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| A Project Report On **ADAPTIVE SLIDING-MODE VOLTAGE CONTROL FOR INVERTER OPERATING IN ISLANDED MODE IN MICROGRID**  **Submitted in partial fulfillment of the requirements for the award of the degree of**  **BACHELOR OF ENGINEERING**  **in**  **ELECTRICAL AND ELECTRONICS ENGINEERING**  **By**  **B.PRIYANKA : 160118734014**  **S.SRAVANI : 160118734019**  **MD.AMAAN FAROOQUI : 160118734028**  **Under the esteemed guidance of**  **D.SATHISH**  **Assistant Professor Department of EEE, CBIT (A), Hyderabad.**  **Department of Electrical and Electronics Engineering**    **Chaitanya Bharathi Institute of Technology (A)**  **(Affiliated to Osmania University) Gandipet, Hyderabad 500075**  **i** |
| **CHAITANYA BHARATHI INSTITUTE OF TECHNOLOGY (A)**  **(Affiliated to Osmania University, Accredited by NAA(UGC)with ‘A’ grade, All UG and 5 PG Programs Accredited by NBA (AICTE) An ISO 9001:2015 Certified Institution)**  **Kokapet (V), Gandipet (M), Hyderabad, RR Dist-500075**  **CERTIFICATE**  This is to certify that the project work entitled “ADAPTIVE SLIDING-MODE VOLTAGE CONTROL FOR INVERTER OPERATING IN ISLANDED MODE IN MICROGRID” is a bonafide work carried out by   |  |  | | --- | --- | | **B.PRIYANKA** | **: 160118734014** | | **S.SRAVANI** | **: 160118734019** | | **MD.AMAAN FAROOQUI** | **: 160118734028** |   In partial fulfillment of the requirement for the degree **BACHELOR OF ENGINEERING** in **ELECTRICAL & ELECTRONICS ENGINEERING** by the Chaitanya Bharathi Institute of Technology(A), Osmania University, Hyderabad during the academic year 2021-2022.The results embedded in this report have not been submitted to any other university or institution for the award of any degree   |  |  | | --- | --- | | **Signature of the Guide** | **Signature of**  **Head of the Department** | | D. Sathish, | Dr. G. Suresh Babu, | | Assistant Professor, | Professor and Head, | | Dept. of EEE, | Dept. of EEE, | | CBIT(A), Hyderabad. | CBIT(A), Hyderabad. |   **ii** |
| DECLARATION This is to certify that the work reported in the present project titled “ADAPTIVE SLIDING-MODE VOLTAGE CONTROL FOR INVERTER OPERATING IN ISLANDED MODE IN MICROGRID**”** is a record of work done by us at Chaitanya Bharathi Institute of Technology (A) Hyderabad under the guidance of D. Sathish, Associate Professor, Dept. of EEE for the award of B.E Degree (E.E.E), this project work has not been submitted to any other university/ institution.  Date:25/05/2022 B.PRIYANKA **160118734014**      **S.SRAVANI**  **160118734019**  **MD.AMAAN FAROOQUI**  **160118734028**  **iii** |
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| **ABSTRACT**  Harmonic current caused by nonlinear loads and parametric variations of output filter of inverters make popular proportional–integral–derivative (PID) voltage controller far beyond excellent performance in case of microgrid operating in islanded mode. Motivated by this limitation, this paper proposes an adaptive sliding-mode controller (ASMC) to enhance disturbance-rejection performance of control system of islanded parallel inverters. And adaptive algorithms are designed to observe external disturbances and internal perturbation so as to guarantee the globe robustness of control system of inverter. The switching gain of control input is designed to be a time-varying value which effectively reduces undesirable chattering of control input signal. Simulating and experimental results are presented that the total harmonic distortion, chattering, and steady-state error of output voltage of islanded parallel inverters are effectively reduced and the dynamic performances and the capability of perturbation rejection of control system of inverter are effectively enhanced.    **1** **ACRONYMS**  |  |  | | --- | --- | | PID | Proportional-integral-derivative | | ASMC | Adaptive sliding-mode controller | | DG | Distributed generation | | EES | Electrical energy storage | | SG | Synchronous generator | | PCC | Point of common coupling | | MPPT | Maximum power-point tracking | | PR | Proportional resonant controller | | SMC | Sliding – mode controller | | PWM | Pulse width modulation | | VSC | Variable – structure- control | | CSMC | Conventional sliding – mode controller | | IGBT | Insulated-gate bipolar transistor | | DSP | Digital – signal - processor |     **2**  **NOMENCLATURE**   |  |  | | --- | --- | |  | Filter capacitor | |  | load | | , | Average output voltages of inverter and filter capacitor during a switching period | |  | Parasitic resistance | |  | Grid side resistance | |  | Grid side inductor | |  | Lumped nonlinear loads | |  | PCC voltage | |  | Amplitude of nominal voltage of droop control | |  | Frequency of nominal voltage of droop control | | , | Internal parameters | |  | Switching term of control input | |  | Tracking term of control input | |  | Coefficients of sliding surface |   **3** LIST OF FIGURES  |  |  |  | | --- | --- | --- | | **s.no** | **Figure name.** | **Page no.** | | Fig 1 | The schematic diagram of parallel inverters system operating in microgrid. | 13 | | Fig 2 | The block diagram of an islanded inverter. | 15 | | Fig 3 | The block diagram of the control structure of ASMC | 21 | | Fig 4 | Simulink Connected Model ASMC2 | 35 | | Fig 5 | + output graphs | 36 | | Fig 6 | Simulink Connected Model ASMC1 | 37 | | Fig 7 | Output graphs | 38 | | Fig 8 | ASMC1 INDUCTANCE P50 | 40 | | Fig 9 | ASMC 1 INDUCTANCE 0 | 41 | | Fig 10 | ASMC 1 INDUCTANCE N50 | 42 |   **4**    **LIST OF TABLES**   |  |  |  | | --- | --- | --- | | **s.no** | **Table name** | **Page no.** | | **1** | Simulating and experimental parameters for electrical and control system of parallel  Inverters. | **22** |         **5**  **CHAPTER 1**  **INTRODUCTION** **Background and Motivation** Distributed generation (DG) units are interfaced with the electrical grid through power electronic switches. And as a consequence of an increasing penetration of DG units in local grid,  the concept of microgrid which consists of a localized grouping of DG units, electrical energy storage (EES) and local loads interconnected by transmission line and communication line realizing autonomous operation through hierarchy control was conceived.Unlike traditional centralized power system based on large synchronous generator (SG), the power electronic-interfaced microgrid possesses two prominent features,grid frequency does not directly couple with rotational speed of DG units due to the absence of large SGs nonlinear dynamics of microgrid is becoming aggravating with an increasing penetration of inverter-based DG units.  To mimic the self-regulating capability of SG-based power system, droop control approaches are used to guarantee the accuracy of power sharing among DG units when microgrid is isolated from the grid. Droop control approaches are categorized into two types P/V and P/f droop.  The former is prevailed in low-voltage networks where the line impedance is dominated by the resistive component. The latter, on the contrary,is more suitable in high-voltage or middle-voltage circumstances where the line impedance is dominated by the inductive component.  the motivation of this study is to design high-performance PWM-based sliding-mode voltage controller to deal with two drawbacks it has. In order to eliminate the reaching phase and to guarantee the global robustness, a three-order PID sliding surface with two adaptive algorithms is designed. In order to reduce chattering, adaptive algorithm to observe internal parameters and boundary of external disturbances are designed. The proposed adaptive SMC (ASMC) can achieve real-time estimation of the values of internal parameters and the boundary of external disturbances by only measuring filter-capacitor voltage. And adaptive switching gain represented the boundary of external disturbance not only completely counter-  act the effectiveness of external disturbance, but also tremendously reduce the chattering of control input signal. **Objectives of the Project** Microgrid can be operated in two modes: grid-connected mode and islanded mode. In grid-connected mode, the  **6**  voltage of point of common coupling (PCC) in microgrid is supported by the grid.  Under this circumstance, current control schemes with maximum power-point tracking (MPPT) algorithms are implemented in inverters to facilitate maximum power supply to the grid.  However, if inverters are operating in islanded mode, it is imperative that the DG units should properly provide voltage and frequency references for the microgrid due to the lack of voltage  support from the grid.  For that reason, voltage control schemes should be taken whereas current control schemes cannot well limit voltage fluctuation.  The conventional voltage schemes for islanded parallel invert-ers have many drawbacks. The closedloop voltage control by using proportional–integral–derivative (PID) or Proportional resonant  (PR) controller are recommended.  However, the PID controller cannot eliminate steady-state error for sinusoidal signals. Additionally, the robustness of the PID closed-loop system cannot be guaranteed unless parametric perturbation of a inverter system is completely eliminated and that is impossible for a real system. Although PR controller has the ability to track sinusoidal signals without steady-state error, the open-loop gain of PR controller for a selected harmonic component is much higher than non-selected ones. Its means that a slightly deviation of the frequency of selected harmonic component will largely deteriorate  control performance.  Therefore, how to design a voltage controller for inverters operating in islanded microgrid with low steady-state tracking error and high robustness has become one of the focuses  of the research.    **7**  **Literature survey**  YAN YANG AND RONG-JONG WAI , Design of Adaptive Fuzzy-Neural-Network- Imitating Sliding-Mode Control for Parallel- Inverter System in Islanded Micro-Grid. 2021 IEEE Journal.  **Observation:** An adaptive fuzzy-neural-network-imitating sliding-mode control (AFNNISMC) is developed for a parallel-inverter system in an islanded micro-grid (MG) via a master-slave current sharing strategy. For ensuring the system-level stability, an entire dynamic model is constructed by viewing the parallel-inverter system as a whole. First, a total sliding-mode control (TSMC) scheme, and the TSMC plus an adaptive observer to form an adaptive TSMC (ATSMC) framework are designed for the parallel-inverter system.  Carlos Alfaro, Ramon Guzman, Luis Garcia de Vicuna, Hasan Komurcugil, Helena Martin Distributed Direct Power Sliding-Mode Control for Islanded AC Microgrids. 2021 IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS  **Observation:** It is to develop a novel distributed direct power sliding-mode control for an islanded AC microgrid. This solution replaces the droop mechanism of each inverter with two separate sliding surfaces working as primary/secondary controllers.  Michele Cucuzzella, Gian Paolo Incremona*,* and Antonella Ferrara, IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS  **Observation:** This paper deals with modeling of complex microgrids and the design of advanced control strategies of sliding mode type to control them in a decentralized way. More specifically, the model of a microgrid including several distributed generation units (DGUs), connected according to an arbitrary complex and meshed topology, and working in islanded operation mode, is proposed. Moreover, it takes into account all the connection line parameters and it is affected by unknown load dynamics, nonlinearities and unavoidable modeling uncertainties, which make sliding mode control algorithms suitable to solve the considered control problem.Then, a decentralized second-order sliding mode control scheme, based on the  **8** |
| suboptimal algorithm is designed for each DGU.    Ahmad Tavakoli, M. Negnevitsky, Sarah Lyden, Osman Haruni, A Decentralized Control Strategy for Multiple Distributed Generation in Islanded Mode IEEE Explore  **Observation:** A technical challenge is designing a controller to control multiple distributed generation (DG) and its local loads by the voltage-sourced converter (VSC) to operate in an islanded mode under the load parameters uncertainty and unbalanced and transient conditions. Model predictive control (MPC) for the autonomous operation of multiple DG is proposed  Chen Yandong, Luo An, Shuai Zhikang, Xie Sanjun. Robust predictive dual-loop control strategy with reactive power compensation for single-phase grid-connected DG system. IET Power Electron 2013;6(7):1320–8.  **Observation:** A robust predictive dual-loop control strategy with reactive power compensation is proposed for single-phase gridconnected distributed generation (DG) system located at the end of the feeder. The proposed control strategy mainly includes improved reactive current detection and robust predictive dual-loop control. To reduce the long time delay in the conventional reactive current detection, the improved reactive current detection method based on the derivative and ip ,iq algorithm is presented.  Kim J, Guerrero JM, Rodriguez P, Teodorescu R, Nam K. Mode adaptive droop  control with virtual output impedances for an inverter-based flexible AC microgrid. IEEE Trans Power Electron 2011;26(3):689–701.  **Observation:** A decentralized power control method in a single-phase exible AC microgrid is proposed in this paper. Droop control is widely considered to be a good choice for managing the power flows between microgrid converters in a decentralized manner. In this work, to enhance the power loop dynamics, droop control combined with a derivative controller is used in islanded mode. In grid- connected mode, to strictly control the power factor in the point of common coupling (PCC), a droop method combined with an integral controller is adopted. Small-signal analysis of    **9**  the proposed control is shown both in islanded and grid-connected mode. The proposed control scheme does not need any mode switching action. Thus, it is relatively simple in control for full mode of operation. **Project Outline** The main purpose of this thesis is designed to be a time-varying value which effectively reduces undesirable chattering of control input signal. Simulating and experimental results are presented that the total harmonic distortion, chattering, and steady-state error of output voltage of islanded parallel inverters are effectively reduced and the dynamic performances and the capability of perturbation rejection of control system of inverter are effectively enhanced  In Chapter 2 an overview of Sliding-mode controller is explained briefly. Basic elements of types of SMC’s, modulation strategies, coefficients of sliding surface by fuzzy logic algorithm, PWM based SMC technique, disadvantages of SMC, advantages of ASMC are explained briefly.  In Chapter 3 operating principles, analysis and control of inverters operating in islanded mode in microgrid are explained. Mathematical analysis and algorithm to observe internal parameters is explained briefly.  In Chapter 4 Adaptive algorithm of switching gain is exp0lained briefly. Dynamics of inverter operating in microgrid, limitations and methods to overcome variable structure control theory are explained briefly.  In Chapter 5, Results of adaptive sliding mode voltage control for inverter operating in islanded microgrid system on Nonlinear loads, plot, comparison of voltage controllers are presented and explained.  In Chapter 6, general conclusions about output of the filter capacitor voltage and the load currents by using different voltage controllers are designed; implementation and test results are presented. Also some suggestions for future work in order to enhance system performance are given.  **10** **CHAPTER 2** **OVERVIEW OF SLIDING – MODE CONTROLLER**  **Sliding-mode controller**  Sliding-mode controller (SMC) is an effective nonlinear robust controller with invariant control effect to internal perturbations and external disturbances if the controlled state trajectory slides along the designed sliding surface. Therefore, SMC is an alternative to control system of inverter operating in islanded microgrid with a lot of nonlinear loads. From the point of view of modulation strategies, SMCs are categorized into two types: hysteresis-based and PWM-based.  switching frequency of hysteresis-based SMC is not fixed. In order to reduce excessively high frequency of power switches, in the signum function of control law is replaced by two-level hysteresis function. And the effectiveness of voltage tracking influenced by filter-capacitance variation is quantitatively analyzed,but the existence region of sliding mode and transient response influenced by the coefficients of sliding surface are only qualitatively analyzed.  In three-level hysteresis function of control law is a substitute for two-level one, which further reduces  switching frequency compared. And the analysis of existence region of sliding mode is quantitatively conducted.  In the coefficients of sliding surface regulated by fuzzy logic algorithm are time-varying values which improve dynamic response speed of output voltage by increasing the slope of two-dimensional sliding surface in the phase space during the transient of load current disturbances.  In spite of hysteresis-based SMC addressing the problem of the excessively high frequency of inverters, the problem of variable switching frequency which makes the process of designing output filter difficult should be carefully handled.  In an adaptive feed-forward control that varies the hysteresis band in the event of any change of input voltage is introduced to keep the switching frequency of hysteresis-based SMC constant. However, in the objective of control is merely focused on single power switch such as buck or boost converter for that reason this approach is not directly applied to multiple-switch inverter. In the signum function of control law is replaced by a reverse-saturating function in order to reduce chattering effectively. The PWM signal is generated by means of the comparison between switching function and triangular carrier. Moreover, the modulating wave is not equivalent control signal during each switching period. Thus, the approach in  **11**  should be categorized into hysteresis-based type.  In order to avoid the problem of frequency variation of hysteresis-based SMC system, PWM-based SMC using equivalent control law is an alternative approach. In a feed-forward reference voltage as a compensation term is added to the output of SMC in order to decrease the steady-state error of voltage tracking. A terminal SMC with non-linear sliding surface is developed and an integral compensation term is added to the control law in order to enhance the convergence rate of voltage-tracking error.  In the switching function in the control loop of stator voltage is replaced by a time-varying feedback gain multiplied by designed sliding surface so as to reduce the chattering of permanent magnet synchronous drive system. The idea of total SMC with three dimensional PID sliding surface is adopted in which the state trajectory in reaching phase is eliminated. And an adaptive prediction of upper boundary of disturbances of induction servomotor system is investigated, reducing the chattering of the control system.  It should be noted that conventional SMCs have two main drawbacks. On the one hand, the robustness (invariability) of SMC system, which means a system is completely insensitive to internally parametric uncertainties and external disturbances, is only possessed in sliding mode. In brief, the robustness of SMC system does not exist in reaching phase. Thus, the SMCs designed with reaching phase cannot guarantee global robustness for the whole control system. Nonetheless, in contrast to sliding mode, the time scale of reaching phase is relatively short.  And three kinds of reaching law approaches are proposed to reduce the reaching time and chattering. On the other hand, large switching gain causes undesirable chattering which might deteriorate ideal sliding-mode dynamics and the robustness of SMC system.  In spite of this drawback, a conservative large switching gain has to be chosen. The reason is that the switching gain of control input should large enough to counteract the effectiveness of the worst external disturbances and internal perturbations for the purpose of fulfilling the existence condition of sliding mode.  However, in engineering practice, the precise boundary of lumped uncertainties and disturbances are difficulty to obtain. Thus,switching gain is always chosen to be conservative large constant value.  **12**  **Chapter 3**  **OPERATING PRINCIPLES and ANALYSIS**  **3.1 Dynamics of inverter operating in islanded microgrid**  parallel inverters operating in islanded microgrid. Subscript n denotes the n-th inverter. i, ic, and io are the currents of filter inductor, the filter capacitor, and the load, respectively; , are the average output voltages of inverter and filter capacitor during a switching period, respectively; Rf is parasitic resistance (equivalent series resistor)in filter inductor;  , are the filter inductor and capacitor,respectively;  , are the grid-side inductance and resistance, respectively;  denotes lumped nonlinear loads; upcc is the PCC voltage;  , are the amplitude and frequency of nominal voltage of droop control, respectively;  is the reference output voltage of inverter.  is the dc bus voltage considered as a constant value due to a capacitor with large inertia commonly placed among the dc bus.      **13**  The average active power is obtained by multiplying io and, and then using a low-pass filter. And the average reactive power is obtained by multiplying io and ninety-degree-delaying of upcc, and  then using a low-pass filter. can be obtained by droop-control algorithm. Due to the limited length of this paper, further discussion with droop control is not included and the references listed are highly recommended. Without considering inverter gain as well as neglecting non-fundamental component inverter output voltage, can also be regarded as the output of voltage controller.  Based on the Kirchhoff’s circuit law, three equations of closed  circuit shown in Fig. 1 are obtained as follows  *= (1)*  *(2)*  *+ (3)*  Then, the dynamics of islanded inverter system can be obtained  by manipulation on Eqs. (1) and (2), expressed as follows  (4)  From Eq. (4), it can be seen that , and io can be regarded as three variables of dynamics of inverter system.  The dynamics of an islanded inverter can be depicted in Fig. 2 through Laplace transformation of Eqs. (3) and (4), where s is the Laplace operator and denotes the expression after Laplace transformation of .  Because represents lumped loads with many power electronic devices possessing time varying and  **14**  nonlinear feature connecting to microgrid, the quantity of which hardly measure in practice. From Fig. 2,  is the function of associated with .  In other words, io is regarded as an external disturbance inherently imposing on the dynamic model of inverter.    **3.2 Adaptive sliding-mode voltage controller**  As mentioned in section ‘Dynamics of inverter operating in islanded microgrid’, is regarded as the inherent disturbance of the controlled system. Then, the dynamics of inverter system is re-expressed as  + (5)  where d is the external disturbance associated with io, and expressed as  d = .  By choosing as the state variable of the controlled system and as the control input, Eq. (5) can be rearranged as  **15**  (6)  Where =-  Assumption that internal parameters h1, h2 are known and without perturbation and d = 0, then, the control law can be designed as  -- (7)  where e denotes voltage-tracking error, defined as e = . , are the coefficients of sliding surface.  By substituting Eq. (7) into Eq. (6), the dynamic equation of inverter turns into  =0 (8)  Properly choosing the values of kp and ki, the designed system’s dynamic characteristics such as rise time, overshoot and settling time can be easily determined by the second-order system described as Eq. (8).  The controlled system, two major uncertainties should NOT be neglected: (1) the influence of the upper boundary of external disturbance associated with io cannot be counteracted until a  sufficiently large switching gain is chosen to cope with the worst operating conditions like islanded/grid-connected mode transition.  However, this switching gain with a large constant value leads to the state trajectory significantly deviating from sliding surface,causing undesirable chattering and non-linear sliding motion, effects, which might reduce robustness of SMC system; (2) the internal perturbation of h1 and h2 reduce the accuracy of the described dynamic model of inverter, which deteriorates the robustness of control system. As a result, if using the control law of (7) without dealing with these uncertainties in practical applications, the control effect of Eq. (8) cannot be guaranteed.  In order to address aforementioned problems, the main guideline of the layout of SMC is to design adaptive algorithms to estimate the upper boundary of external disturbances and to real-timely observe    **16**  internal parameters. And theoretical analysis and the design for adaptive algorithms will be further discussed in this section.  **3.3 Adaptive algorithm to observe internal parameters**  For the purpose of eliminating reaching phase and decreasing steady errors causing by nonlinear sliding motion, the three-order sliding surface is selected, expressed as  =e+ (9)  where , , and are the coefficients of sliding surface.Taking the time differentiation of Eq. (9) as  =e= (10)  and the control law could be designed as follows  (11)  where ; are the switching term and the tracking term of control input, respectively; is the switching gain and should fulfill with the existence condition of sliding mode given by ; ; are the observational values of ; ,respectively. And the adaptive algorithm of ; could be designed as  where , are the positive constants and represent the adaptive coefficients of , , respectively.  In order to prove the stability of SMC system for inverters operating in islanded microgrid in which the dynamics of an individual inverter depicted as Eq. (6) and the voltage controller described as Eq. (11) and the adaptive observer of internal parameter shown in Eq. (12), a Lyapunov candidate function is    **17**  figured out as follows  + (13)  where = - = - ; are defined as the observational errors of , respectively.  Taking time differentiation of Eq. (13) as  = (14)  then, substituting (11) and (12) into (14), we get  (15)  According to (13) and (15), are positive definite and negative semi-definite function, respectively. Furthermore, the conditions of > 0 and < 0 are NOT always fulfilled until [  . Hence, the origin of SMC system,namely [ = [0,0,0], is asymptotically stable.  Multiplying both sides of Eq. (6) by and then substituting Eq. (11) into Eq. (6), we get  [  = [  If the switching gain and the observational errors of h1 and h2  fulfill the conditions as follows  **18**  (17)    then, Eq. (16) turns into  + = 0 (18)  According to Eqs. (18) and (15), it implies that and , this means that the sliding-mode motion of state trajectory is guaranteed throughout the whole control period (t > 0).  In other words, the reaching phase of motion state of the SMC system is completely eliminated.  It should be noted that the design of SMC which has reaching phase needs to ensure  , is a positive constant. And g specifies the dynamic characteristics of state trajectory approaching to sliding surface on which the robustness of SMC system is possessed [25]. Nonetheless, the control law of Eq. (11) with adaptive observer of Eq. (12) in the case of satisfying the conditions of Eq. (17) can eliminate the reaching phase and ensure global robustness of the control system.  Therefore, the reaching condition of sliding surface can be fulfilled by Eq. (15).  The existence condition of sliding mode is fulfilled by should track the boundary of external disturbance associated with io. In spite of the fact that should be larger than the upper boundary of worst disturbance so as to satisfy the existence condition of sliding mode, The switching gain with a large constant value multiplied with a signum function of sgn(s(t)) will result in serious chattering phenomena in control input signal then will significantly deviate state trajectory from sliding surface and will eventually deteriorate the robustness of control system.  **19**  **CHAPTER 4**  **DESIGN AND IMPLEMENTATION**  **Adaptive algorithm of switching gain**  The discontinuity of the switching term of control input signal is the essential reason for chattering. An underlying assumption in variable-structure-control (VSC) theory is that the control can be switched from one value to another at will, infinitely fast. In the control system of inverters, however, it is impossible to achieve sufficiently high switching control which is necessary to most SMC designs. There are three reasons for this. One cause is finite time  delays for adaptive-control computation and signal sampling of DSP. The second cause is the inductance exists in LC filters, transformers and power cable in which the current is impossible to switch at infinitely fast rate. The last cause is the limitation of switching frequency of power switches. Since it is impossible to switch the control at infinite rate, chattering always occurs in sliding mode of SMC system and can only be diminished under a  certain extent.  When it comes to choosing a proper switching gain, there is a tradeoff between chattering reduction and the fulfillment of existence condition of sliding mode. For one thing, chattering  reduction requires a small switching gain. For another, in order to satisfy the existence condition of sliding mode, switching gain should be larger than the boundary of lumped disturbances. To address this paradoxical problem, an adaptive algorithm of  switching gain is proposed in this subsection and it may be one of the sophisticated solutions. The range of the boundary of lumped disturbances associated with io can be estimated real-timely. The adaptive switching gain possessing time-varying feature not only completely counteracts the effectiveness of external disturbance imposing on inverters, but also tremendously alleviates the chattering of control input signal.  The following adaptive algorithm of switching gain is considered, expressed as      **20**  where is the observational value of , and > 0 denotes the adaptive coefficient of switching gain.  Substituting (t) for in Eq. (11), and the switching term of control input is re-expressed as  The block diagram of the control structure of ASMC is depicted in Fig. 3. The block of calculation refers to Eq. (9); the block of tracking term refers to Eq. (11); the block of switching term refers to Eq. (20); the block of observer refers to Eqs. (12) and (19).  The whole control system described as follow: The dynamics of inverter operating in islanded microgrid is depicted as Eq. (6); the tracking term and the switching term of control input of ASMC are described as Eqs. (11) and (20), respectively; And the adaptive algorithms for h1, h2, and d are designed as Eqs. (12) and (19), respectively.    In order to prove the global asymptotic stability of sliding surface of Eq. (9) where state trajectory of the whole control system slide along, a Lyapunov candidate function is figured out as follows  (t) + (t)+(t) (21)  **21** |
| where is defined as observational errors of Setting time differentiation of and taking Eqs. (14), (15), and (19) into account, we get  +(- (- +(-  -  Since is a negative semi-define function, the energy function is a non-increasing function with respect to time. Furthermore, it can deduce that  and are bounded functions.Defining the following function  **TABLE 1**  Simulating and experimental parameters for electrical and control system of parallel  inverters.   |  |  |  | | --- | --- | --- | | parameters | symbol | values | | Inverter switching  Frequency  Filter inductor  Filter capacitor  Parasitic resistance in filter inductor  Nonlinear load  Coefficients of PID  Coefficients of CSMC  Coefficiency of ASMC  Adaptive coefficients  Switching gain of CSMC | f | 12.8 kHz  1 mH  20  0.2 ohms  (5 ohms + 80 µH)//2 mF  20 ohms+4mH+1000  5/2500/0.00013  5/2500/0.13  5/2500/0.13  10/10/10  1.3e6 |   - |d(t)|)| - (23)  and taking the time integral of Eq. (23), we get  **22** |
| - (24)  Since is a bounded function, and is a non-increasing and bounded function,we get  is uniformly continuous. According to Barbalet’s Lemma, the following result can be concluded:  This result implies that sliding surface of will converge to the origin as time approaching infinity ( as t ). As a result,the global asymptotic stability of proposed control system is guaranteed and global robustness of the control system can be obtained without excessive chattering.  **23**  **CHAPTER 5**  **EXPERIMENTAL RESULTS OF ADAPTIVE SLIDING – MODE VOLTAGE CONTROL FOR INVERTER OPERATING IN ISLANDEDMODE IN MICROGRID AND MATLAB \ SIMULINK**  **INTRODUCTION TO MATLAB:**  MATLAB is a software package for computation in engineering, science, and applied mathematics.    It offers a powerful programming language, excellent graphics, and a wide range of expert knowledge. MATLAB is published by and a trademark of The Math Works, Inc.  The focus in MATLAB is on computation, not mathematics: Symbolic expressions and manipulations are not possible (except through the optional Symbolic Toolbox, a clever interface to maple). All results are not only numerical but inexact, thanks to the rounding errors inherent in computer arithmetic. The limitation to numerical computation can be seen as a drawback, but it’s a source of strength too: MATLAB is much preferred to Maple, Mathematical, and the like when it comes to numeric.  On the other hand, compared to other numerically oriented languages like C++ and FORTRAN, MATLAB is much easier to use and comes with a huge standard library.1 the unfavorable comparison here is a gap in execution speed. This gap is not always as dramatic as popular lore has it, and it can often be narrowed or closed with good MATLAB programming (see section 6). Moreover, one can link other codes into MATLAB, or vice versa, and MATLAB now optionally supports parallel computing. Still, MATLAB is usually not the tool of choice for  **24**  maximum-performance Computing.  The MATLAB niche is numerical computation on workstations for non-experts in computation. This is a huge niche—one way to tell is to look at the number of MATLAB-related books on mathworks.com. Even for supercomputer users, MATLAB can be a valuable environment in which to explore and fine-tune algorithms before more laborious coding in another language. Most successful computing languages and environments acquire a distinctive character or culture.  In MATLAB, that culture contains several elements: an experimental and graphical bias, resulting from the interactive environment and compression of the write-compile-link-execute analyze cycle; an emphasis on syntax that is compact and friendly to the interactive mode, rather than tightly constrained and verbose; a kitchen-sink mentality for providing functionality; and a high degree of openness and transparency (though not to the extent of being open source software).  **The fifty-cent tour**  When you start MATLAB, you get a multipaneled **desktop**. The layout and behavior of the desktop and its components are highly customizable (and may in fact already be customized for your site).  The component that is the heart of MATLAB is called the **Command Window**, located on the 1Here and elsewhere I am thinking of the “old FORTRAN,” FORTRAN 77. This is not a commentary on the usefulness of FORTRAN 90 but on my ignorance of it.  INTRODUCTION  Right by default. Here you can give MATLAB commands typed at the prompt, >>. Unlike FORTRAN and other compiled computer languages, MATLAB is an interpretedenvironment—you give a command, and MATLAB tries to execute it right away before asking for another.  At the top left you can see the **Current Directory**. In general MATLAB is aware only of files in the current directory (folder) and on its **path**, which can be customized. Commands for  **25**  working with the directory and path include cd, what, addpath, and editpath (or you can choose “File/Set path. “From the menus). You can add files to a directory on the path and thereby add commands to MATLAB; we will return to this subject in section 3.  Next to the Current Directory tab is the **Workspace** tab. The workspace shows you what variable names are currently defined and some information about their contents. (At start-up it is, naturally, empty.) This represents another break from compiled environments: variables created in the workspace persist for you to examine and modify, even after code execution stops. Below the Command Window/Workspace window is the **Command History** window. As you enter commands, they are recorded here. This record persists across different MATLAB sessions, and commands or blocks of commands can be copied from here or saved to files.  As you explore MATLAB, you will soon encounter some **toolboxes**. These are individually packaged sets of capabilities that provide in-depth expertise on particular subject areas. There is no need to load them  Explicitly—once installed, they are always available transparently. You may also encounter Simulink, which is a semi-independent graphical control-engineering package not covered in this document.  **Graphical versus command-line usage:**  MATLAB was originally entirely a command-line environment, and it retains that orientation. But it is now possible to access a great deal of the functionality from graphical interfaces—menus, buttons, and so on. These interfaces are especially useful to beginners, because they lay out the available choices clearly.2 As a rule, graphical interfaces can be more natural for certain types of interactive work, such as annotating a graph or debugging a program, whereas typed commands remain better for complex, precise, repeated, or reproducible tasks. One does not always need to make a choice, though; for instance, it is possible to save a figure’s styles as a template that can be used with different data by pointing and clicking. Moreover, you can package code you want to distribute with your own graphical interface, one that itself may be designed with a combination of graphical and command-oriented tools. In the end, an advanced MATLAB user should be able to exploit both modes  **26**  of work to be productive.  That said, the focus of this document is on typed commands. In many (most?) cases these have graphical interface equivalents, even if I don’t explicitly point them out.  In particular, feel free to right-click (on Control-click on a Mac) on various objects to see what you might be able to do to them.  **WHAT IS SIMULINK**  Simulink (Simulation and Link) is an extension of MATLAB by Math works Inc. It works with MATLAB to offer modeling, simulating, and analyzing of dynamical systems under a graphical user interface (GUI) environment. The construction of a model is simplified with click-and-drag mouse operations. Simulink includes a comprehensive block library of toolboxes for both linear and nonlinear analyses. Models are hierarchical, which allow using both top-down and bottom-up approaches. As Simulink is an integral part of MATLAB, it is easy to switch back and forth during the analysis process and thus, the user may take full advantage of features offered in both environments. This tutorial presents the basic features of Simulink and is focused on control systems as it has been written for students in my control systems.  Getting Started  To start a Simulink session, you'd need to bring up Matlab program first. From Matlab command window, enter:  >> simulink  Alternately, you may click on the Simulink icon located on the toolbar as shown  **27**    To see the content of the blockset, click on the "+" sign at the beginning of each toolbox.  To start a model click on the NEW FILE ICON as shown in the screenshot above.  Alternately, you may use keystrokes CTRL+N.  A new window will appear on the screen. You will be constructing your model in this window. Also in this window the constructed model is simulated. A screenshot of a typical working (model) window that looks like one shown below:  **28**    To become familiarized with the structure and the environment of Simulink, you are encouraged to explore the toolboxes and scan their contents.  You may not know what they are all about but perhaps you could catch on the organization of these toolboxes according to the category. For instant, you may see Control System Toolbox to consist of the Linear Time Invariant (LTI) system library and the MATLAB functions can be found under Function and Tables of the Simulink main toolbox. A good way to learn Simulink (or any computer program in general) is to practice and explore. Making mistakes is a part of the learning curve. So, fear not, you should be.  A simple model is used here to introduce some basic features of Simulink. Please follow the steps below to construct a simple model.  STEP 1: CREATING BLOCKS.  From BLOCK SET CATEGORIES section of the SIMULINK LIBRARY BROWSER window, click on the "+" sign next to the Simulink group to expand the tree and select (click on) Sources.  **29**    A set of blocks will appear in the BLOCKSET group. Click on the Sine Wave block and drag it to the workspace window (also known as model window)    I am going to save this model under the filename: "simexample1". To save a model, you may click on the floppy diskette icon. Or from FILE menu, select Save or CTRL+S. All Simulink model file will have an extension ".mdl". Simulink recognizes file with .mdl extension as a simulation model (similar to how MATLAB recognizes files with the extension .m as an MFile).  Continue to build your model by adding more components (or blocks) to your model window. We'll continue to add a Scope from Sinks library, an Integrator block from  **30**  continuous library, and a Mux block from Signal Routing library.  NOTE: If you wish to locate a block knowing its name, you may enter the name in the SEARCH WINDOW (at Find prompt) and Simulink will bring up the specified block.  To move the blocks around, simply click on it and drag it to a desired location. Once all the blocks are dragged over to the work space should consist of the following components:    You may remove (delete) a block by simply clicking on it once to turn on the "select mode" (with four corner boxes) and use the DEL key or keys combination CTRL-X.  STEP 2: MAKING CONNECTIONS  To establish connections between the blocks, move the cursor to the output port represented by ">" sign on the block. Once placed at a port, the cursor will turn into a cross "+" enabling you to make connection between blocks.  To make a connection: left-click while holding down the control key (on your keyboard) and drag from source port to a destination port.      **31**  The connected model is shown below.    Figure : Simulink connected model  A sine signal is generated by the Sine Wave block (a source) and is displayed by the scope. The integrated sine signal is sent to scope for display along with the original signal from the source via the Mux, whose function is to multiplex signals in form of scalar, vector, or matrix into a bus.  STEP 3: RUNNING SIMULATION  You now can run the simulation of the simple system above by clicking on the play button (alternatively, you may use key sequence CTRL+T, or choose Start submenu under Simulation menu).  Double click on the Scope block to display of the scope.    **32**  **Simulating and experimental verification**  For the purpose of evaluating the performances of ASMC of inverters operating in islanded microgrid, comparative simulations and experiments between PID voltage controller, conventional Sliding-Mode Controller (CSMC), and ASMC are investigated. Two sets of H-bridge inverters with LC output filters operating in parallel providing energy to local non-linear load are simulated through Matlab/Simulink. Simulating step size is set to 7.8125 ls. And non-linear load is composed of a diode rectifier parallel with RLC load ((5 X + 80 lH)||2 mF). The simulation model of islanded parallel inverters is depicted in Fig. 4. Each inverter’s control unit includes a power-calculation and power-droop unit and a voltage-control unit. In Fig. 4, the ASMC is adopted as voltage-control unit. The circuit and control parameters are selected to be the same in both simulation and experiments, as listed in Table 1.  The detailed simulation block of ASMC is depicted ,which includes five units: differential calculation, surface calculation, observer, tracking control and switching control.  All of these units are built by using S-Function. The function of differential calculation unit is to obtain the values of and during each simulating step size; The function of surface calculation unit is to achieve the effectiveness of Eq. (9); The function of observer unit is to predict the values of , and by using Eqs. (12) and (19);  The tracking control unit and switching control unit achieve the function of Eqs. (20) and (11), respectively.  The state trajectories of the control system of inverter in the phase space by using three types of voltage controllers are depicted . And the structure of CSMC and PID voltage controller are respectively. The ideal control performance presents that state trajectory could quickly move toward the sliding surface (equilibrium surface) from initial point and then slide along the surface and finally tend to the origin.  However, by using PID voltage controller, the nonlinear load makes the state trajectory of the control system seriously deviate from equilibrium surface in phase space, By using the CSMC, the initial point of state trajectory is far from the sliding surface. It means that the CSMC system of inverter has reaching phase. In spite of the existence of reaching phase, the state trajectory moves toward the sliding surface then stays on it and eventually tends to the origin. Owing to the chattering, the state trajectory appears obviously periodic oscillation    **33**  around the origin. Because of eliminating reaching phase, the initial point of the state  trajectory of ASMC system stays on the sliding surface. In contrast to CSMC scheme, the oscillation of the state trajectory in phase space around the origin is apparently alleviated.  **34** |
| **ASMC2**  When the amplitude of reference voltage arise to 220 V from 110 V at 0.065 s, the transient responses of the filter-capacitor voltage and the load current of a single inverter by using different voltage controllers are depicted, respectively.  By using PID voltage controller, the tracking performance of the filter-capacitor voltage for reference voltage is poor, as shown, and the THD of the filter-capacitor voltage is up to 8.6%.  However, by using CSMC, a better tracking performance it has, highly-frequency vibration occurs in the filter-capacitor voltage, as shown, which is caused by the chattering of control input signal. And the THD of the filter-capacitor voltage decreases to 3.49%. High steady-state and dynamic performance can be guaranteed by using ASMC in inverter system, as shown, and the THD of the filter-capacitor voltage is merely 0.14%. Although the chattering of control input signal in VSC is objective existence and cannot be eliminated completely, it can be diminished within an acceptable limitation as shown.      **35**  Io, uc2, io+uc2  **36**    **ASMC 1**  To compare with PID voltage controller and CSMC, the transient period of nonlinear load current by using ASMC during reference-voltage transient is shorter, as shown.  Considering the value of filter inductor varying from 50% to 50% of nominal value in most practical cases, the perturbation-rejection performances of three voltage controllers and their transient responses during the period of reference voltage arising to 220 V from 110 V are depicted. It is obvious that PID voltage controller does not possess perturbation-rejection capability, as shown. By using CSMC, the perturbation-rejectionperformance depends on the identification precision of filter inductance. The perturbation-rejection performance of CSMC system deteriorates severely as the variation of filter inductance from 30% to 50% of nominal value, as shown. In spite of variation of filter inductance from 50% to 50% of nominal value,high perturbation-rejection performance is obtained by using ASMC,as shown, which exactly verifies the invariance of sliding mode control to system perturbation.  **37**  and  **38**  When another set of nonlinear load of the same size suddenly connects among two parallel inverters at 0.065 s, the filter-capacitor voltages and the load currents from one of the two inverters by using different voltage controllers during the transient are depicted. By comparison, it can be seen that ASMC system can distinctly reduce current peak and shorten the settling time during the transient of sudden load connection.  In order to verify whether ASMC system has better robustness compared with the systems using PID voltage controller and CSMC, a prototype is built based on the test panel of 2KW  single-phase photovoltaic inverter system in our laboratories. The prototype consists of photovoltaic array, DC/DC boost circuits, fully-controlled H-bridge inverters, LC filter circuits and nonlinear load.  The photovoltaic array uses single crystal silicon solar cells with 2 kW rated power. The photovoltaic array connects inverter through DC/DC boost circuit. In order to clamp dc-link voltage of inverter from oscillation, the parallel capacitor (3000 lF, 450 V) installed in dc link is needed.  In the fully controlled H-bridge inverter, an insulated-gate bipolar transistor (IGBT) intelligent power modules (PM50B5LA060), manufactured by Mitsubishi Corporation, is selected.  The designed algorithms in this study are implemented by 32-bits digital-signal-processor  (DSP) TMS320F2812 which manufactured by TI Company. And carrier frequency of PWM is set up to 12.8 kHz. The nonlinear load is composed of a diode rectifier paralleled with RLC load(100 X + 4 mH + 1000 lF). Other parameters are same as in  simulation (in Table 1).      **39**  **ASMC1 INDUCTANCE P50**    **40**  **ASMC 1 INDUCTANCE 0**    **41**  **ASMC 1 INDUCTANCE N50**      **42**  The experimental waveforms of the filter-capacitor voltages and the load currents of a single inverter by using three controllers during the transient of the amplitude of reference-voltage signal arising to 220 V from 110 V. The steady-state tracking error of the filter-capacitor voltage by using PID controller is worse. And the chattering occurred on filter-capacitor voltage by using CSMC is obvious. By using ASMC, filter-capacitor voltage has less steady-state error, less chattering and better dynamic performance,and the current peak of load current is lower than by using other controllers.  experimental waveforms of the filter-capacitor voltages and the load currents of inverter 1 by using three controllers during the transient that another set of nonlinear load of the same size is suddenly connected among two parallel inverters. By using PID controller and CSMC, the voltages of filter capacitor appear obviously peak during the load transient.The invariance characteristic of ASMC system, the filter-capacitor voltage is less sensitive to this transient.    **43**  **CHAPTER 6**  **CONCLUSIONS AND FOTURE WORK**  **Conclusions**  This paper presents a nonlinear voltage controller for parallel inverters operating in islanded microgrid. The global asymptotic stability of proposed ASMC system is rigorously proofed by using Lyapunov second law. For one thing, the designed ASMC can eliminate the reaching phase of motion state of control system of inverter and makes the control system obtain global robustness by designing adaptive algorithm to observe filter parameters.  For another, the chattering of control-input signal is greatly reduced by designing adaptive algorithm of switching gain which does not need make a tradeoff between stability and chattering reduction. Simulating and experimental results are presented that the ASMC can ensure the excellent dynamic and steady-state tracking ability of filter-capacitor voltage, and have ability to reject the disturbances caused by filter-inductor variation, and can ensure volt-age peak of filter capacitor within a shorter transient period in the case of sudden load connection.  **44**  **Future work**  Design need to work on different voltage controllers and implementation on adaptive sliding mode voltage controller.    **45**  **References**  [1] Guerrero JM, de Vicuna LG, Matas J, Castilla M, Miret J. Output impedance  design of parallel-connected UPS inverters with wireless load-sharing control.  IEEE Trans Ind Electron 2005;52(4):1126–35.  [2] Guerrero JM, Matas J, de Vicuna LG, Castilla M, Miret J. Decentralized control  for parallel operation of distributed generation inverters using resistive output  impedance. IEEE Trans Ind Electron 2007;54(2):994–1004.  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