ROBUST DYNAMIC CONTROL STRATEGY FOR STANDALONE PHOTOVOLTAIC SYSTEM UNDER VARYING LOAD AND ENVIRONMENTAL CONDITIONS

WAQAS ANJUM

UNIVERSITI TEKNOLOGI MALAYSIA

ROBUST DYNAMIC CONTROL STRATEGY FOR STANDALONE PHOTOVOLTAIC SYSTEM UNDER VARYING LOAD AND ENVIRONMENTAL CONDITIONS

WAQAS ANJUM

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosphy

School of Electrical Engineering
Faculty of Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2022

ACKNOWLEDGEMENT

Foremost, I would like to express my sincere gratitude to my supervisor Associate Professor Dr. Abdul Rashid bin Husain for the continuous support throughout my research tenure, for his patience, motivation and immense knowledge. His comprehensive guidance helped me in all the time of research and writing of this thesis. I could not have imagined having a better advisor and mentor for my PhD study.

Besides my supervisor, I would like to extend my gratitude to my co-supervisor Associate Professor Dr. Junaidi bin Abdul Aziz for his guidance and insightful comments.

The acknowledgment is also due to The Islamia University of Bahawalpur and Higher education commission (HEC) Pakistan for awarding me study leave and scholarship to pursue my PhD study. I am also greatful to the Universiti Teknologi Malaysia for providing the needed resources.

I also owe heartiest gratitude to my lab mates for their continuous support especially Hasan Alqraghuli and Dr. Abbass Abbasi for their support in coding and simulation. I am also thakful to Dr. Izzudin, Dr. Siti Fadilah, Dr. Bashar Othman, Syed Muhammad Fasih ur Rehman and all UTM friends, for their enthusiastic support and encouragement .

To conclude, I would like to say thank you to my devoted wife, Dr. Kanwal Ejaz, for her thoughtful patience in dealing with my mood swings. It would have been impossible for me to complete my PhD without her support. I also offer my love to my children, my brothers and my sister for their prayers and wishes.

ABSTRACT

Standalone photovoltaic (PV) systems are widely considered as an alternative source of utility grid due to the notable merits such as inexhaustible solar energy, pollution and noise free power generation, ease of assembly and relatively low costs. However, the major drawbacks of these systems are their environmentally-dependent characteristics and performance degradation due to sudden load variations. In order to address these challenges, two objectives must be met simultaneously for consistent and reliable output of PV system. First, the efficient tracking of maximum power point of the PV array in changing environmental conditions and secondly, the smooth conversion of the direct current (DC) input voltage into the desired level of alternating current (AC) output voltage in the presence of load variations. In this thesis, a standalone PV system with two independent control strategies have been presented. At the first stage, a hybrid non-linear maximum power point (MPPT) technique based on the perturb and observe and integral back-stepping control algorithm is proposed to extract the maximum power from the PV array. The integral action in the MPPT algorithm significantly reduces the oscillations in the PV array output that is fed to the DC-AC inverter at the second stage. Then, at the second stage, a dynamic disturbance rejection strategy based on super twisting sliding mode control (ST-SMC) has been proposed to regulate AC power for a variety of loads at the system output. The PV inverter load parameter disturbances and their effect on the system dynamics are aggregated into a perturbation, which is then estimated online by a newly designed higher-order sliding mode observer. The estimated perturbation is then compensated by the ST-SMC such that a better control performance could be achieved with significant robustness against load disturbances. The proposed control algorithms are evaluated and benchmarked with the existing back-stepping controller (BSC) in terms of dynamic response, efficiency, steady-state error and total harmonic distortion (THD) handling capability under varying environmental and load conditions. The designed control strategy reaches the steady-state in 0.005 sec and gives a DC-DC conversion efficiency of 99.85% for the peak solar irradiation level as compared to the 0.008 sec and 99.7% for BSC. The AC-stage steady-state error is minimized to 0.005 V compared to 0.51 V of BSC whereas, THD is limited to 0.07% and 0.11% for linear and non-linear loads respectively for the proposed algorithm as compared to 0.34% and 2.04% for BSC.

ABSTRAK

Sistem fotovolta (PV) kendiri dianggap sebagai satu sumber alternatif kepada pembekalan kuasa grid kerana kelebihan yang dimiliki seperti bekalan sumber tenaga solar berterusan, penghasilan tenaga bebas dari pencemaran dan hingar, mudah dipasang dan relatifnya lebih murah. Bagaimanapun, kelemahan utama sistem ini adalah kebergantungan kepada alam sekitar dan penurunan prestasi disebabkan oleh perubahan beban. Untuk mengatasi permasalahan ini, dua okjektif mesti dipenuhi secara serentak bagi memastikan keluaran sistem PV yang konsisten dan dipercayai dapat dihasilkan. Pertama, penjejakan titik kuasa maksimum (MPPT) yang efisen apabila berlaku perubahan alam sekitar dan kedua, penukaran kuasa masukan arus terus (DC) kepada keluaran voltan arus ulangalik (AC) yang rata dihasilkan dalam keadaan perubahan beban. Dalam tesis ini, sistem PV dengan dua strategi kawalan tidak bergantung diberikan. Di peringkat pertama, teknik hibrid tak linear MPPT berasaskan kawalan ganggu dan lihat dan pengamiran langkah-belakang dicadangkan untuk mendapatkan kuasa maksimum dari tatasusun PV. Pengamiran dari algoritma MPPT ini mengurangkan ayunan dengan berkesan dalam keluaran PV yang seterusnya disuap ke penyongsang DC-AC di peringkat kedua. Di peringkat kedua, strategi penolakan gangguan dinamik berasaskan kawalan ragam gelincir putaran tinggi (ST-SMC) dicadangkan untuk melaras kuasa AC di keluaran sistem pada beban yang pelbagai. Gangguan bebanan pada penyongsang PV dan kesannya kepada sistem dinamik disatukan sebagai satu kelas gangguan dan seterusnya dianggar secara atas talian oleh pemerhati ragam gelincir peringkat tinggi. Anggaran gangguan ini akan diimbangi menggunakan ST-SMC dimana prestasi kawalan yang baik dapat dicapai dengan ketegapan sistem kepada perubahan beban. Algoritma kawalan yang dicadangkan dinilai dan dibandingkan dengan pengawal langkah-belakang (BSC) dari segi tindakbalas dinamik, kecekapan, ralat keseimbangan dan jumlah gangguan harmonik (THD) dibawah perubahan alam sekitar dan keadaan beban. Strategi kawalan yang dicadangkan menghasilkan keseimbangan dalam 0.005 saat dan kecekapan penukar DC-DC sebanyak 99.85% untuk keseluruhan profil radiasi berbanding 0.008 saat dan 99.7% oleh BSC. Pada peringkat AC, ralat keseimbangan dikurangkan kepada $0.005V$ berbanding $0.51V$ oleh BSC. Selain itu THD dihasilkan adalah pada 0.07% untuk beban linear dan 0.11% untuk beban tak linear berbanding 0.34% dan 2.04% pada beban linear dan tak linear untuk BSC.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASMC	-	Adaptive sliding mode control
AI	-	Artificial Intelligence
ANN	-	Artificial Neural Network
ADRC	-	Active disturbance rejection control
ACO	-	Ant colony optimization
BSC	-	Back-stepping control
CV	-	Constant voltage method of MPPT
ESO	-	Extended state observer
FOCV	-	Fractional open circuit voltage
FL	-	Fuzzy logic
FLC	-	Feedback linearization control
GA	-	Genetic algorithm
GWO	-	Grey wolf optimization
HOSMC	-	Higher order sliding mode control
HOSMO	-	Higher order sliding mode observer
IC	-	Incremental conductance
IBSC	-	Integral back-stepping control
ISMC	-	Integral sliding mode control
MPP	-	Maximum power point
MPPT	-	Maximum power point tracking
MPC	-	Model predictive control
NN	-	Neural network
NLESO	-	Non-linear Extended state observer
PV	-	Photovoltaic
P&O	-	Perturb and observe
PWM	-	Pulse width modulation
PSO	-	Particle swarm optimization

PR	-	Proportional resonant control
PCC	-	Parabolic current control
PID	-	Proportional integral derivative control
qZSI	-	Quasi Z-source inverter
RESs	-	Renewable energy sources
RC	-	Repetitive control
SMC	-	Sliding mode control
STC	-	Super twisting control
STA	-	Super twisting algorithm
ST-SMC	-	Super twisting sliding mode control
THD	-	Total harmonic distortion
VSI	-	Voltage source inverter

LIST OF SYMBOLS

c_1, c_2	-	Weighting factor of PSO
C_{in}	-	Input side capacitance of DC-DC boost converter
C_o	-	Output side capacitance of DC-DC boost converter
C	-	Filter capacitor for inverter
e_1, e_2, e_3	-	HOSMO estimation errors
$f(t)$	-	Lumped parameter disturbances
G	-	Solar irradiance level
i_{LB}	-	Boost converter inductor current
I_{ph}	-	Photo current
I_{pv}	-	PV array output current
i_C	-	Second stage capacitor current
i_L	-	Second stage inductor current
i_o	-	Inverter load current
i	-	Number of particle used in PSO
k	-	Number of iterations in PSO
K_1, K_2, K_3	-	Higher order sliding mode observer gain
L_b	-	Inductance of boost converter
L	-	Filter inductor for inverter
n	-	Number of parameters tunned by PSO
R_0	-	Nominal resistive load
r_1, r_2	-	STC controller gain
S_1, S_2, S_3, S_4	-	Inverter IGBTs Switches
s	-	Sliding surface
T	-	Environment temperature in C^o
U_1	-	Duty ratio of DC-DC stage boost converter
u	-	Duty ratio for inverter switches
V_{pv}	-	PV array output voltage

V_{C_o}	-	Output voltage of DC-DC boost converter
V_{pv-ref}	-	Reference voltage for integral back-stepping controller
v_{ref}	-	Reference sinusoidal voltage for second stage
v_o	-	Inverter load voltage
$V(e)$	-	Lyapunov candidate for obserser stability proof
w	-	PSO weighting factor
x_1, x_2	-	AC stage inverter states
z_1, z_2, z_3	-	HOSMO states and disturbance estimates
β_1	-	Integral back-stepping controller gain
β_2	-	Integral back-stepping controller gain
ϵ_1	-	First error term in integral back-stepping controller
ϵ_2	-	Second error term in integral back-stepping controller
γ	-	Intergral term in integral back-stepping controller
Γ	-	Transformation matrix
$\gamma_1, \gamma_2, \gamma_3, \gamma_{12}, \gamma_{23}$	-	Coefficients of the matrix Γ
λ	-	Sliding surface constant
ζ^T	-	Quadratic form of of vector $V(e)$

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

A growing world population and the increase of industrialization have resulted in a exponential increase in energy demand. A significant amount of global energy is produced by fossil fuels, such as coal, oil, and natural gas. However, fossil fuel sources have major drawbacks, such as fluctuating prices, limited supply and environmental pollution [1]. Global warming has been intensified due to carbon dioxide emissions resulting from the combustion of fossil fuels. These fossil fuels are expected to generate about 40.4 giga tons of CO2 by 2030 [2] which will affect the climate by creating the greenhouse effect. In spite of climate change, fossil fuels are not evenly distributed around the globe, resulting in geopolitical conflicts. In addition, the energy generated from this fossil fuel poses safety risks as well, such as leakages or explosions during their combustion. In the present context, renewable energy sources (RESs) are viewed as a viable option for replacing conventional fossil fuel plants in order to increase energy production and to overcome environmental pollution. In the future, RESs such as wind, geothermal and solar energy represent natural, free, and inexhaustible resources that are expected to dominate the energy sector. Over the past few years, most countries around the world have been motivated to increase their use of renewable energy. For instance, by 2030, the European Union aims to generate 32% of its energy from renewable sources, with the goal of reaching 100% by 2050 [3].

Due to the sustainability, clean, and safe nature of solar photovoltaic(PV), it is regarded as one of the most appealing renewable energy resources. It is estimated that about $1.8 \times 10^{11} MW$ of solar radiation reaches the surface of the earth, which is way greater than the global electricity demand [4]. Additionally, it can be installed anywhere with suitable weather conditions and the desired generation capacity. Reports from the international renewable energy agency indicate that solar energy's capacity has risen exponentially over the last decade [5] as presented in Figure 1.1. Another

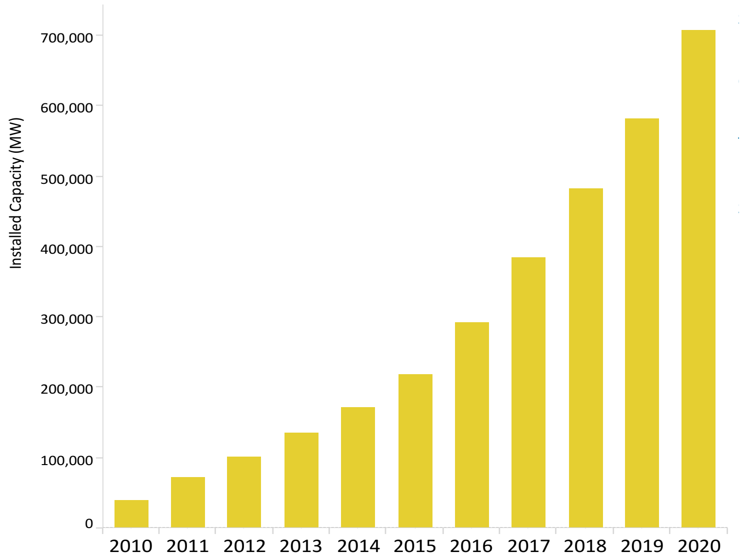

Figure 1.1: Solar energy statistics [5]

reason behind the rapid expansion of the PV system is that the average cost of installing the PV system has declined dramatically over the last decade as illustrated in Figure 1.2. Though, PV systems are growing at a rapid rate worldwide, factors such as stability, reliability, and efficiency have proven to be major barriers to their introduction to the market.

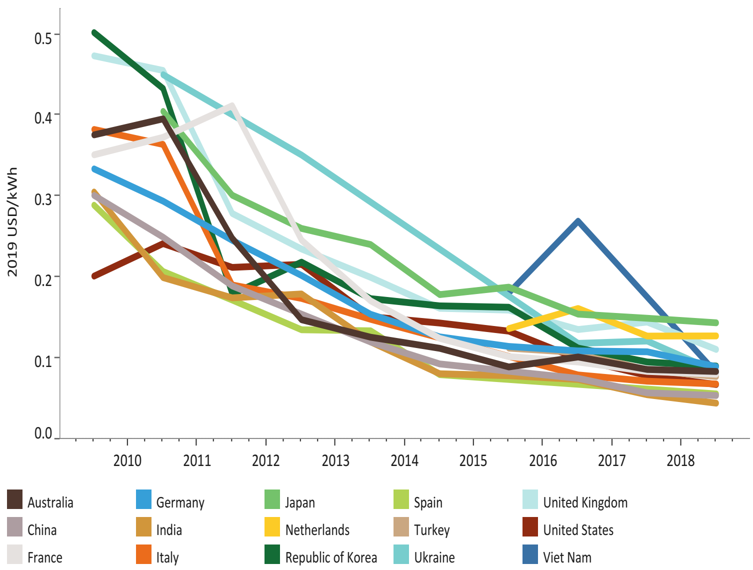

Figure 1.2: Solar energy average cost statistics around the globe [5]

1.2 PV based generation system

Generally, PV systems fall into two categories: grid-connected PV systems and standalone PV systems as shown in Figures 1.3 and 1.4, respectively. In grid connected PV system the generated energy is fed directly to the national grid whereas, the PV systems that deliver power directly to the load are known as standalone PV systems. In general, when the PV system is connected with grid, the main aim is to control the active and reactive power under the normal and faulty grid conditions [6] while in standalone mode, voltage and frequency control under variable load conditions are the prime objectives [7, 8]. In this study, the later category is put in focus, which is widely deployed around the globe due to its ease of installation at remote locations. A standalone PV system consists of a PV array, power conversion devices and end-user load equipment. Therefore, electricity generated by this system is delivered directly to the consumer during sunny weather conditions.

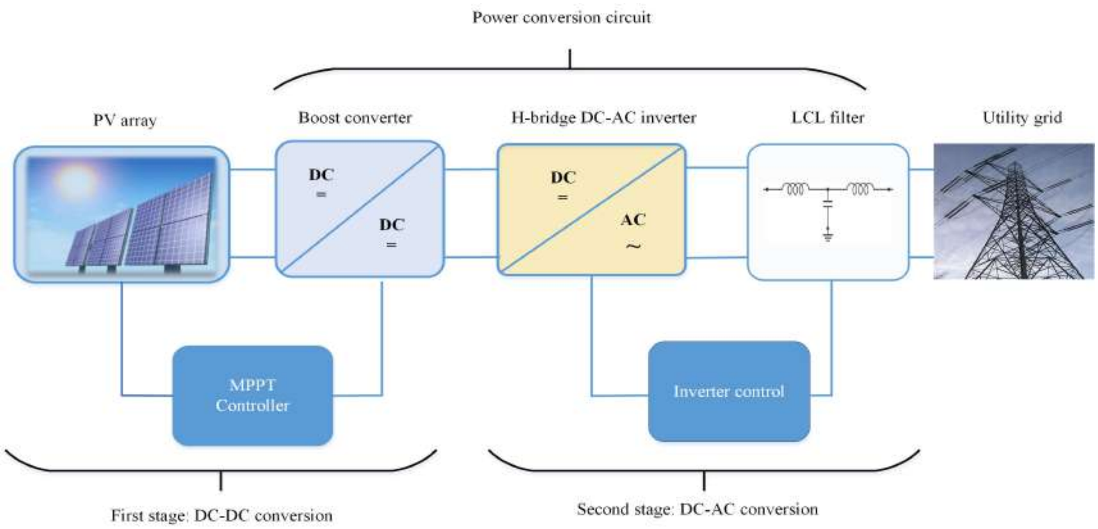

Figure 1.3: PV based grid-connected generation system

To convert DC photovoltaic energy into AC electricity, power converters are essential. Power converters function in two fundamental ways; at the first stage, they ensure that the maximum power is extracted from the solar cells, which is known as maximum power point (MPP) extraction. Whereas, at the second stage, it is ensured that the power converter outputs must match the grid output in terms of stability, frequency and phase in order to be considered as a substitute for the utility grid [9].

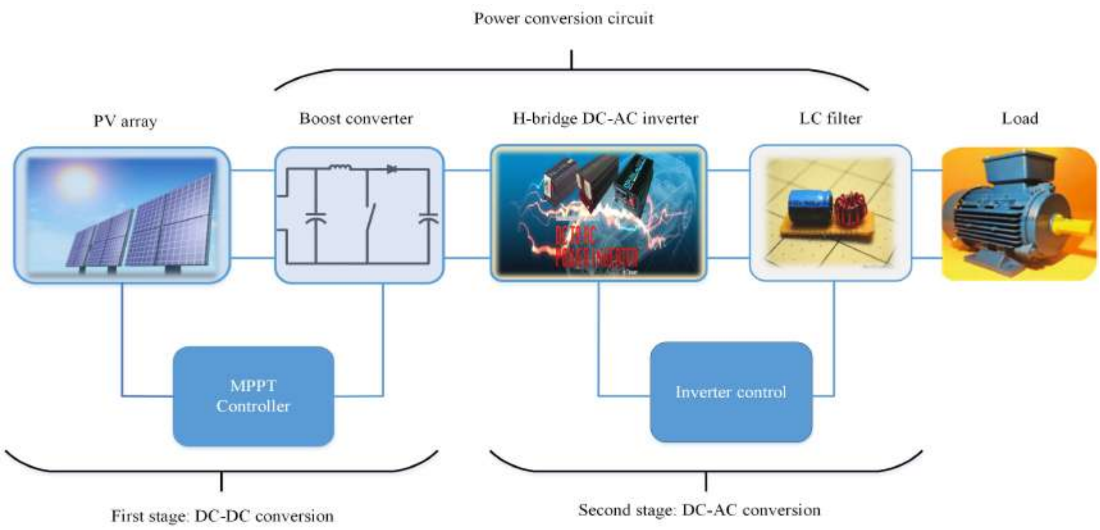

Figure 1.4: PV based standalone generation system

However, the major drawbacks of PV systems are their highly non-linear characteristics and low efficiency that can be in the range from 9 to 16% only [10]. To overcome these challenges, a number of solutions in the literature have been proposed for improving PV system performance. The purpose of using these solutions is to achieve maximum efficiency from the PV array in a shorter response time. The maximum power point tracking (MPPT) techniques represent one of the most common solutions to reach and maintain the optimal operating point in the PV module.

1.2.1 Maximum power point tracking with DC-DC converters

The output and efficiency of the PV system depends heavily on environmental conditions like solar irradiation level and temperature. As a result, the optimal output point at which maximum power can be obtained change its position continuously as shown in Figure 1.5. Several solutions are proposed in the literature to improve the performance and efficiency of PV systems in order to achieve a consistent and reliable power output particularly, in changing environmental conditions. The maximum power point tracking (MPPT) techniques represent one of the most convenient solutions to reach and maintain the optimal operating point in the PV module. These techniques use DC-DC power converters and a control algorithm that generates the duty ratio of the power converter in such a way that the PV array and converter impedance are matched and the maximum power can be extracted. The most common MPPT algorithms employed in the literature include perturb and observe P&O and incremental

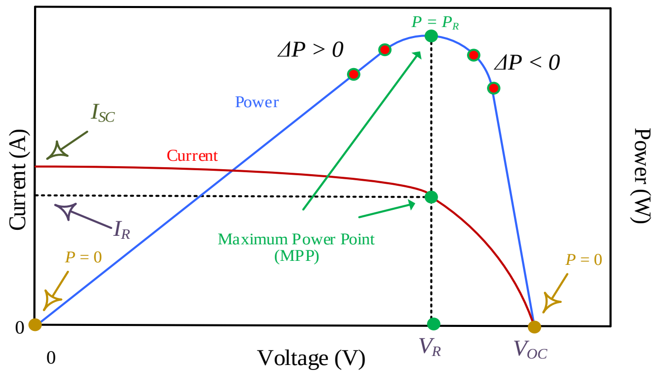

Figure 1.5: Maximum power point tracking

conductance (IC) technique. In P&O based algorithms, the output voltage of PV module is perturbed and the change in output power, $\Delta Power$, is observed. If the $\Delta Power > 0$, then the voltage will be further perturbed in the same direction and vice versa [11]. In [12] the P&O parameters are optimized at the same pattern to generate the duty ratio for the converter switch to attain MPP. In [13], the P&O algorithms generate the reference for PI controller to generate the control input for boost converter to extract MPP. As the algorithm makes periodic perturbations in voltage and duty ratio of the boost converter to track the MPP, therefore it creates an oscillatory operating point. To overcome the oscillatory nature of MPP incremental conductance (IC) algorithm has been presented in [14, 15, 13]. The strategy utilizes the current and voltage measurements to determine the trajectory of working point thus, gives better performance for uniform whether conditions. However, whenever the atmospheric conditions are changing the tracking becomes exponentially harder because of continuous change in the slope of the PV curve [16]. Although, in terms of oscillatory response, IC method performs better than P&O algorithm but the cost of better performance is increased complexity and the execution of larger number of instructions to accurately perform the necessary calculations. Both of these classical algorithms have the common problem of oscillation around the operating point in the steady-state if there is a change in the surrounding environment [17]. These oscillations in the output not only causes power losses in the DC stage but also effects the output of the next AC stage when used in coupled mode.

Another class of MPPT algorithms is intelligent controller such as fuzzy logic and artificial neural network (ANN) based algorithm have been proposed in [18, 19] to track the maximum power point. These non-linear techniques are not only robust and efficient but also do not require any system knowledge to perform their operation. However, on the downside, the performance of fuzzy based systems and its computational complexity rely on adapted fuzzy model based on the system's behavior in varying environment [20]. On the other hand, ANN required rigorous training mechanism for the algorithm to perform their operation under varying environmental conditions.

In addition to the techniques listed above, other hybrid non-linear tracking techniques have been proposed to track the MPP with improved accuracy. In these techniques the conventional algorithms such as P&O are used for reference generation whereas, non-linear controllers such as sliding mode control (SMC) [15, 21] and back-stepping control (BSC)[9] are used to control the operation of DC-DC converter to extract the MPP. SMC is well suited for variable structure converter system and inherits the properties of robustness and tolerance against external disturbances however, it suffers from chattering. The BSC proved stable and efficient for non-linear systems because of its rigorous stability criterion design nature. In [11], BSC has been presented for MPP tracking with buck converter whereas, similar control scheme has been adopted in [9] for boost converter. Although the algorithm proves itself in robustness and efficiency but still there are oscillations in the output because of its recursive nature and the requirement of derivative of virtual states. The steady-state oscillations around MPP can be reduced by including the integral action during the BSC design process.

Once the MPP is tracked, the optimal output power obtained at the first DC-DC converter stage is fed to the second DC-AC voltage source inverter (VSI) stage where, the inverter is responsible for the conversion of DC power to AC power that is a matched alternative to the power supplied by the utility grid in terms of amplitude, phase and frequency.

1.2.2 Voltage source inverter (VSI)

Inverter is a semiconductor device that is known for the conversion of DC power into AC power. The output of the inverter is an AC signal with amplitude, frequency and phase which is controlled through a controller to achieve the desired signal level. A generalized structure of DC-AC inverter with DC input (1^{st} stage output) and variable

AC output is shown in Figure 1.6. Inverters can be classified into two categories depending upon the type of input. If a constant current source is present at the input then, it can be termed as current source inverter (CSI) and if a DC voltage source is present at the input then it can be classified as VSI. The VSI is extensively used in

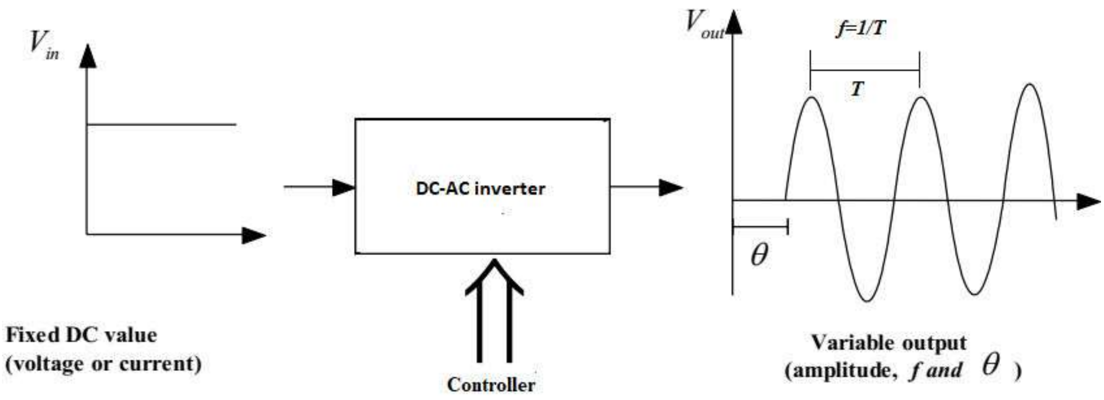

Figure 1.6: Simple structure of VSI

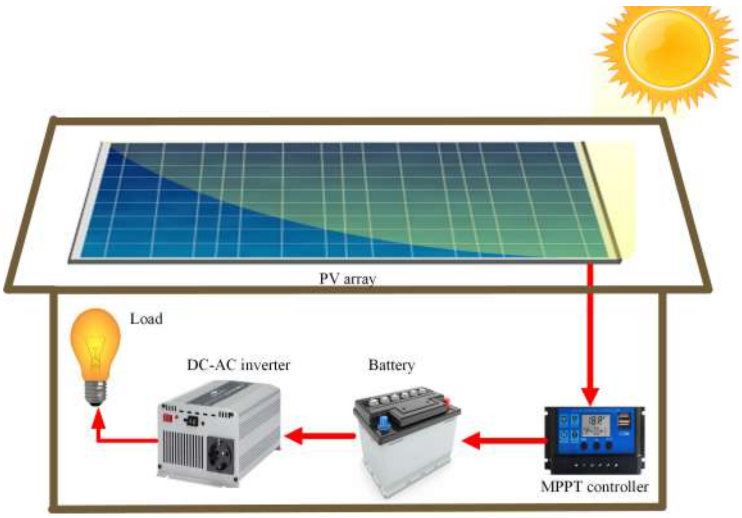

Figure 1.7: PV based house-hold generation system

PV-based power generation systems and it must be controlled appropriately to ensure proper operation as, the output of a VSI suffers from distortion when the input DC voltage is not constant or the inverter load is variable. For instance, in PV based system where the solar energy is converted into AC power through inverter as shown in Figure

1.7, the DC output of the solar panels depends upon various factors such as radiation level, temperature and angle of radiation impact. Thus, the PV output is not constant and the controller is designed for the inverter to convert this varying DC to desired AC level. Therefore, the inverter control for varying DC input and changes in load is an important research area because of its vast impact on PV based industrial applications.

1.3 VSI control objectives

A standalone PV based generation system requires the inverter to provide stable and smooth sinusoidal output with fast transient response, minimal steady-state errors and low total harmonic distortion (THD). In order to achieve these objectives, a smooth continuous control signal is essential. Additionally, when non-linear loads like rectifiers or motors are applied to the generation system, they also draw reactive power along with active power which leads to the harmonic distortion on the supply line.

As the inverter system is subjected to the variety of external disturbances like input variations, measurement noises, variable linear and non-linear loads, thus, the output waveform of VSI experience distortion and the controller is essential to provide a pure sinusoidal waveform at the output with desired amplitude and frequency. Therefore VSI controller is designed to perform the following tasks:

1. **Output voltage regulation.** For a controlled VSI, the output voltage should track the desired sinusoidal reference voltage to ensure minimum tracking error.
2. **Suppressing the influence of external disturbances.** Disturbances such as load or source variations may effect the system performance thus, in case of any external disturbance, the controller is expected to regulate the output at desired level by compensating or rejecting the effect of those disturbances.
3. **Fast dynamic response with small steady-state error.** The controller should have fast response in attaining the reference value and the difference between the reference value and controlled output must be negligible.
4. **To reduce the harmonic distortion.** When subjected to the non-linear loads such as rectifiers or motors, the harmonic problem rises that needs to be suppressed by the controller.

1.4 Traditional control schemes for VSI and their limitations

Various control techniques have been presented in the literature to control the VSI for desired performance however, the factors such as controller ability to accommodate system non-linearities, input voltage & load parameters variation sensitivity and complex gain tuning mechanism of traditional controllers does not guarantee the efficient operation of the VSI [22]. In the framework of standalone PV inverter the main purpose of controller is to produce a pure sinusoidal output waveform with desired frequency and amplitude with minimized steady-state error and low THD [23].

At present, there are two types of control strategies being developed to achieve these objectives, namely linear control and nonlinear control. In the former category, proportional-integral (PI) control [24] and hysteresis control [25, 26] are the most common control schemes in inverters due to their advantage of the ease of implementation. As long as the system is linearized at the equilibrium point, these control strategies can provide satisfactory performance. However, their control performance may degrade as the PV source usually exhibits a strongly nonlinear electrical behavior resulted from the variation of solar irradiation and surrounding temperature together with the fact that the inverter may be subjected to sudden load variations [22].

In the later category, in order to obtain the rapid dynamic response from VSI various robust and non-linear techniques such as H_∞, model predictive control (MPC), artificial intelligence (AI) & neural network (NN) based techniques and sliding mode control (SMC) has also been studied. H_∞ and MPC control methods give robust performance when applied to VSI [27, 28, 29] by optimizing the system based on selected weighing factors and can accommodate various input and load constraints in its design. However, its implementation requires the complete knowledge of the PV system states, constraints on the system and weighing factors [30]. AI based techniques such as fuzzy and NN has been applied to VSI in [35][36] for rapid transient response. Although, these techniques are robust, model independent and insensitive to load parameter variations [31] however, in these techniques, database of control rules are tabulated or the controller is trained through rigorous simulations for all maximum possible loading conditions [30] which make its implementation a challenging task.

In terms of properties such as model independence, insensitivity to load parameter variance and input disturbances, SMC gives fast dynamic response with offset free tracking errors when applied to VSI [32]. However, the major challenges while designing SMC for VSI is its discontinuous nature and over conservative gain selection originated from the use of upper bound of disturbances in the system that results in waveform distortion and high THD in the inverter output. Super twisting sliding mode control (ST-SMC) has been introduced in [33, 34] as a way of overcoming the discontinuous nature of SMC for varying load parameters and environmental conditions however, the switching gain of the STC is still kept greater than the upper bound of the disturbances.

The inherent over conservativeness of ST-SMC can be reduced significantly by adapting a disturbance estimation and rejection strategy [22]. In this technique, uncertainties in the system are estimated by using a disturbance observer and then, rejected through a feed forward loop instead of switching gain adjustment. This approach is reported in [35] [32] for a single phase VSI and can address load/source disturbances effectively and proven efficient against steady-state oscillations and THD mitigation.

1.5 Problem statement

The power conversion in the PV system is accomplished in two stages. In the first stage, the MPPT control algorithm is employed to maximize the PV array output. The MPPT is a control technique that uses DC-DC power converters and a control algorithm to deliver the maximum power under variable temperature and solar irradiation levels. In general, several factors are crucial while designing an MPPT controller for a PV system such as robustness, level of oscillations in the output and MPP tracking accuracy. Even though existing hybrid non-linear BSC technique provide robust and efficient extraction of the MPP under changing environmental conditions, there is still a considerable amount of steady-state oscillations in the output response due to its recursive nature. By incorporating integral action into the hybrid non-linear BSC algorithm, the challenge of steady-state oscillations around the MPP under changing environmental conditions can be effectively addressed. At the second stage of the PV system, a DC-AC VSI is used to supply power to the AC loads. The VSI is a non-linear dynamic system and is subjected to various source and load disturbances. These disturbances degrade the control performance that results in high steady-state error and undesirable harmonic ripples in the VSI output which can cause damage to the sensitive loads. Thus, the precise regulation of the output voltage in the presence of these disturbances is a critical task. Although SMC is less sensitive to source and load parameter uncertainties, however, there is a constant steady-state error and harmonic ripples in the output response of VSI due to its discontinuous nature and high switching gain. The issue can be counteracted by employing a disturbance rejection ST-SMC control strategy in a robust manner.

1.6 Objectives of the study

The following objectives are proposed for the study:

I To design a hybrid integral back-stepping (IBS) MPPT controller for the DC-stage of PV system that can extract the maximum available power from the PV array with reduced amount of oscillations under rapidly changing weather conditions.

II To design a robust dynamic disturbance rejection based ST-SMC for the AC-stage of PV system to attain regulated sinusoidal output with minimum steady-state tracking error and THD in the presence of input and load variations.

III To evaluate the performance of the proposed algorithms for a standalone PV system in Matlab simulations, focusing on the output of the system under the various weather and load conditions.

1.7 Scope of the research and methodology

The study applies to control of standalone PV system for the following research scope.

I The PV array is configured by using Soltech STH-245-WH" PV modules to generate the maximum DC output voltage of 120.8 V with a current of 8.1 A at MPP [9].

II The MPPT controller is designed to extract MPP from the PV array under sudden variation in temperature from 25^oC to 50^oC [14].

III The varying irradiation level is initially defined as $600W/m^2$, then, after each $0.2sec$, it is changed to the following values: $200W/m^2$, $700W/m^2$, $1000W/m^2$ and $900W/m^2$ in order to have instantaneous step values of irradiance in a short time for testing the capability of the controller to track the maximum value of power generated by the PV array [9].

IV The boosted output DC voltage is then converted into $220V$ sinusoidal output with $50Hz$ frequency whereas, the switching frequency of $15kHz$ is used for PWM block.

V A single phase two level VSI is employed for DC-AC conversion where, the nominal value of inverter load is selected as $100\,\Omega$ [9].

VI The LC filter for the inverter is designed by selecting the cutoff frequency of $500Hz$

VII Based on the guidelines provided in [36], linear load variations are made by increasing and decreasing the nominal load by 50% instantly.

VIII To check the system response against non-linear load, a full wave bridge rectifier load has been designed according to the guideline provided in [37].

IX The entire system is simulated in Matlab Simulink environment and the stability of the entire algorithm is proved using Lyapunov stability criteria.

1.8 Significance of the study

The main contribution to the thesis are as follows;

I At the first DC-DC conversion stage of the PV system, the proposed hybrid non-linear control algorithm tracks the MPP with great accuracy and efficiency for entire solar irradiation profile. Because of the integral action present in the controller, the output of the boost converter is smooth which contributes to the smooth conversion of solar energy into desired sinusoidal AC output. The inherent Lyapunov based controller design criterion ensures the stability and reliability of the proposed MPP tracking controller for all weather conditions.

II For the second DC-AC conversion stage of PV system, the proposed algorithm will be completely model independent and only the VSI output information will be sufficient for its implementation thus, the non-linearities of the VSI model will not affect the controller performance. The inverter output will track the reference value in a robust manner, steady-state errors will be minimized and there will be no significant effect of sudden load variation and input disturbances on the output voltage. Moreover, the application of non-linear loads to the inverter will have a little impact on the output and the duty ratio will be a fixed frequency continuous control signal that will not only reduce the THD but also be beneficial in reducing the switching stress in the VSI.

1.9 Thesis organization

There are seven chapters in this thesis, beginning with this introduction. The rest of the chapters are outlined as follows;

Chapter 2 provides a review of PV-based power generation systems. The chapter begins with the modelling and working principle of PV cell, then the review of the prominent techniques for calculating maximum power points are covered. In addition to PV generation, a detailed assessment of VSI control techniques for reference tracking is discussed followed by a detailed review of SMC and various disturbance rejection techniques used in SMC is presented to solve the tracking issues related to DC-AC inverters.

Chapter 3 illustrates the detailed methodology of the proposed algorithm along with the simulation setup. This chapter also contains a detailed description of the BSC algorithm used for bench-marking the proposed algorithm. Additionally, the detail of the PV array, along with the characteristic values of the various components used in the simulation is also provided.

Chapter 4 describes a control strategy for tracking the MPP of PV array with the DC-DC boost converters that forms the first stage of the PV system. The Lyapunov theory is used to develop integral back-stepping control to track the optimal power point under sudden fluctuations in temperature and the solar irradiation profile.

Chapter 5 presents the basic principles of super twisting control and disturbance rejection based reference tracking control algorithm for the second stage of the standalone PV system. A HOSMO is designed to estimate the system states and aggregates the system disturbances as a lumped parameter that is then rejected by the proposed control law. The cascaded structure of the overall control loop is discussed and characteristics of both controller and observer are explained. It also elaborates the construction and stability of the overall control loop using Lyapunov theory.

Chapter 6 illustrates the simulation results which is comprised of three sections. In the first section DC-DC stage controller performance is presented for MPPT whereas, in the second section cascaded PV system performance is described under varying environment. In the third section DC-AC stage dynamic controller performance is elaborated for linear and non-linear loads. The results show the efficiency of both the newly designed controllers for this class of PV system.

Chapter 7 summarizes the thesis's findings and suggests the research opportunities for the future directions in this area of research work.

REFERENCES

1. Luna-Rubio, R., Trejo-Perea, M., Vargas-Vázquez, D. and Ríos-Moreno, G. J. Optimal sizing of renewable hybrids energy systems: A review of methodologies. *Solar Energy*, 2012. 86(4): 1077–1088. ISSN 0038092X. doi:10.1016/j.solener.2011.10.016.

2. Quadrelli, R. and Peterson, S. The energy-climate challenge: Recent trends in CO2 emissions from fuel combustion. *Energy Policy*, 2007. 35(11): 5938–5952. ISSN 03014215. doi:10.1016/j.enpol.2007.07.001.

3. Shah, R., Mithulananthan, N., Bansal, R. C. and Ramachandaramurthy, V. K. A review of key power system stability challenges for large-scale PV integration. *Renewable and Sustainable Energy Reviews*, 2015. 41: 1423–1436. ISSN 13640321. doi:10.1016/j.rser.2014.09.027.

4. Panwar, N. L., Kaushik, S. C. and Kothari, S. Role of renewable energy sources in environmental protection: A review. *Renewable and Sustainable Energy Reviews*, 2011. 15(3): 1513–1524. ISSN 13640321. doi:10.1016/j.rser.2010.11.037.

5. IREA. *Renewable capacity statistics 2021*. Technical report. 2021.

6. Merabet, A., Labib, L., Ghias, A. M., Ghenai, C. and Salameh, T. Robust Feedback Linearizing Control with Sliding Mode Compensation for a Grid-Connected Photovoltaic Inverter System under Unbalanced Grid Voltages. *IEEE Journal of Photovoltaics*, 2017. 7(3): 828–838. ISSN 21563381. doi:10.1109/JPHOTOV.2017.2667724.

7. Pichan, M. and Rastegar, H. Sliding-mode control of four-leg inverter with fixed switching frequency for uninterruptible power supply applications. *IEEE Transactions on Industrial Electronics*, 2017. 64(8): 6805–6814. ISSN 02780046. doi:10.1109/TIE.2017.2686346.

8. Hossain, M. A., Pota, H. R., Issa, W. and Hossain, M. J. Overview of AC microgrid controls with inverter-interfaced generations. *Energies*, 2017. 10(9): 1–27. ISSN 19961073. doi:10.3390/en10091300.

9. Diouri, O., Es-Sbai, N., Errahimi, F., Gaga, A. and Alaoui, C. Modeling and Design of Single-Phase PV Inverter with MPPT Algorithm Applied to the Boost Converter Using Back-Stepping Control in Standalone Mode. *International Journal of Photoenergy*, 2019. ISSN 1687529X. doi: 10.1155/2019/7021578.

10. Chaibi, Y., Salhi, M. and El-Jouni, A. Sliding mode controllers for standalone PV systems: Modeling and approach of control. *International Journal of Photoenergy*, 2019. ISSN 1687529X. doi:10.1155/2019/5092078.

11. Iftikhar, R., Ahmad, I., Arsalan, M., Naz, N., Ali, N. and Armghan, H. MPPT for photovoltaic system using nonlinear controller. *International Journal of Photoenergy*, 2018. ISSN 1687529X. doi:10.1155/2018/6979723.

12. Femia, N., Petrone, G., Spagnuolo, G. and Vitelli, M. Optimization of perturb and observe maximum power point tracking method. *IEEE Transactions on Power Electronics*, 2005. 20(4): 963–973. ISSN 08858993. doi:10.1109/TPEL.2005.850975.

13. De Brito, M. A. G., Galotto, L., Sampaio, L. P., De Azevedo Melo, G. and Canesin, C. A. Evaluation of the main MPPT techniques for photovoltaic applications. *IEEE Transactions on Industrial Electronics*, 2013. 60(3): 1156–1167. ISSN 02780046. doi:10.1109/TIE.2012.2198036.

14. Faraji, R., Rouholamini, A., Naji, H. R., Fadaeinedjad, R. and Chavoshian, M. R. FPGA-based real time incremental conductance maximum power point tracking controller for photovoltaic systems. *IET Power Electronics*, 2014. 7(5): 1294–1304. ISSN 17554543. doi:10.1049/iet-pel.2013.0603.

15. Fang, Y., Zhu, Y. and Fei, J. Adaptive intelligent sliding mode control of a photovoltaic grid-connected inverter. *Applied Sciences*, 2018. 8(10). ISSN 20763417. doi:10.3390/app8101756.

16. Bollipo, R. B., Mikkili, S. and Bonthagorla, P. K. Critical Review on PV MPPT Techniques: Classical, Intelligent and Optimisation. *IET Renewable Power Generation*, 2020. 14(9): 1433–1452. ISSN 17521424. doi:10.1049/iet-rpg.2019.1163.

17. Mostafa, M. R., Saad, N. H. and El-sattar, A. A. Tracking the maximum power point of PV array by sliding mode control method. *Ain Shams Engineering Journal*, 2020. 11(1): 119–131. ISSN 20904479. doi:10.1016/j.asej.2019.09.003.

18. Na, W., Chen, P. and Kim, J. An improvement of a fuzzy logic-controlled maximum power point tracking algorithm for photovoltic applications. *Applied Sciences (Switzerland)*, 2017. 7(4). ISSN 20763417. doi:10.3390/app7040326.

19. Elobaid, L. M., Abdelsalam, A. K. and Zakzouk, E. E. Artificial neural network-based photovoltaic maximum power point tracking techniques: A survey. *IET Renewable Power Generation*, 2015. 9(8): 1043–1063. ISSN 17521424. doi:10.1049/iet-rpg.2014.0359.

20. Kalibatien, D. and Miliauskait, J. A Hybrid Systematic Review Approach on Complexity Issues in Data-Driven Fuzzy Inference Systems Development. *Informatica*, 2021. 32(1): 85–118. ISSN 08684952. doi:10.15388/21-INFOR444.

21. Ali, H. G., Arbos, R. V., Herrera, J., Tobón, A. and Peláez-Restrepo, J. Non-linear sliding mode controller for photovoltaic panels with maximum power point tracking. *Processes*, 2020. 8(1): 1–14. ISSN 22279717. doi:10.3390/pr8010108.

22. Yang, B., Yu, T., Shu, H., Zhu, D., An, N., Sang, Y. and Jiang, L. Perturbation observer based fractional-order sliding-mode controller for MPPT of grid-connected PV inverters: Design and real-time implementation. *Control Engineering Practice*, 2018. 79(4): 105–125. ISSN 09670661. doi:10.1016/j.conengprac.2018.07.007.

23. Zheng, L., Jiang, F., Song, J., Gao, Y. and Tian, M. A Discrete Time Repetitive Sliding Mode Control for Voltage Source Inverters. *IEEE Journal of Emerging and Selected Topics in Power Electronics*, 2017. 6(3). ISSN 21686785. doi:10.1109/JESTPE.2017.2781701.

24. Cherati, S. M., Azli, N. A., Ayob, S. M. and Mortezaei, A. Design of a current mode PI controller for a single-phase PWM inverter. *2011 IEEE*

Applied Power Electronics Colloquium, IAPEC 2011. Johor Bahru, Malaysia. 2011. ISBN 9781457700088. 180–184. doi:10.1109/IAPEC.2011.5779864.

25. Gupta, R. Generalized frequency domain formulation of the switching frequency for hysteresis current controlled VSI used for load compensation. *IEEE Transactions on Power Electronics*, 2012. 27(5): 2526–2535. ISSN 08858993. doi:10.1109/TPEL.2011.2175750.

26. Mao, H., Yang, X., Chen, Z. and Wang, Z. A hysteresis current controller for single-phase three-level voltage source inverters. *IEEE Transactions on Power Electronics*, 2012. 27(7): 3330–3339. ISSN 08858993. doi:10.1109/TPEL.2011.2181419.

27. Li, Z., Member, S., Zang, C., Zeng, P. and Yu, H. Control of A Grid-Forming Inverter Based on Sliding Mode and Mixed H 2 /H-infinity Control. *IEEE Transactions on Industrial Electronics*, 2017. 64(5): 3862–3872. doi:10.1109/TIE.2016.2636798.

28. Mohamed, I., Zaid, S., Abu-Elyazeed, M. and Elsayed, H. Implementation of model predictive control for three-phase inverter with output LC filter on eZdsp F28335 Kit using HIL simulation. *International Journal of Modelling, Identification and Control*, 2016. 25(4). ISSN 17466180. doi:10.1504/IJMIC.2016.076830.

29. Hassine, I. M. B., Naouar, M. W. and Mrabet-Bellaaj, N. Model predictive-sliding mode control for three-phase grid-connected converters. *IEEE Transactions on Industrial Electronics*, 2017. 64(2): 1341–1349. ISSN 02780046. doi:10.1109/TIE.2016.2618867.

30. Shahgholian, G., Faiz, J. and Jabbari, M. Voltage control techniques in uninterruptible power supply inverters: A review. *International Review of Electrical Engineering*, 2011. 6(4): 1531–1542. ISSN 18276660. doi:10.1109/ICCEE.2009.99.

31. Kang, D. S. and Chen, Y. An Algorithm for the Output Waveform Compensation of Spwm Inverters Based on Fuzzy Repetitive Control. *Journal of Electrical Engineering*, 2004. 55(3): 64–70.

32. Zhao, Z., Yang, J., Li, S., Yu, X. and Wang, Z. Continuous Output Feedback TSM Control for Uncertain Systems with a DC-AC Inverter Example. *IEEE Transactions on Circuits and Systems II: Express Briefs*, 2018. 65(1): 71–75. ISSN 1549-7747. doi:10.1109/TCSII.2017.2692256.

33. Gudey, S. K. and Member, S. Second Order Sliding Mode Control for a Single Phase Voltage Source Inverter. *TENCON 2014 - 2014 IEEE Region 10 Conference*. Bangkok, Thailand. ISBN 9781479940752.

34. Guo, B., Su, M., Sun, Y., Wang, H., Dan, H., Tang, Z. and Cheng, B. A Robust Second-Order Sliding Mode Control for Single-Phase Photovoltaic Grid-Connected Voltage Source Inverter. *IEEE Access*, 2019. 7: 53202–53212. ISSN 21693536. doi:10.1109/ACCESS.2019.2912033.

35. Wang, Z., Li, S., Yang, J. and Li, Q. Current sensorless sliding mode control for direct current-alternating current inverter with load variations via a USDO approach. *IET Power Electronics*, 2018. 11(8): 1–10. ISSN 17554543. doi:10.1049/iet-pel.2017.0569.

36. Dai, C., Yang, J., Wang, Z. and Li, S. Universal active disturbance rejection control for non-linear systems with multiple disturbances via a high-order sliding mode observer. *IET Control Theory & Applications*, 2017. 11(8): 1194–1204. ISSN 1751-8644. doi:10.1049/iet-cta.2016.0709.

37. Sun, X., Chow, M. H. L., Leung, F. H. F., Xu, D., Wang, Y. and Lee, Y. S. Analogue implementation of a neural network controller for UPS inverter applications. *IEEE Transactions on Power Electronics*, 2002. 17(3): 305–313. ISSN 08858993. doi:10.1109/TPEL.2002.1004238.

38. Tian, W., Wang, Y., Ren, J. and Zhu, L. Effect of urban climate on building integrated photovoltaics performance. *Energy Conversion and Management*, 2007. 48(1): 1–8. ISSN 01968904. doi:10.1016/j.enconman.2006.05.015.

39. Tan, Y. T., Kirschen, D. S. and Jenkins, N. A model of PV generation suitable for stability analysis. *IEEE Transactions on Energy Conversion*, 2004. 19(4): 748–755. ISSN 08858969. doi:10.1109/TEC.2004.827707.

40. Shah, R., Mithulananthan, N., Bansal, R. C. and Ramachandaramurthy, V. K. A review of key power system stability challenges for large-scale PV

integration. *Renewable and Sustainable Energy Reviews*, 2015. 41: 1423–1436. ISSN 13640321. doi:10.1016/j.rser.2014.09.027.

41. Orioli, A. and Di Gangi, A. Load mismatch of grid-connected photovoltaic systems: Review of the effects and analysis in an urban context. *Renewable and Sustainable Energy Reviews*, 2013. 21: 13–28. ISSN 13640321. doi:10.1016/j.rser.2012.12.035.

42. Pandey, A., Dasgupta, N. and Mukerjee, A. K. A simple single-sensor MPPT solution. *IEEE Transactions on Power Electronics*, 2007. 22(2): 698–700. ISSN 08858993. doi:10.1109/TPEL.2007.892346.

43. Leedy, A. W., Guo, L. and Aganah, K. A. A constant voltage MPPT method for a solar powered boost converter with DC motor load. *Conference Proceedings - IEEE SOUTHEASTCON*, 2012. ISSN 07347502. doi:10.1109/SECon.2012.6196885.

44. Subudhi, B. Maximum power point tracking techniques for photovoltaic systems: A comparative study. *IEEE Transactions on Sustainable Energy*, 2013. 4(1): 89–98.

45. Esram, T. and Chapman, P. L. Comparison of photovoltaic array maximum power point tracking techniques. *IEEE Transactions on Energy Conversion*, 2007. 22(2): 439–449. ISSN 08858969. doi:10.1109/TEC.2006.874230.

46. Loukriz, A., Haddadi, M. and Messalti, S. Simulation and experimental design of a new advanced variable step size Incremental Conductance MPPT algorithm for PV systems. *ISA Transactions*, 2016. 62: 30–38. ISSN 00190578. doi:10.1016/j.isatra.2015.08.006.

47. Kollimalla, S. K. and Mishra, M. K. Variable perturbation size adaptive P&O MPPT algorithm for sudden changes in irradiance. *IEEE Transactions on Sustainable Energy*, 2014. 5(3): 718–728. ISSN 19493029. doi:10.1109/TSTE.2014.2300162.

48. Ahmed, J. and Salam, Z. A Modified P and O Maximum Power Point Tracking Method with Reduced Steady-State Oscillation and Improved Tracking Efficiency. *IEEE Transactions on Sustainable Energy*, 2016. 7(4): 1506–1515. ISSN 19493029. doi:10.1109/TSTE.2016.2568043.

49. de Oliveira, F. M., Oliveira da Silva, S. A., Durand, F. R., Sampaio, L. P., Bacon, V. D. and Campanhol, L. B. Grid-tied photovoltaic system based on PSO MPPT technique with active power line conditioning. *IET Power Electronics*, 2016. 9(6): 1180–1191. ISSN 17554543. doi:10.1049/iet-pel.2015.0655.

50. Ben Smida, M. and Sakly, A. Genetic based algorithm for maximum power point tracking (MPPT) for grid connected PV systems operating under partial shaded conditions. *7th International Conference on Modelling, Identification and Control (ICMIC) 2015*. Tunisia -. 2015. doi:10.1109/ICMIC.2015.7409433.

51. Mohanty, S., Subudhi, B. and Ray, P. K. A new MPPT design using grey Wolf optimization technique for photovoltaic system under partial shading conditions. *IEEE Transactions on Sustainable Energy*, 2016. 7(1): 181–188. ISSN 19493029. doi:10.1109/TSTE.2015.2482120.

52. Sundareswaran, K., Vigneshkumar, V., Sankar, P., Simon, S. P., Srinivasa Rao Nayak, P. and Palani, S. Development of an Improved P&O Algorithm Assisted Through a Colony of Foraging Ants for MPPT in PV System. *IEEE Transactions on Industrial Informatics*, 2016. 12(1): 187–200. ISSN 15513203. doi:10.1109/TII.2015.2502428.

53. Jyothy, L. P. and Sindhu, M. R. An Artificial Neural Network based MPPT Algorithm for Solar PV System. *Proceedings of the 4th International Conference on Electrical Energy Systems, ICEES 2018*, 2018: 375–380. doi:10.1109/ICEES.2018.8443277.

54. Ben Salah, C. and Ouali, M. Comparison of fuzzy logic and neural network in maximum power point tracker for PV systems. *Electric Power Systems Research*, 2011. 81(1): 43–50. ISSN 03787796. doi:10.1016/j.epsr.2010.07.005.

55. Bahrami, M., Gavagsaz-Ghoachani, R., Zandi, M., Phattanasak, M., Maranzana, G., Nahid-Mobarakeh, B., Pierfederici, S. and Meibody-Tabar, F. Hybrid maximum power point tracking algorithm with improved dynamic performance. *Renewable Energy*, 2019. 130: 982–991. ISSN 18790682. doi:10.1016/j.renene.2018.07.020.

56. Shahdadi, A., Barakati, S. M. and Khajeh, A. Design and implementation of an improved sliding mode controller for maximum power point tracking in a SEPIC based on PV system. *Engineering Reports*, 2019. 1(4): 1–13. ISSN 2577-8196. doi:10.1002/eng2.12042.

57. Pradhan, R. and Panda, A. Performance evaluation of a MPPT controller with model predictive control for a photovoltaic system. *International Journal of Electronics*, 2020. 107(10): 1543–1558. ISSN 13623060. doi:10.1080/00207217.2020.1727027.

58. Irmak, E. and Güler, N. A model predictive control-based hybrid MPPT method for boost converters. *International Journal of Electronics*, 2020. 107(1): 1–16. ISSN 13623060. doi:10.1080/00207217.2019.1582715.

59. Khan, R., Khan, L., Ullah, S., Sami, I. and Ro, J. S. Backstepping based super-twisting sliding mode mppt control with differential flatness oriented observer design for photovoltaic system. *Electronics (Switzerland)*, 2020. 9(9): 1–30.

60. Charaabi, A., Zaidi, A., Barambones, O. and Zanzouri, N. Implementation of adjustable variable step based backstepping control for the PV power plant. *International Journal of Electrical Power and Energy Systems*, 2022. 136(9): 1–13.

61. Martin, A. D. and Vazquez, J. R. Backstepping Controller Design to Track Maximum Power in Photovoltaic Systems. *Automatika*, 2014. 55(1): 22–31.

62. Ajangnay, M. O., Alsokhiry, F., Adam, G. P. and Alabdulwahab, A. Backstepping Control of Off-Grid PV Inverter. *9th International Conference on Renewable Energy Research and Applications, ICRERA 2020*. Glasgow, UK. 2020. 384–389.

63. Huang, J., Xu, D., Yan, W., Ge, L. and Yuan, X. Nonlinear Control of Back-to-Back VSC-HVDC System via Command-Filter Backstepping. *Journal of Control Science and Engineering*, 2017. 2017.

64. Xu, D., Dai, Y., Yang, C. and Yan, X. Adaptive fuzzy sliding mode command-filtered backstepping control for islanded PV microgrid with energy storage system. *Journal of the Franklin Institute*, 2019: 1–10.

65. El Malah, M., Ba-Razzouk, A., Abdelmounim, E. and Madark, M. Integral backstepping based nonlinear control for maximum power point tracking and unity power factor of a grid connected hybrid wind-photovoltaic system. *Indonesian Journal of Electrical Engineering and Informatics*, 2020. 8(4): 706–722. ISSN 20893272. doi:10.11591/ijeei.v8i4.2327.

66. Ali, K., Khan, Q., Ullah, S., Khan, I. and Khan, L. Nonlinear robust integral backstepping based MPPT control for stand-alone photovoltaic system. *PLoS ONE*, 2020. 15(5): 1–31. ISSN 19326203. doi:10.1371/journal.pone.0231749.

67. Min, W. and Liu, Q. An improved adaptive fuzzy backstepping control for nonlinear mechanical systems with mismatched uncertainties. *Automatika*, 2019. 60(1): 1–10.

68. Rodríguez-Abreo, O., Garcia-Guendulain, J. M., Hernández-Alvarado, R., Rangel, A. F. and Fuentes-Silva, C. Genetic algorithm-based tuning of backstepping controller for a quadrotor-type unmanned aerial vehicle. *Electronics (Switzerland)*, 2020. 9(10): 1–24.

69. Mohd Basri, M. A., Husain, A. R. and Danapalasingam, K. A. Enhanced Backstepping Controller Design with Application to Autonomous Quadrotor Unmanned Aerial Vehicle. *Journal of Intelligent and Robotic Systems: Theory and Applications*, 2015. 79(2): 295–321.

70. Chang, F.-J., Chang, E.-C., Liang, T.-J. and Chen, J.-F. Digital-signal-processor-based DC/AC inverter with integral-compensation terminal sliding-mode control. *IET Power Electronics*, 2011. 4(1): 159–167. ISSN 17554535. doi:10.1049/iet-pel.2010.0071.

71. Chen, Y., Shuai, Z., Luo, A. and Xie, S. Robust predictive dual-loop control strategy with reactive power compensation for single-phase grid-connected distributed generation system. *IET Power Electronics*, 2013. 6(7): 1320–1328. ISSN 1755-4535. doi:10.1049/iet-pel.2013.0011.

72. Luo, A., Chen, Y., Shuai, Z. and Tu, C. An improved reactive current detection and power control method for single-phase photovoltaic grid-connected dg system. *IEEE Transactions on Energy Conversion*, 2013. 28(4): 823–831. ISSN 08858969. doi:10.1109/TEC.2013.2277658.

73. Rezkallah, M., Sharma, S. K., Chandra, A., Singh, B. and Rousse, D. R. Lyapunov Function and Sliding Mode Control Approach for the Solar-PV Grid Interface System. *IEEE Transactions on Industrial Electronics*, 2017. 64(1): 785–795. ISSN 02780046. doi:10.1109/TIE.2016.2607162.

74. P.C.Loh, R. T. . F. B. . M. L. . Proportional-resonant controllers and filters for grid-connected voltage-source converters. *IEE Proceedings-Electric Power Applications*, 2006. 153(5): 750 – 762. doi:10.1049/ip-epa:20060008.

75. Lu, W., Zhou, K. and Yang, Y. Robust repetitive control scheme for three-phase constant-voltage-constant-frequency pulse-width-modulated inverters. *IET Power Electronics*, 2012. 5(6): 669–677. ISSN 1755-4535. doi:10.1049/iet-pel.2011.0259.

76. Zhang, B., Zhou, K. and Wang, D. Multirate repetitive control for PWM DC/AC converters. *IEEE Transactions on Industrial Electronics*, 2014. 61(6): 2883–2890. ISSN 02780046. doi:10.1109/TIE.2013.2274423.

77. Chen, S. *Control Techniques for Improving the Static and Dynamic Performance of Switch Mode DC- AC Inverters*. Ph.D. Thesis. The Hong Kong Polytechnic University. 2009.

78. Gupta, R. and Gudey, S. K. Reduced state feedback sliding-mode current control for voltage source inverter-based higher-order circuit. *IET Power Electronics*, 2015. 8(8): 1367–1376. ISSN 1755-4535. doi:10.1049/iet-pel.2014.0707.

79. Wang, G. and Li, Y. W. Parabolic PWM for current control of voltage-source converters (VSCs). *IEEE Transactions on Industrial Electronics*, 2010. 57(10): 3491–3496. ISSN 02780046. doi:10.1109/TIE.2009.2038342.

80. Zhang, L., Born, R., Zhao, X., Lai, J.-s. and Ma, H. A Parabolic Current Control Based Digital Current Control Strategy for High Switching Frequency Voltage Source Inverters. *IEEE Transactions on Power Electronics*, 2016: 3243–3247.

81. Zhang, L., Born, R., Gu, B., Chen, B., Zheng, C., Zhao, X. and Lai, J. S. J. A Sensorless Implementation of the Parabolic Current Control for Single-Phase

Stand-Alone Inverters. *IEEE Transactions on Power Electronics*, 2016. 31(5): 3913–3921. ISSN 08858993. doi:10.1109/TPEL.2015.2464292.

82. Mattavelli, P. An improved deadbeat control for UPS using disturbance observers. *IEEE Transactions on Industrial Electronics*, 2005. 52(1): 206–212. ISSN 02780046. doi:10.1109/TIE.2004.837912.

83. Kawabata, T., Miyashita, T. and Yamamoto, Y. Dead Beat Control of Three Phase PWM Inverter. *IEEE Transactions on Power Electronics*, 1990. 5(1): 21–28. ISSN 19410107. doi:10.1109/63.45996.

84. Lim, J. S., Park, C., Han, J. and Lee, Y. I. Robust tracking control of a three-phase DC-AC inverter for UPS applications. *IEEE Transactions on Industrial Electronics*, 2014. 61(8): 4142–4151. ISSN 02780046. doi:10.1109/TIE.2013.2284155.

85. Han, J. From PID to active disturbance rejection control. *IEEE Transactions on Industrial Electronics*, 2009. 56(3): 900–906. ISSN 02780046. doi:10.1109/TIE.2008.2011621.

86. Yang, J., Ding, Z., Chen, W.-H. and Li, S. Output-based disturbance rejection control for non-linear uncertain systems with unknown frequency disturbances using an observer backstepping approach. *IET Control Theory & Applications*, 2016. 10(9): 1052–1060. ISSN 1751-8644. doi:10.1049/iet-cta.2015.1160.

87. Mehraban, M., Toulabi, M. R. and Ranjbar, A. Voltage Control of Three Phase Inverters by Using Active Disturbance Rejection Control. *30th IEEE Power System Conference*. Tehran. 2015. ISBN 9781509027057.

88. Li, S. and Xiong, H. Active disturbance rejection control of single phase grid connected inverter. *2016 IEEE International Conference on Mechatronics and Automation, IEEE ICMA 2016*, 2016: 2344–2348. doi:10.1109/ICMA.2016.7558931.

89. Muangruk, N. and Nungam, S. Direct Power Control of Three-phase Voltage Source Converters Using Feedback Linearization Technique. *Procedia Computer Science*. Chiang Mai: The Author(s). 2016, vol. 86. ISSN 18770509. 365–368. doi:10.1016/j.procs.2016.05.100.

90. Kim, D. E. and Lee, D. C. Feedback linearization control of three-phase UPS inverter systems. *IEEE Transactions on Industrial Electronics*, 2010. 57(3): 963–968. ISSN 02780046. doi:10.1109/TIE.2009.2038404.

91. Yazdanpanah, M., Semsar, E. and Siahkolah, B. An H-infinity Robust Controller for Single-Phase Pwm Inverters. *IFAC Proceedings*, 2002. 35(1): 289–294. ISSN 14746670. doi:10.3182/20020721-6-ES-1901.00382.

92. Willmann, G., Coutinho, D. F., Pereira, L. F. A. and Líbano, F. B. Multiple-Loop H-Infinity Control Design for Uninterruptible Power Supplies. *IEEE Transactions on Industrial Electronics*, 2007. 54(3): 1591–1602. ISSN 02780046. doi:10.1109/TIE.2007.894721.

93. Baghaee, H. R., Mirsalim, M., Gharehpetian, G. B. and Talebi, H. A. A Decentralized Robust Mixed H2/H-infinity Control Scheme to Improve Small/Large-Signal Stability and FRT Capability of Islanded Multi-DER Microgrid Considering Load Disturbances. *IEEE Systems Journal*, 2017: 1–12. ISSN 19379234. doi:10.1109/JSYST.2017.2716351.

94. Zhu, Y. and Fei, J. Adaptive Global Fast Terminal Sliding Mode Control of Gridconnected Photovoltaic System Using Fuzzy Neural Network Approach. *IEEE Access*, 2017. 5(1): 109–112.

95. Sun, X., Chow, M. H. L., Leung, F. H. F., Xu, D., Wang, Y. and Lee, Y. S. Analogue implementation of a neural network controller for UPS inverter applications. *IEEE Transactions on Power Electronics*, 2002. 17(3): 305–313. ISSN 08858993. doi:10.1109/TPEL.2002.1004238.

96. Yunkai Zhu, J. F. and Liang, X. Sliding Mode Control of Single-Phase PV Grid-connected Inverter. *ICIC Express Letters*, 2017. 5(9): 1417–1424.

97. Wang, Z., Li, S., Yang, J. and Li, Q. Current sensorless finite-time control for buck converters with time-varying disturbances. *Control Engineering Practice*, 2018. 77(5): 127–137. ISSN 09670661. doi:10.1016/j.conengprac.2018.05.014.

98. Liu, J. and Wang, X. *Advanced Sliding Mode Control for Mechanical Systems*. Springer. 2011. ISBN 978-3-642-20906-2. doi:10.1007/978-3-642-20907-9.

99. Fallaha, C. J., Saad, M., Kanaan, H. Y. and Al-Haddad, K. Sliding-mode robot control with exponential reaching law. *IEEE Transactions on Industrial Electronics*, 2011. 58(2): 600–610. ISSN 02780046. doi:10.1109/TIE.2010.2045995.

100. Yasin, A. R., Ashraf, M. and Bhatti, A. I. Fixed frequency sliding mode control of power converters for improved dynamic response in DC micro-grids. *Energies*, 2018. 11(10). ISSN 19961073. doi:10.3390/en11102799.

101. Lauria, D. and Coppola, M. Design and control of an advanced PV inverter. *Solar Energy*, 2014. 110: 533–542. ISSN 0038092X. doi:10.1016/j.solener.2014.09.040.

102. Benchouia, M. T., Ghadbane, I., Golea, A., Srairi, K. and Benbouzid, M. H. Design and implementation of sliding mode and PI controllers based control for three phase shunt active power filter. *Energy Procedia*, 2014. 50: 504–511. ISSN 18766102. doi:10.1016/j.egypro.2014.06.061.

103. Shinde, U. K., Kadwane, S. G. and Member, S. Sliding Mode Control of Single-Phase Grid connected qZSI. *IEEE Access*, 2017. 5.

104. Bag, A., Subudhi, B. and Ray, P. K. Comparative Analysis of Sliding Mode Controller and Hysteresis Controller for Active Power Filtering in a Grid connected PV System. *International Journal of Emerging Electric Power Systems*, 2018. 19(1): 1–13. ISSN 1553779X. doi:10.1515/ijeeps-2017-0044.

105. Kamal, S., Moreno, J. A., Chalanga, A., Bandyopadhyay, B. and Fridman, L. M. Continuous terminal sliding-mode controller. *Automatica*, 2016. 69: 308–314. ISSN 00051098. doi:10.1016/j.automatica.2016.02.001.

106. L.Y.Yang, J.H.Liu, C. W. Sliding Mode Control of Three-Phase Four-Leg Inverters via State Feedback. *Journal of Power Electronics*, 2014. 14(5): 1028–1037.

107. Kukrer, O., Komurcugil, H. and Doganalp, A. A three-level hysteresis function approach to the sliding-mode control of single-phase UPS inverters. *IEEE Transactions on Industrial Electronics*, 2009. 56(9): 3477–3486. ISSN 02780046. doi:10.1109/TIE.2009.2016512.

108. Gan, M. G., Zhang, M., Zheng, C. Y. and Chen, J. An adaptive sliding mode observer over wide speed range for sensorless control of a brushless DC motor. *Control Engineering Practice*, 2018. 77(5): 52–62. ISSN 09670661. doi:10.1016/j.conengprac.2018.05.004.

109. Sabzehgar, R., Roshan, Y. M. and Fajri, P. Modelling and sliding-mode control of a single-phase single-stage converter with application to plug-in electric vehicles. *IET Power Electronics*, 2019. 12(3): 620–626. ISSN 17554543. doi:10.1049/iet-pel.2018.5664.

110. Levant, A. High-order sliding modes, differentiation and output-feedback control. *International Journal of Control*, 2003. 76(9): 924–941.

111. J.Ramirez, A.Castro, P.Zuniga, A. A. High order sliding mode control for shunt active power filter. *2015 IEEE International Autumn Meeting on Power, Electronics and Computing (ROPEC)*. Ixtapa, Mexico. 2015. ISBN 9781467371216. doi:10.1109/ROPEC.2015.7395111.

112. Han, Y., Ma, R. and Cui, J. Adaptive higher-order sliding mode control for islanding and grid-connected operation of a microgrid. *Energies*, 2018. 11(6). ISSN 1996-1073. doi:10.3390/en11061459.

113. D.P. Andrea, D.N.L.Pio, M. S. Super Twisting Sliding Mode control of Smart inverters grid- connected for PV Applications. *6th International Conference on Renewable Energy Research and Applications.* San Diego, USA. 2017, vol. 5. ISBN 9781538620953. 793–796.

114. Zeb, K., Busarello, T. D. C., Islam, S. U., Uddin, W., Raghavendra, K. V. G., Khan, M. A. and Kim, H. J. Design of Super Twisting Sliding Mode Controller for a Three-Phase Grid-connected Photovoltaic System under Normal and Abnormal Conditions. *Energies*, 2020. 13(15). ISSN 19961073. doi:10.3390/en13153773.

115. Li, P., Yu, X., Member, S. and Xiao, B. Adaptive Quasi-Optimal Higher Order Sliding Mode Control Without Gain Overestimation. *IEEE Transactions on industrial informatics*, 2018. 14(9): 3881 – 3891. doi:10.1109/TII.2017.2787701.

116. Plestan, F., Shtessel, Y., Brégeault, V. and Poznyak, A. New methodologies for adaptive sliding mode control. *International Journal of Control*, 2010. 83(9): 1907–1919.

117. Shtessel, Y., Fridman, L. and Plestan, F. Adaptive sliding mode control and observation. *International Journal of Control*, 2016. 89(9): 1743–1746. ISSN 13665820. doi:10.1080/00207179.2016.1194531.

118. Taleb, M., Plestan, F. and Bououlid, B. Higher order sliding mode control based on adaptive first order sliding mode controller. *Proceedings of the 19th World Congress*. Cape Town, South Africa: IFAC. 2014, vol. 47. ISBN 9783902823625. ISSN 14746670. 1380–1385. doi:10.3182/20140824-6-ZA-1003.02487.

119. Huang, Y.-J., Kuo, T.-C. and Chang, S.-H. Adaptive Sliding-Mode Control for NonlinearSystems With Uncertain Parameters. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 2008. 38(2): 534–539. ISSN 1083-4419. doi:10.1109/TSMCB.2007.910740.

120. Chen, Z., Luo, A., Wang, H., Chen, Y., Li, M. and Huang, Y. Adaptive sliding-mode voltage control for inverter operating in islanded mode in microgrid. *International Journal of Electrical Power and Energy Systems*, 2015. 66: 133–143. ISSN 01420615. doi:10.1016/j.ijepes.2014.10.054.

121. Hou, B., Liu, J., Dong, F. and Mu, A. An adaptive complementary sliding-mode control strategy of single-phase voltage source inverters. *Journal of Electrical Engineering and Technology*, 2018. 13(1): 168–180. ISSN 20937423. doi:10.5370/JEET.2018.13.1.168.

122. Gautam, A. R., Gaurav, K., Guerrero, J. M. and Fulwani, D. Ripple Mitigation with Improved Line-Load Transients Response in Two-Stage DC-DC-AC Converter: Adaptive SMC Approach. *IEEE Transactions on Industrial Electronics*, 2017. 65(4): 3125–3135. ISSN 02780046. doi:10.1109/TIE.2017.2752125.

123. Ghanbarian, M. M., Nayeripour, M., Rajaei, A. and Mansouri, M. M. Design and implementation of a new modified sliding mode controller for grid-connected inverter to controlling the voltage and frequency. *ISA Transactions*, 2016. 61: 179–187. ISSN 00190578. doi:10.1016/j.isatra.2015.11.023.

124. Fei, J. and Zhu, Y. Adaptive fuzzy sliding control of single-phase PV grid-connected inverter. *PLoS ONE*, 2017. 8(12): 1233–1238. doi:10.1109/ICMA.2017.8015993.

125. Hou, L., Li, W., Shen, H. and Li, T. Fuzzy Sliding Mode Control for Systems with Matched and Mismatched Uncertainties/Disturbances Based on ENDOB. *IEEE Access*, 2019. 7: 666–673. ISSN 21693536. doi:10.1109/ACCESS.2018.2885595.

126. Fei, J., Zhu, Y. and Hua, M. Disturbance observer based fuzzy sliding mode control of PV grid connected inverter. *IEEE Access*, 2018. 6: 18–22. ISSN 21693536. doi:10.1109/ICEEE2.2018.8391293.

127. Zhu, Y. and Fei, J. Adaptive Global Fast Terminal Sliding Mode Control of Grid-connected Photovoltaic System Using Fuzzy Neural Network Approach. *IEEE Access*, 2017. 5: 9476–9484. ISSN 21693536. doi:10.1109/ACCESS.2017.2707668.

128. W. Hart Danial. *Power Electronics*. 2011th ed. Tata McGraw-Hill. 2010. ISBN 9780073380674.

129. Abouchabana, N., Haddadi, M., Rabhi, A., Grasso, A. D. and Tina, G. M. Power efficiency improvement of a boost converter using a coupled inductor with a fuzzy logic controller: Application to a photovoltaic system. *Applied Sciences (Switzerland)*, 2021. 11(3): 1–19. ISSN 20763417. doi:10.3390/app11030980.

130. Chan, P.-W. and Masri, S. DC-DC Boost Converter with Constant Output Voltage for Grid Connected Photovoltaic Application System. *Industrial Electronic Seminar*. Kuala Lumpur, Malaysia. 2010.

131. Anjum, W., Husain, A. R., Aziz, J. A., Abbas Abbasi, M. and Alqaraghuli, H. Continuous dynamic sliding mode control strategy of PWM based voltage source inverter under load variations. *PLoS ONE*, 2020. 15(2): 1–20. ISSN 19326203. doi:10.1371/journal.pone.0228636.

132. Wang, D., Tan, D. and Liu, L. Particle swarm optimization algorithm: an overview. *Soft Computing*, 2018. 22(2): 387–408. ISSN 14337479. doi:10.1007/s00500-016-2474-6.

133. Moreno, J. A. Lyapunov function for Levant's Second Order Differentiator. *Proceedings of the IEEE Conference on Decision and Control*, 2012. 2: 6448–6453. ISSN 01912216. doi:10.1109/CDC.2012.6426877.

134. Komurcugil, H., Altin, N., Ozdemir, S. and Sefa, I. An extended lyapunov-function-based control strategy for single-phase UPS inverters. *IEEE Transactions on Power Electronics*, 2015. 30(7): 3976–3983. ISSN 08858993. doi:10.1109/TPEL.2014.2347396.

LIST OF PUBLICATIONS

Journal with Impact Factor

1. Anjum, W., Husain, A. R., Aziz, J. A., Abbas Abbasi, M. and Alqaraghuli, H. Continuous Dynamic Sliding mode Control Strategy of PWM Based Voltage Source Inverter Under Load Variations. Plos One, 2020 15(2): ISSN 19326203 (IF=2.77 Q2)
2. Anjum, W., Husain, A. R., Aziz, J. A., Fasih-ur-rehman, S. M., Bakht, P. and Alqaraghuli, H.A Robust Dynamic Control Strategy for Standalone PV System under Variable Load and Environmental Conditions. sustainability 2022 14 (8): doi.org/10.3390/su14084601 (IF= 3.2 Q2)
3. Anjum, W., Husain, A. R., Aziz, J. A., Fasih-ur-rehman, S. M., Bakht, P. and Alqaraghuli, H. Effective Dynamic Disturbance Rejection Scheme Based On Higher-order Sliding Mode Control for DC-AC Inverter Under Load Variation. Measurement and control . (IF=1.64) (accepted)

Book chapter

1. Anjum, W., Husain, A. R., Aziz, J. A. and Alqaraghuli, H. Super Twisting Control of DC-AC Inverter with Higher Order Exact Robust Differentiator. Studies in Control and System Automation. 2019 . Penerbit UTM Press