IET Renewable Power Generation

Research Article

Fuzzy PI controlled inverter for grid interactive renewable energy systems

ISSN 1752-1416
Received on 22nd November 2014
Revised on 30th January 2015
Accepted on 16th February 2015
doi: 10.1049/iet-rpg.2014.0404
www.ietdl.org

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Abstract: In this study, a fuzzy-PI controlled grid interactive inverter has been designed and implemented. The proportional and integral gains of the PI controller are decided and tuned by the fuzzy logic controller (FLC) according to required operation point of the system. Thus, adaptive nature of the FLC and robust structure of the PI controller are synthesised. Eventually, an adaptive PI controller which can adopt changes because of different operation conditions, grid disturbances and natural effects with fast transient response is obtained. Simulation studies are validated with experimental results. Both simulation and experimental results show that proposed system has fast dynamic response and tracks reference current with a low overshot and short settling time. In addition, the waveform of the inverter output current is sinusoidal and also the current is in same phase and frequency with the line voltage. Furthermore, the total harmonic distortion level of the inverter current meets the international standards. In addition, the proposed inverter system is compared with conventional PI controlled grid interactive inverter with various proportional and integral gains.

1 Introductıon

The need for energy is increasing non-linearly day by day with the development of the technology, the increasing standard of living and the increase in world population. Number of studies about renewable energy sources (RES) has increased in last two decades with this increase in world energy demand, necessity of economic and secure energy sources, global warming because of greenhouse gasses, reducing reserve of the conventional fossil-based energy sources and negative aspects of nuclear energy. As a result of these studies, some RES such as solar, wind, biomass and wave energy have gained importance and their usage have begun grow up. In addition, power system authorities are interested in RES-based distributed generation systems along with the conventional centralised generation, transmission and distribution systems. The distributed generation and microgrid applications are attracted attention all over the word, especially in developed countries to increase the efficiency and reliability of the power system. The grid interactive inverter is one of the most important parts of the distributed generation and microgrid systems. However, in these systems some requirements which are defined by the grid authority should be fulfilled. The national and international standards are presented such as IEEE 1547, IEEE 929-2000, IEC61727, EN61000-3-2, EN 50330-1 and U.S. National Electrical Code (NEC) 690 for the purpose of reducing the impact of the distributed generation system on the grid. These standards define some properties of the grid interactive inverters such as power factor, power quality, RFI/EMI and islanding mode detection [1–3].

With development of renewable energy technologies, different inverter structures and control systems are investigated for renewable energy supplied inverters. In the past literature, studies on grid interactive inverters were focused on different inverter topologies, and generally linear controllers were used in these studies [4–9]. Although voltage source inverters were commonly used, current source inverters, multi-level inverters and various topologies such as flying inductor inverter and HERIC inverter were proposed to achieve high-converter efficiency [3–10]. Moreover, different types of the transformerless inverter topologies are investigated to obtain higher inverter efficiencies. In these studies, linear controllers and hysteresis current controller are usually employed as current controller. Although, hysteresis current control has some advantages such as simple implementation, high stability, fast dynamic response, robust structure, this method introduces some undesired specifications, such as variable switching frequency and thereupon audio noises, difficulty in filter design, high frequency limit-cycle operation and high switching loss [11, 12].

In addition, the deadbeat control method was introduced for single phase grid interactive inverters [13]. However, the control time delay and variations on passive elements' values affect the deadbeat controller performance. The feedforward control of the line voltage and inverter current to improve the dynamic performance of the inverter were also proposed [14]. Although, line voltage feedforward is frequently utilised to obtain a well dynamic response, inaccurate compensations increases the preexisting voltage harmonics in the current waveform in this method [15].

Recently, proportional resonant (PR) controllers which are widely used in power factor correction rectifiers also have gained attention in grid interactive systems and used as current controller [16]. The PR controller introduces an infinite gain at a determined resonant frequency and eliminates steady-state error. However, the harmonic compensators of the PR controllers are limited to several low-order current harmonics, because of the system instability when the compensated frequency is out of the bandwidth of the system. In addition, this method requires resonant frequency information and because of the grid frequency variations, this may be a disadvantage in grid interactive inverter control system [9, 17].

Linear controllers such as conventional PI or PID controllers are widely used to control power electronic converters and grid interactive inverters. Using PI controller with fixed gains for a determined operating point provides an acceptable performance, but poor transient performance is often obtained when the inverter operation point varies continuously because of changing dynamics of the plant. Operating points of the grid interactive inverters vary with the natural conditions such as solar radiation or wind speed. Moreover grid specifications such as grid voltage, frequency and impedance might change during operation of inverter [1, 3].

Therefore performances of the linear controllers with fixed gains are limited and vary with the system parameters. The grid interactive inverter is to be operable under these variable circumstances as well as the inverter should comply with the international standards. Therefore current controller with adaptive nature must be used in these applications to prevent the effects of these parameter variations [18–21].

Fuzzy logic control (FLC) is a non-linear and an adaptive control technique, and exhibits powerful performance beneath parameter variation and load disturbances [22–26]. Various applications of the FLC have been proposed in the literature since Mamdani published the experimental results on a test-bed plant [27]. Thus, simulation of the FLC grid interactive inverter, fuzzy logic-based maximum power extraction methods have been proposed [28, 29].

Fuzzy-PI controllers are obtained via combination of the adaptive and detached natures of the FLC and fast response characteristics of the PI controllers. In fuzzy-PI controllers, fuzzy logic defines the proportional (K_P) and integral (K_I) gains of the PI controller according to operation point of the system simultaneously. Consequently, dependence of the controller on the parameter changes the system and external effects can be minimised [30].

Since supply specifications and grid conditions are variable, adaptive control of the grid interactive inverters is important to fulfil the grid connection requirements. In this study, a fuzzy-PI controller for grid interactive inverters is proposed. The FLC defines the K_P and K_I gains of the PI controller according to the system operation conditions, thus an adaptive controller structure which is required in grid interactive inverter applications is achieved. Consequently, fast dynamic response and strong stability are obtained via proposed adaptive controller even under the varying operation conditions. A line frequency transformer (LFT) is used at the output of the inverter. Therefore inverter output voltage is stepped up to the line voltage, DC current injection is prevented and galvanic isolation is obtained. A LCL output filter is used to obtain unity power factor with low total harmonic distortion (THD). The dynamic response of the fuzzy-PI controller is tested by changing the inverter reference current and input DC voltage level. Moreover, performance of the proposed fuzzy-PI controller and conventional PI controller with different K_P and K_I gains are given and compared. According to the simulation and experimentation results, the output current of inverter is in sinusoidal waveform and tracks the reference current with great performance and is synchronised with the line voltage even if reference current changes. It is observed that the inverter current quality meets the requirement of the international standards ($4.4\% < 5\%$).

2 Grid interactive inverter

Grid interactive inverters are used to connect the RES to the grid and to ensure more efficient operation by transmitting surplus energy to the grid. It is possible to supply the whole or some part of the loads from inverter. Even a user which has a small PV system and a grid interactive inverter may switch to vendor status at certain times of days. Although these types of inverter have not been used for long times because of its control difficulty; studies on the grid interactive inverters have increased rapidly with the effects of the developments in microcontrollers, digital signal processors and power electronics.

The first applications of the grid interactive inverters are based on inverters that were installed on motor drives without concerning properties and characteristics of the RESs. Generally, power levels of these inverters are high. Studies in 1990s declared that these inverters, designed to transfer energy to grid, had many deficient [31]. Although cost of these inverters are low, additional filter circuits requirements to improve the quality of the output current increase the total cost.

The RES prices are tending to go down with increasing usage and interest on them. Reduced prices of RES increased the impact of the inverter system on the total cost of the system, and studies on a new, highly efficient and low-cost inverter design have been increased [1, 31]. Moreover, because of the limitations of the international standards about the current harmonics that can be called strict; the usage of IGBT/MOSFET equipped grid interactive inverters at lower power levels instead of high power thyristor equipped grid interactive inverters is become common. Moreover, efficient current control methods for grid interactive inverters are investigated [1, 31].

In grid interactive operation, if a blackout occurs because of any reason, an electric island would appear in places that fed by inverter. Although it is essential that the presence of island mode grid is proved and the inverter is disconnected from the grid immediately, since it is really dangerous for the people those are not aware of the electrical island. Active and passive methods are developed to detect the island mode [32].

Since obtaining unity power factor is important in grid interactive operation, the frequency and phase angle of line voltage should be determined. Usually phase locked loop (PLL) circuits have been used to achieve information about the frequency and phase of the electric circuits. In grid interactive inverters, PLL circuits produce synchronised current reference. Therefore PLL circuits affect the grid interactive inverter performance [1].

Grid interactive inverter structure may consist of one, two or more converter. Single-stage inverters, which consist only one converter, perform all purposes such as maximum power point tracking (MPPT), current controlling and stepping up the voltage if it is essential. Hence control of this type of grid interactive inverters may be more complex, but total power converter efficiency is improved. In two and more stage inverters, an additional DC–DC converter steps up the DC voltage and realises the MPPT and the inverter converts the DC energy to AC energy and export the energy to the grid [31]. Although control complexity of these grid interactive inverters is decreased, their efficiencies are lower than single stage grid interactive inverter systems [33].

If the total voltage of PV modules is lower than the peak voltage of grid, the inverter output voltage becomes lower than grid voltage, and energy transfer does not happen. In this situation, a transformer is used to match the inverter output voltage and grid voltage. Although some inverters contain high-frequency transformers embedded with DC–DC converters or DC–AC inverters, some inverters use LFTs. Usage of LFT prevents DC current injection which is limited in IEEE and IEC standards, and causes saturation of distribution transformers. At the same time, the LFT provides electrical isolation between the PV and the grid, avoids common mode voltages and also facilitates grounding. The low-sized high-frequency transformers cannot solve the DC current injection problem. However, it eases the grounding of RES [6].

3 Proposed fuzzy-PI controlled grid interactive inverter

PI and PID controllers commonly used in the control of power electronic converters can also be used in control of grid interactive inverters. The gains of the PI and PID controllers are usually determined by using different methods and the mathematical model of the system such as Ziegler–Nichols methods [34]. Performance of these controllers is affected by variations of the system parameters and external factors such as noise. In addition, the grid interactive inverters operate in a wide operation range and their parameters are affected by environmental factors such as wind speed and solar radiation. Variations in environmental factors and system parameters change the operation point of the system. However, transient response of the inverter with a fixed gain controller cannot be sufficiently fast and inverter output current quality cannot fulfil the international standards. Therefore grid interactive inverters should be controlled with an adaptive controller which can set its parameters for fitting to new conditions of the system.

Fuzzy-PI controllers can be obtained by combining FLC, which is adaptive and independent from system parameters, and PI controller which has fast response. In this controller K_P and K_I gains of the PI controller are adjustable and they are determined by FLC according

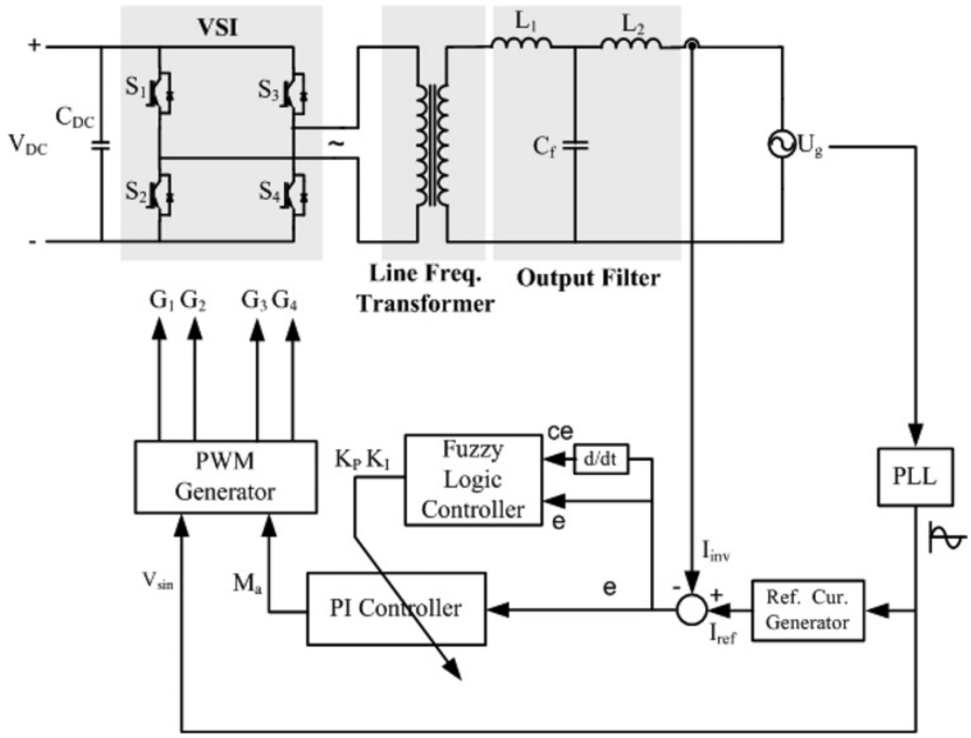


Fig. 1 *Block diagram of the proposed fuzzy-PI controlled grid interactive inverter*

to system operation points for defined inputs. The block diagram of the grid interactive inverter which is fuzzy-PI controlled is shown in Fig. 1. K_P and K_I gains of the PI controller are determined by two input–two output FLC simultaneously. As shown in the figure, grid interactive inverter consists of voltage source inverter, LFT, LCL output filter, PLL circuit and fuzzy-PI current controller. In this study, the LFT is used to step up the inverter output voltage to the gird voltage. In addition, galvanic isolation is obtained and DC current injection is prevented.

3.2 Design of the fuzzy-PI controller

Defining the input and the output variables, and membership functions of the controller is one of the most important stages in FLC design process. In this study, since the inverter current is controlled, current error (e) and change in current error (ce) are defined as input variables to the FLC. These two input variables have five triangle membership functions for each one as seen in Fig. 2. The linguistic variables 'positive large (PL)', 'positive small (PS)', 'zero (Z)', 'negative small (NS)', 'negative large (NL)' for two input variables are used to express the fuzzy variables. The commonly used Min–Max inference method and centre of gravity defuzzification method are utilised [35].

K_P and K_I are output variables of the FLC . Three singleton membership functions, which are expressed by linguistic variables 'small (S)', 'medium (M)', 'large (L)', are determined for the output variables of the FLC as seen in Fig. 3. The proposed FLC has two-rule bases for output variables K_P and K_I. The rules are established on the basis of information about the system and its operation according to variations of error and change in error inputs to obtain fast transient response. The rule bases of the FLC for output variables K_P and K_I are seen in Table 1.

Various performance indices can be utilised to define the performance of controller. In this study, mean relative error (MRE), the integral of time multiply absolute error (ITAE) and the integral of time multiply squared error (ITSE), which can be calculated by (1)–(3), respectively, are used as performance

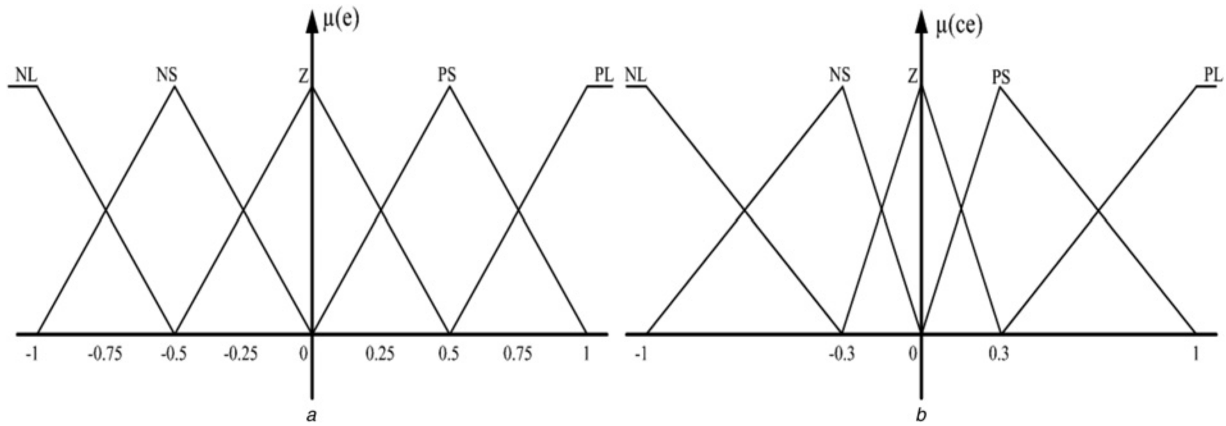


Fig. 2 *Membership functions for input variables*

a Membership functions of error
b Membership functions of change in error

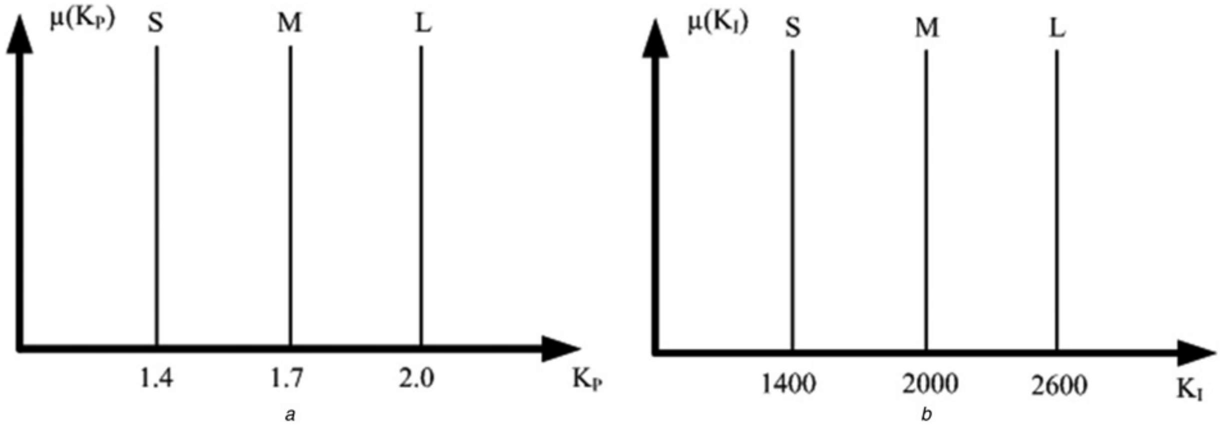


Fig. 3 *K_P and K_I output variable of FLC*
a Membership functions for K_P output variable of FLC
b Membership functions for K_I output variable of FLC

Table 1 Rule base for K_P and K_I output variables

Output (K_p)		Error (e)					Output (K_I)		Error (e)				
		NL	NS	Z	PS	PL			NL	NS	Z	PS	PL
Change in error (ce)	NL	L	L	M	M	S	Change in error (ce)	NL	S	S	M	L	L
	NS	L	L	M	S	S		NS	S	S	M	L	L
	Z	M	M	M	M	M		Z	M	M	M	M	M
	PS	S	M	M	M	L		PS	L	L	M	S	S
	PL	S	S	M	L	L		PL	L	L	M	S	S

indices of the proposed controller

$$\mathrm{MRE} = \frac{\sum_{i=1}^{n} I_{\mathrm{ref}i} - I_{\mathrm{inv}i}/I_{\mathrm{inv}i}}{n} \quad (1)$$

$$\mathrm{ITAE} = \int_0^\infty t\left|e(t)\right|\mathrm{d}t \quad (2)$$

$$\mathrm{ITSE} = \int_0^\infty te^2(t)\mathrm{d}t \quad (3)$$

where, $I_{\mathrm{ref}i}$ is ith value of inverter reference current, I_{inv} is ith value of actual inverter current, n is number of sample, t is time, $e(t)$ is error.

3.2 LCL filter design

L, LC and LCL type filters are connected to the output of the inverters to eliminate switching noise. L filters have 20 dB/decade attenuation and they need very high switching frequency. Although LC filters are generally employed in uninterruptible power supply applications, variation of the filter resonance frequency with the line impedance limits the usage of them in grid interactive inverter applications [9, 36]. Thus, LCL filter is chosen in this study. The transfer function of the LCL filter in Fig. 1 is given in (4)

$$G_{\mathrm{f}}(s) = \frac{I_{\mathrm{inv}}}{U_{\mathrm{inv}}} = \frac{1}{L_1 s}\frac{(s^2 + 1/L_2C_{\mathrm{f}})}{(s^2 + L_1 + L_2/L_1L_2C_{\mathrm{f}})} \quad (4)$$

where, I_{inv} is inverter output current, U_{inv}, inverter voltage, L_1 is inverter side inductance, L_2 is grid side inductance and C_{f} is the capacitor of the LCL filter. Only filter components' values determine the resonance frequency of the LCL filter [9, 37] as seen in (5)

$$f_{\mathrm{r}} = \frac{1}{2\pi}\sqrt{\frac{L_1 + L_2}{L_1L_2C_{\mathrm{f}}}} \quad (5)$$

LCL filters have advantages such as lower reactive power requirement, 60 dB/decade attenuation over the resonance frequency, allowing lower switching frequencies. Resonance frequency and the component values of the LCL filter are determined in accordance with switching frequency, line frequency and inverter power, voltage, current and impedance values.

The performance of the LCL filter is affected by the resonance frequency, capacitor C_{f}, inductors' L_1 and L_2 values. Resonance frequency of the LCL filter can be calculated using (6)

$$10f_{\mathrm{g}} \le f_{\mathrm{r}} \le f_{\mathrm{sw}}/2 \quad (6)$$

where the f_{g} is the grid frequency and f_{sw} is switching frequency of the inverter. A similar criterion is required for inductor and capacitor values of filter. Normalised values for LCL filter, which helps to explain these criteria, are given in Table 2. There, S_n is the nominal output power of the inverter, U_{g} is the grid voltage and subscript REF represents the normalised values. Filter capacitor C_{f} reduces the power factor. Thus, the value of the filter capacitor is generally limited by (7) in grid interactive inverter applications to

Table 2 Normalised values of LCL filter

Quantity	S_{REF}	Z_{REF}	f_{REF}	I_{REF}	U_{REF}	L_{REF}	C_{REF}
Value	S_n	$U_{\mathrm{REF}}^2/S_{\mathrm{REF}} = U_{\mathrm{REF}}/I_{\mathrm{REF}}$	f_{g}	$S_{\mathrm{REF}}/U_{\mathrm{REF}}$	U_{g}	$Z_{\mathrm{REF}}/2\pi f_{\mathrm{REF}}$	$1/2\pi f_{\mathrm{REF}}Z_{\mathrm{REF}}$

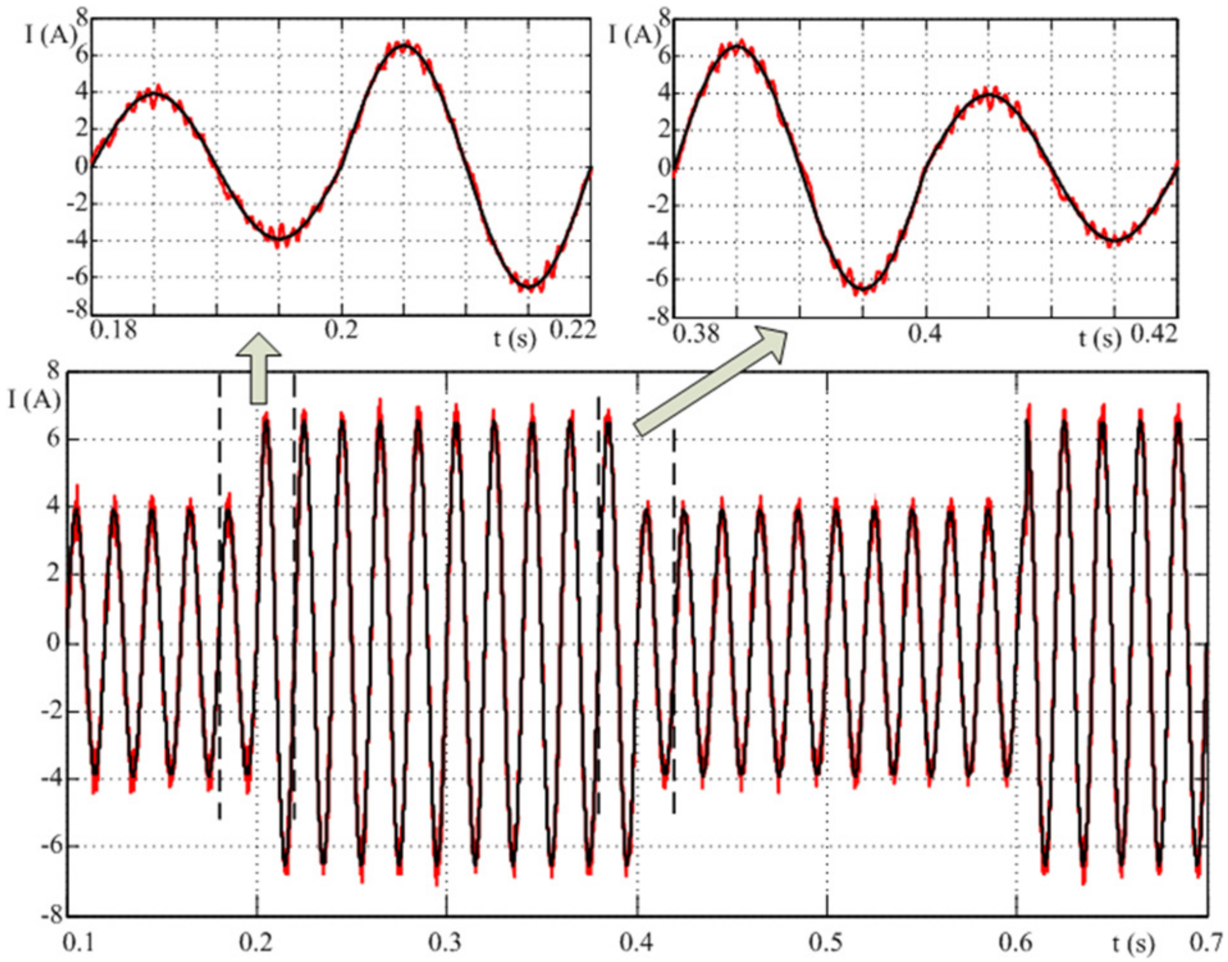


Fig. 4 *Inverter output current and reference current*

achieve unity power factor [9, 36]

$$C_f = 0, 05C_{REF} \quad (7)$$

Low capacitance values for each resonance frequency increase inductor impedance values. Moreover, higher impedance values increase the system cost and size. Therefore C_f capacitance value is selected close to the limits of (7). In addition, required DC voltage level is affected by total inductance owing to the voltage across the inductor. As DC voltage level gets higher, the switching losses will increase. Accordingly, total inductance value should be less than the 10% of L_{REF} [9, 36]. Various L_1 and L_2 values could be chosen for a unique value of the total inductance. In this study, the relation between the L_1 and L_2 is determined as given in the following equation

$$L_1 = 2L_2 \quad (8)$$

The LCL line filter's components values of the grid interactive inverter are calculated using (5)–(8) and are given in (8)–(10). The resonance frequency of the filter is tuned as 2500 Hz

$$L_1 = 5\,\text{mH} \quad (9)$$

$$L_2 = 2.5\,\text{mH} \quad (10)$$

$$C_f = 3\,\mu\text{F} \quad (11)$$

4 Simulation and experimental results

Integration ability of the MATLAB/Simulink simulations and hardware control in a system makes DS1104 dSPACE control card very popular. The proposed grid interactive inverter control system is also employed with this control card. The PWM switching signals for IGBTs are generated by slave DSP TMS320F240. 10 kHz is selected as the switching frequency. The PWM signals are optically isolated and buffered for driving the IGBT gates. The voltage source inverter is equipped with Mitsubishi CM75DU-12H module IGBTs. A LFT is used to prevent DC current injection, to obtain galvanic isolation and to step up the output voltage to the line voltage. In addition, the LCL filter is used to filter high frequency switching noise.

The proposed fuzzy-PI controlled grid interactive inverter is simulated using MATLAB/Simulink. To sense the grid voltage frequency and phase which are used for reference current generation, a PLL is used. The FLC determines the K_P and the K_I gains of the PI controller and the modulation index is generated by the PI controller according to current error. The FLC is designed with fuzzy Logic Toolbox.

In Fig. 4, the inverter output current and reference current are shown. The current reference of the inverter is increased 60% at $t = 0.2$ s, and 60% decreased at $t = 0.4$ s. Moreover, at $t = 0.605$ s, when the current reference is at its peak value, its value is increased 60% again. This moment is seen in Fig. 5. The output current of the fuzzy-PI controlled grid interactive inverter tracks the reference current with a small overshot and small settling time, and the fuzzy-PI current controller has fast transient response. Moreover, the inverter is tested for input DC voltage variation. Input DC voltage is increased from 200 to 300 V and decreased to 200 V again at $t = 0.9$ s and $t = 1.1$ s, respectively. As seen from

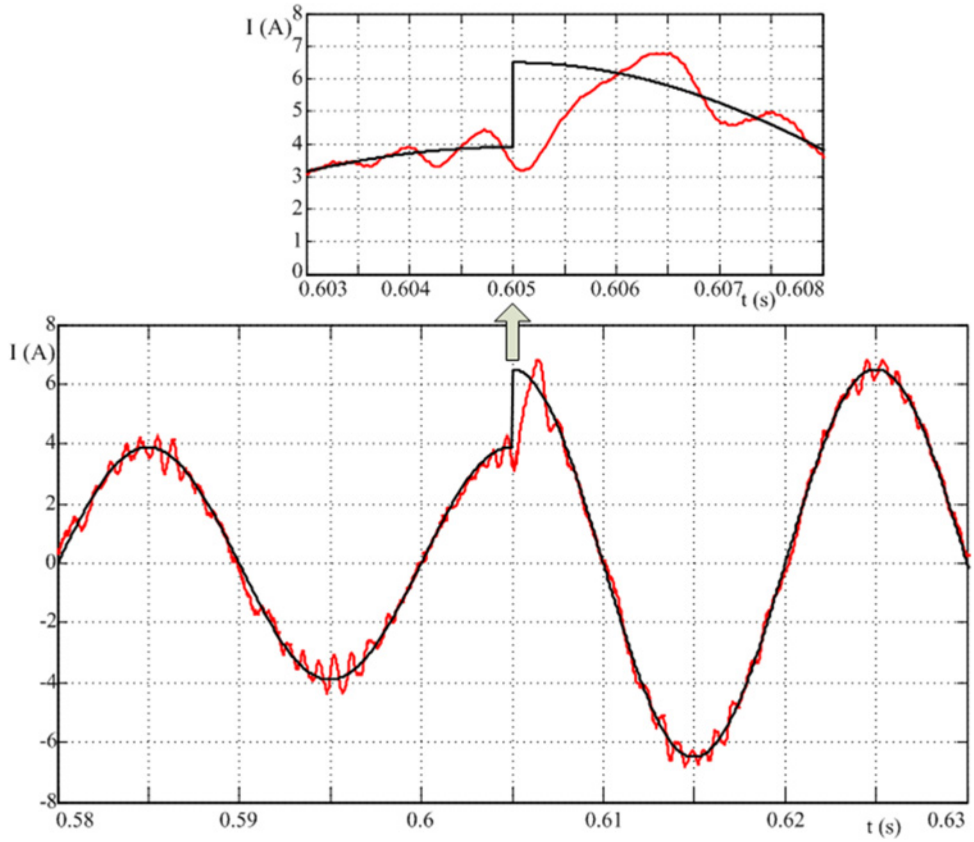


Fig. 5 *Inverter output current and reference current*

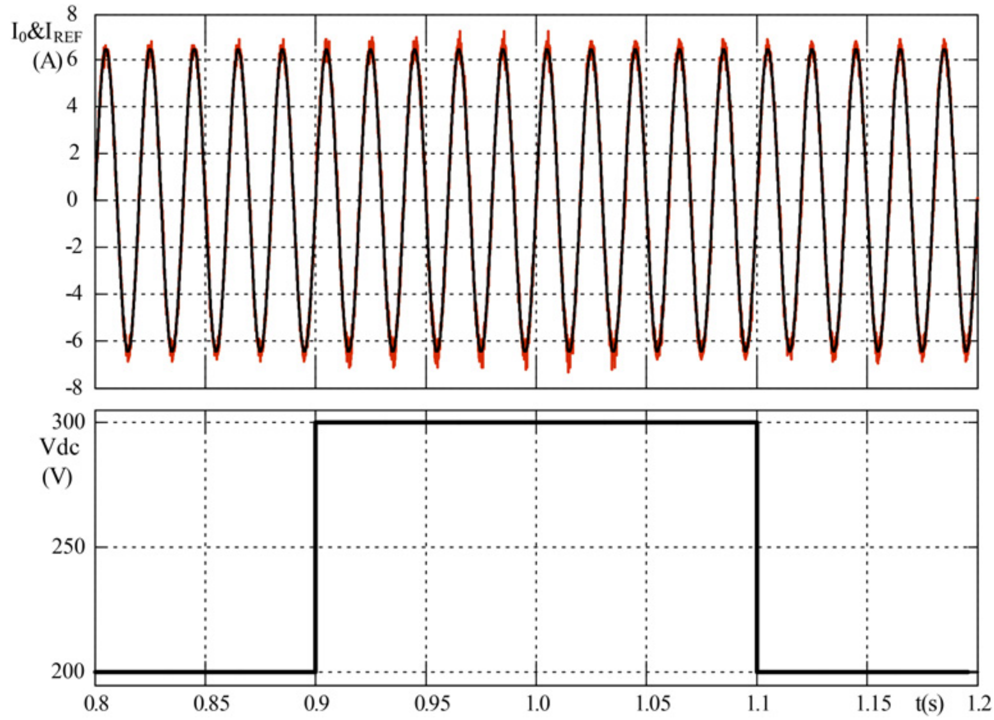


Fig. 6 *Inverter output current and reference current under input DC voltage variations*

Fig. 6, the inverter output current also tracks the reference current when there are variations in input DC voltage.

The output current of the inverter and the grid voltage are depicted in Fig. 7. The inverter output current is in sinusoidal waveform and synchronised with frequency and phase angle of the line voltage. Moreover the THD level of the inverter output current is calculated as 3.85% and this value meets the requirements of the international standards such as IEEE1547 and IEC61727 (<5%).

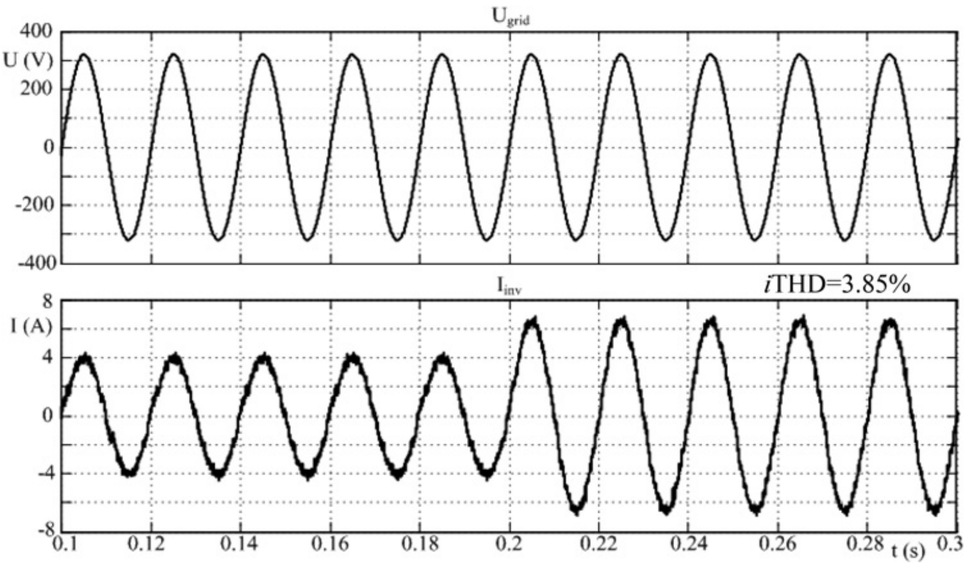


Fig. 7 *Line voltage and inverter output current*

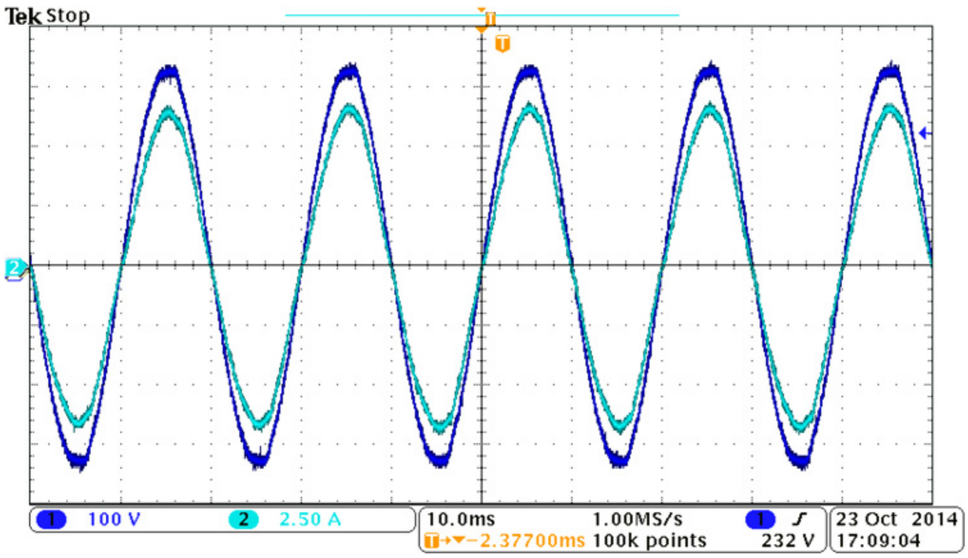
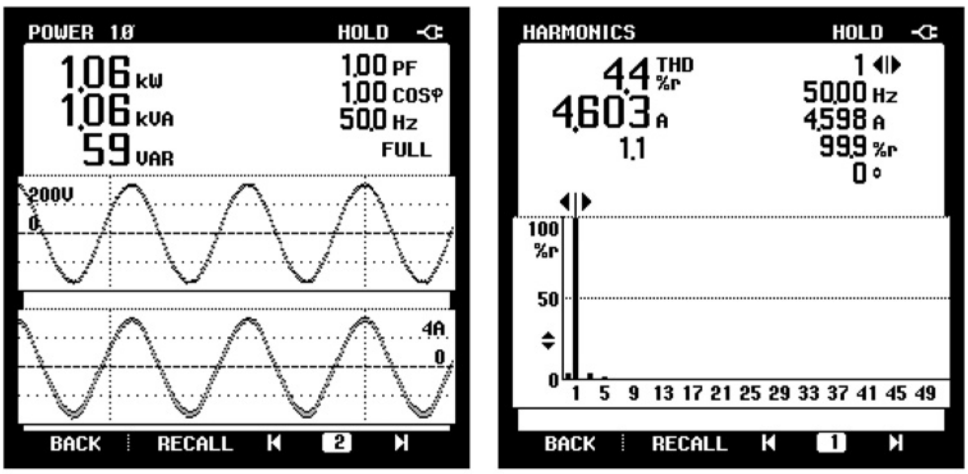


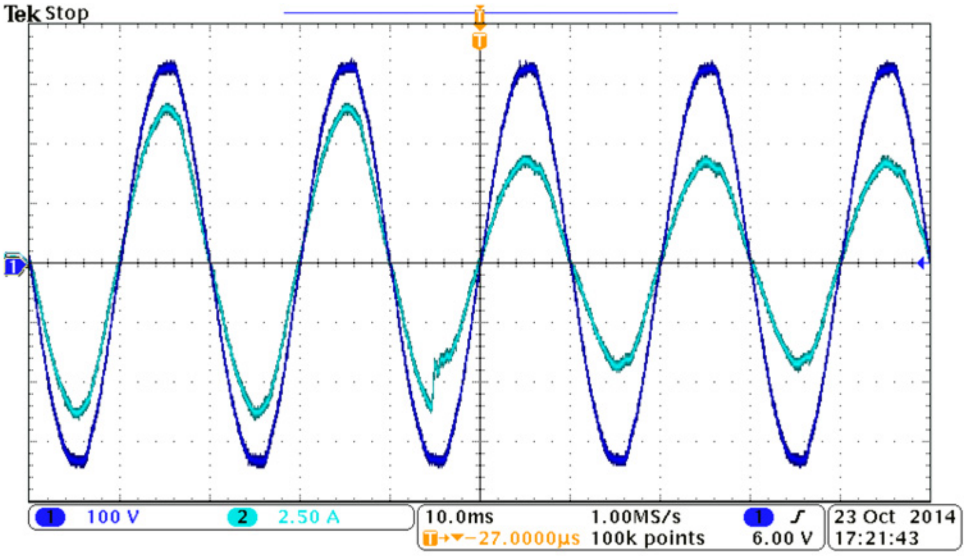
Fig. 8 *Grid interactive inverter output current (Ch. 2) and line voltage (Ch. 1)*



a *b*

Fig. 9 *Output current harmonics, power and the power factor values of inverter*

a Inverter output current harmonics
b Inverter output current, line voltage, power and power factor values



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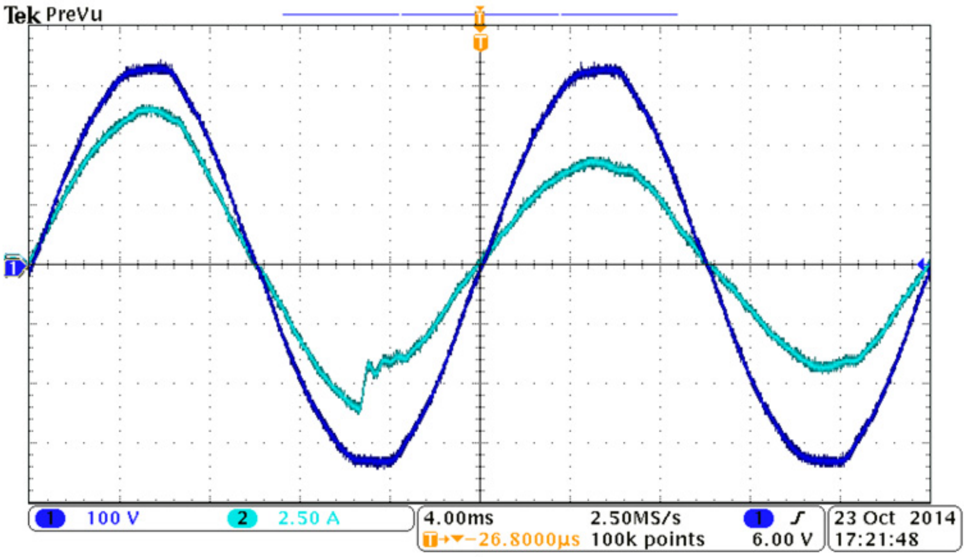

b

Fig. 10 *Dynamic response of the proposed fuzzy-PI controlled grid interactive inverter (line voltage, Ch. 1 and output current of the inverter, Ch. 2)*

After completing simulation task, the process of reading analogue signal and generating switching signals are carried out with the dSPACE blocks are added to the Simulink model. When this model is 'Build', the C source code is generated and then it is automatically loaded into the microprocessor.

In Fig. 8, the inverter output current and the grid voltage obtained from experimental studies are shown. The inverter output current is in sinusoidal waveform and in phase with the grid voltage. In addition, output current harmonics, power and the power factor values of inverter are shown in Fig. 9. These results are measured with Fluke 43B power quality analyser which can analyse up to 51st harmonics. It is seen that the inverter power quality indices (output current THD and PF) are compatible with the international standards.

The dynamic response of the proposed current control scheme is tested by decreasing the reference current value of the inverter to 60% of its nominal value and increased to its nominal value. The inverter output current and the grid voltage waveforms at these step change instants are presented in Figs. 10 and 11. It is seen from the figures that, the proposed fuzzy-PI controlled grid interactive inverter has fast transient response, and inverter output current tracks the reference current with high performance. Thus, simulation results are validated by experimental studies.

The simulation and experimental results and calculated values of performance indices by using (1)–(3) are given in Table 3 for conventional PI controllers with different gains and the proposed fuzzy-PI controller. The power factor value is same for all methods for both simulation and experimental studies. According to other performance indicators, the fuzzy-PI controller has better performance compared with the conventional PI control. Lower values of MRE, ITSE and ITAE indicate that proposed controller has fast transient response and tracks the reference signal successfully.

5 Conclusions

In this study the fuzzy-PI controlled grid interactive inverter has been designed and implemented. The K_P and K_I gains of the PI controller are determined by FLC according to system operation point. Thus, an adaptive control structure which is important for grid interactive inverters has been obtained. The performance of the proposed method is investigated for both steady state operation and transient conditions such as current reference variations and DC voltage variations. The obtained results from both simulation and experimental studies confirmed that the inverter output current is

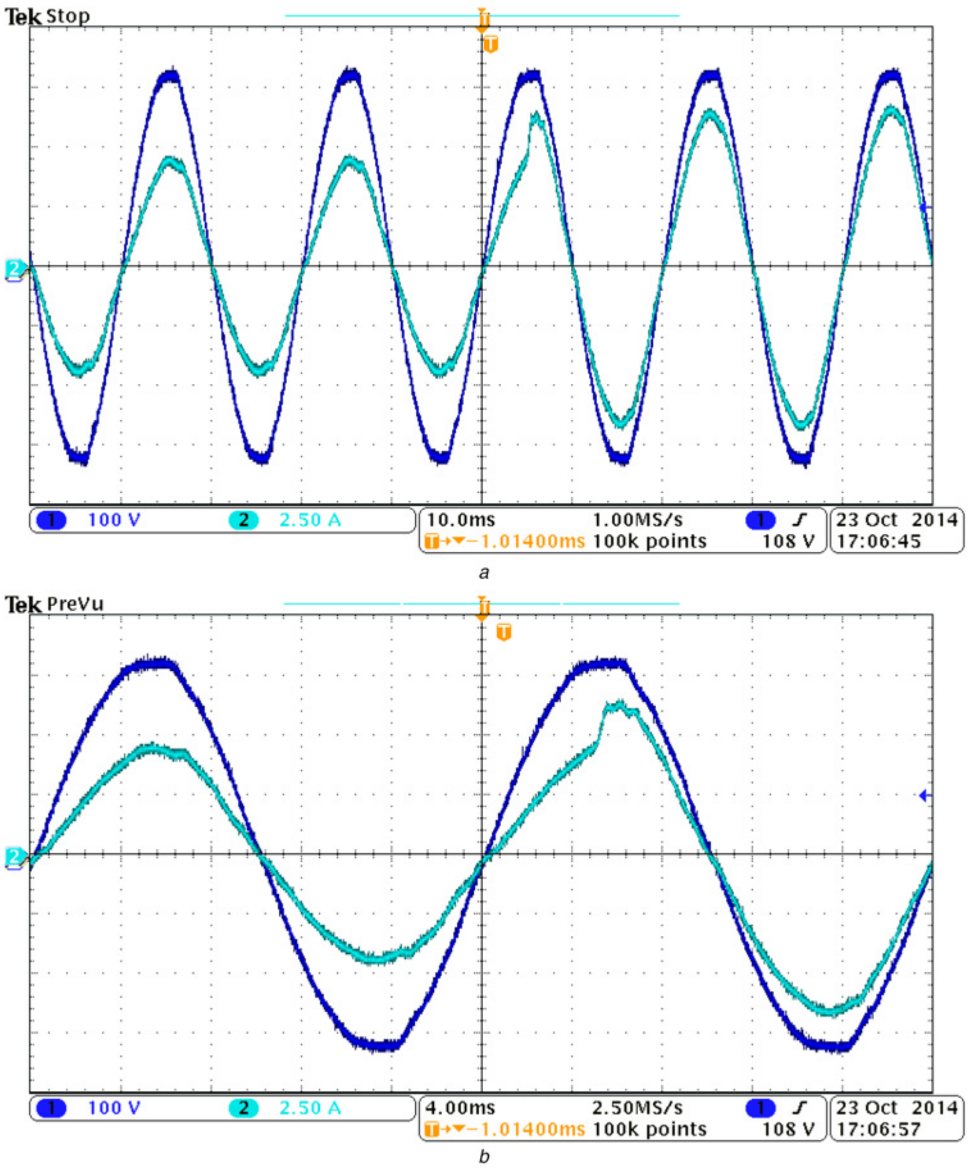

Fig. 11 *Dynamic response of the proposed Fuzzy-PI controlled grid interactive inverter (line voltage, Ch. 1 and output current of the inverter, Ch. 2)*

Table 3 Summary of simulation and experimental results for PI and fuzzy-PI controllers

Control Method	Simulation results					Experimental results	
	THD%	PF	MRE	ITSE	ITAE	THD%	PF
Fuzzy-PI	3.85	0.999	0.02969	0.0231	0.0572	4.4	0.995
PI (Kp = 1.4 KI = 1400)	4.77	0.999	0.03384	0.0264	0.0618	4.9	0.999
PI (Kp = 1.4 KI = 2000)	4.46	0.999	0.0315	0.0254	0.0611	4.7	0.999
PI (Kp = 1.4 KI = 2600)	4.92	0.999	0.03479	0.0262	0.0627	4.8	0.999
PI (Kp = 1.7 KI = 1400)	4.57	0.999	0.03276	0.0260	0.0612	4.8	0.999
PI (Kp = 1.7 KI = 2000)	4.57	0.999	0.03239	0.0254	0.0611	4.7	0.999
PI (Kp = 1.7 KI = 2600)	4.78	0.999	0.03268	0.0248	0.0615	4.7	0.999
PI (Kp = 2.0 KI = 1400)	4.41	0.999	0.03376	0.0262	0.0613	4.8	0.999
PI (Kp = 2.0 KI = 2000)	4.37	0.999	0.03293	0.0256	0.0613	4.7	0.999
PI (Kp = 2.0 KI = 2600)	4.68	0.999	0.03188	0.0265	0.0617	4.9	0.999

synchronous with the grid voltage and the frequency, and the harmonics distortion level of the inverter current meets requirements of the international standards. Moreover, it is seen that, the fuzzy-PI controlled grid interactive inverter has fast transient response than conventional PI controlled inverter and it is suitable for conditions of input variation and grid disturbances which are common in renewable energy applications. In addition, the use of dSPACE system shortens the duration of control system design. Moreover, it enables the monitoring of analog and digital signals, and control variables. As future study, the rule base and membership functions of the FLC can be determined with other intelligent methods to obtain the best solution.

6 References

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