Power quality assessment in a stand-alone photovoltaic / battery system supplying an asynchronous motor through an adjustable speed drive

E. Tchoffo Houdji, D. Yamegueu, G.B. Tchaya, M. Kamta, Haman-Djalo, G.J. Kayem

Abstract— The issue of electric power quality is gaining importance as the society is increasingly becoming dependent upon the electrical supply. For example, a small power outage could have a great economic impact on industrial consumers. More generally, new equipments are more sensitive to power quality variations. In this paper, the influence of the irradiance fluctuations on the power quality of a photovoltaic / battery system powering an asynchronous motor is assessed. Especially, the current and voltage harmonic distortions are considered. The harmonic distortion parameters, the electric power parameters of the system, and the irradiance were collected simultaneously using a power analyzer and a pyranometer. An adjustable speed drive was used to apply a vector control to the motor operating under its nominal conditions. The PV/battery system was configured so that the motor active power is constant throughout the experiment. The data analysis shows that when the solar irradiance decreases, the harmonic distortion parameters and the reactive power of the motor increase linearly and vice versa. The controlled motor generates current and voltage harmonic distortions with amplitudes higher than those recommended by the IEEE standards. The harmonics of rank 5, 7 and 11 are the main component of harmonic contents. The controlled motor behaves as a capacitive load for irradiance about 800 W/m².

Keywords-- Adjustable speed drive, asynchronous motor, harmonic distortion, power quality, PV/battery system.

1 Introduction

The cost of solar photovoltaic (PV) modules is declining today [1], [2]. However, the popularization of this technology remains limited by many technological constraints. Some of these constraints concern power quality issues. Indeed, the integration of PV systems to a utility grid could have negative impact on power quality if appropriate measures are not implemented [3]. The power quality requirements are commonly related to voltage and frequency regulation, power factor correction and harmonics [4]. Thus, the insertion of both linear and non-linear electric loads in standalone photovoltaic systems faces many challenges related to the nature of energy source (Photovoltaic sources are intermittent and produce a direct current) and the specificities of these electric loads. In the case of non-linear loads such as electric motors, challenges to be solved are related both to the type of the electric machine and the characteristics of the load being driven [5]. Many previous works on the electric supplying of systems containing electrical machines by standalone PV systems are presented mainly for pumping systems [6], [7], [8], [9]. These works are mainly focused on the improvement of the pumping system performances. Recent work on the study of the power quality of a PV system supplying a pump for irrigation shows that the value of the voltage total harmonic distortion generated during the low irradiance intervals is more than 15%. The main harmonic content is the 3rd harmonic; the 11th and 13th harmonics also have important values (more than 2%). For the higher irradiance values and when the pump operates at its nominal frequency, the values of the voltage total harmonic distortion become less than 9% [10]. In others works, the study of the influence of the irradiance fluctuations on the power quality of a grid-connected PV system shows that regardless the nature of the loads present in the grid, the PV system is a source of power quality disruption due to its intermittent nature [11], [12], [13], [14]. This is the case mainly for low (less than 200W/m²) and medium (between 200 and 900W/m²) irradiances that significantly impact the harmonic distortions of the current [11], [14]. The reactive power produced depends non-linearly on solar irradiance; it takes higher values at low irradiances [11]. Another study base on the power quality of a grid-connected PV system supplying a network of two adjustable speed drives (ADS) with two motors shows the influence of their use as a function of the rotation frequency of the motors and their loads rates [15]. The total harmonic distortions of the current injected into the power system by the speed drives system are very high. They are between 50% and 1700% for the frequency of 60Hz for one of the motors and 50Hz for the other, the load rate ranging from 0 to 50%. The voltage total harmonic distortions are relatively low, they vary between 2% and 4% [15].

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As shown in [16] and [17] the adjustable speed drives help to limit energy losses and to improve the power factor in systems with electric motors. In addition, they allow smooth starting of the motor and operation at speeds higher than the rated speed. However, they contribute to degrading the power quality of the power system as they constitute non-linear loads and introduce harmonic distortions of the current and voltage in the system [18], [19]. Power inverters interfacing Photovoltaic arrays to AC loads also produce additional harmonic currents and eventually increase the total harmonic distortion (THD) at the point of common coupling (PCC) [20], [21], [22], whereas the degradation of power quality in the system with regard to harmonics is mostly because of the type of load [23]. There are many techniques to reduce harmonic distortions. Some of these techniques are: the use of line reactors, multi-pulse systems, broad-spectrum passive filters, active filters, Unified Power Quality Conditioner (UPQC) [24], [25]. However, their implementation requires additional investment [26].

In the present work, the power quality of a standalone PV/battery system supplying an asynchronous motor under irradiance fluctuation conditions is assessed. Especially, the study is mainly focused on current and voltage harmonic distortions, and the reactive power of the controlled motor based on experimental tests. Tests are conducted for the controlled motor powered by PV/battery system on one hand and on other hand without the contribution of the PV generator as a control test.

2 Material and methods

2.1 Experimental setup

The experimental setup is composed of the equipments listed in Table 1. These equipments are put together to form the experimental set up as shown in Fig. 1.

TABLE 1. EQUIPMENTS USED FOR LABORATORY SETUP

Equipments	Rating
A photovoltaic field	7.35kWp
A park of lead-acid battery	3600Ah, 48V
Three inverters/chargers (SMA SI 5048)	3 x 5kVA
One PV grid-inverter (SMA STP 8000TL-10)	8kVA
A three-phase ASD (ATV32HU55N4)	5.5kW, 400V
A three-phase wound-rotor asynchronous motor (LeRoy SOMER, type: NVA132A3)	4.5kW, 400V, 14A, 1395 rpm, cos Phi 0.76
A shunt-excited DC generator (DCG) (LeRoy SOMER, type: LSC132MC7)	3kW, 1500rpm
A resistive load bench	4kW

The standalone PV/battery system produces the AC voltage necessary to power the asynchronous motor through one grid inverter and three inverters/chargers as shown in Fig. 1.

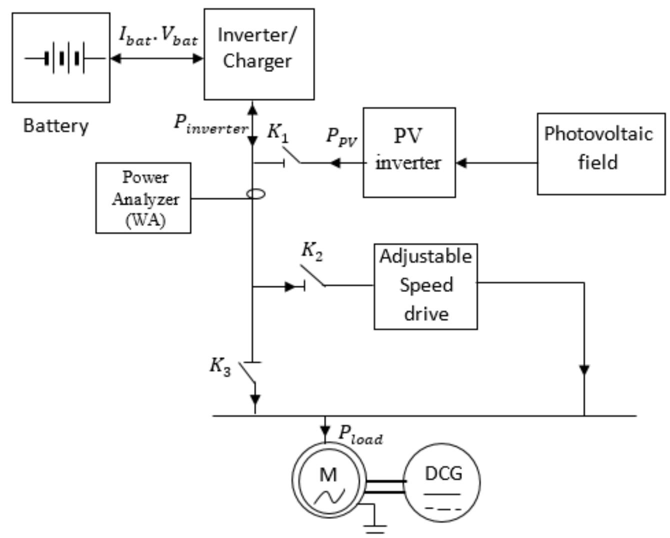

Fig. 1. Diagram of the system configuration

2.2 Methodology

Tests were done for the nominal conditions of the motor and carried out several times in a day. For tests on the motor without PV generator contribution, the breaker K_1 was opened. For tests on the motor controlled through the adjustable speed drive (ASD), the breaker K_2 was closed and the breaker K_3 was opened. For tests on the motor without control, the breaker K_2 was opened and the breaker K_3 was closed. A power analyzer was used and connected as indicated in Fig. 1. The vector control has been implemented during the tests. Each test was done for 30 minutes.

The PV/battery system used in this study is such that the PV generator is the main energy source and the battery the secondary one. This battery system behaves as a backup source to fill the power gaps due to the fluctuations of the irradiance. Indeed, the power produces by the PV generator have to be consumed in real time. It is therefore not ideal to pass through the batteries to inject it on the AC bus as in the common stand-alone PV/ battery systems [27]. In this regard, a direct connection of the PV generator on the AC bus through PV inverters is necessary. The inverter/charger used is thus able to monitor the charging and discharging of the battery as well as the power flows through the AC bus in such a way that at any moment, the load absorbs a constant active power.

2.3 Instrumentation and electric parameters measured

During the experimentation, the following electric variables were assessed for the controlled motor: the reactive (Q) and active powers (P); the voltage and current harmonic distortions rates (individuals harmonics: V_h and I_h; and total harmonic distortions: THD_U and THD_I). These electric variables were measured using a power analyser connected at the Point of Common Coupling (PCC) of a three-phase PV / battery system supplying the nonlinear load. The power analyser model used was the C.A. 8335 (Qualistar +) of Chauvin Arnoux, France [28]. The foregoing parameters were calculated on the basis of definitions of EN50160 standards [29]. The expressions of these parameters are given by equations (1) to (10).

The total harmonic distortion of the current is given by equation (1):

$$THD_I = \frac{\sqrt{\sum_{n=2}^{50} I_n^2}}{I_1} \quad (1)$$

With I_1, the rms value of the fundamental of the current, I_n is the rms value of the n-order harmonic of the current.

The voltage total harmonic distortion is given by equation (2):

$$THD_U = \frac{\sqrt{\sum_{n=2}^{50} U_n^2}}{U_1} \quad (2)$$

With U_1, the rms value of the fundamental of the compound voltage, U_n is the rms value of the n-order harmonic of this voltage.

The active power of the phase i, with $i \epsilon [1\,;3]$, is given by equation (3):

$$P[i] = \frac{1}{NechSec} . \sum_{n=0}^{NechSec-1} V[i][n] . I[i][n] \quad (3)$$

The $NechSec$ is the number of samples per second.

The apparent power of the phase i, with $i \epsilon [1\,;3]$, is given by equation (4):

$$S[i] = V_{rms}[i] . I_{rms}[i] \quad (4)$$

The reactive power of the phase i, with $i \epsilon [1\,;3]$, is given by equation (5):

$$Q[i] = \sqrt{S[i]^2 - P[i]^2} \quad (5)$$

The total active power is given by equation (6):

$$P = P[1] + P[2] + P[3] \quad (6)$$

The total apparent power is given by equation (7):

$$S = S[1] + S[2] + S[3] \quad (7)$$

The total reactive power is given by equation (8):

$$Q = Q[1] + Q[2] + Q[3] \quad (8)$$

The power factor of the phase i, with $i \epsilon [1\,;3]$, is given by equation (9):

$$PF[i] = \frac{P[i]}{S[i]} \quad (9)$$

The total power factor is given by equation (10):

$$PF = \frac{PF[1] + PF[2] + PF[3]}{3} \quad (10)$$

The motor torque was determined from a dynamo-generator containing a shunt-excited DC generator (DCG) feeding a resistive load. Data concerning electric battery parameters were recorded through a data acquisition system included in the monitoring system of the inverters/chargers. The irradiance was measured through a meteorological station with a pyranometer (CM 11 pyranometer).

3 Results and Discussion

In this section, the experimental results concerning the variations of the individuals and the total harmonic distortion rate of the current and voltage are displayed and discussed. The reactive power of the controlled motor and the irradiance for different tests conducted are also given.

3.1 Harmonic distortions parameters of the controlled motor

3.1.1 Individual voltage and current harmonic distortions

The variations of the odd current and voltage harmonic distortions up to the rank 13 as a function of time are displayed in Fig. 2 for test done with the PV/battery system and the one done without the PV generator contribution. These results show that in the system under consideration, the harmonics of rank 5, 7 and 11 respectively have the most important contributions in the current and voltage harmonic distortions. For the PV/battery system, the current harmonic of rank 13 has an amplitude comparable to that of rank 11. The harmonics of a rank multiple of three are the weakest in all the cases studied. One can also observe that the variations of the individual voltage and current harmonics are affected by the fluctuations of irradiance, mainly on those of greater amplitude. They increase when the irradiance decrease and vis-versa. Their values at low irradiance (less than about 350 W/m²) tend to those for tests without the PV generator contribution (i.e. for test only with battery system). Their mean values for tests with the battery system are: $I_5 = 23.43\%$, $I_7 = 11.70\%$, $I_{11} = 3.20\%$, $V_5 = 15.25\%$, $V_7 = 7.86\%$ and $V_{11} = 1.66\%$. A comparison of these values with those allowed by the standards and gathered in Tables 2 and 3 shows that they are all higher than those allowed by the standard. One can conclude at this level that to efficiently supply an asynchronous motor controlled via an adjustable speed drive and operating under its nominal conditions by a PV/battery system, a harmonic distortion filter for the harmonics of ranks 5, 7, 11 and 13 must be inserted between the power source and the controlled motor.

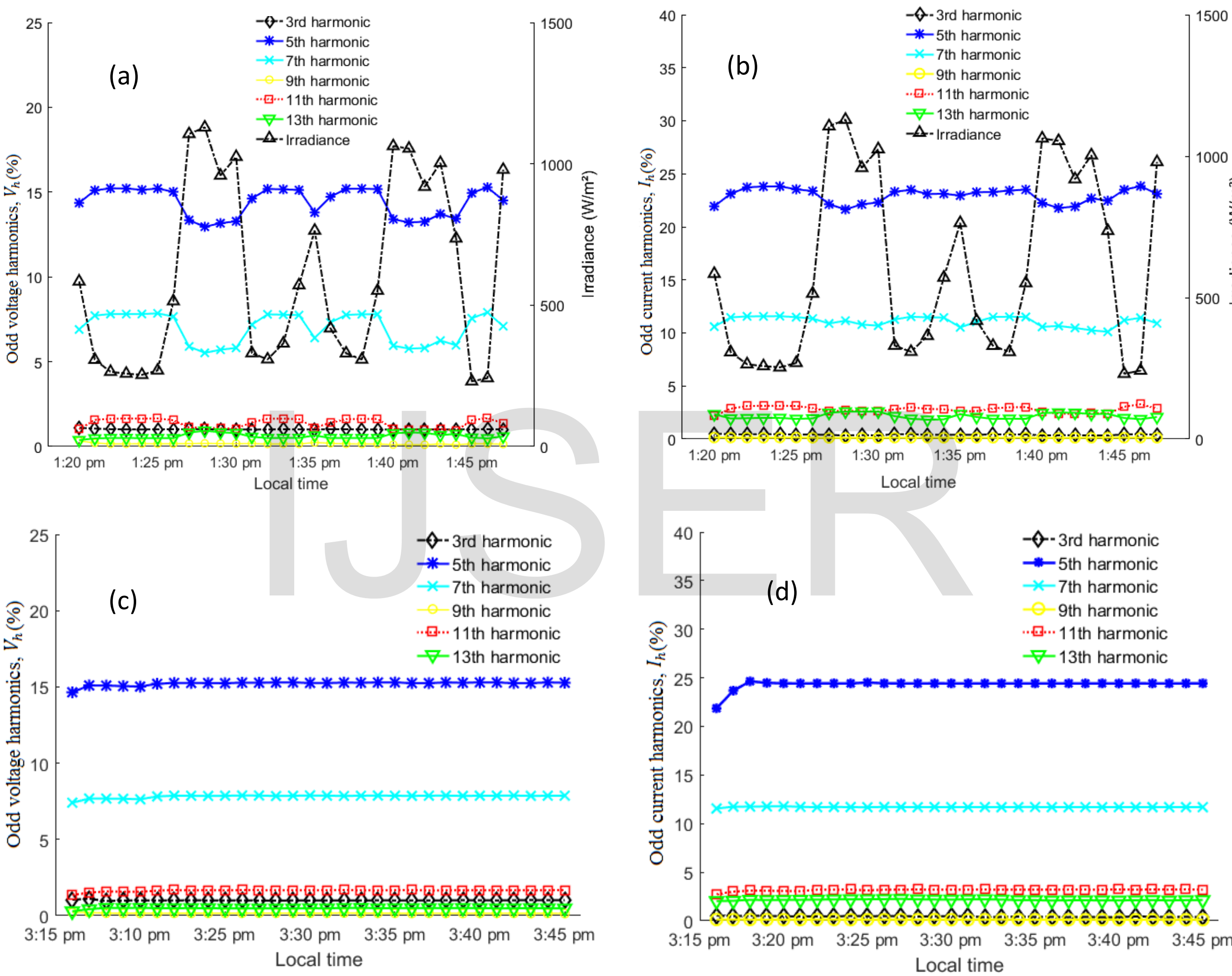

Fig. 2. The odd current harmonics (I_3 to I_{13}) and voltage harmonics (V_3 to V_{13}) as a function of time: (a) and (b) for tests with PV/battery system; (c) and (d) for test with battery system

It should be noted that the individual current and voltage harmonics of the odd ranks multiple of three respect the values permitted by the standard. Their mean values for the individual harmonics of current are: $I_3 = 0.40\%$; $I_9 = 0.13\%$ and $I_{15} = 0.081\%$ for tests with the PV/battery system; and $I_3 = 0{,}45\%$; $I_9 = 0.13\%$ and $I_{15} = 0.08\%$ for tests with the battery system. For the individual voltage harmonics they are: $V_3 = 1.12\%$; $V_9 = 0.27\%$ and $V_{15} = 0.42\%$ for tests with the PV/battery system; and $V_3 = 1\%$; $V_9 = 0.16\%$ and $V_{15} = 0.45\%$ for tests with the battery system.

TABLE 2. VALUES OF THE ODD-ORDER INDIVIDUAL HARMONICS OF THE VOLTAGE FOR A LOW-VOLTAGE ELECTRICAL POWER SYSTEM [29], [30]

Odd harmonics				Even harmonics	
Ranks not multiples of 3		Ranks multiples of 3			
order (h)	V_h (%)	order (h)	V_h (%)	order (h)	V_h (%)
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.5	6 to 24	0.5
13	3	21	0.5		
17	2				
19	1.5				
23	1.5				

TABLE 3. RANGES OF VALUES OF THE ODD-ORDER INDIVIDUAL HARMONICS OF THE CURRENT FOR AN ELECTRICAL ENERGY SYSTEM WITH VOLTAGE BETWEEN 120V AND 69KV [30], [31]

Maximum harmonic current distortion in % of I_L and the individual harmonic order (odd harmonics)						
I_{sc}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h < 50$	THD
< 20	**4.0**	**2.0**	**1.5**	**0.6**	**0.3**	**5.0**
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

I_{sc}: maximum short-circuit current at PCC (Point of Common Coupling in the grid)
I_L: maximum demand load current (fundamental frequency component) at PCC.

3.1.2 Total harmonic distortions of the current

The total harmonic distortion rate of the current (THD_I) measures the degree of global deformation of the current brought by the harmonic distortions of the current compared to the fundamental signal which is a sine wave. The variations of the irradiance and the THD_I generated by the adjustable speed drive controlling the motor with vector control and fed by a PV/battery system, are represented as a function of time in Fig. 3 for the period from 9:15 am to 1:45 pm. From this figure, it can be observed that the variations of the irradiance have an impact on the THD_I. Thus, it can be noticed globally that the THD_I evolves in the opposite direction to that of the irradiance. For the irradiance higher than about 800 W/m², the system generates little harmonic distortions of the current compare to those generated for the irradiance less than about 550 W/m². In other words, when the contribution of the PV generator to the power absorbed by the controlled motor is small, the level of harmonic distortions of the current generated is high. These curves also show that during these tests, the THD_I fluctuate over time between 23% and 27%. This last value is nearer that of the THD_I generated by the system powered only by the battery system which is constant during the established steady-state at a value of about 27.70% as shown in Fig. 4. The electrical system studied here delivers a nominal voltage of 400V between phases. The maximum power is 15kW. Therefore, the total harmonic distortion of the current allowed should then be less than 5.0% according to the IEEE 519-1992 standard [30], [31] as indicated in table 3. Thus, one can state that the system consisting of the asynchronous motor controlled via an adjustable speed drive, operating under rated conditions and powered by a PV/battery system does not comply with the IEEE 519-1992 standard for harmonic distortion of the current.

The correlations between the total harmonic distortion rate of the current (THD_I) and the irradiance (I_r) for the system studied is displayed in Fig. 5. One can see that this correlation can be adjusted by a linear function. The coefficients of this fitting and its quality are given in Table 4. The statistics parameters R^2 and $RMSE$ (Root Mean Squared Error) are evaluated with the "$cftool$" in $Matlab$ software. It is shown that the total harmonic distortion of the current (THD_I) generated by the controlled motor decreases as the irradiance increases.

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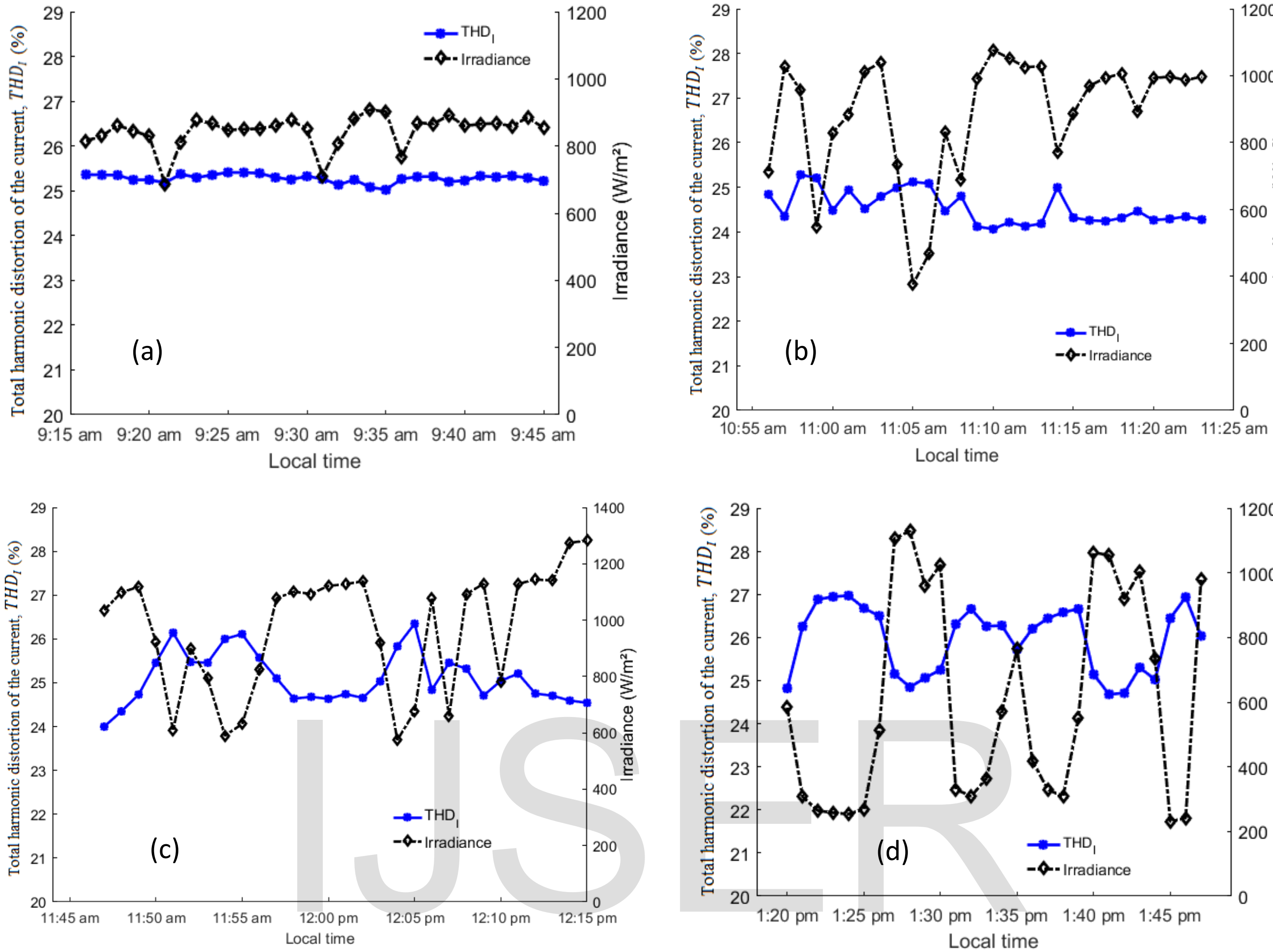

Fig. 3. The irradiance and the total harmonic distortion of the current (THD_I) of the controlled motor as a function of time (from 9:15 am to 1:45 pm)

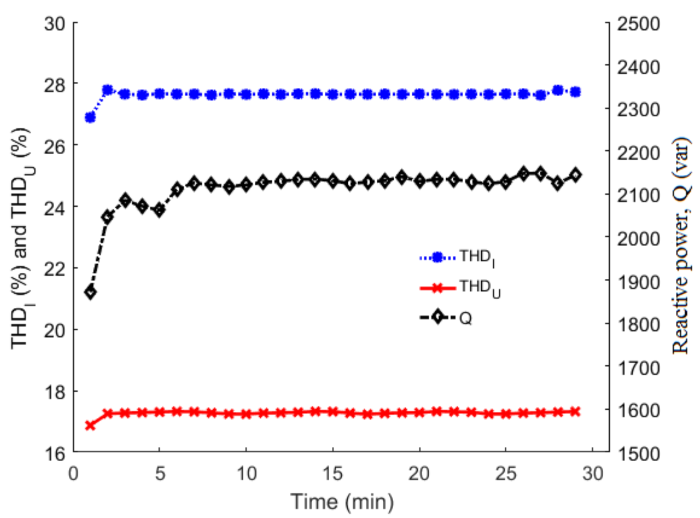

Fig. 4. Total harmonic distortion of the current (THD_I) and the voltage (THD_U) and of the reactive power of the controlled motor without the PV contribution as a function of time

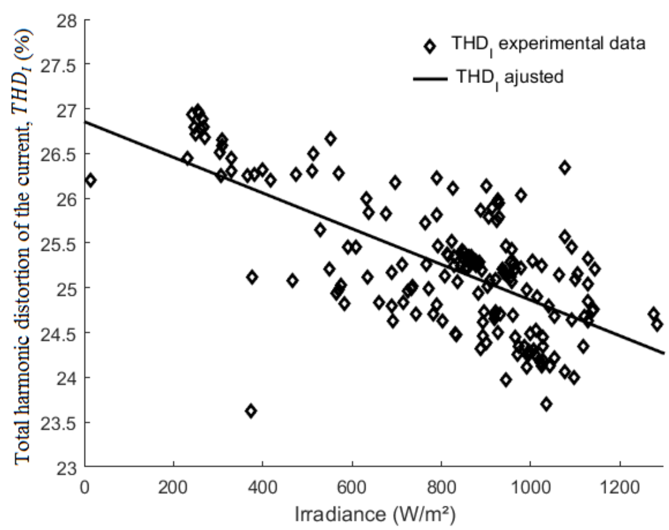

Fig. 5. Total harmonic distortion of the current (THD_I) of the controlled motor as a function of irradiance (I_r)

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3.1.3 Total harmonic distortions of voltage

The variations of the irradiance and the voltage total harmonic distortion (THD_U) generated by the motor subjected to a vector control and fed by a PV/battery system, are represented as a function of time in Fig. 6 for the period from 9:15 am to 1:45 pm. The previous observations made on the impact of the irradiance on the variations of the THD_I remain verified with the THD_U. For tests performed with the PV/battery system, the THD_U fluctuate over the time between 14% and 17.3%. The THD_U obtained with the test in which the controlled motor is powered by the park of batteries via the inverter keeps a constant value of about 17.25% during the established steady-state as shown in Fig.4.

As with harmonic distortions of the current, the levels of harmonic distortions of the voltage in the system are greater when the controlled motor is powered by a battery system. For irradiance below the value of about 550 W/m², the harmonic distortions levels of the voltage when the controlled motor is power by the two power systems are almost identical. The total harmonic distortion of the voltage allowed should be less than 8.0% according to the IEEE 519-1992 standard. Thus, the system constituted by the asynchronous motor controlled via an adjustable speed drive, operating under nominal conditions and powered by a PV/battery system does not comply with the IEEE 519-1992 standard for harmonic distortion of the voltage. The study of the correlations between the total harmonic distortion rate of the voltage (THD_U.) and the irradiance (I_r) in the studied system is given in Fig. 7. This correlation can also be adjusted by a linear function. The coefficients of this fitting and the statistical parameters of his quality are given in Table 4. It is shown that the total harmonic distortion of the voltage (THD_U) generated by the controlled motor decreases as the irradiance increases.

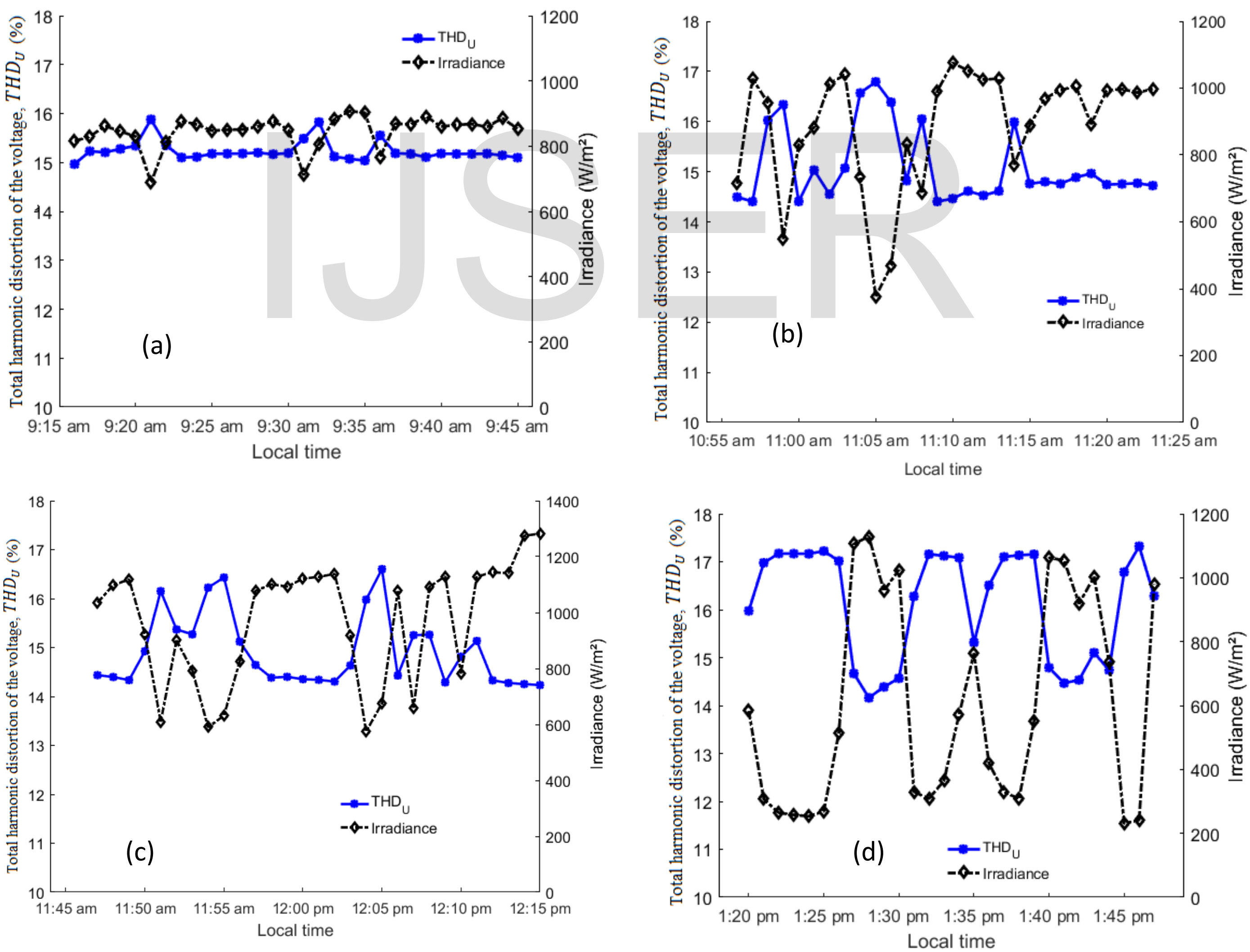

Fig. 6. The irradiance and the voltage total harmonic distortion (THD_U) of the controlled motor as a function of time (from 9:15 am to 1:45 pm)

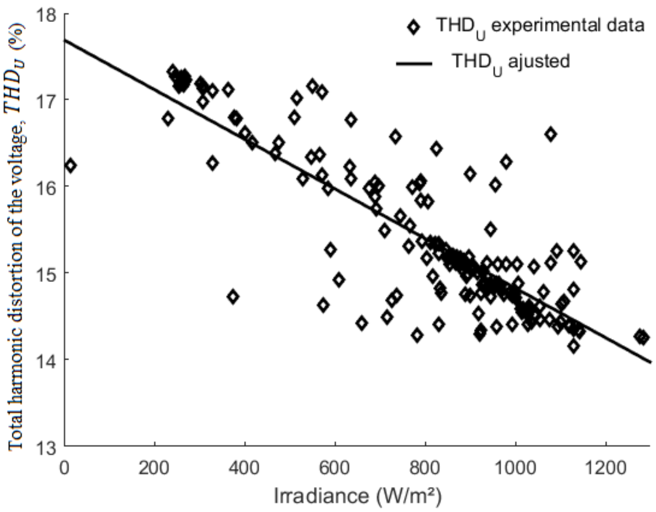

Fig. 7. Voltage total harmonic distortion (THD_U) of the controlled motor as a function of irradiance (I_r)

3.2 Reactive power of the controlled motor

The variations of the irradiance and the reactive power (Q) exchanged between the controlled motor and the power supply system are given as a function of time in Fig. 8 for the period from 9:15 am to 1:45 pm. It appears from this figure that the reactive power exchanged between the controlled motor and the power supply system varies between -2050 var and 2150 var depending on the level of the irradiance or the contribution of the PV generator to the power absorbed by the load. The curves of the reactive power for each test show similar behavior to that of the total harmonic distortions of the voltage and current: the reactive power increases when the irradiance decreases and inversely. For irradiances below the value of about 550 W/m², the controlled motor primarily absorbs reactive power with constant values of about 2134.39 var. This value of the reactive power is near to that absorbs by the system when the load is powered by the battery system. Indeed, when the motor is powered only by the battery system, it absorbs reactive power whose value varies slightly around an average of 2132.09 var as shown in Fig. 4. For irradiances above the value of about 800 W/m², the controlled motor primarily generates reactive power. The controlled motor behave for these irradiances as a capacitive load. These observations made on the behavior of the reactive power as a function of irradiance can be better verified from the study of the correlation between the two parameters as represented in Fig. 9. This correlation can also be adjusted by a linear function. The coefficients of this fitting and the statistical parameters of his quality are given in Table 4. It is shown that the reactive power (Q) of the controlled motor decreases as the irradiance increases.

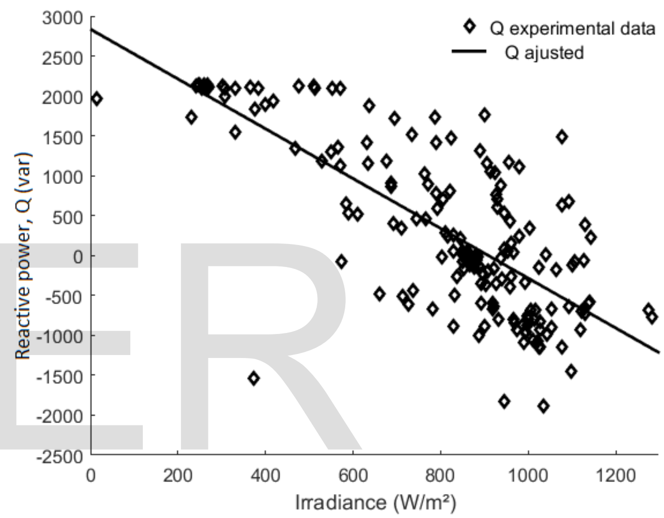

Fig. 9. Reactive power (Q) of the controlled motor as a function of irradiance (I_r)

TABLE 4. FIT STATISTIC COEFFICIENTS OF THE TOTAL HARMONIC DISTORTION OF THE CURRENT (THD_I) AND OF THE VOLTAGE (THD_U) AND OF THE REACTIVE POWER (Q) OF THE CONTROLLED MOTOR AS A FUNCTION OF IRRADIANCE (I_r)

	Fit type	Fit coefficient		Goodness of fit statistic coefficient	
		P_1	P_2	R^2	$RMSE$
$THD_I = f(I_r)$	$THD_I = P_1.I_r + P_2$	-2.26.10^{-3} m²/W (%)	27.19 (%)	0.98	0.085
$THD_U = f(I_r)$	$THD_U = P_1.I_r + P_2$	-3.32.10^{-3} m²/W (%)	18.05 (%)	0.99	0.073
$Q = f(I_r)$	$Q = P_1.I_r + P_2$	-3.48 var.m²/W	3041var	0.99	105.800

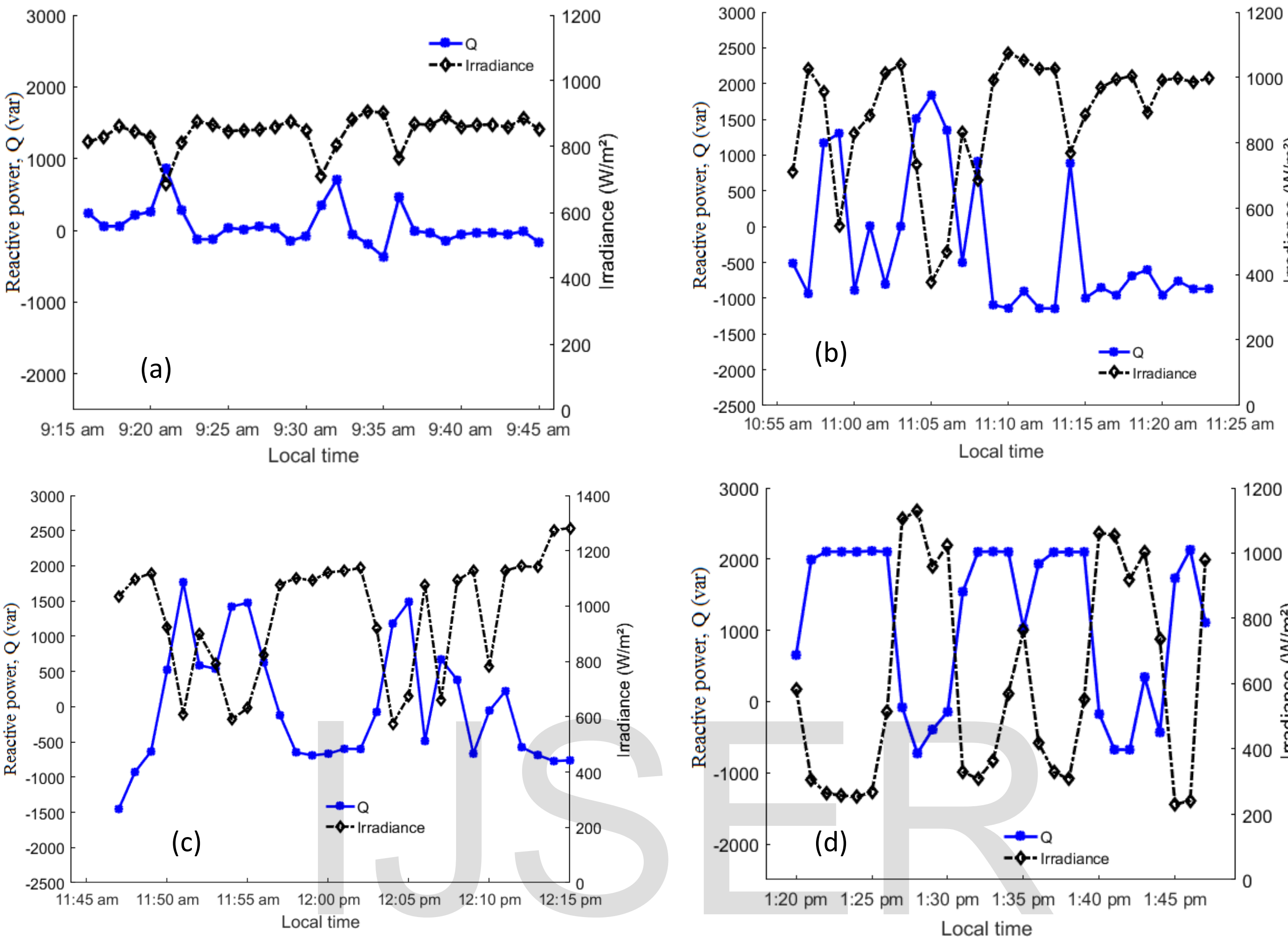

Fig. 8. The irradiance and the reactive power (Q) of the controlled motor as a function of time (from 9:15 am to 1:45 pm)

4. Conclusion

In this work, the power quality parameters of a standalone PV/battery system powering an asynchronous motor via an adjustable speed drive is assessed. Voltage and current harmonic distortions, and the reactive power of the controlled motor are the main parameters considered. The results obtained show that voltage and current harmonic distortions amplitudes are above those recommended by standards. The individual harmonics of the current and voltage of ranks 5, 7 and 11 are the main component of harmonic contents.

The impact of the irradiance on the harmonic distortions and reactive power has also been assessed. It has been noticed that the fluctuations of the irradiance induce those of the voltage and current harmonic distortions and those of the reactive power of the PV/battery system. Indeed, when the irradiance is greater than about 800 W/m², the voltage and current harmonic distortions in the system reach their smallest values of about 14% and 24.5% respectively. Under these values of irradiance, the controlled motor generates reactive power and behave as a capacitive load.

When the irradiance is less than about 550 W/m², the voltage and current harmonic distortions in the system reach their greatest values of about 17.3% and 27% respectively. Under these values of irradiance, the controlled motor absorbs reactive power whose value can reach that absorbed when the motor is powered by the park batteries system alone.

Conflicts of Interest

"The authors declare no competing interests in relation to the work".

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