

Stand-alone Photovoltaic-Based Reduction of Harmonic Current Using a 12-Pulse AC/DC Power Conversion System with Trapezoidal Voltage Waveform

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Abstract

This paper presents an application of stand-alone Photovoltaic (PV) systems for improving the total harmonic distortion (THD) of line input current in twelve-pulse AC/DC power conversion systems. In these control systems, the trapezoidal voltage is generated from a PV stand-alone and injected into line input voltage. The process control system uses a 12-pulse diode rectifier, using a conventional 3-phase bridge 6-pulse diode rectifier. The results are from experiments and simulation of the trapezoidal voltage waveform. The results of the process can reduce the total Harmonic current (THD) of line input current. The simulation results by MATLAB program are used as a guideline for analyzing and designing the parameters of a control system. The experimental results show, that the performance of the proposed control system in the case of THD of line input current and electrical system quality, are improved.

Keyword: Stand-alone Photovoltaic, Trapezoidal voltage waveform, 12-pulse AC/DC power conversion , power quality, harmonic current.

1. Introduction

Frequently found problems in the distribution system involve harmonics current. (IEEE 1159-1995) [1]. AI-Mathnani et al.[2] presented a simulation model of a twelve-pulse, parallel two-level three phase inverter, Dynamic Voltage Restore (DVR) using photovoltaics as a means of providing an alternative energy source for the DVR [2]. Simulations were carried out using the

PSCAD/EMTDC. Simulation results proved the capability of the photovoltaic-based DVR in mitigating voltage sag in a distribution system [2]. Sinusoidal pulse-width-modulation (SPWM) inverters are frequently found in variable-speed ac motor drives. Several modulation strategies have been developed. One of the most widely used, due to its simplicity, is the sinusoidal modulation [3]. Having many reported cases, harmonic current is found in a lot of

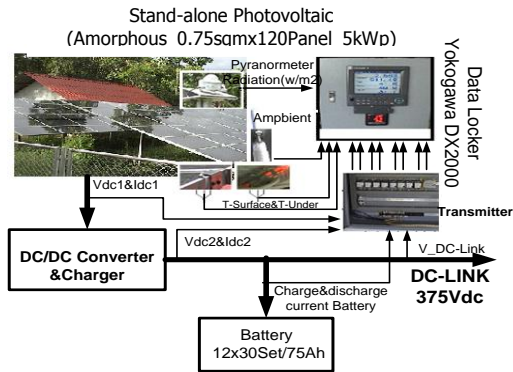
industrial factories. This indicates problems in the power quality of electricity used. Power loss in electric generators, power loss in transmission line systems and power loss in transformers, as well as electromagnetic interference (EMI) are produced as a result of harmonic current arising from installing devices such as power converters, power inverters, electroplating, welding machines, and induction furnaces. These devices normally contain power electronics such as power diode-rectifiers used to convert alternating current (AC) to direct current (DC). Theoretical input current harmonics for rectifier circuits are a function of pulse number and can be expressed as $(h = (NP + 1))$ where $N = 1, 2, 3, \dots$. The isolation transformer with a delta primary, a Delta connected secondary, and a Wye secondary are connected to obtain the necessary phase shift. For a six-pulse rectifier, the input current will have harmonic components at the following multiples of the fundamental frequency 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, etc. For the twelve-pulse system shown in Fig.1, the input current will have theoretical harmonic components at the following multiples of the fundamental frequency: 11, 13, 23, 25, 35, 37, etc. The harmonic order of the 5th and 7th harmonics are absent in the 12-pulse system. Since the magnitude of each harmonic is proportional to the reciprocal of the harmonic number, the twelve-pulse system has a lower theoretical harmonic current distortion. The number of uses of such devices increases according to factories' technological advancements. Concerning harmonic current problems in Thailand, the electricity committee has considered power quality as an important part of an electricity system. Electric Generating Authority of Thailand (EGAT), Metropolitan Electricity Authority (MEA) and Provincial Electricity Authority (PEA) have installed inductors and capacitors as detained filters and it is found that harmonic current is not totally taken out from the

system. One alternative method to reduce harmonic current that could perform better than detained filters is to improve 6-pulse converters to be 12-pulse AC/DC power conversion systems. Twelve-pulse drives have provided a simpler and more cost effective approach to achieve higher current ratings than direct paralleling of power semiconductors. The authors propose an application by Stand-alone Photovoltaic-Based reduction of harmonic current using 12-Pulse AC/DC power conversion System with trapezoidal voltage wave form. For the PV Stand-alone system, one example of a station is at Baan Pukem School in Phetchaburi. The Measurement Diagram for PV stand-alone is shown in Fig.1 and installation site is shown in Fig.5 (a), (b). The system control unit is PWM battery charger DC/DC converter and power inverter unit.

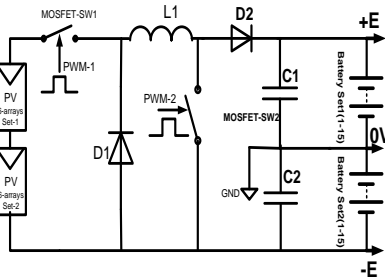
2. Stand-alone Photovoltaic and converter

A PV Stand-alone system has been installed at Baan Phukhem School, Phetchaburi province in the central region of Thailand. Fig.1 exhibits PV stand-alone [5] consisting of panels of amorphous silicon PV Panels. A total of 120 panels, 0.75square meter each with 42.11W/44.6/0.97A, are linked into 12 arrays providing 5 kW_p/375Vdc. The charger controller is a dc-dc buck-boost converter. A total of 30 sets of sealed lead acid 12V/75Ah battery model UB12750 manufactured by Universal Power Group are installed. A Yokogawa recorder DX2000 has been used to continuously record data every 4 minutes. This supports various measurements such as irradiation (W/m^2), temperature(c), dc-voltage (DC-link), dc-current (battery charge & discharge current) and energy consumption (kWh). Irradiation is detected with a Kipp&Zonen CMP11 pyranometer, with high accuracy. For the DC/DC converter

and battery charger (see Fig.1 (b)), details of non-inverting buck-boost converter can be found in [6], [7]. The converter used in this study contains battery (DC-Link) stabilized at 375Vdc with an average voltage: (+E=187.50Vdc) and (-E=187.50 Vdc).



(a)



(b)

Fig. 1 PV stand-alone and PWM battery charger DC/DC converter (a) Measurement Diagram for PV stand-alone installed at Baan Phukhem School, Phetchaburi province.(b) Circuit diagram of Buck-boost converter for battery charger.

3. Technical design of Power supply Trapezoidal voltage waveform

The Signal-mixing technique between sine-waveform and trapezoidal waveform is performed and the result is a periodic waveform. However, when the utility power system recovers from an interruption, the command to the inverter is replaced with wave-shaping voltages to be a trapezoidal waveform. Equation (1) is

followed and corresponds to the block diagram in Fig.2.

$$f(\text{tra}(\omega t)) = f(\sin(\omega t)) - f(\text{Periodic}(\omega t)) \quad (1)$$

$$S_L(\text{VA}) = (P_{inj} + P_s) + j(Q_{inj} + Q_s) \quad (2)$$

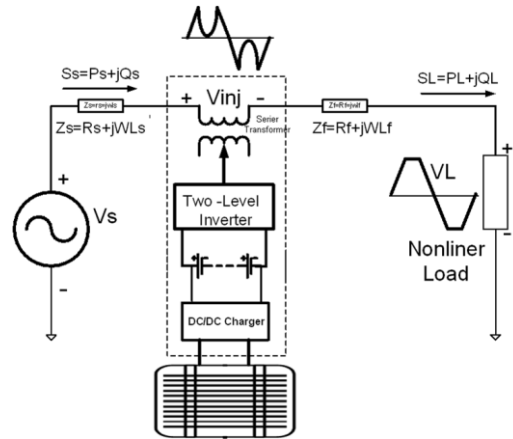


Fig. 2 Signal mixing of the block diagram power supply trapezoidal voltage

When Equation. (2) is followed, the terms S_{inj} , P_{inj} , Q_{inj} are apparent, active, and reactive power compensation, respectively. When P_{inj} , Q_{inj} are applied to series transformer, P_s and Q_s are obtained from the active and reactive power supply. Merging of power transmission P_{inj} , Q_{inj} , P_s , and Q_s supplied according to load requirements creates the total apparent power supply to the load $S_L(\text{VA})$.

4. Twelve -Pulse AC/DC power conversion system applied trapezoidal voltage

The ac supply is from a transformer having two secondaries, Wye-connected and Delta-connected. In this manner, the three-phase voltage supplying the two bridges is displaced by a phase angle of 30 degrees. Hence the two six-pulse output are

symmetrically displaced to give an overall twelve-pulse output [4]. A twelve-pulse system can also be constructed from two six-pulse rectifiers connected in parallel. It has been known that total harmonic current distortion from twelve-pulse converters is better than that from six-pulse converters. When a trapezoidal voltage is applied, total harmonic current distortion is further improved as shown in Fig.3. It consists of a combination of a double-series diode rectifier rated at 5kVA and SPWM inverter with a peak voltage and current rating of 5kVA.

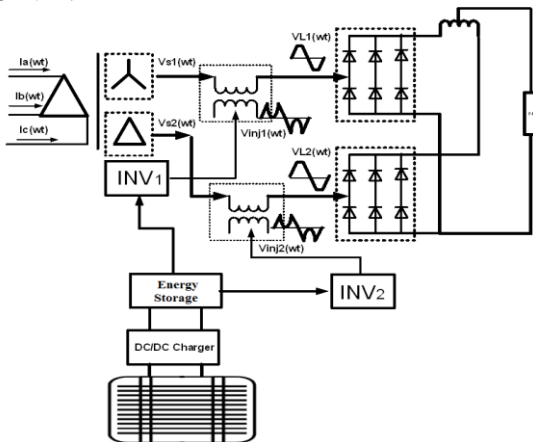


Fig.3 Twelve-pulse AC/DC power conversion system applied trapezoidal voltage waveform

5. Modeling of trapezoidal voltage waveform within MATLAB

Modeling of trapezoidal voltage source is proposed as a control strategy for reduction of harmonic current by applying a trapezoidal voltage source. The modeling blocks diagram consists of phase lock loop (PLL), decoder, sine-cosine-ROM and trapezoidal -ROM. The sine-cosine-ROM is vital for in-phase strategy. The applied signal is transformed from two phase coordinates stationary reference frame ($\alpha\beta$) into two phase coordinates, rotating synchronously with a flux coordinate (dq command) as given in Equation. (1). For the other path, the dq censoring signal obtained from abc three phase coordinates and $\alpha\beta$ is expressed in Equation. (3) and (4). Difference of signal from both paths is detected for a periodic voltage signal. The Output signal from the process then passes to PI-controller. Thereafter, the received signal in dq coordinate is transformed into abc coordinate as written in Equation. (7) and (8). Two-level inverter is further applied to the process.

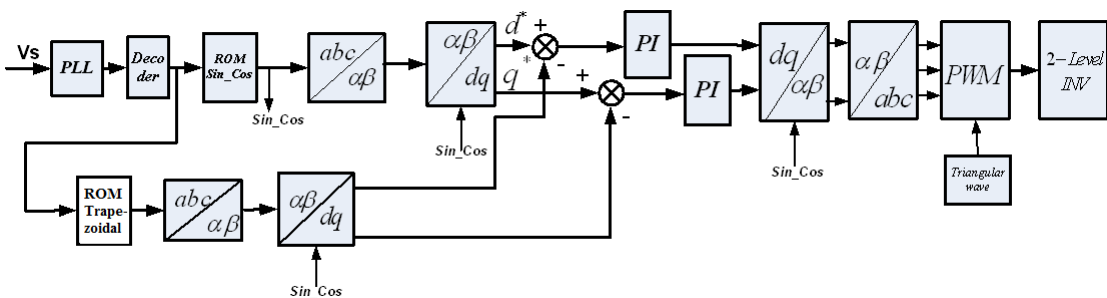


Fig.4 The proposed control strategy for reduction of harmonic current by applying trapezoidal voltage waveform.

$$Va(t) + Vb(t) + Vc(t) = 0 \quad (3)$$

$$\begin{bmatrix} V\alpha(t) \\ V\beta(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \cos \frac{2\pi}{3} & \cos \frac{4\pi}{3} \\ 0 & \sin \frac{2\pi}{3} & \sin \frac{4\pi}{3} \end{bmatrix} \begin{bmatrix} Va(t) \\ Vb(t) \\ Vc(t) \end{bmatrix} \quad (4)$$

$$V(t) = V\alpha(t) + jV\beta(t) \quad (5)$$

$$V(t) = \sqrt{\frac{2}{3}} \left[Va(t) + Vb(t)e^{j\frac{2\pi}{3}} + Vc(t)e^{j\frac{4\pi}{3}} \right] \quad (6)$$

$$\begin{bmatrix} Vd(t) \\ Vq(t) \end{bmatrix} = \begin{bmatrix} \cos \omega t & \sin \omega t \\ -\sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} V\alpha(t) \\ V\beta(t) \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} Va(t) \\ Vb(t) \\ Vc(t) \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \cos \frac{2\pi}{3} & \sin \frac{2\pi}{3} \\ \cos \frac{4\pi}{3} & \sin \frac{4\pi}{3} \end{bmatrix} \begin{bmatrix} V\alpha(t) \\ V\beta(t) \end{bmatrix} \quad (8)$$

Table. 1 Main system parameters for the experimental & simulation trapezoidal voltage waveform.

Description	Rated-value	Per unit-value
Load rating	5kVA	1.0 pu
PV stand-alone	5kWp	1.0 pu
Load voltage	230V	1.0 pu
Input voltage	230V	1.0 pu
Trapezoidal	230V	1.0 pu
DC-link	375V	1.63 pu
Power-frequency	50Hz	1.0 pu
SW-frequency(SPWM)	10kHz	200 pu

Table 1. Describes main system parameters for the experimental and simulation trapezoidal voltage source setup for voltage supply $V_s(V)$ equal to 1.0 pu and injected voltage $V_{inj}(V)$ equal to 1.0 pu having battery energy storage rated 375V/75Ah, and containing load rating of 5 kVA.

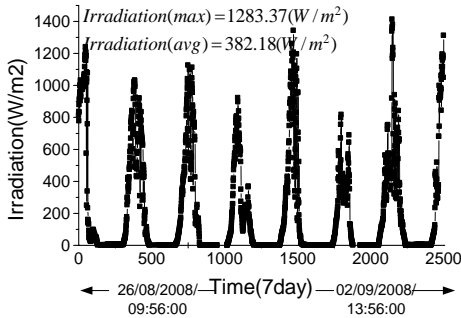
4. Study Results

4.1 Study results of stand-alone PV system

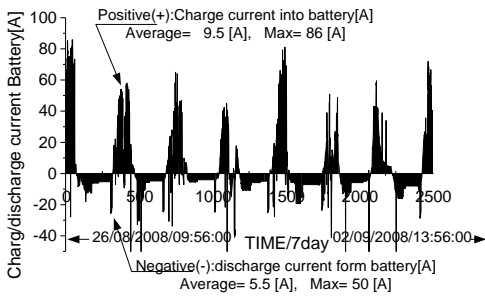
According to the test of PV stand-alone installed at Baan Pukem school (Fig.5 (a),(b)) the work performed on the collected and gathered data IEA PVPS task 2 [8], from seven consecutive days data is comprised of irradiation, average temperature of a solar panel consisting of T-under and T-surface, and ambient temperature [9]. A Yokogawa recorder DX2000 has been used to continuously record average data every four minutes with high accuracy. Irradiation (W/m^2) is detected with Kipp&Zonen CMP11 pyranometer, with high accuracy. Consumption level of battery controlled by buck-boost converter has charge battery average current of 9.5A and discharge battery average current of 5.5A as in Fig.5 (d), producing output voltage of battery (DC-Link) stabilized at 375Vdc with the average, voltage (+E=187.50Vdc) and (E=187.50Vdc). Value of some parameters are as follows: Inductor $L1=75\mu H$, capacitor: $C1=C2=470\mu F$, MOSFET SW(360/750V), Diode: D1, D2 (60A/750V), duty cycle (D=0.30-0.95) and switching frequency 75 kHz as in Fig.1 (b) and result given in Fig.5 (c)-Fig.5 (e). The Average of measured irradiation is $382 W/m^2$. Ambient temperature is maximum at $43.20^\circ C$ with an average of $28.01^\circ C$. Module temperature from T-under and T-surface is maximum at $65.65^\circ C$ with an average of $31.66^\circ C$, Output power of PV-array is maximum 5.6 kWp and average 1.2 kW/day, Potential-energy 247.54 kWh.d. The efficiency of the PV-array is maximum of 19% with an average of 5.45% as in Fig.5 (f).



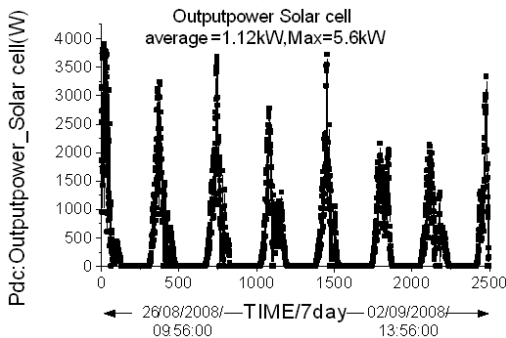
(a) (b)



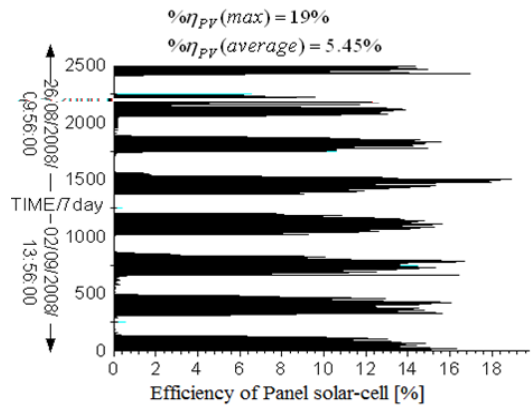
(c)



(d)



(e)

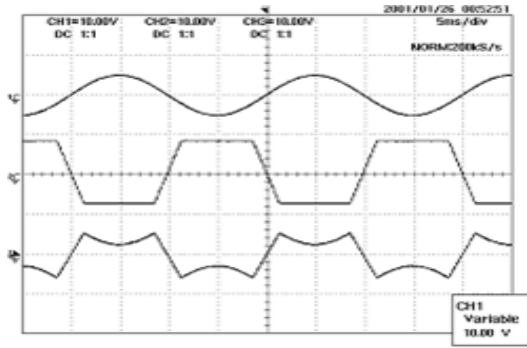


(f)

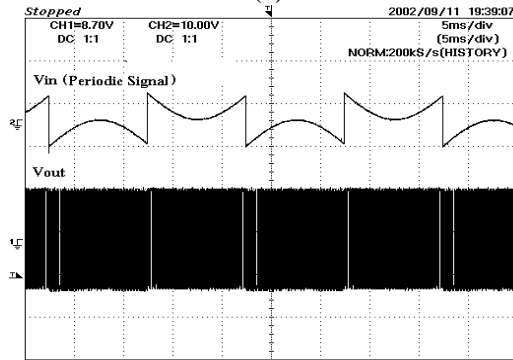
Fig.5 PV Stand-alone system consumption level (a) installation site (b) Data logger Inverter and charger controller (c) irradiation data (d) battery charge & discharge current data (e) Output power of PV consumption (f) efficiency of PV-array system

4.2 Testing SPWM inverter having trapezoidal voltage

Trapezoidal voltage waveform is generated by power inverter circuit system that contains sine-waveform signal sensor, and a periodic voltage waveform, for the phase lock loop (PLL). Under normal state, PLL is employed to synchronize the wave-shaping voltage with the utility sinusoidal voltage. With freely run PLL, the output is a 50Hz trapezoidal voltage waveform. Notably, SPWM is then connected to power drive circuit, via power IGBT switch frequency which is equal to 10 kHz (200pu). Equations. (1)-(8) are followed and corresponds to the block diagram in Fig.4, Fig.6 and Fig.7 show experimental waveform, sine-waveform, trapezoidal-waveform, and periodic-waveform.

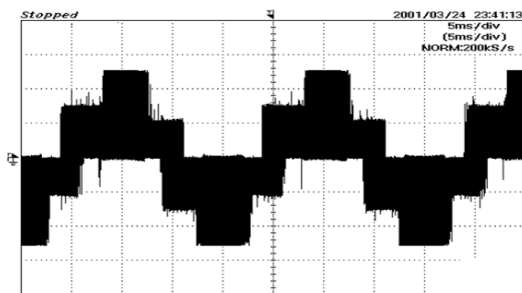


(a)

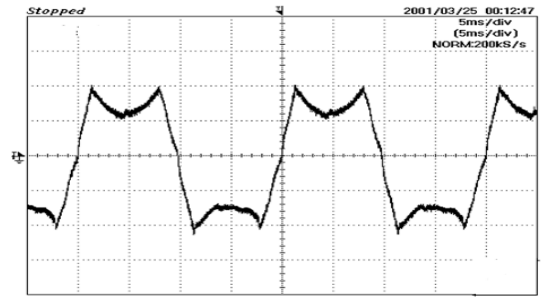


(b)

Fig.6 (a) Experimental waveform Input-Output signal mixing (b) output signal SPWM when having periodic waveform input



(a)

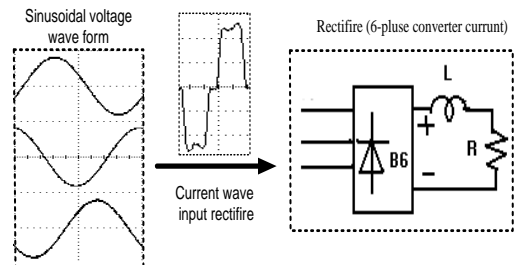


(b)

Fig.7 Experimental waveform of Periodic voltage waveform (a) before and (b) after filtered

4.3 Comparing harmonic current for Six-Pulse AC/DC power conversion

For experimental testing under the same load conditions, a comparison can therefore be made between using sinusoidal wave voltage source (Fig.8) and trapezoidal voltage source (Fig.9). From trial experiments, it is found that the best trapezoidal voltage source should have 1 ms rising time and 1 ms falling time with 30 degrees delay offset between phase-to-phase as shown in Fig.9 (a). The main reason for such conditions is that the input 6-pulse converter current will be nearly a sinusoidal waveform. Further, this causes total harmonic current distortion (%THDi) to be reduced by 15.6% (compare Fig.8 and Fig.9).



(a)

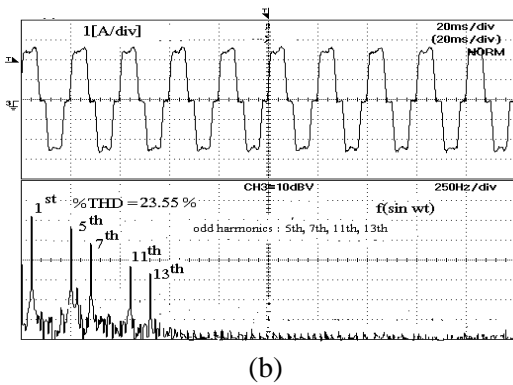


Fig. 8 Experimental (a) Input current when using sine wave voltage source and (b) Spectrum that generates harmonic current when using sinusoidal voltage waveform

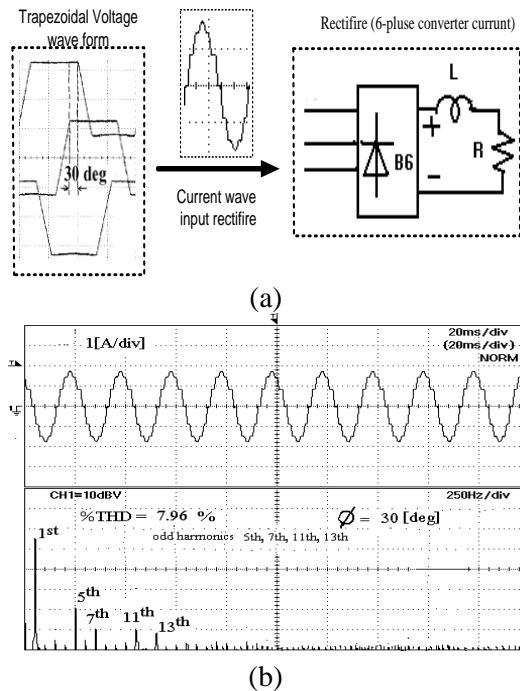


Fig.9 Experimental (a) Input current when using trapezoidal voltage source and (b) Spectrum that generates harmonic current when using trapezoidal voltage waveform.

4.4 Twelve-Pulse AC/DC power conversion system applied trapezoidal voltage source with MATLAB Simulation

The ac supply is from a transformer having two secondaries, Wye-connected

and Delta-connected. In this manner, the three-phase voltage supplying the two bridges is displaced by a phase angle of 30 degrees. Hence, the two six-pulse output are symmetrically displaced to give an overall twelve-pulse output. It has been known that total harmonic current distortion from a twelve-pulse converter is better than that from a six-pulse converter. When trapezoidal voltage is applied, total harmonic current distortion is further improved as shown in Fig.3. It consists of a combination of a double-series diode rectifier rated at 5kVA. A clear advantage is from using DC link from PV stand-alone. The ac terminal of each sinusoidal SPWM inverter is connected in series with a power line of $\Delta/\Delta/Y$ transformer rated 5kVA, $\Delta/\Delta/Y$, 380/220/220V,50Hz. This case study uses computer program MATLAB simulation, modeling of trapezoidal voltage waveform within MATLAB (Fig.3 and Fig.4). From this simulation, relevant parameters are given in the transformations, parameter of three winding power transformer. [Δ /Primary ($R1=0.0025pu$), ($L1=0.08pu$)], secondary winding [Δ /Secondary ($R2=0.0025pu$), ($L2=0.08pu$)] and [Y /Secondary ($R3=0.0025pu$), ($L3=0.08pu$)], DC-Link (375Vdc), two-level inverter using IGBT-devices of Fall-time T_f ($1\mu s$) and tail time T_t ($2\mu s$), frequency-SPWM ($fsw=10kHz$) and LC-Filter ($L=300\mu H$), ($C=20\mu F$). A comparison study, conducted by comparing results obtained from a conventional 12-pulse power converter, is nearly a sinusoidal waveform when applied trapezoidal voltage. From Fig.10, it is learnt that input current primary transformer is nearly a sinusoidal waveform (Fig.10 (a), against Fig.10 (b)). A comparison can easily be seen from the figures. For this simulation, total harmonic current distortion (THDi) can be reduced by 14 percent (comparing Fig. 10 (c) and Fig. 10 (d)) at harmonic spectrum in order 11th, 13th, 23th, 25th, 35th, 37th, 47th and 49th.

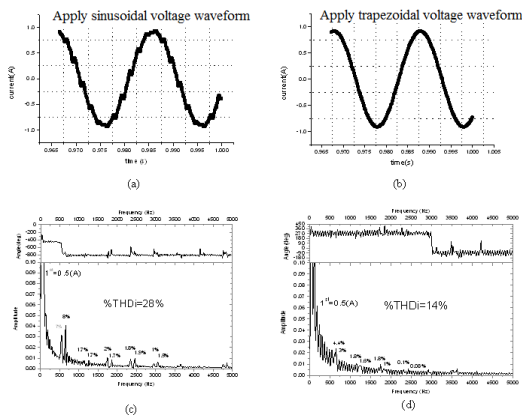


Fig. 10 Simulation result waveform (a) before starting current into primary winding, when applying sinusoidal voltage waveform (b) after starting current into primary winding, when applying trapezoidal voltage waveform (c) Spectrum that generates harmonic current when using sinusoidal waveform voltage (d) Spectrum that generates harmonic current when using trapezoidal voltage waveform

5. Concluding Remarks

Application of stand-alone Photo-voltaic (PV) systems for improving the total harmonic distortion current (THDi) by experimental study involves design, testing, and simulation twelve-pulse diode rectifier AC/DC Power Conversion system applied trapezoidal voltage waveform. Study conclusions and remarks can be summarized as follows.

1. When applying trapezoidal voltage source to 6-pulse diode rectifier, total harmonic current distortion can be reduced by 15.6%. From Fig.8 and Fig.9, the best trapezoidal voltage source should have 1 ms rising time and falling time, with 30 degrees delay offset between phase-to-phase, shown in Fig.9 (a).

2. From simulation, by applying trapezoidal voltage, 12-pulse diode rectifier can decrease total harmonics current distortion (%THDi) of line input current of three winding power transformer ($\Delta/\Delta/Y$)

by 14%, shown in Fig.10 (d). This process can be repeated to get even lower total harmonic current distortion, i.e. 12 -pulse converter to 24-pulse converter.

3. Size of capacitor filter output DC voltage is smaller because trapezoidal voltage helps to lessen percent ripple factor.

4. The designed 12-pulse converter is very beneficial when line voltage from transmission line is interrupted. The reason is from signal-mixing technique as previously discussed (Fig.2, Fig.3).

5. According to the test of PV stand-alone system (amorphous silicon PV Panels (0.75x120 Panel (5 kWp)) the average of measured radiation is 382 W/m². Average ambient temperature of PV cell is 28.01°C. Module temperature PV cell has an average of 31.66°C. The Output power of PV is a maximum of 5.6 kWp. The average of measured PV-Array (Pdc) is 1.2 kW/day. Potential-energy is 247.54 kWh.d. The efficiency of PV-array system is a maximum of 19% with an average of 5.45%.

6. This provides guidelines to further analyze and improve power quality in an electrical system by a PV stand-alone photovoltaic-based system for energy storage (DC-link).

6. Acknowledgements

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