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Universal Power Electronic Interface for Distributed Generation Resources

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ABSTRACT: Many efforts have recently been observed to improve efficiency, reduce the greenhouse gas and risky particle transmission leading to the urgency of the “more electric” concept from various industries including transportation; in other to bring a solution to the problem and a smooth transition unto a more reliable, diverse and efficient power grid for future applications the concept of universal power electronic interface (UPEI) is introduced.

KEYWORDS: converters; Distributed generation; LCL filter; harmonics; renewable energy, Phase locked Loop (PLL)

I. INTRODUCTION

In order to reduce potential impacts on the distribution generation (DG), universal power electronic (UPE) interfaces is introduced to integrate the DG with an existing electrical power system. To tackle higher harmonics from DG, the UPE interface offers a unique capability over traditional interconnection technologies to be developed as a link between any DG units and consumers, UPE interface separates any DG unit and grid, it provides reactive power, fault current limiting and quality power to the distribution grid and consumer network. Renewable energy based on DG can be a relief of the conventional power plant; yet this will increase the transmission of infrastructure investment. Many localized power generations could be an alternative to centralise generation pattern which offers opportunity to incorporate energy storage for power influences.

II. PRESENTATION OF THE SYSTEM

The system to present for this research paper is to investigate the main benefit of using universal power electronic interfaces for distributed generation systems by developing a new design and building a PE interface in which if any energy (AC or DC type) is connected to the interface it will be able to control and give a reliable and required output voltage and current to the grid or load as shown on the figure below. An energy storage system is also included in the circuit in other to keep the system running when renewable energy will not be able to produce required energy to run the system due to the weather conditions [1].

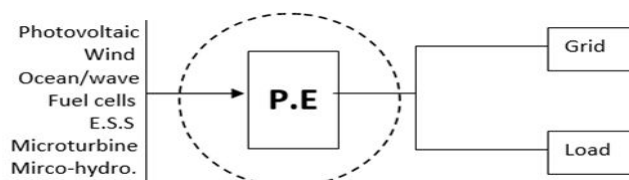


Figure1: Illustration of power electronic interface.

1. INPUT SOURCES

The DC sources used in this research paper are renewable energy resource generally referred as distributed generation systems, there systems configurations and topologies have been discussed in details by the following authors [2]; [3] & [4]. In other to implement this project we have chosen to work with four of the DG systems with an input voltage source

set to be 200V for each input source: Fuel cell (V_{FC}); Photovoltaic (V_{PV}); Battery ($V_{Battery}$) and Wind (V_{Wind}). Fig. 2 below presents how the system is connected to the grid/load for energy power generation.

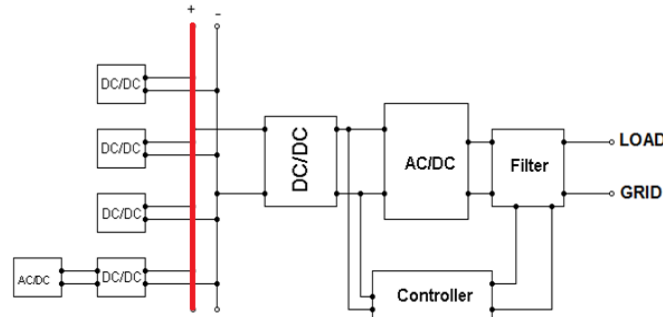


Figure 2: study model

Fig.2 presents the study model which contains three main components: the DC sources, the three-phase inverter and the filter connected to the load or grid. The DC source integrates the primary source including: fuel cell, photovoltaic, battery and wind turbine which are all connected to the inverter via a dc link. In the case of wind generators or an AC input source, an AC to DC converter is set before the power bus. And a DC to DC converter (in the case of DC input sources) is connected. The inverter which provides the DC / AC conversion is a voltage inverter phase controlled by a pulse Width Modulation (PWM) interceptive. The filter to the load connection is an LCL filter which serves to minimize the switching harmonics.

2. MODELLING OF THE INVERTER

A six switch three-phase inverter topology is used in this paper as part of the inverter. The topology is made up of six switches arranged in such a way that three parallel branches are connected to the dc sources, it is also arranged in a way that two switches are connected in series on each branch with each switch cell made up of a transistor and a diode connected in anti-parallel with an added diode in parallel. Hence the DC input sources are applied to the three upper and lower parallel branches of the inverter throw two dc link capacitor connected in series with the branch. The result of the three phase AC output takes place between the two switches of each branch hence making the inverter configuration very simple, widely used, and a good topology to integrate more inverter features which makes it very desirable for this research paper.

The switching sequence of the inverter IGBT is represented in the table below:

Table 1: Switching pattern of SPWM

IGBT Switch	Sine wave voltage	$V_s > V_o$	$V_s < V_o$
S1	V_{Oa}	ON	OFF
S6		OFF	ON
S2	V_{Ob}	ON	OFF
S5		OFF	ON
S3	V_{Oc}	ON	OFF
S4		OFF	ON

The IGBT switches connected on each branch of the inverter are switched on/off alternatively therefore it results in the flow of output current continuously. The typical modulating index is set to be between 0 and 1 this is to limit the voltage magnitude of the inverter on the AC output side as presented in Fig.3. The principal AC side voltage waveform magnitude and amplitude of the inverter when Switching PWM is applied and can be determined using the equations as follow [5].

$$V_{rms} = \frac{1}{\sqrt{2}} \times V_{dc} = 0.707 V_{dc} (1)$$

$$V_{rms} = \frac{\sqrt{3}}{2\sqrt{2}} \times V_{dc} = 0.612 V_{dc} (2)$$

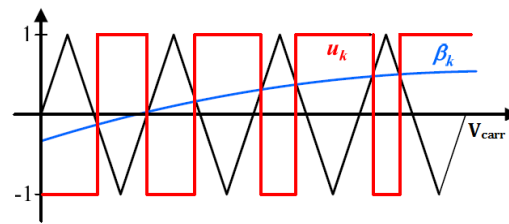


Figure 3: switching instants in the case of a PWM interceptive

u_k is the switching function which takes the value of 1 when the upper switches are closed (S1, S2 or S3) and -1 when the lower switches are closed (S4, S5 or S6). This switching function is obtained when comparing two signals (Fig.3), the modulating β_k , which is a reference wave representation of the desired output voltage between -1 and 1, and the carrier voltage V_{carr} which is the wave triangular PWM frequency much higher than the frequency of β_k hence determines the inverter switching frequency.

3. CONTROL BASED POWER OF THE INVERTER

Due to the nature of renewable energy, all loads are interfaced to the network by a DC to AC voltage inverter which is equipped with a detuned filter cutting. For setting the local controllers, renewable energy has been considered as the dynamics sources of energy. Indeed the inverters will be connected to the DC bus which will continuously supply enough energy to ensure proper response to various transient on the system.

The power stage inverter designed for the research converts the 800V DC output voltage of the three-phase converter to the grid voltage of about 400V AC phase voltage and 230V line to line voltage at a 50 Hz frequency. The purpose of choosing a high DC link voltage in this study is that its voltage will never be lower than the required voltage for the inverter grid voltage. The control of the grid current with the voltage drop across the semiconductor devices and filter voltage is not an easy task to operate.

The general model based on a voltage inverter considered in this study is a three-phase bidirectional DC to AC inverter topology with pulse technique as presented in Fig.4. Basically this three phase two level inverter will convert the DC output voltage into AC voltage at a desired load output voltage and frequency. This can be achieved using different inverter topologies and control schemes having each their benefits and drawbacks.

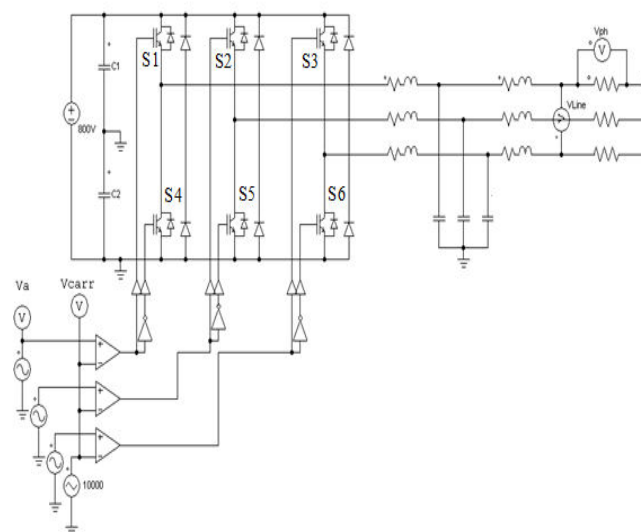


Figure 4: Bidirectional DC to AC inverter

The inverter switching is controlled by PWM technique in order to generate an unfiltered output voltage. The whole inverter system is improved using a sinusoidal PWM switching approach. The Sinusoidal pulse width modulation (SPWM) is used to generate the switching signals for the inverter at a desired magnitude and switching frequency with a

comparison of a three-phase sinusoidal wave with a triangular wave (V carrier). The frequency of the inverter is set by the frequency of the triangular signal which result into pulses that drives the gate signal of the IGBT.

The modelling of reference sinusoidal waveforms are given using the following equations:

$$v_{0a_ref} = A \sin(2\pi ft + \theta) \quad (3)$$

$$v_{0b_ref} = A \sin(2\pi ft + (\theta - 120^\circ)) \quad (4)$$

$$v_{0c_ref} = A \sin(2\pi ft + (\theta + 120^\circ)) \quad (5)$$

4. MODELLING AND DESIGN OF THE LCL FILTER

The PWM converter having a higher switching frequency generally results in a lower LC filter size. However this switching frequency is mostly limited to high power applications for two reasons:

1. It has a better attenuation than the LC filter with the same size.
2. The LCL filter provides inductive output at the grid (load) point in other to prevent inflow current compared to the LC filter.

The equivalent circuit of the LCL filter model is represented in Fig.5 where L_1 represent the inverter side and L_2 is the grid inductor side, C_1 is the capacitor with a series R_f damping resistor, R_1 and R_2 are inductors resistances, V_i is the inverter input voltage and V_g is the inverter output voltage. The currents i_i , i_c , i_g are inverter output current, capacitor current and the grid current respectively. The functional block diagram for the grid connected inverter with LCL filter is presented in Fig.5. More information on the modelling and design technique of the LCL filter can be found in [6]; [7] & [8].

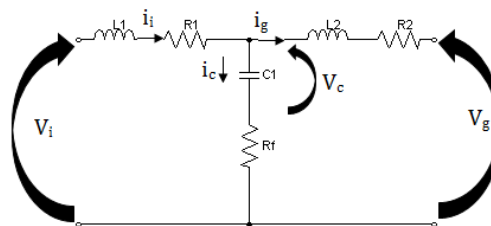


Figure 5: Per phase model of the LCL filter

The first design consideration when designing a LCL filter is to meet the IEEE std. 519 requirements. Therefore the inverter inject the ripple current into the grid due to the PWM switching, the switching frequency of the inverter is set to 10 KHz at a given power level of (15 kW) and the IGBTs are used as power electronic switching devices. In the case that the grid inverter is a power generation equipment, it is then subjected to a 0.3% of current limit. Which means the current ripple at 10 KHz should be less than 0.3% of the rated current [9].

Some parameters are important to be consider when selecting the LCL filter such as the power rating of the inverter, the grid frequency and the switching frequency [6]. The flow chart which summarizes the procedure of designing the LCL filter is presented in [6] & [8].

Table 2 below shows the parameters used for calculation of the filter components, these parameters are designed to handle reactive and active power of approximately 10KVA of 15KW, the parameters are the ratings of the inverter power stage hence very important for the inverter design.

TABLE 2: LCL FILTER DESIGN PARAMETERS

Parameters	Entitled	Values
Inverter Nominal rating	P_n	15 kw, 3 phase
Line to line AC Voltage	V_{LL}	400V
AC Phase voltage	V_{ph}	230V
Period	T_s	100 μ s
DC – link voltage	V_{Bus}	800V
Grid frequency	f_g	50 HZ
Inverter switching frequency	f_{sw}	10 KHZ
Modulation range	m_a	$0 < m_a < 1$

Using the parameters provided in table 2 the base impedance and capacitance are calculated as follow

$$Z_b = \frac{V_{LL}^2}{P_n} = \frac{400^2}{15\,000} = 10.667\,\Omega$$

$$C_b = \frac{1}{\omega_n Z_b} = \frac{1}{2\pi 50 \times 10.667} = 298.406\mu F \text{ with } \omega_n = 2\pi f$$

By minimising the ripples in the output current of the inverter side, the inductor is usually from 10% to 20% of the nominal current. And choosing the inverter side inductor to be 5% of the total base impedance therefore allows current ripple to meet the limit requirement of 10% of nominal current value.

After performing calculations, the following result are obtained and presented in table 3. The calculation process is explained by [7] & [6].

Table 3: LCL filter design parameters values.

Parameters	Entitled	Values
Inductance of filter LCL (inverter side)	L1	1.698mH
Capacitance of filter LCL	C1	14.9203 μ F
Inductance of filter LCL (Grid side)	L2	1.358mH
Resistance of inductor is approximate	r1	0.5 Ω

5. CIRCUIT CONTROL

The Control of the circuit is done using the PLL technique, from the sampled phase voltages are obtained the stationary reference voltages V_gA , V_gB , V_gC . These voltages are after transformed to voltages V_d and V_q (in the frame of reference synchronised to the utility frequency) by using $\alpha\beta$ and dq transformation, more information are found in [6]. The circuit in Fig.6 present how the whole circuit is connected to the direct PI control.

The control of the grid-connected inverter which supplies the system with the active and reactive power system is implemented using the current control technique approach. By using the current control technique and the direct PI control as presented in Fig.6, the control of the grid-connected inverter that supplies the system with active and reactive power system is implemented. The VSI block represents the inverter connected to the grid via the filter and the load.

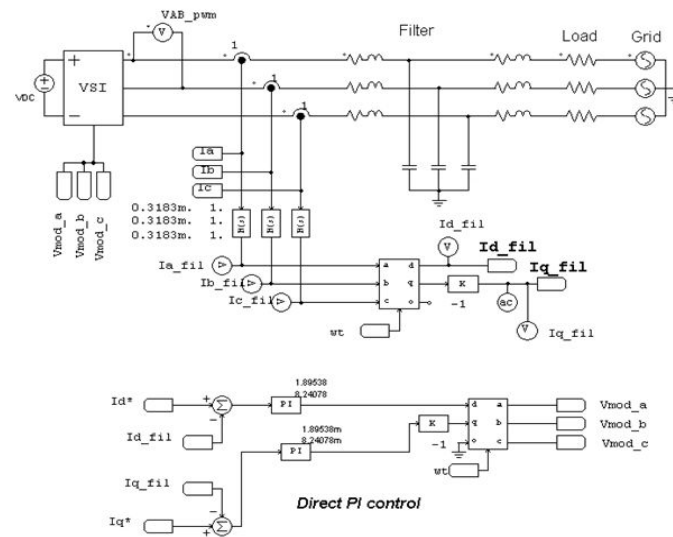


Figure 6: Current control model with direct PI control

6. FREQUENCY RESPONSE AND TRANSFER FUNCTION

An important transfer function whereby the grid voltage is considered to be an ideal voltage source capable of dumping all harmonic frequencies is given by $H_{LCL} = i_g/v_i$ extracted by the transfer function above. If the grid voltage is assumed to be an ideal voltage source and represents a short circuit for harmonics frequencies, therefore for the analysis of the filter V_g is set to be $V_g = 0$. Hence for example in the case of current-controlled inverters, the LCL transfer function by neglecting the damping will be:

$$H_{LCL}(S) = \frac{1}{L_1 C_f L_2 S^3 + (L_1 + L_2)S} \quad (6)$$

After manipulations of the transfer function with damping resistance then becomes:

$$H_{LCL}(S)_{dampin} = \frac{C_f S R_f + 1}{L_1 C_f L_2 S^3 + (L_1 + L_2) C_f R_f S^2 + S(L_1 + L_2)} \quad (7)$$

Detailed information on the frequency response are presented by authors [5] & [6].

7. THE HARMONICS

The output Current harmonics injected to the utility grid by the inverter might be diminished with a legitimately planned LCL filter as contrasted with a basic L or LC filter. Having in mind the end goal to exhibit this, the frequency response of these filters (LCL and L) are analysed. By Accepting lossless parts and good sinusoidal grid voltage at the fundamental frequency, the harmonic model of a LCL filter can be obtain as shown in Fig.7[10] & [11].

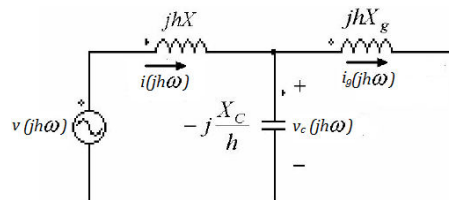


Figure 7: Single phase harmonic model of a LCL filter for $h \neq 1$.

III. CIRCUIT DESIGN

The design of the universal power electronic interface for distributed generation systems mode was developed and simulated using Psim software simulation platform.

A. The Power Bus

The universal input converter can combine several input power sources where voltage levels and/or power capacity are different to obtain regulated output voltage for the load. Therefore, the converter can control power flow between sources with each other and load. A power bus universal Input DC/AC replaces several numbers of parallel connection connected to a single converter. From the power bus as seen in Fig.8, input sources from 1 to N source can be composed of any kind of energy source combinations are all connected to a power bus.

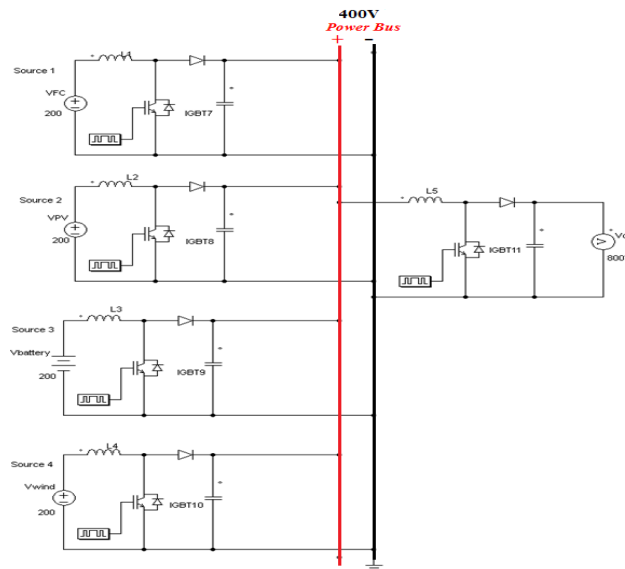


Figure 8: Universal input voltage converter

B. Grid connected

The grid connected is considered to be ideal and the DC-link voltage (V_{DC}) serves as the input voltage to the grid-connected inverter system it was considered also to be an ideal voltage source which comes from the DG systems as presented in Fig.9.

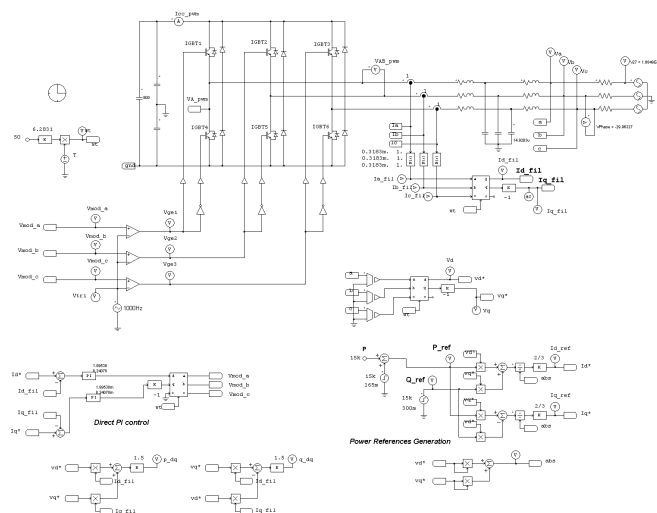


Figure 9: Grid connected to the inverter model

IV. SIMULATION RESULTS

Different instances of analysis and performance evaluation of the designed grid-connected inverter model have been performed. The inverter output voltage and output current as well as the grid-side voltage and output have been studied. The harmonic analysis of the injected current into the grid was also studied. By using the inverter performing with pulse width modulation at a higher switching frequency of about 10 KHz compared to the nominal frequency of the modulated signals, the conversion of the DC to AC is done. Hence the result measured of V_a and I_a are presented in Fig 10 & 11.

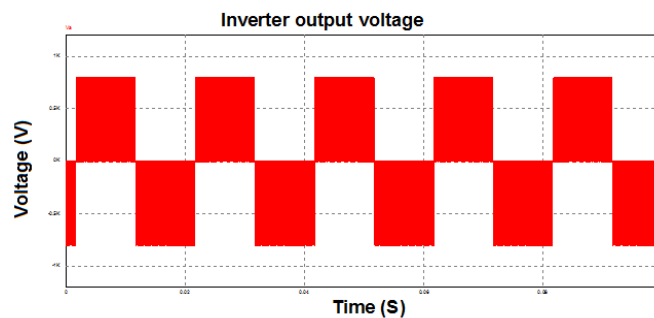


Figure 10: inverter output voltage before the LCL filter

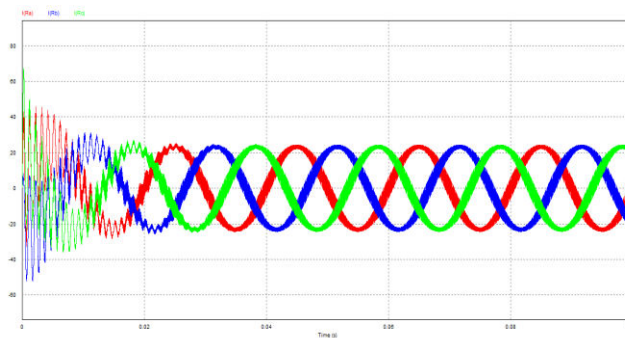


Figure 11: inverter three-phase output current before the LCL filter

Now using the LCL filter the harmonic that are present in the output of the inverter have been filtered. Comparing these wave forms meaning the simulated output voltage and current of the inverter before the LCL filter on one side and the simulated result of output voltage and current after the filter on the other side clearly prove the importance of the filter which is to be interconnected from the inverter to a utility grid in order to filter the harmonics which are produced by the inverter.

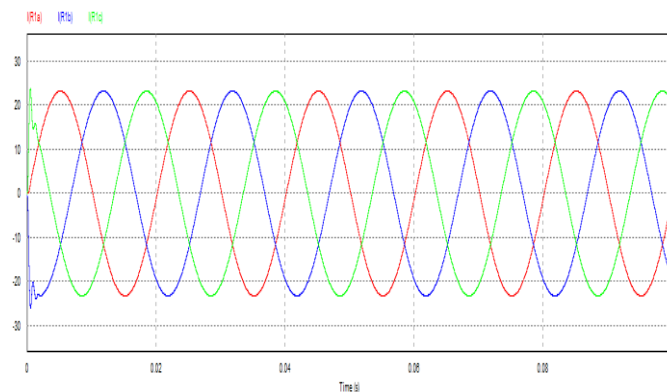


Figure 12: inverter output current after the LCL filter

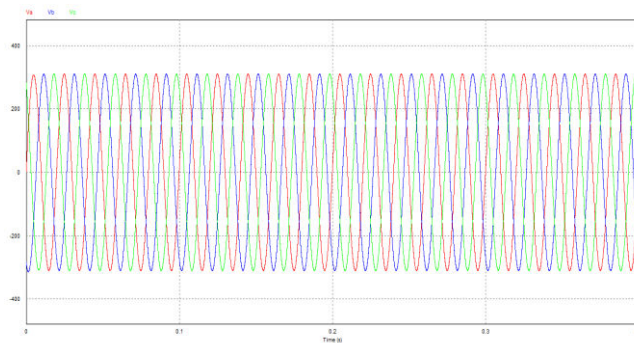


Figure 12: Inverter filtered output voltage of three-phase grid-connected inverter

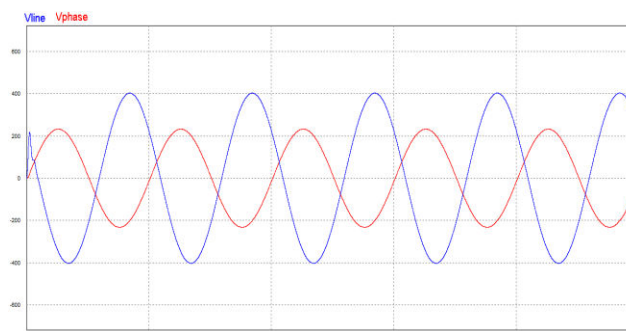


Figure 13: Inverter filtered output voltage Vline and Vphase.

Fig.14 and 15 show the flow of active power (KW) and reactive (KVAR) power injected into the Grid which is set to be zero at the beginning, these powers are supplied by the grid connected inverter.

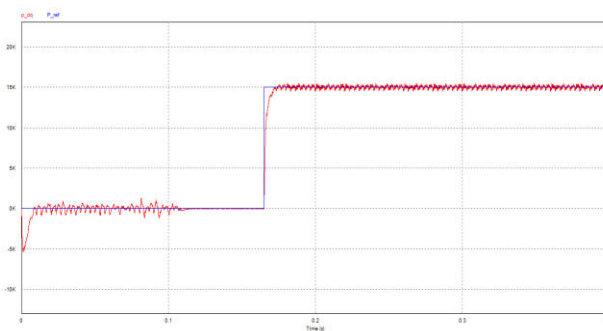


Figure 14: Active Power (KW) injected to the grid

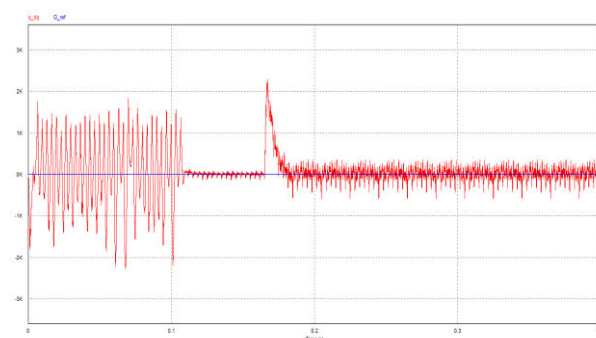


Figure 15: reactive Power (KVAR) injected to the grid

The response of the d current component is plotted in Fig.16. Showing the capability of the controller for the d axis to decently tracking the set power.

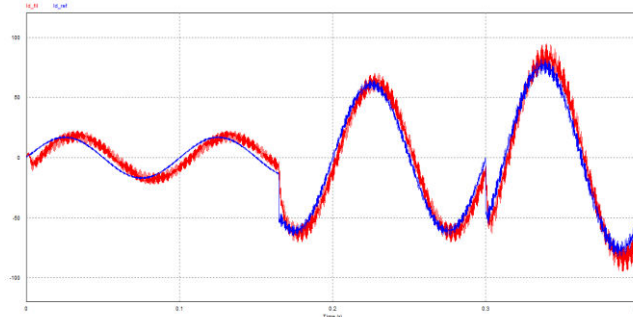


Figure16: id current response to reference command

The tracking response of the q current component has also been plotted in Fig 17. It shows the capability of the controller for the q axis decently tracking the set power.

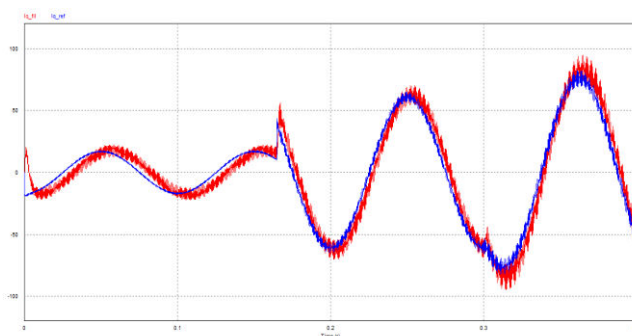


Figure 17: iq current response to reference command

The tracking response of the d and q measured voltage is plotted in Fig 18. Both the d and the q axis of the inverter voltage is regulated.

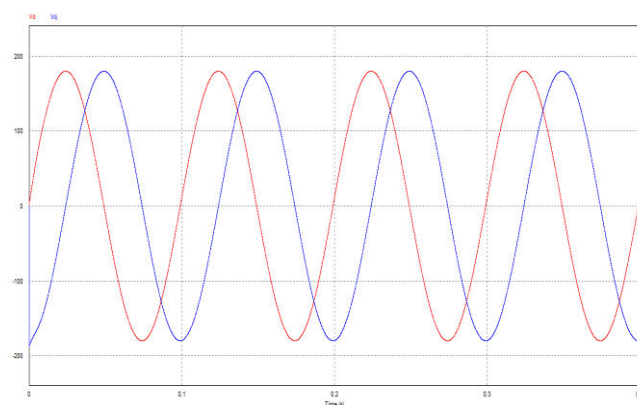


Figure17: the d and the q measured voltage

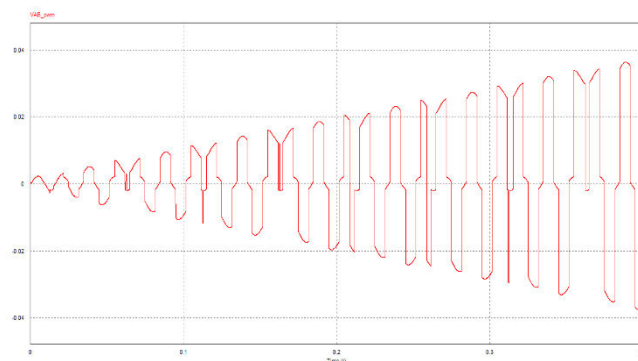


Figure 18: Modulating signals directed to the PWM

Fig.16 and Fig.17 present the reference tracking current of the d-axis and q-axis current in response to the corresponding references, it is clearly observed the ability of the controller for the q axis to decently tracking the set power. From the measured voltage, the d and q components are also shown in Fig. 18. It is shown in Fig.18 the modulating signals directed to the PWM generator.

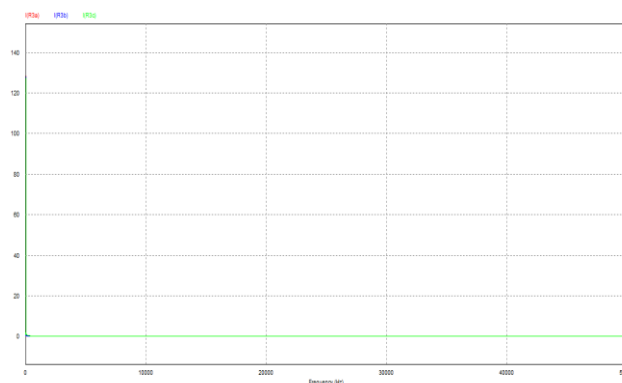


Figure 19: FFT Analysis of THD on the three phase current injected to the grid

Fig.19 presents the analysis performed on the current injected to the grid at 50HZ frequency by performing the FFT in the simulation software platform, the above result is obtained and it is observed that the harmonics on the current injected to the grid are very less approximately less than 0.3% of the rated current.

V. CONCLUSION

The aim of this paper is to propose a method of control of a universal input power source station for the production of electricity composed of conventional sources and renewable energy sources as well as a storage element. The development and the design of a three-phase grid connected inverter was studied. The research was able to reach its objectives by designing, modelling, analysis and simulations of the circuit using Psim software package that have helped to check the performance of the proposed control system. Instead of an L filter, a LCL filter was implemented in other to eliminate the high frequency harmonics which are imposed by the grid side current as result of PWM switching. The LCL filter effectiveness was confirmed because the low current harmonics injected to the grid to full fil the IEEE standards. The ability of the current control to perform in the grid-connected mode have been presented through the response of the system on tracking capability of varied active and reactive references.

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