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Control Performance Study of Single Stage Three Levels Inverter Output Voltages for South Algeria PV System

K. Benamrane, T. Benslimane, O. Abdelkhalek, T. Abdelkrim

***Abstract*—In this paper a new control algorithm for a single stage stand-alone three levels NPC voltage source inverter for photovoltaic system in Ghardaïa city is proposed. To maintain the output voltage around its reference, two algorithms are presented and detailed. In first time the space vector pulse width modulation select the reference voltage vector from the space vector diagram. After that the first proposed algorithm calculates the new inverter modulation index r in order to maintain all the day the output inverter voltage around its reference of 230V. The second proposed algorithm uses the redundant states of voltage vectors for maintaining the capacitors voltages Uc1 and Uc2 equal. Two different profiles of solar irradiation and temperature obtained by radiometric station in Ghardaïa city are used to test the performance of proposed control. The simulation results show that the inverter output voltage is stable despite the variation of solar irradiation, temperature and load. The THD obtained is in the limits of international standards. With proposed solution, we do not need to introduce a DC/DC converter to stabilize the DC bus; consequently the size and the cost of the system are decreased.**

***Index Terms*— Multi-level inverter, Photovoltaic system, Solar irradiation, SVPWM**

I. Introduction

Because the pollution produced by fossil fuels and increasing need for energy, the demand for renewable energy has increased significantly over the years. From different types of renewable energy sources, solar and wind energies have become popular and demanding due to advancement in power electronics technologies equipment and techniques. Solar energy converted to electricity via photovoltaic panels is used today in many applications as they have the advantages of being maintenance and pollution free [1]. These photovoltaic modules are used as power plant to the grid connected systems, photovoltaic pumping, and also in domestic use with storage systems. This last application allows the user has to sell the excess electricity produced it does not consume.

Solar irradiation intensity on Algerian territory indicates that Algeria has a strong solar potential source (Fig. 1) [2]. Ghardaïa is a dry and arid city in the south, characterized by a great sunshine (more than 3,000 hours per year) where the mean annual of the global solar irradiation measured on horizontal plane exceeds 20 MJ/m2. This great potential of solar energy can be used to produce electricity and reduce fossil fuels to preserve the environment [3].

Solar-powered photovoltaic panels convert the sun's rays into electricity. The type and number of converters used depend on the specified application. In this paper, authors are interested in supplying an Alternative Current (AC) load. In this case one or more than one stage converter can be used (Fig. 2) [4-6].

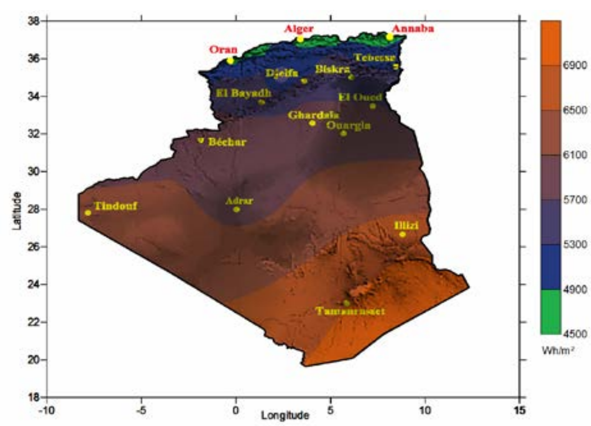

Fig. 1. Average annual global solar irradiation received on a horizontal plane

The multilevel converters concept was established in the early 1980s when the Neutral Point Clamped (NPC) structure, the capacitor clamped (or Flying Capacitor (FC)) structure and the cascaded H-bridge (CHB) structure were proposed [7-8]. These new converters are finding increased attention in academia and industry as one of the best choices of electronic power conversion for medium and high power applications [9-11]. But these converters have a voltage unbalance problem in the DC bus [12]. Many solutions in the literature were proposed to solve this problem like the use of linear or nonlinear regulators [13], add additional circuit [14] or applied SVPWM associated to redundant switching states [15].

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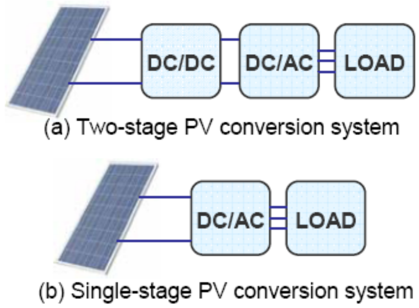

Fig. 2. PV conversion systems

This paper study the conversion of solar energy to electricity via cascaded photovoltaic array-three levels inverter as presented in figure 3. In this case two problems must be solved to get a stable output voltage. These problems are the unbalance of DC capacitors voltage and the variations of photovoltaic array voltage. As solution, authors propose two new algorithms to maintain the output voltage equal to its reference. The first apply a proportional regulator of inverter modulation index to keep at stable value the output voltage around its reference. The second use the redundant states of vectors with a new algorithm that takes into account the variations of both photovoltaic array and load currents.

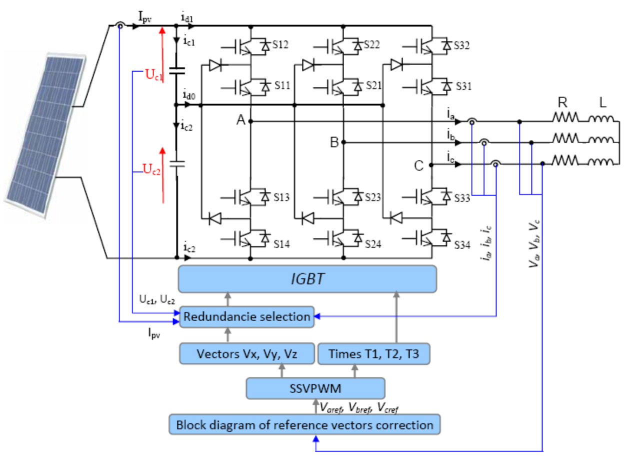

Fig. 3. Photovoltaic array-three levels inverter

II. THREE LEVELS INVERTER CONTROL

A. *Reference Voltage Vector Amplitude Correction (RVVAC)*

In this part, a proportional regulator of modulation index r of three levels inverter is used. The reference voltage vector of inverter is given by:

$$V^{*}=\begin{pmatrix}V_{aref}\\ V_{bref}\\ V_{cref}\end{pmatrix}=\begin{pmatrix}r\times V_m\times\sin(\omega t)\\ r\times V_m\times\sin(\omega t-2\pi/3)\\ r\times V_m\times\sin(\omega t-4\pi/3)\end{pmatrix}=r\times V_m\begin{pmatrix}\sin(\omega t)\\ \sin(\omega t-2\pi/3)\\ \sin(\omega t-4\pi/3)\end{pmatrix} \tag{1}$$

Where: $V_m=\sqrt{3}/2$ and $0<r<1$

This algorithm consists to correct the reference amplitude voltage vector (modulation index r) after each 20ms. The voltage $V_{rms(t)}$ at time (t) is compared to its previous $V_{rms(t-1)}$ (time (t-1)) and also compared to V_{rmsref} and based to the errors obtained; the new modulation index r is calculated as presented below.

$$\begin{cases}\text{if } Er_{rms}>0 \;\Rightarrow\; r_{(t+1)}=r_{(t)}-P_{r(t)}\\ \text{if } Er_{rms}<0 \;\Rightarrow\; r_{(t+1)}=r_{(t)}+P_{r(t)}\\ \text{if } Er_{rms}=0 \;\Rightarrow\; r_{(t+1)}=r_{(t)}\end{cases} \tag{2}$$

Where:

$$Er_{rms}=V_{rms(t)}-V_{rmsref} \tag{3}$$

$V_{rmsref}=230V$

And

$$P_{r(t)}=\left|Er_{rms}\right|/(Er_{rms21}\times P_{r(t-1)}) \tag{4}$$

Er_{rms} : error between the root mean square value of output voltages at times t and the reference.

$P_{r(t)}$ is the amplitude correction of r at time t. It is limited by a constant value $P_{r\,max}$.

$V_{rms(t)}$: root mean square value of output voltage at time t

The error between the root mean square values of output voltages at times t and $(t\text{-}1)$ Er_{rms21} is defined:

$$Er_{rms21}=\left|V_{rms(t)}-V_{rms(t-1)}\right| \tag{5}$$

The block diagram of the reference vectors vector amplitude correction is presented in Fig. 4.

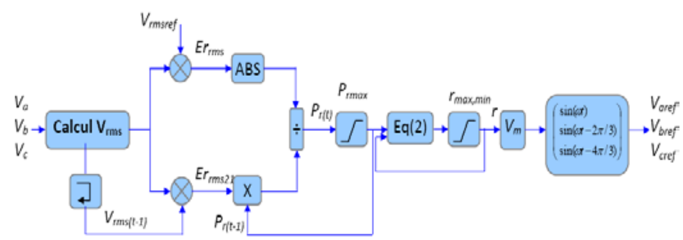

Fig. 4. Block diagram of RVVAC

B. *Reference voltage vector selection*

In this work, we applied the Simplified Space Vector Pulse Width Modulation (SSVPWM) of three levels inverter [16]. This simple and fast method divides the space vector diagram of three levels inverter (Fig 5) into six small hexagons. Each hexagon is space vector diagram of two levels inverter, as shown in figure 6.

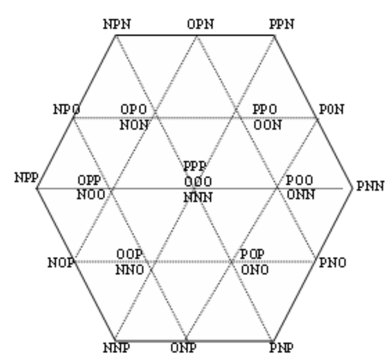

Fig. 5. Space vector diagram of a three levels inverter

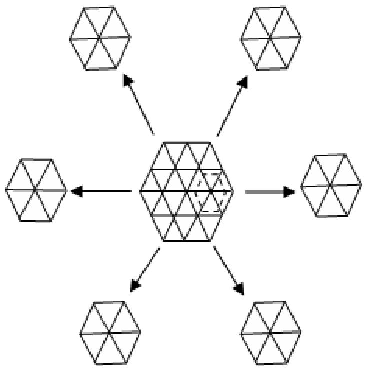

Fig. 6. Decomposition of space vector diagram of a three levels inverter to six hexagons

C. *Redundancy Selection (RS)*

To choose the redundancy to be used to balance the DC bus, we must know the impact of each one on capacitors voltages. The following steps present the detail of this algorithm.

Step 1: This step consists in definition of the relationship between capacitors current (i_{c1} and i_{c2}), photovoltaic array current I_{pv} and load currents i_a, i_b and i_c (Fig. 3) for each vector with redundant states (6).

$$\begin{cases} i_{c1} = I_{pv} - F_{11}^{b} \times i_a - F_{21}^{b} \times i_b - F_{31}^{b} \times i_c \\ i_{c2} = I_{pv} + F_{10}^{b} \times i_a + F_{20}^{b} \times i_b + F_{30}^{b} \times i_c \end{cases} \quad (6)$$

F_{ij}^{b} : are the connection functions of half legs.

Tables I resume relationships between capacitors, photovoltaic array and load currents for vectors with redundant state.

Step 2: To reduce the size of control algorithm, the second step consists in constituting vectors groups that have the same disposition in Tables I the equations S1, S2 and S3. Two groups have been constituted.

Group 1 (G1): *V1, V3, V5*.

Group 2 (G2): *V2, V4, V6*.

TABLE I

RELATIONSHIPS LOAD CURRENTS, PHOTOVOLTAIC ARRAY CURRENT AND CAPACITOR CURRENTS

Vectors			i_{c1}	i_{c2}	*S1=*	*S2=*	*S3=*
V1	A	ONN	*S3*	*S1*	$I_{pv}+i_b+i_c$	$I_{pv}-i_a$	I_{pv}
	b	POO	*S2*	*S3*			
V2	a	PPO	*S1*	*S3*	$I_{pv}-i_a-i_b$	$I_{pv}+i_c$	I_{pv}
	b	OON	*S3*	*S2*			
V3	a	NON	*S3*	*S1*	$I_{pv}+i_a+i_c$	$I_{pv}-i_b$	I_{pv}
	b	OPO	*S2*	*S3*			
V4	a	OPP	*S1*	*S3*	$I_{pv}-i_b-i_c$	$I_{pv}+i_a$	I_{pv}
	b	NOO	*S3*	*S2*			
V5	a	NNO	*S3*	*S1*	$I_{pv}+i_a+i_b$	$I_{pv}-i_c$	I_{pv}
	b	OOP	*S2*	*S3*			
V6	a	POP	*S1*	*S3*	$I_{pv}-i_a-i_c$	$I_{pv}+i_b$	I_{pv}
	b	ONO	*S3*	*S2*			

Step 3: This step consists to analyzing the influence of each redundancies of constituted groups on capacitors voltages variations. From Table II, it can remark that all vectors depend on three equations *S1*, *S2* and *S3*. Considering the photovoltaic array current $I_{pv} > 0$, we can obtain three possibilities *Pi* of load variation (7).

$$\begin{cases} Pi = P_1 \ \text{if} \ \ S1 > 0,\ S2 < 0 \\ Pi = P_2 \ \text{if} \ \ S1 < 0,\ S2 > 0 \\ Pi = P_3 \ \text{if} \ \ S1 < 0,\ S2 < 0 \end{cases} \quad (7)$$

TABLE II

THE VECTORS GROUP

Vectors		i_{c1}	i_{c2}
G1	a	*S3*	*S1*
	b	*S2*	*S3*
G2	a	*S1*	*S3*
	b	*S3*	*S2*

Applying these possibilities of load variations, we obtain the capacitors voltages increasing or decreasing as presented in Table III.

TABLE III

EFFECT OF REDUNDANCIES OF GROUPS G1 AND G2 ON CAPACITORS VOLTAGES

Groups	Redundancy	possibilities	U_{c1}	U_{c2}
G1	a	*P1*	↑	↑
		P2	↑	↓
		P3	↑	↓
	b	*P1*	↓	↑
		P2	↑	↑
		P3	↓	↑
G2	a	*P1*	↑	↑
		P2	↓	↑
		P3	↓	↑
	b	*P1*	↑	↓
		P2	↑	↑
		P3	↑	↓

Step 4: This step consists to select the redundancy to be used to cancel the unbalance in capacitor voltages (Table IV).

TABLE IV

SELECTED REDUNDANCY FOR GROUPS G1, G2

Groups		G1			G2		
Derivation \ possibilities		*P1*	*P2*	*P3*	*P1*	*P2*	*P3*
1	$U_{c1} < U_{c2}$	a	a	a	b	b	b
2	$U_{c1} > U_{c2}$	b	b	b	a	a	a

III. SIMULATION RESULTS

To test the performance of proposed control, a real data of solar irradiation and temperature profiles obtained by a radiometric station installed in Ghardaïa city (32°26'N 03°46'E) are used (Fig. 7).

Two days in 2013 with different profiles of solar irradiation and temperature are selected.

Figure 8 presents the Global Horizontal Irradiance *GHI* (W/m^2), the Diffus Horizontal Irradiance *DHI* (W/m^2), the Direct Normal Irradiance *DNI* (W/m^2) and the ambient Temperature T_a *(°C)* of January 31.

We note that January 31 is a nice day without atmospheric perturbation. The sunshine duration measured is 10 hours and T_a is between 14°C and 22°C.

Figure 9 presents the DC bus voltages $U_{c1}$and U_{c2} of three levels inverter. One remarks that after application of *RL* load at $t=9^{H}40$, voltages U_{c1} and U_{c2} are not equal. Consequently the inverter output voltage will be with bad *THD*.

In the next simulations the *RVVAC* and *RS* algorithms are applied at $t=9^{H}00$. The Variation of inverter load are shown in table V

TABLE V
SIMULATION STEPS

Time	*R*	*L*	*RS*	*RVVAC*
$t = 09^{h}00$	0Ω	0H	ON	ON
$t = 09^{h}40$	50 Ω	0.1H	ON	ON
$t = 12^{h}20$	50 Ω	0.05H	ON	ON
$t = 13^{h}40$	50 Ω	0.2H	ON	ON

Figure 10 presents the photovoltaic array voltage V_{pv}, current I_{pv} and power *P*. This last increase and decrease each time of load variation (Fig. 11). The voltages U_{c1} and U_{c2} are all time equal showing the effectiveness of RS proposed algorithm (Fig. 12-a). The modulation index *r* after application of *RVVAC* increase when U_{c1} and U_{c2} decrease and vice versa (Fig 12-b) in order to maintain the output inverter voltage stable and around its reference at presented in figure 13.

The output voltage and its spectral analysis are illustrated in figure 14. It is shown that the total harmonic distortion is less than 4%.

Fig. 7. Radiometric devices (Sun tracker)

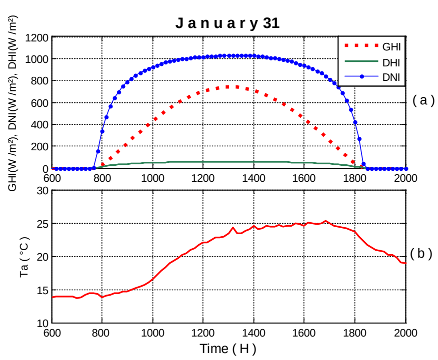

Fig. 8. (a)- Global Horizontal Irradiance (GHI), Diffus Horizontal Irradiance (DHI),
Direct Normal Irradiance (DNI),
(b)-Ambient Temperature (Ta)

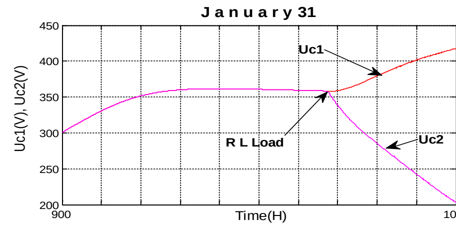

Fig. 9. DC bus voltages Uc1(V), Uc2(V)

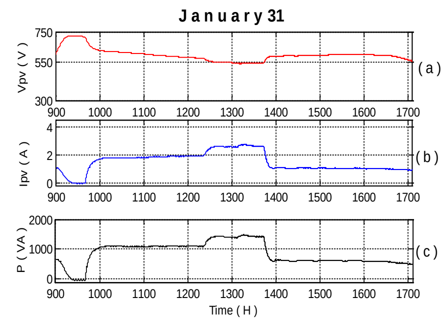

Fig. 10. Photovoltaic array voltage Vpv(V), current Ipv(A) and power P(VA)

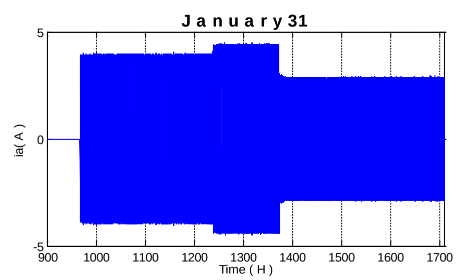

Fig. 11. Load current i_a

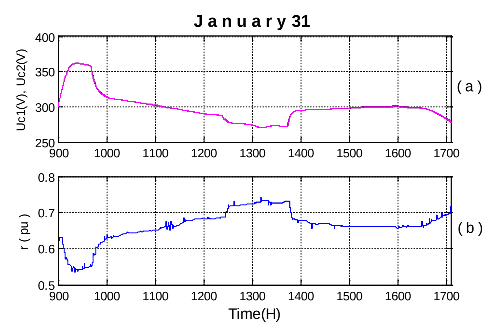

Fig. 12. (a) DC bus voltages U_{c1}, U_{c2}
(b)- Modulation index *r*

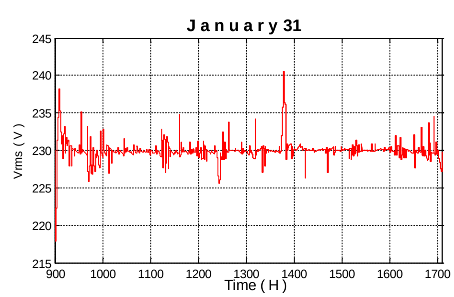

Fig. 13. Root mean square voltage V_{rms}

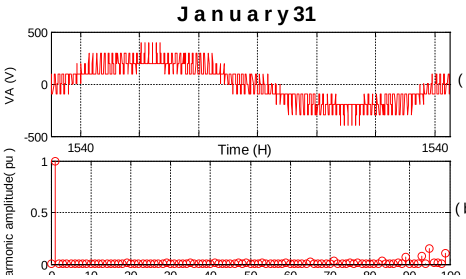

Fig. 14. Output voltage V_A and its spectral analysis, *THD* =3.32%

To test the performance of proposed control in severe weather conditions, the second day selected is July 24 were the sunshine duration measured is more than 13 hours. As presented in figure 15, this day presents great solar irradiation perturbations between $t=08^H$ and $t=13^H$. The *GHI* presents a variation of 600 W/m^2 (between 400 W/m^2 and more than 1000 W/m^2). The temperature T_a exceeds 40°*C*.

In this simulations the *RVVAC* and *RS* algorithms are applied at $t=7^H00$. The Variation of inverter load is the as shown in previous table V

Figure 16 presents the photovoltaic array voltage V_{pv}, current I_{pv} and power *P*. One remarks that voltage V_{pv} is stable but the photovoltaic current present a perturbation caused by solar irradiation perturbations between $t=08^H$ and $t=13^H$.

As presented in figure 17.a, voltages U_{c1} and U_{c2} are equal all the day up to 16^H. After that start decreasing because the decreasing of solar irradiation less than 400 W/m^2. The proposed *RVVAC* correct the modulation index *r* (Fig. 17.b) in order to maintain the AC voltage stable and around its reference of $V_{rms}=230V$ at presented in figure 18.

The output inverter voltage presents a good total harmonic distortion *THD*=3.22% as shown in figure 19.

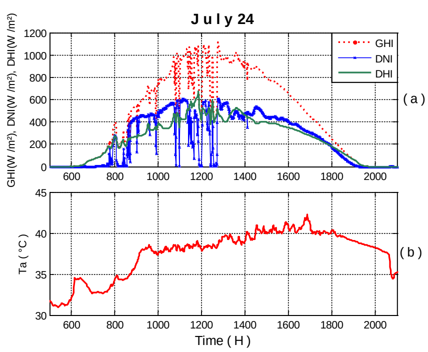

Fig. 15. (a) Global Horizontal Irradiance (*GHI*),
Diffus Horizontal Irradiance (*DHI*),
Direct Normal Irradiance (*DNI*),
(b)- Ambient Temperature (T_a)

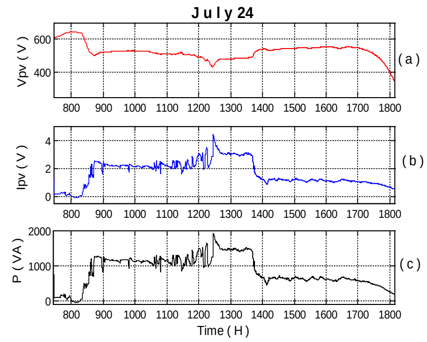

Fig. 16. Photovoltaic array voltage $V_{pv}(V)$, current $I_{pv}(A)$ and power *P(VA)*

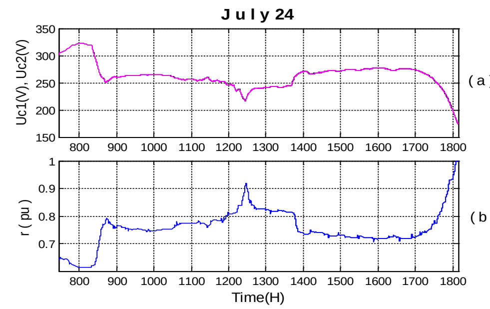

Fig. 17. (a) DC bus voltages U_{c1}, U_{c2}
(b)- Modulation index *r*

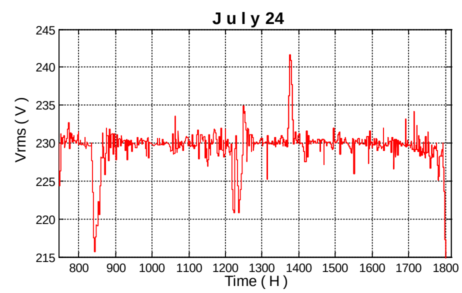

Fig. 18. Root mean square voltage V_{rms}

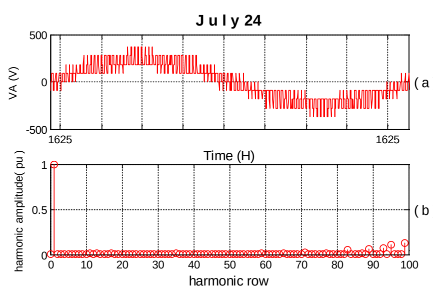

Fig. 19. Output voltage V_A and its spectral analysis, *THD* = 3.22 %

IV. Conclusion

In this paper a stand-alone three-phase three levels NPC voltage source inverter performance control for photovoltaic system in south Algeria weather condition was studied. Two algorithms used to correct the output voltages have been presented and detailed. In first time the simplified space vector pulse width modulation select the reference voltage vector from the space vector diagram. After that the first proposed algorithm calculates the new modulation index *r* in order to maintain all the day the output inverter voltage around its reference. The second proposed algorithm uses the redundant states of voltage vectors for maintaining the capacitors voltages equal.

Two profiles of solar irradiation and temperature obtained by a radiometric station installed in Ghardaïa city are used to test the performance of proposed control.

The simulation results show that the inverter output voltage is stable despite the variation of both solar irradiation and load. Also the *THD* value of the voltages is in the limits of international standards.

With this proposed solution, we do not need to introduce a DC/DC converter to stabilize the DC bus consequently the size and the cost of the system are decreased and total efficiency is increased.

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