Abstract—This study mainly develops a novel power control scheme for a stand-alone photovoltaic (PV) generation system. In order to make the PV generation system more flexibility and expandability, the later power circuit is composed of a high step-up converter and a pulse-width-modulation (PWM) inverter. In the dc-dc power conversion, the high step-up converter is introduced to improve the conversion efficiency in conventional boost converters and to allow the parallel operation of low-voltage PV modules. Moreover, an adaptive total sliding-mode control (ATSMC) system is designed for the voltage control of the PWM inverter to maintain a sinusoidal output voltage with lower total harmonic distortion (THD) and less variation under various output loads. Experimental results are given to verify the validity and reliability of the high step-up converter and the PWM inverter control for a stand-alone PV generation system.

I. INTRODUCTION

In the past century, global surface temperatures have increased at a rate near 0.6°C/century because the global warming is taking place due to effluent gas emissions and increases in CO₂ [1], [2]. Problems with energy supplies and use are related not only to global warming but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction, and radioactive substance emissions. To prevent these effects, some potential solutions have evolved including energy conservation through improved energy efficiency, a reduction in fossil fuel use and an increase in environmentally friendly energy supplies. Recently, energy generated from clean, efficient and environmental-friendly sources has become one of the major challenges for engineers and scientists. Among them, photovoltaic (PV) generation system has been received a great attention in research because it appears to be one of the possible solutions to this environmental problem [3]–[7].

In recent, dc-dc converters with steep voltage ratio are usually required in many industrial applications. For examples, the front-end stage for clean-energy sources, the dc back-up energy system (UPS), high-intensity discharge lamps for automobile headlamps, and telecommunication industry [8]–[11]. The conventional boost converters cannot provide such a high dc voltage gain, even for an extreme duty cycle. It also may result in serious reverse-recovery problem and increase the rating of all devices. As a result, the conversion efficiency is degraded and the electromagnetic interference (EMI) problem is severe under this situation [12]. In order to increase the conversion efficiency and voltage gain, many modified step-up converter topologies have been investigated in the past decades [13]–[17]. Although voltage-clamped techniques are manipulated in the converter design to overcome the severe reverse-recovery problem of the output diode in high-level voltage applications, there still exists large switch voltage stresses and the voltage gain is limited by the turn-on time of the auxiliary switch [13], [14]. Wai and Duan [17] investigated a novel coupled-inductor converter strategy to promote the voltage gain of a conventional boost converter with a single inductor, and deal with the problem of the leakage inductor and demagnetization of transformer in a conventional coupled-inductor-based converter. In this study, the high step-up converter topology in [17] is introduced to boost and stabilize the output dc voltage of PV modules for the utilization of a later inverter.

Developments in microelectronics and power devices have made the widespread applications of pulse-width-modulation (PWM) inverters to industries. The basic mechanism of a PWM inverter is to convert the dc voltage to a sinusoidal ac output through the inverter-LC filter blocks. The performance is evaluated by the total harmonic distortion (THD), the transient response, and the efficiency. Thus, much attention has been paid to the closed-loop regulation of PWM inverters to achieve good dynamic response under different types of load in the past decade [18]–[21]. Variable structure control (VSC) with sliding mode, or sliding-mode control (SMC), is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode [22], [23]. The insensitivity of the controlled system to uncertainties exists in the sliding mode, but not during the reaching phase, i.e., the system dynamic in the reaching phase is still influenced by uncertainties. Recently, some researchers have adopted the idea of total sliding-mode control (TSMC) to get a sliding motion through the entire state trajectory [24]–[26], i.e., no reaching phase exists in the control process, so that the controlled system through the whole control process is not influenced by uncertainties. This study attempts to extend an adaptive total sliding-mode control (ATSMC) from [25] to the voltage control of a PWM inverter. Up to now, this is the first time to investigate the application of TSMC to the power electronics control.

II. SYSTEM DESCRIPTION

In this study, the configuration of a stand-alone photovoltaic (PV) generation system is depicted in Fig. 1. The system is mainly composed of PV modules, a high step-up converter, a full-bridge inverter, a system
controller, and an output load. Due to the photo-voltaic effect, the voltage of a PV cell is not very high. However, the PV module with a higher output voltage is difficult to fabricate and it may be failure when any single cell is inactive. Besides, the corresponding output voltage \(V_{pv}\) is varied easily with respect to the variation of loads. In order to satisfy the requirement of high-voltage demand, a high-efficiency dc-dc converter with high voltage gain is one of the essential mechanisms in the stand-alone PV generation system. In this study, a high step-up converter \cite{17} is implemented to reduce the series-connected numbers of PV modules and to maintain a constant dc bus voltage \(V_b\) for the utilization of a later inverter.

![Fig. 1. Configuration of stand-alone PV generation system.](image)

A unipolar pulse-width-modulation (PWM) full-bridge inverter including four power semiconductors and a low-pass filter is regarded as the dc/ac power conversion circuit to meet the requirement of an ac power source. Since the PWM inverter dominates the performance in converting the dc voltage source to an ac voltage source, the quality of the ac output waveform of the PV generation system is highly dependent on the performance of the PWM inverter. Thus, an adaptive total sliding-mode control (ATSMC) system \cite{25} is introduced by way of switching four power semiconductors in this inverter to maintain a sinusoidal output voltage \(v_o\) with lower total harmonic distortion (THD) and less variation under various output loads.

In this study, the PWM inverter control is carried out using Turbo C language inserted into a system controller, i.e., a digital-signal-processor (DSP) development module. This development module has a Texas Instruments TMS320LF2407A central processing unit with an evaluation module (EVM), 16 channel 10-bit analog-to-digital, 4 channel 12-bit digital-to-analog converters and programmable I/O ports. The central processing unit has a 40MIPS 16-bit fixed point DSP core, 16 PWM channels, 4 general purpose timers and 2 encoder channels.

III. HIGH STEP-UP CONVERTER

The architecture of a high step-up converter introduced from \cite{17} is depicted in Fig. 2, where it contains seven parts including a photovoltaic (PV) module input circuit, a primary-side circuit, a secondary-side circuit, a passive regenerative snubber circuit, a filter circuit, a dc output circuit, and a feedback control mechanism. In this strategy, a coupled inductor with a lower-voltage-rated switch is used for raising the voltage gain whether the switch is turned on or turned off. Moreover, a passive regenerative snubber is utilized for absorbing the energy of stray inductance so that the switch duty cycle can be operated under a wide range, and the related voltage gain is higher than other coupled-inductor-based converters. In addition, all devices in this scheme also have voltage-clamped properties and their voltage stresses are relatively smaller than the output voltage. Thus, it can select low-voltage low-conduction-loss devices, and there are no reverse-recovery currents within the diodes in this circuit. Furthermore, the closed-loop control methodology is utilized to overcome the voltage drift problem of the power source under the load variations. As a result, this converter topology can promote the voltage gain of a conventional boost converter with a single inductor, and deal with the problem of the leakage inductor and demagnetization of transformer for a coupled-inductor-based converter.

![Fig. 2. Architecture of high step-up converter.](image)

The major symbol representations are summarized as follows. \(V_{pv}\) and \(I_{pv}\) denote dc input voltage and current, and \(C_{dc}\) is an input filter capacitor in the PV module input circuit. \(L_1\) and \(L_2\) represent individual inductors in the primary and secondary sides of the coupled inductor \((T_1)\), respectively. \(Q\) is a switch in the primary-side circuit; \(V_d^*\) and \(T_Q\) are the output voltage command and the trigger signal in the feedback control mechanism. \(C_1\), \(D_1\) and \(D_2\) denote a clamped capacitor, a clamped diode and a rectifier diode in the passive regenerative snubber circuit. \(C_2\) is a high-voltage capacitor in the secondary-side circuit. \(D_3\) and \(C_O\) are the output diode and the filter capacitor in the filter circuit. \(V_a\) and \(I_d\) describe dc output voltage and current in the dc output circuit.

The coupled inductor in Fig. 2 could be modeled as an ideal transformer, a magnetizing inductor \((L_m)\), and a leakage inductor \((L_k)\). The turns ratio \(n\) and coupling coefficient \(k\) of this ideal transformer are defined as

\[
n = N_2 / N_1
\]
\[ k = \frac{L_m}{L_2 + L_m} \]  

where \( N_1 \) and \( N_2 \) are the winding turns in the primary and secondary sides, respectively. The voltages across the switch, the primary and secondary winding of the ideal transformer, and the leakage inductor are denoted as \( v_{DS} \), \( v_{in} \), \( v_{C2} \) and \( v_{L2} \), respectively. Moreover, the primary current \((i_{L1})\) of the coupled inductor is composed of the magnetizing current \((i_{Lm})\) and the primary induced current \((i_1)\). The secondary current \((i_{L2})\) is formed by the primary induced current \((i_1)\) through the ideal transformer, and its value is related to the turns ratio \((n)\). In addition, the conductive voltage drops of the switch \((Q)\) and all diodes \((D_1, D_2\) and \(D_2\)) are neglected to simplify circuit analyses.

According to the detailed circuit analyses in [17], the voltage gain \((G_v)\) of the high step-up converter and the corresponding switch voltage \((v_{DS})\) can be represented as

\[
G_v = \frac{V_d}{V_{pv}} = 2 + nk \quad \frac{D(1-k)(n-1)}{1-D} \quad (3)
\]

\[
v_{DS} = \frac{V_{pv}}{1-D} + \frac{D(1-k)(n-1)}{2(1-D)} V_{pv} \quad (4)
\]

where \( D \) is the duty cycle of the switch \((Q)\). Because the voltage gain \((G_v)\) is less sensitive to the coupling coefficient \((k)\), (4) and (5) can be rewritten with \( k = 1 \) as

\[
G_v = \frac{V_d}{V_{pv}} = (2 + n)/(1-D) \quad (5)
\]

\[
v_{DS} = \frac{V_{pv}}{1-D} \quad (6)
\]

According to (5) and (6), one can obtain

\[
v_{DS} = \frac{V_d}{(n+2)} \quad (7)
\]

By analyzing (7), the switch voltage \((v_{DS})\) is not related to the input power source \((V_{in})\) and the switch duty cycle \((D)\) if the values of the output voltage \((V'_d)\) and the turns ratio \((n)\) are fixed. Thus, it can ensure that the maximum sustainable voltage of the switch \((Q)\) is constant. As long as the input voltage is not higher than the switch voltage rating, the high step-up converter can be applied well to low-voltage PV power sources even with large voltage variations.

IV. PWM INVERTER CONTROL

A Dynamic Model Description

Figure 3 illustrates the PWM inverter framework including four power semiconductors and a low-pass filter. In Fig. 3, \( r_s \) and \( r_c \) are the equivalent series resistors of the inductor \((L_s)\) and the capacitor \((C_f)\) in the low-pass filter; \( Z_{o} \) is the output load; \( v_{in} \), \( v_{Cf} \) and \( v_{o} \) are the output voltage of the full-bridge inverter, the voltage across the filter capacitor, and the load voltage, respectively; \( i_L \), \( i_C \) and \( i_o \) are the filter inductor current, the filter capacitor current and the load current, respectively; the current source \( i_{id} \) emulates the disturbance incurred by load variations. In order to analyze conveniently, the following assumptions are made in this study: (i) the values of \( r_s \) and \( r_c \) are smaller enough to ignore; (ii) the conduction and switching losses are zero since all power switches are assumed to be ideal devices; (iii) the delay time between the switch turn-on and turn-off states is smaller enough to neglect; (iv) the control signal and input/output voltages are taken as constant values because the switching frequency is more greater than the system dynamic frequency.

![PWM Inverter Framework](image)

Due to the symmetry property of the positive-half and negative-half period in the unipolar PWM switching, the dynamic equation during the positive-half period can be represented via the state-space average method [12] and the linearization technique as

\[
\frac{\dot{i}_{L1}}{L_f} = (D V_d - V_{Cf}) / L_f \quad (8)
\]

\[
\frac{\dot{i}_{Cf}}{C_f} = (i_{L1} + i_{id} - i_o) / C_f \quad (9)
\]

\[
v_o = v_{Cf} \quad (10)
\]

where \( D \) is the duty cycle of the switches \( T_{A} \) and \( T_{B} \) during one switching period. Define the duty cycle and the power gain as \( D = v_{con} / \hat{V}_{tri} \) and \( K_{PWM} = V_d / \hat{V}_{tri} \), where \( v_{con} \) is a sinusoidal control signal and \( \hat{V}_{tri} \) is the amplitude of a triangular carrier signal \((v_{tri})\), then the dynamic equation of the PWM inverter can be given as

\[
\frac{\dot{v}_o}{L_f C_f} = -\frac{1}{L_f C_f} v_o + \frac{K_{PWM}}{L_f C_f} v_{con} - \frac{1}{C_f} i_o + \frac{1}{C_f} i_{id} \quad (11)
\]

By choosing the ac output voltage \((v_o)\) as the system state and the control signal \((v_{con})\) as the control input, (11) can be rearranged as

\[
\dot{x}(t) = a_p x(t) + b_p u(t) + c_p z(t) + m(t)
\]

\[
= (a_p + \Delta a_p) x(t) + (b_p + \Delta b_p) u(t)
\]

\[
+ (c_p + \Delta c_p) z(t) + m(t)
\]

\[
= a_p x(t) + b_p u(t) + c_p z(t) + w(t)
\]

where \( x(t) = v_o \), \( u(t) = v_{con} \), \( a_p = -1/(L_f C_f) \), \( b_p = K_{PWM}/(L_f C_f) \), \( c_p = -1/C_f \), \( z(t) = i_o \) and \( m(t) = i_{id}/C_f \); \( a_p \), \( b_p \) and \( c_p \) denote the nominal values of \( a_p \), \( b_p \) and \( c_p \), respectively; \( \Delta a_p \), \( \Delta b_p \) and \( \Delta c_p \) represent the system parameter variations; \( w(t) \) is called the lumped uncertainty and defined as
\[ w(t) = \Delta a_{pm} x(t) + \Delta b_{pm} u(t) + \Delta c_{pm} z(t) + m(t) \]  
Here the bound of the lumped uncertainty is assumed to be given; that is, 
\[ |w(t)| < \rho \]  
where \( |\cdot| \) is the operator of an absolute value, and \( \rho \) is a given positive constant.

\section*{B. ATSMC System}

The objective of the PWM inverter control is to force the system state \( x = v_{cmd} \) to track a reference output voltage \( (x_d = v_{cmd}) \) under the possible occurrence of system uncertainties. An adaptive total sliding-mode control (ATSMC) system as shown in Fig. 4 is introduced for the voltage control of the PWM inverter, where \( s \) is the Laplace operator, and the control error is chosen as \( e = x - x_d = v_{o} - v_{cmd} \). Define a sliding surface \([25]\) as
\[ s_i(t) = c(e) - c(e_o) - \int_0^t \frac{\partial c}{\partial e} A e d\tau \]  
where \( e = [e^T] \); \( A = \begin{bmatrix} 0 & 1 \\ -k_2 & -k_1 \end{bmatrix} \), in which \( k_i \) and \( k_2 \) are non-zero positive constants; the function \( c \) is designed to satisfy the condition of \( \partial c/\partial e = [0 \ b^{-1}] \); \( e_o \) is the initial state of \( e(t) \).

In the ATSMC system, it is divided into three main parts. The first part addresses the performance design. The object is to specify the desired performance in terms of the nominal model, and it is referred to as the baseline model design \( (u_o) \). Following the baseline model design, the second part is the curbing controller design \( (u_c) \) to totally eliminate the unpredictable perturbation effect from the parameter variations and external disturbance so that the baseline model design performance can be exactly assured. Finally, the third part is the adaptive observation design \( (\hat{\rho}) \) to estimate the upper bound of the lumped uncertainty for alleviating the chattering phenomenon caused by the inappropriate selection of a conservative constant control gain in the curbing controller. The entire control methodologies of the ATSMC system are summarized in the following theorem.

\textbf{Theorem 1:} If the PWM inverter scheme shown in (12) is controlled by the three-part ATSMC system described by (16) – (18) with the adaptive observation design shown in (19), then the stability of the ATSMC system for the voltage control of the PWM inverter can be guaranteed.

\[ u = u_o + u_c \]  
\[ u_o = -b_{pm}^{-1}(a_{pm} x + c_{pm} z - \dot{x}_d + k_e + k_c e) \]  
\[ u_c = -\hat{\rho}(t) b_{pm}^{-1} \text{sgn}(s_i(t)) \]  
\[ \dot{\hat{\rho}}(t) = b_{pm}^{-1} |s_i(t)|/\lambda \]  
where \( \lambda \) is a positive constant.

\textit{Proof:} According to Lyaponov analyses \([22, 23]\), the stability of the controlled system can be assured. The proof of Theorem 1 is similar to \([25]\) and is omitted here.

\section*{V. EXPERIMENTAL RESULTS}

The validity and reliability of the high step-up converter and the PWM inverter control in the stand-alone PV generation system are verified by the following experimental results. The input side consists of six 75W PV modules manufactured by the MOTECH Company (F-MSN-75W-R-02) connecting in parallel as a low-voltage power source. The specifications of a single PV module for the standard condition \((1kW/m^2, 25^\circ C)\) are rated power = 76.78W, rated voltage = 17.228V, rated current = 4.567A, open-circuit voltage = 21.61V, short-circuit current = 4.9649A, and PV efficiency = 11.92%.

\section*{A. Experimental Results of High Step-Up Converter}

In experimentation, the high step-up converter is designed initially to operate from the variability dc input of PV modules to deliver a constant dc output, \( V_o = 200V \). Assume that the maximum value of the switch voltage is clamped at 34V, the turns ratio \( n = (V_o/V_{dc(max)}) - 2 \approx 4 \) according to (7). From (6), the related duty cycle, \( D = 0.7 \), is reasonable in practical applications if the minimum input voltage is assumed to be 10V. In order to solve the problem of the output voltage of PV modules varied with the load variations, this converter with dc voltage feedback control is utilized to ensure the system stability, and a PWM control IC TL494 is adopted to achieve this goal of feedback control. The prototype with the following specifications is designed to illustrate the design procedure given in Section III. Switching frequency: \( f_s = 100kHz \);
Coupled inductor: \( L_1 = 9\mu H \), \( L_2 = 143\mu H \); \( N_1 : N_2 = 3:12 \), \( k = 0.97 \), EE-55 core;
Capacitor: \( C_{IN} = 3300\mu F/50V*2 \), \( C_e = 6.8\mu F/100V \), \( C_s = 1\mu F/250V*2 \), \( C_{op} = 47\mu F/450V*2 \); Switch: Q: IRFP048N (55V/64A); Diode: \( D_1 \) : Schottky diode SR2060, TO-220AC (60V/20A); \( D_2 \) : \( D_3 \): Schottky diode SB20200CT, TO-220AB (200V/20A).

The experimental voltage and current responses of the high step-up converter operating at 320W-output power \((P_o)\) are depicted in Fig. 5. From Fig. 5(a), the switch voltage \((V_{fsc})\) is clamped at 34V that is much smaller than
the output voltage, $V_o = 200\text{V}$, and the curve of the switch current ($i_{\text{on}}$) is similar to a square wave so that it can further reduce the conduction loss of the switch ($Q$). By observing Fig. 5(b) and (c), the primary current ($i_{\text{cl}}$) keeps about 30A, thus only a smaller core capacity is necessary for $L_i = 9\mu\text{H}$. According to Fig. 5(d)-(j), the reverse-recovery currents in all diodes ($D_{j1}$, $D_{j2}$ and $D_{j3}$) can be alleviated effectively, and the voltages of the clamped capacitor ($C_{v1}$) and the high-voltage capacitor ($C_{v2}$) are close to constant values. Therefore, it can alleviate the reverse-recovery problem and exhibit the voltage-clamped effect for further raising the conversion efficiency. Figure 6 summarizes the experimental conversion efficiency of the high step-up converter under different output powers. As can be seen from this figure, the conversion efficiency at light powers is over 95% and the maximum efficiency is over 96.5%, which is comparatively higher than conventional converters.

![Fig. 6. Conversion efficiency of high step-up converter with $V_i = 200\text{V}$ under different output powers.](image)

**B. Experimental Results of PWM Inverter Control**

The circuit components of the PWM inverter scheme are ( $T_{A+}, T_{A-}, T_{B+}, T_{B-}$ ) IRFP264 (250V/38A), $L_f = 7.5\text{mH}$, and $C_f = 26.8\mu\text{F}/250\text{V}$; the reference output voltage ($x_d = v_{\text{ref}}$) is set at ac 110Vrms, 60Hz; the switching frequency is $f_o = 20\text{kHz}$. Moreover, the parameters of the ATSMC systems for the PWM inverter scheme are given as follows:

$$k_1 = 2.49, \quad k_2 = 830, \quad \lambda = 1.66 \quad (20)$$

All the parameters in the ATSMC system are chosen to achieve the best transient control performance by considering the requirement of stability. In order to exhibit the necessity of the curbing controller, the experimental results of the baseline model control (BMC) in (17) and the ATSMC for the PWM inverter of the stand-alone PV generation system with fixed resistive load ($R = 100\Omega$) are depicted in Fig. 7. The control performance of the ATSMC system with 0.07% total harmonic distortion (THD) improvement and less corner voltage deviation is superior to the one of the BMC.

![Fig. 7. Experimental results of stand-alone PV generation system with fixed resistive load ($R = 100\Omega$): (a) BMC for PWM inverter; (b) ATSMC for PWM inverter.](image)

The experimental results of the stand-alone PV generation system with the ATSMC system for the PWM inverter under resistive load step changes are given to examine the load variation effect. In Fig. 8(a), the resistive load is changed from light load ($R = 300\Omega$) to heavy load ($R = 100\Omega$); reversely, the resistive load is changed from heavy load ($R = 100\Omega$) to light load ($R = 300\Omega$) in Fig. 8(b). As can be seen from this figure, the control performance of the ATSMC system for the PWM inverter is insensitive to the abruptly load changes.

![Fig. 8. Experimental results of stand-alone PV generation system with ATSMC for PWM inverter under resistive load change: (a) light load ($R = 300\Omega$) to heavy load ($R = 100\Omega$); (b) heavy load ($R = 100\Omega$) to light load ($R = 300\Omega$).](image)

To further verify the effectiveness of the ATSMC...
system for the PWM inverter, Fig. 9 illustrates the experimental results under different load situations including a RC load ($R = 100\Omega$, $C = 30\mu F$), a RL load ($R = 100\Omega$, $L = 245\, mH$), and a rectifier with RC load ($R = 500\Omega$, $C = 47\mu F$). By observing Fig. 9, the output voltage ($v_o$) can almost follow the reference output voltage ($v_{ref}$), and the THD value of the PWM inverter under different loads is less than 5%, which satisfies the demand of the harmonic standards in industrial applications.

![Image](image-url)

Fig. 9. Experimental results of stand-alone PV generation system with ATS MFC for PWM inverter under different load situations: (a) RC load ($R = 100\Omega$, $C = 30\mu F$); (b) RL load ($R = 100\Omega$, $L = 245\, mH$); (c) rectifier with RC load ($R = 500\Omega$, $C = 47\mu F$).

VI. CONCLUSIONS

This study has successfully developed a novel power control scheme for a stand-alone photovoltaic (PV) generation system. The effectiveness of the high step-up converter and the PWM inverter control for the stand-alone PV generation system was verified by realistic experimentations. According to the experimental results, the maximum conversion efficiency of the high step-up converter is over 96.5% that is comparatively higher than conventional converters. Moreover, the ac output voltage of the PWM inverter can almost maintain at a sinusoidal waveform, and the corresponding THD values under different loads are less than 3.2% that satisfies the demand of the harmonic standards in industrial applications. Although the developed PV generation system belongs to a stand-alone generation strategy, it can further merge a maximum-power-point-tracking algorithm and modify the voltage-type PWM inverter control into a current-type one to form a grid-connected generation framework in the future.

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