The interest in this research area for PV integration with BSS (PV-BSS) has rapidly grown and is expected to expand as many industries begin to generate a large output scale of PV generation [12-14]. Most research on BSS proves its potential to be used with PV generation. Despite its potential, many aspects must be considered before integrating BSS with PV into distribution networks, including power loss, power quality issues, stability, and security system [15].

1.2 Problem Statement

With the growing interest in integrating RE sources and energy storage systems, power quality issues, including power losses and voltage deviation, are increasing, particularly with improper allocation and sizing of PV-BSS. Even though significant studies have resolved these problems in the distribution network, some methodological limitations still exist, as follows:

First, most research for integrating solar PV in the distribution system is performed using a constant load model and a dispatchable generation unit. Most researchers assumed that the PV output is dispatchable and did not consider the uncertainties of PV output power that are dependent on solar irradiance availability and weather factors. They only considered peak loads when sizing and locating PV units. The utilization of historical weather data and time-varying loads is disregarded. In practical, the renewable generation unit and load demand vary in real life, and the optimum PV size at the peak demand varies accordingly with loading levels.

Second, the research methodology in most studies omitted some critical aspects to size and utilize energy from PV and batteries where batteries are assumed to supply the required power demand without considering the hourly optimum energy levels to discharge the batteries. The assumptions are typically made to charge the batteries during periods only when the output powers from the PV exceed the required power demand. However, in practical, no excess power might be generated during specific periods due to unpredictable weather conditions. Hence the power output from PV will be inconsistent. In that case, the decision to charge the batteries only when the output of the PV is greater than the load demand might not be accurate.

Lastly, the time and rate of battery charge/discharge were determined without knowing the exact technical benefits to the distribution networks. Most PV-BSS studies have mostly been done from a techno-economic viewpoint, and the method to design the PV-battery follows those similar methods in a standalone system rather grid-connected system where the benefits to both utilities and customers were disregarded. Most methodologies presented to size and locate PV-BSS and battery charge/discharge operation to supply electric power during peak times to reduce high-cost maximum demand charges from utility providers that consider the latest Time of Use (ToU) tariffs, historical weather PV generation and time-varying load data is not well conducted.

1.3 Research Questions

The research questions highlighted while analyzing the impacts of PV and BSS in the distribution network based on technical and economic bill-saving benefits are as follows:

i. What are the significant impacts when considering non-constant (time-varying) loads and historical weather-dependent generation rather than constant load models and predetermined generation size?

ii. What is the suitable optimization model subject to several constraints that can be used to determine the optimal location and size of PV and battery to provide the lowest power loss in the system considering different types and sizes of load models?

iii. Apart from the power loss impact, can PV and BSS provide significant changes to the other power system's performances, such as voltage profile, active and reactive power indices, voltage deviation index, and PV penetration level?

iv. Can the integration between PV and BSS provide positive impacts not only on the technical aspect but on the economic aspects too? If yes, how can utility and consumer benefit from the proposed PV-BSS model?

1.4 Research Objectives

Based on the problems and research questions mentioned above, the main idea of this thesis is to locate, to size, and to operate the renewable-based distributed generation resources and associated storage units in the distribution networks strategically by considering the technical and economic aspects. To achieve the goal, the detailed objectives of this research include the following:

i. To formulate an optimization model for the optimal location and size of PV considering historical weather data and time-varying loads in the distribution system using Particle Swarm Optimization (PSO) and Genetic Algorithm (GA).

ii. To formulate an optimization model for the optimal location and size of PV-BSS and determine battery charge/discharge operation considering historical weather data and time-varying loads in the distribution system using PSO.

iii. To analyze the technical performance of the distribution system and electricity bill savings for the proposed PV-BSS optimization model based on the maximum demand charge minimization considering Time of Use (ToU) tariff.

1.5 Scope of Work

This research is limited to the following scopes:

i. Various types of renewable Distributed Generations (DG) and storage systems are available. However, the focus of this research work is limited to the use of PV and battery storage only.

ii. Meteorological data is primarily taken from ground stations and satellites. For this research, 13 years of Malaysia solar irradiation data from 2007 to 2020 at coordinates (Latitude: 3.139003, Longitude: 101.686855) is acquired through a daily global solar radiation tracking system database [16].

iii. The Beta probability density function (Beta-PDF) is used to handle large historical weather data. The Beta-PDF uses the hourly historical weather data as the input and calculates the probability of occurrence of a range of possible values for solar irradiances during each hour.

iv. Five load models (constant, industrial, residential, commercial, and mixed) are considered during the analysis of optimal allocation and sizing of PV-BSS to reduce power loss and improve bus voltage in the distribution system.

v. The optimization of multiple locations and sizes of PVs ranging from one to three sizes at three different locations is performed on a commercial load model only to compare the power loss reduction with a single PV unit and PV-BSS.

vi. The battery allocation for PV-BSS modelling is assumed to be placed at the same bus as PV to avoid complex system modelling and additional power losses.

vii. The battery is assumed to be charged by the PV unit only to avoid additional losses in the bus distribution system if the battery were charged from the grid. This also ensures that no reverse power flow occurs.

viii. Tenaga Nasional Berhad (TNB) imposed maximum demand (MD) penalty charges for commercial and industrial customers at medium and high voltage levels. The penalty does not imply to small customers at low voltage levels. Therefore, only commercial and industrial load users are accessed in the electricity bill savings analysis to reduce peak load and save maximum demand charges from PV-BSS.

ix. Optimization algorithms are formulated to model optimal PV-BSS sizing based on technical and economic aspects to reduce the maximum peak load during peak hours. The algorithm does not deal with off-peak load hours.

x. The IEEE 33-bus and 69-bus systems are used as bus tests to validate the performance of the developed modelling using MATLAB software. All values follow IEEE Radial Distribution System (IEEE-RDS) standard. All buses are assumed insensitive to variations in voltage on load characteristics.

1.6 Significance of Research Work

Several researchers have attempted to minimize power losses and improve bus voltage in distribution networks by integrating DG. Although several studies have been conducted using the optimization method to determine the optimal sizing and allocation of PV, there is a general lack of research considering historical weather data and non-constant (time-varying) load data. Previous studies disregarded the implication of solar irradiation, which is highly dependent on weather conditions. The proposed PV modelling based on geographical location and historical weather data determines the expected output power and provides the means to construct solar irradiance patterns. The generated patterns can further be used for scenario analysis in power system studies, especially in load flow analysis that requires the integration of weather-dependent generation. Scenario analysis requires multiple irradiance patterns to construct an appropriate and equitable pattern that mimics the irradiance patterns of the other days.

Also, this research work contributed to a knowledge modelling of the optimal sizing of PV-BSS and scheduling of charge/discharge batteries in the distribution networks. Unlike previous studies which determined battery charge/discharge times and rates without considering technical benefits to distribution networks, the method for charge/discharge batteries in this proposed research work is designed to improve distribution network quality over technical and economic benefits. The optimization model is developed to calculate the optimum sizes for PV-BSS and determine the optimum charge/discharge operation for batteries to supply the peak load and minimize maximum demand charges. Considering the most recent ToU tariffs, Malaysian historical weather data, and time-varying loads, the optimization for PV-BSS using PSO helped to reduce the burden on electric utilities during peak hours. Based on the findings, the proposed model solution is theoretically feasible and robust for real-time implementation, considering any size and type of load, including in Malaysia's market.

1.7 Organization of Thesis

This thesis consists of five chapters which are organized as follows:

Chapter 1 describes the overview of this research work related to the integration of PV in the distribution system, previous methods, and issues with the sizing and placement of PV integrated with batteries. Based on the problem highlighted, the planning for PV-BSS that could achieve technical and economic benefits is proposed. Besides, the scope of work and the significance of this research work is highlighted. The flowchart of this thesis is also presented.

Chapter 2 reviews the existing works related to the integrations of PV and battery in the distribution systems with the methodology and techniques used in the related work to solve the PV and PV-BSS planning problems. This chapter also highlighted the gap in previous research on the integration and sizing of PV-BSS. The concept of maximum demand and ToU tariff introduced by the utility provider is presented in this chapter.

Chapter 3 explains the methodologies adopted to execute research works in this thesis. This chapter includes and elaborates on the modelling of PV using historical weather data, load modelling, battery storage, problem formulations, and network constraint for PV and PV-BSS integrations. Besides, the mathematical expressions of impact indices and PV penetrations levels are also included. The proposed method is explained in the flowchart, and the setting parameters for the algorithm are provided. The proposed optimization model to size PV-BSS based on technical and economic aspects are covered in this chapter. Finally, the formulation of sizing PV-BSS over the total maximum demand reduction considering the latest ToU tariffs, historical weather data, and time-varying loads is presented.

Chapter 4 presents the simulated results, and the discussions of the results are divided into two parts, namely, the technical analysis and the electricity bill savings analysis. The results obtained using the proposed optimization model include the optimal location and sizing, power loss reduction, bus voltage improvement, power loss indices, voltage deviation, and PV penetration are presented in the technical analysis part. The results validation using the PSO technique is performed considering a few test cases and the GA technique. Finally, the optimization results based on the optimal sizing of PV-BSS on the maximum demand reduction, charge/discharge of the battery operation during peak hours, and total bill savings are presented in the electricity bill savings analysis part.

Chapter 5 concludes the findings and contributions of this research work and suggests several possible future works to improve the gap in this research work that is worth exploring.

The flowchart that summarizes the research work presented in this thesis is depicted in Figure 1.1.

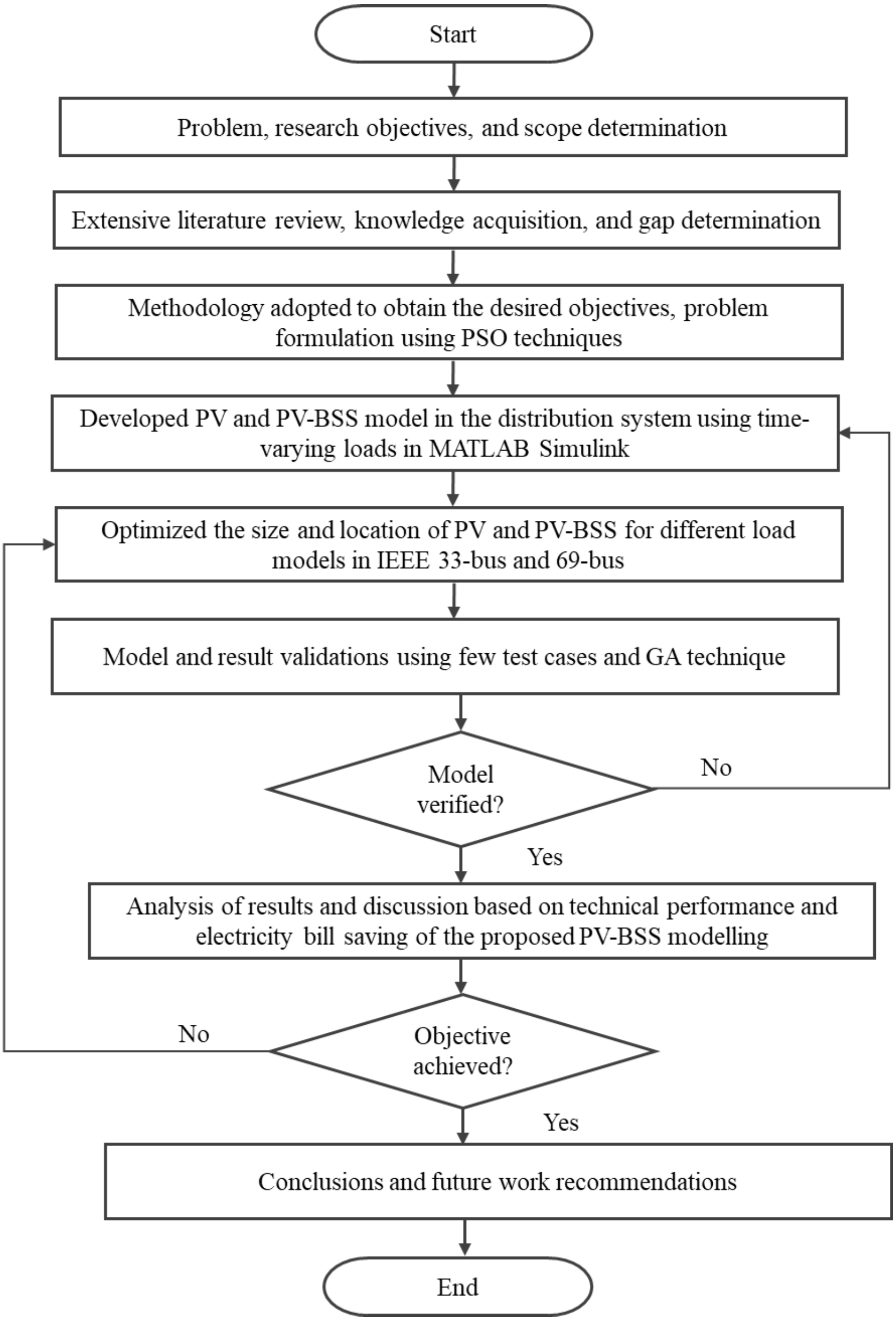

Figure 1.1 Flowchart of the research work

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2. **H. F. Jamahori**, M. P. Abdullah and A. Ali, "Integration of PV Distributed Renewable Energy Generation into Distribution System using Time-Varying Weather and Load Data," *2021 IEEE 19th Student Conference on Research and Development (SCOReD)*, 2021, pp. 295-299. **(Indexed by SCOPUS)**

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1. **H. F. Jamahori**, M. P. Abdullah and A. Ali, "Impact and Evaluation of Optimized PV Generation in The Distribution System with Varying Load Demands," *Jurnal Teknologi*, vol. 85(3) pp. 61-73, 2023. **(Q3, IF:1.4)**

2. **H. F. Jamahori**, M. P. Abdullah, A. Ali, A. Alkassem "Optimal Design and Performance Analysis of Multiple PV with Grid-Connected Commercial Load," *International Journal of Technology*, 2022. Under Review **(Q2, IF:2.4)**