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Improvement of Voltage Profile of the Hybrid Power System connected to the Grid

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Abstract— This paper presents the analysis of Renewable Hybrid Power System (Wind Turbine and Solid Oxide Fuel Cell) connected to the Grid and the performances of front-end three phase power Inverter. In order to Inject more power to the Grid Safely, without creating disturbances at the Grid, the Power Conditioning System (PCS) is used. This type of Combination (Wind Turbine and Solid Oxide Fuel Cell) is most efficient and Reliable one. The Solid Oxide Fuel Cell (SOFC) improves the Voltage Profile in the DC link and helps the system to maintain desired Output. An AC-AC Back to Back Converter is used for the Wind – Turbine Power Conversion. A common DC link is connected to the Grid Inverter in order to convert DC to AC, and injects the converted power to the Grid. On the other side of DC link, Wind Turbine Rectifier Circuit and Solid Oxide Fuel Cell DC-DC Converter are connected in Parallel. Hence it is the Cost Efficient one. The Final Power Conditioning System has the Advantages: control of the reactive power, offering a nearly unity power factor operation capability, DC link voltage regulation, fast disturbance compensation capability, high reliability, and low cost. The Control Block diagram for the Hybrid system connected to the grid is modeled and simulated by using MATLAB/SIMULINK.

***Index terms*—** Hybrid System, wind-turbine, Solid oxide fuel cell (SOFC), Power conditioning system (PCS), Grid Interface, permanent magnet synchronous generator (PMSG)

I. INTRODUCTION

Electricity demand is growing continuously all over the word, and this opens a clear path for new forms of producing energy to be strengthened. As the environmental pollution increases, the current policies search for the reduction of toxic emissions and opting for more efficient power generating systems, employing the existing resources in the best way.

The conventions energy sources (Oil, natural gas, and coal) are finite and generate pollution. On the other side, the alternative energy sources (anything other sources than deriving energy via fossil fuel combustion) are clean and abundantly available in nature. Alternative energy sources can help in reducing the dependency on fossil fuels [1].

Various forms of alternative energy sources are: wind, fuel cell, solar, biogas/biomass, tidal, geothermal, hydrogen energy, gas micro turbines and small hydropower farms [2]-[5]. The basic principle of the alternative energy relates to issues of sustainability, renewability and pollution reduction. The low energy conversion and the cost of the photovoltaic systems compared with the wind power promote using the wind power systems. In the recent years, the fuel cell power systems have attracted a lot of attention.

There are different types of synchronous generators, but the multi-pole Permanent Magnet Synchronous Generator (PMSG) is taken for power generation via wind turbine. It offers better performance due to higher efficiency and less maintenance since it does not have rotor current and can be used without a gearbox, which also implies a reduction of the weight of the nacelle and a reduction of costs [6].

The fuel cell generation systems are the most efficient from all the types of alternative sources [7]. In addition, the fuel cell power systems offer low pollution and reusability of exhausted heat [8]. The aforementioned advantages conduct to the forming of a hybrid power system which includes both types of alternative energy: wind and fuel cells. In order to meet the continually increasing demand of alternative power sources, the power conditioning units are necessary.

The main objective of the power conditioning system is to convert DC power from the fuel cell/wind power converter to AC feeding the grid at maximum efficiency. The additional requirement for a power distribution system is to exchange the power between the source and load.

The DC bus capacitor is the prime factor of degradation of power conditioning system reliability. By replacing the DC link electrolytic capacitor (which is bulky, heavy and suffers from the degradation of electrolytic media being a source of failures) the reliability of the system is improved, the size and the cost of the power unit decreasing. The consequence is that of increasing the lifetime of the power converter. The power quality function of the power conditioning system is assured through a proper control of the power system [9]-[10].

II. SYSTEM DESCRIPTION

The grid connected wind turbine fuel cell generating system block is shown in fig.1. This system consists of a wind generator, the fuel-cell generator and the associated power converter units. The power conditioning circuits for the fuel cells consist of DC/DC converters and inverters. The wind turbine pulse-width modulation (PWM) rectifier and the SOFC DC-DC converter outputs are parallel connected forming a common DC link. Therefore, only one DC-AC inverter is necessary in order to grid connect. This topology reduces the cost of the power conditioning unit of the hybrid system. The reasons of using DC-DC converter are: firstly, to boost the DC voltage of the fuel cell in order to assure the compatibility with the existent DC link voltage and secondly, the DC isolation for the inverter. The H-bridge forward converter is well developed and very stable being a matured product. In order to improve the switching loss and to reduce the size of the transformer a soft switching type is necessary.

A) *AC/DC active rectifier*

To prevent the uncontrolled rectifier operation through the freewheeling diodes, the DC link voltage must be higher than the generator peak value. The DC-link voltage is obtained both from the wind generator and the fuel cell. At low speeds, the DC voltage being available from fuel cell, the controlled rectifier ensures the current flow in the intermediate circuit. Additionally, an ultra capacitor or a battery can be inserted in a fuel cell power system side. The vector control scheme assures a variable control of the generator's current vector, as well as the resulting torque.

B) *Fuel Cell Power Conditioning*

The fuel cell is an electrochemical device which produces DC power directly without any intermediate stage. It has high power density and zero emission of green house gases. Fuel cell stacks were connected in series/parallel combination to achieve the rating desired. The main issue for the fuel cell power converter design is the fuel cell current ripple reduction. The problem is solved by introducing an internal current loop in the DC/DC converter control. In order to speed-up the response of the fuel cell DC-DC converter current loop, a load feedforward component is added to the reference, $*\ I\ ffwd$. A buffer battery must be introduced in order to compensate the slow dynamics of the fuel cell.

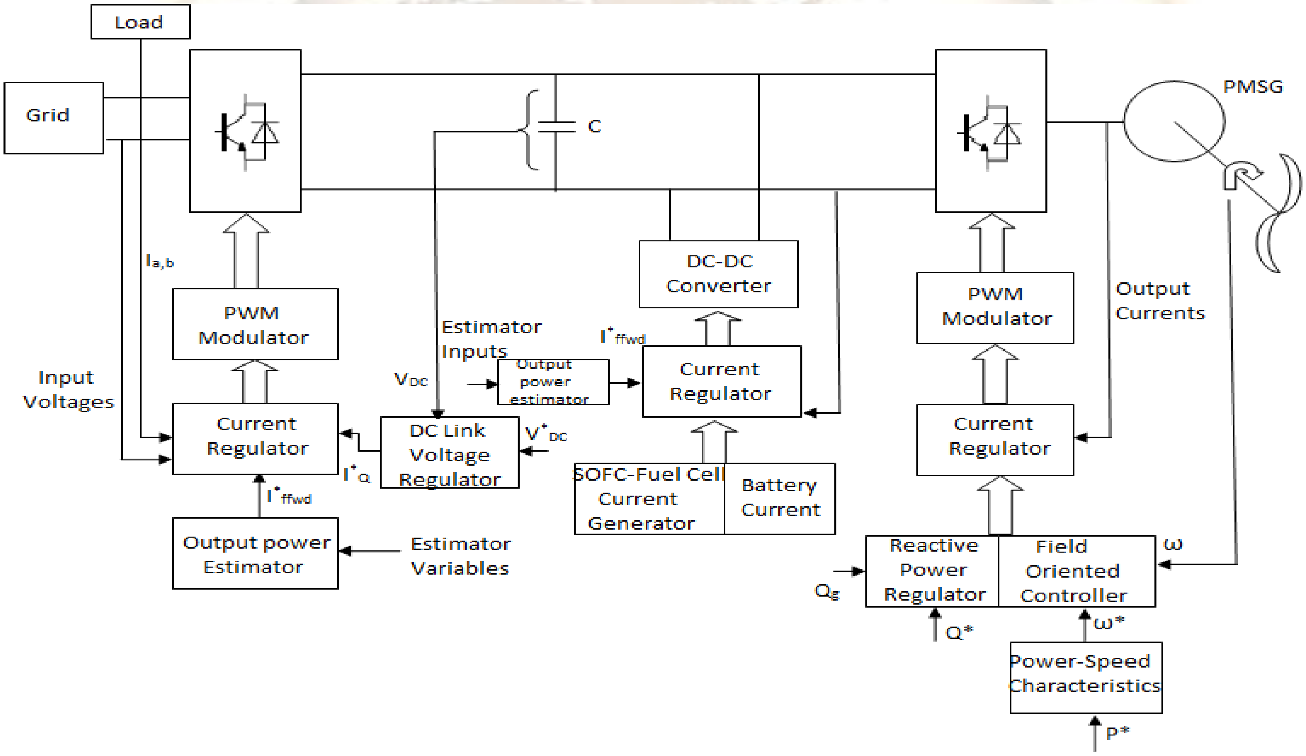

Fig 1. The Block diagram of Grid connected wind turbine/fuel cell power conditioning system

C) *Grid connected inverter*

The output of the fuel cell array was connected to a DC bus by using a DC/DC converter. The DC bus voltage was kept constant via a DC bus voltage controller. The DC bus voltage was then interfaced with the utility power grid and/or a custom load through a three-phase DC/AC inverter, together with its DC link voltage and current regulators. The 50 (Hz) frequency of the grid is assured through a phase-locked loop (PLL) control. The grid converter is a full-bridge IGBT transistor based converter and normally operates in inverter mode such that the energy is transferred from hybrid source to the utility grid and/or to the load.

D) *Grid Interface*

On the grid side a d*i*/d*t* filter limits the rate of current rise during the commutation of the current from a conducting freewheeling diode to a turning-on IGBT. Its main function is the limitation of harmonic currents to a level.

III. GRID INVERTER MODELING

The following assumptions for the system modeling have been made: the AC grid voltages are balanced and distortion free, the inverter switches are ideal, the DC voltage reference is constant, the load is balanced with a 0.86 inductive power load.

The decoupled state model in the *d-q* synchronous reference frame is presented by:

$$\begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} E_q \\ E_d \end{bmatrix} - \begin{bmatrix} \frac{1}{L} & 0 \\ 0 & \frac{1}{L} \end{bmatrix} \begin{bmatrix} V_q \\ V_d \end{bmatrix} \qquad (1)$$

$$C\frac{dV_{DC}}{dt} = I_{inDC} - I_{outDC} \qquad (2)$$

Where:

- the inverter voltage components are denoted by *V*d and *V*q, respectively
- the grid voltage components by *E*d and *E*q, respectively
- the line current components by *i*d and *i*q, respectively
- the DC-link voltage by *V*DC
- the fuel cell output current by *Ifc=IinDC*

A) *DC link*

Assuming that there is no battery storage system connected at the DC link, the total energy delivered by the fuel cells may overcharge the DC capacitor. Neglecting the switching harmonic frequencies on the inverter output currents the following balance energy can be written for the capacitor *C* (Fig. 2)

$$\int_{-\alpha}^{t} \left(V_{DC} i_{fc} - P_c\right) d\alpha = \frac{1}{2} C v^2{}_{DC} \qquad (3)$$

where: *v*DC is the instantaneous DC capacitor voltage (V); *i*fc is the instantaneous fuel cell current (A); *p*c is the instantaneous real power at pulse width modulation voltage source inverter (PWM-VSI) terminals (W).

The energy balance equation (3) shows that the energy stored in the DC capacitor is given by the integral of the instantaneous difference of DC source (fuel cell output) and real power at PWM-VSI terminal powers.

The DC link capacitor voltage (2) becomes:

$$\frac{dV_{DC}}{dt} = \frac{I_{fc}}{C} - \frac{3}{2}\frac{V_d I_d + V_q I_q}{CV_{DC}} \qquad (4)$$

Thus, it is possible to independently control the AC converter currents *I*d and *I*q by acting upon *V*d and *V*q, respectively.

By aligning the *d-q* synchronous reference frame with the input voltage vector, through PLL circuit, the *E*d supply voltage *d*-component becomes zero. Thus, the following equations are available:

$$E_d = 0, \quad E_q = E \qquad (5)$$

where *E* is the maximum value of the grid phase voltage.

IV. GRID INVERTER CONTROL

To achieve full control of the utility-grid current, the DC link voltage must be boosted to a level higher than the amplitude of the grid line-line voltage. The power flow of the grid side inverter is controlled in order to keep the DC-link voltage constant, while the control of the wind turbine side is set to suit the magnetization demand and the reference speed. The structure of the AC/AC converter control system is shown in Fig. 1.

A) *The grid inverter control*

On the basis of a DC voltage reference *V**DC, DC voltage feedback signal (*V*DC), AC input voltages (*E*ab and *E*bc), current feedback signals (*I*a, *I*b), and the load power signal (got through a load power estimator), The DC-AC control (DC link voltage and current loops) system is operated and generates the firing gate signals to the PWM modulator. The task of the DC link voltage and the current regulation has been accomplished by means of the Proportional-Integral (PI) controller type, because of its good steady-state and dynamic behavior with the AC-DC converter. It is important to underline that the PI controller performances are parameters sensitive, because of its design procedure, based on the DC bus capacitor and inductor values. However, in these specific applications, the system parameters values are known with reasonable accuracy.

A phase locked loop (PLL) ensures the synchronization of the reference frame with the source phase voltages by maintaining their *d* component at zero (*E*d=0) through a PI regulator. The control of the grid inverter is based on the minor current loop in a synchronous rotating-frame with a feedforward load current component added in the reference, completed with the DC voltage control loop in a cascaded manner. Using the synchronous rotating frame, the active and reactive power can be controlled independently by proportional-integral (PI) current controllers that ensure zero steady state error. The load feedforward was introduced in order to increase the dynamic response of the bus voltage to changes in load. The load feedforward component is added to the current reference of the grid inverter in order to ensure the power balance between the source converter and the load converter. Thus, improved performances are obtained during the transients. For fast control response to load changes, the feedforward component has been introduced in the inner control loop of the system. The consequence is the low-level DC voltage variation.

1) *Design of the current PI controller with direct compensation of the disturbance and decoupling of the q-d axes*

In order to improve the converter performances of the converter, it is necessary to decouple the two axes. Moreover, the main voltages components *E*D and *E*Q represent the disturbance signals that act on the system. Such voltages have been already measured from the system because they serve to the reference frame rotational angle. Therefore, it is possible to perform the direct compensation of such disturbances. The *d*-*q* axes decoupling is obtained by canceling the (ω· *L*) signal, that acts on *d* axis, and the (-ω· *L*) one, that acts on *q* axis. Due to the *d*-*q* axes decoupling, the transfer function of the system under control, *P*dis(s), will become an integrator

$$P_{dis}(s)=\frac{V^*{}_Q}{I^*{}_Q}=-\frac{1}{Ls} \qquad (6)$$

Thus, theoretically speaking, a pure proportional controller could be used since the transitory null error is already assured from the integral system under control. But in order to have a robust control system to disturbs, the use of a proportional integral controller is preferred. The control system under the hypothesis that the *q*, *d* axes are decoupled and with direct compensation of the disturbances, turns out

$$P_{dis}(s)=-\frac{1}{Ls} \qquad (7)$$

The transfer function of the PI controller is

$$C_{PIc}(s)=K_{pc}\left(1+\frac{1}{T_{ic}s}\right) \qquad (8)$$

The calculation of the *PI* controller coefficients, *K*pc (proportional gain) and *T*ic (integral time), is done imposing the phase margin φmc (in radian) and the bandwidth, ωc, (in radian per second). Imposing these two conditions, the following relations for *K*pc and *T*ic are obtained

$$\left.\begin{aligned} T_{ic}&=\frac{1}{\omega_c\tan\left(-\frac{\pi}{2}-\phi_{mc}\right)}\\ K_{pc}&=\frac{-T_{ic}\omega_c{}^2L}{\sqrt{1+(T_{ic}\omega_c)^2}} \qquad (9)\end{aligned}\right\}$$

Where the module and the phase (in radian), *M* and φ*c*, of the system *P*dis(s) under control were replaced by *M=1/L* ωc and φ*c* = -*π*/2 . The negative sign in the formulas derives from the fact that the gain of the system under control is negative. Because of the *d*-*q* axes control symmetry, the *d* axis controller is set-up exactly with the *q* axis controller parameters.

2) *Design of DC-link voltage controller*

For the voltage control loop designing, the *d* current component is assumed to be null.

Figure 2 shows a block diagram of a proposed scheme to transfer the energy from the DC capacitor to the AC system controlling the voltage across the DC capacitor, where Δ*VDC* is the deviation of the DC voltage.

The capacitor voltage, Δ*VDC* , is measured and compared with a reference voltage, * Δ*VDC* . The output, * *Q* Δ*I* , of the voltage controller, *C*PIv(s), is the desired deviation of the *q* current component Δ*I** *Q* . The transfer function of the system under control between Δ*I** *Q* and Δ*VDC* (i.e. *P*v(s)) is as follows

$$P_v(s)=\frac{\Delta V_{DC}}{\Delta I^*{}_Q}=\frac{K_{pc}(T_{ic}s+1)(k_3Ls-k_2)}{(T_{ic}Ls^2-K_{pc}T_{ic}s-K_{pc})(s-k_1)} \qquad (10)$$

where *k*1, *k*2, *k*3 are the specific constants.

The total linearized system (10) includes also the current loop.

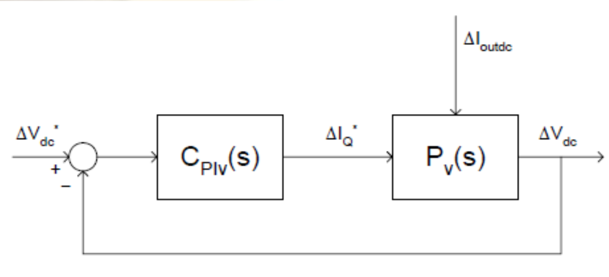

Fig 2. Block Diagram of Control System

The calculation of the controller coefficients, *K*pv (proportional gain) and *T*iv (integral time), is made imposing the following two conditions:

1. The phase magnitude φmv (in radian)
2. The bandwidth ωcv (in radian per second)

The *K*pv and *T*iv controller parameters calculation are obtained in the same manner as in the current PI controller design case.

B) *The active rectifier control*

To control the generator speed (coupled to the wind-turbine through a gearbox) the speed output characteristic can be used. The control is performed in rotor field oriented reference frame. The active and reactive power errors are processed by the PI controllers to obtain *d*-*q* current references. After adding a compensation term (in order to obtain a decoupled control), the final current references are obtained, then they are compared with the measured currents. By using other *PI* stage the corresponding PWM reference voltages are obtained.

V. EXPERIMENTAL RESULTS

The control block diagram of the Grid connected wind turbine/fuel cell power conditioning system (fig.1) is implemented by using the MATLAB SIMULINK.
The control block diagram is simulated at different values of wind speed, as it varies with respect to time. With and Without using the Solid Oxide Fuel Cell (SOFC) are simulated separately.

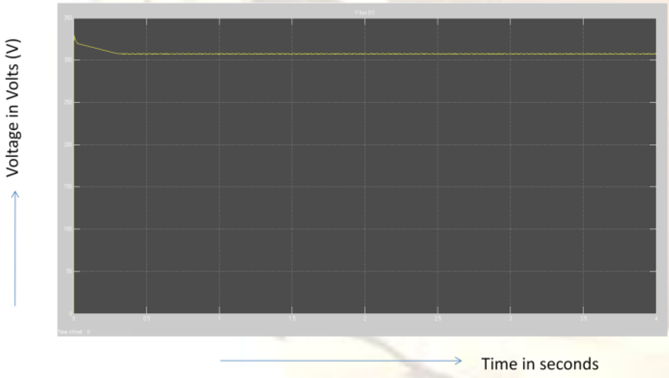

Fig 3. DC link voltage profile when SOFC not connected

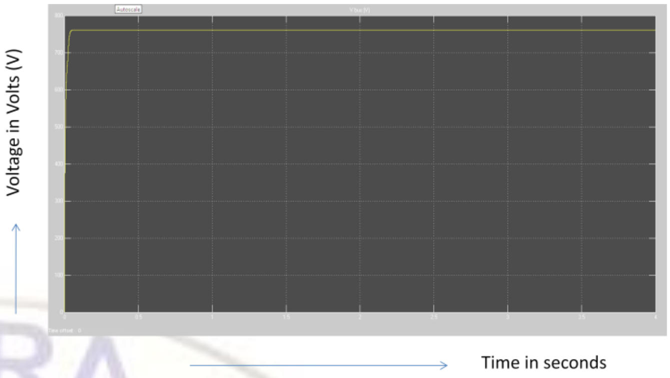

Fig 4. DC link voltage profile when SOFC is connected

The System is simulated with and without the SOFC (fig.3 and fig.4). The DC link voltage profile variation happens. When SOFC is connected in parallel to the Wind turbine, the voltage profile is boosted. The DC link voltage is greater than the grid voltage.

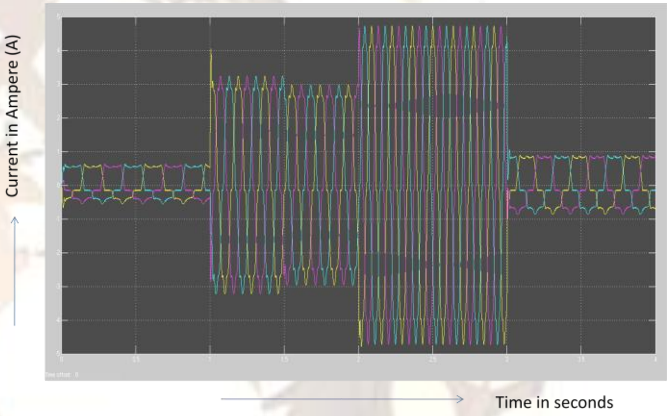

Fig 5. Wind Generator output currents

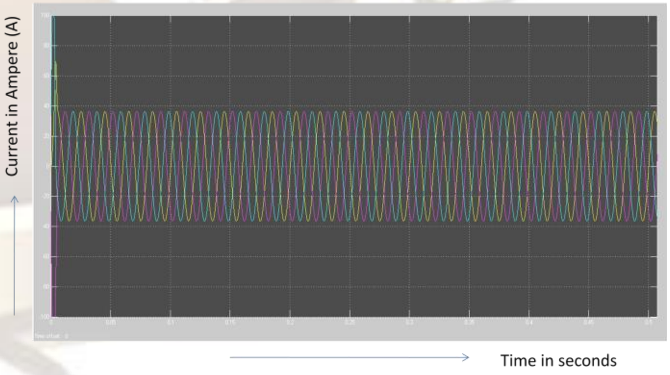

Fig 6. Grid inverter currents

The currents at the wind generator side and the inverter side are shown in fig.5 and fig.6. At the time the generator not able to supply the desired current, the current drawn from the SOFC. The current drawn by the load at different load conditions are tabulated in Table.1.

Load (MW)	Load current (A)	DC Link Voltage (V)
1	361	761
0.8	358	761
0.4	345	761
0.1	245	761

Table 1. Currents at Inverter side for different load conditions

The DC link voltage is maintained constant for different load conditions because of the SOFC, as it has the capability to supply instantly.

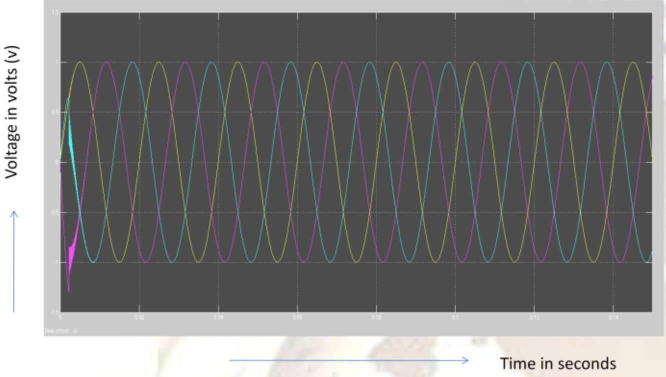

Fig 7. Inverter Voltages at the grid side

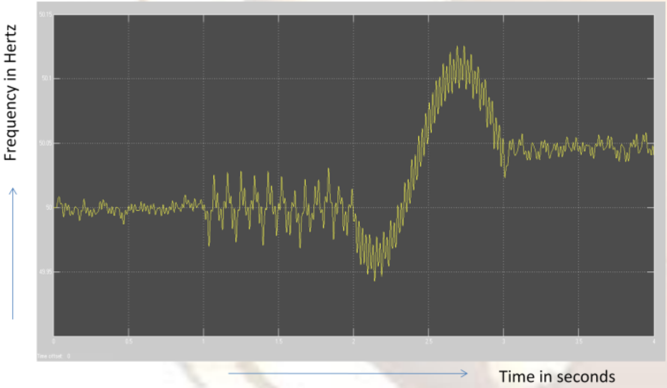

Fig 8. Frequency of the system without power conditioning system

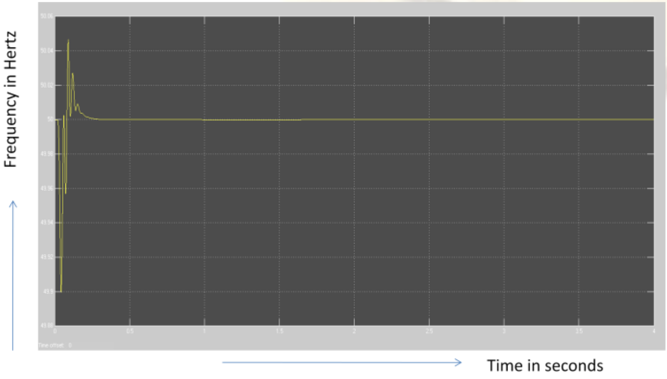

Fig 9. Frequency at the grid with Power conditioning system

The frequency of the system is getting smoothed after it is equipped with Power conditioning system(fig.8 and fig.9).
Figure 7 shows the experimental steady state phase voltage of grid connected PWM-VSI supplying active power to the utility AC system. The control presents above works properly under distorted unbalanced line voltage.
The trace of A phase of the line current is in phase with A phase of the grid inverter voltage, which clearly demonstrates unity power factor operation from fig.6 and fig.7.

VI. CONCLUSIONS

This topology assures a constant DC link voltage, integration of the alternative energy into the grid, the power quality issues, active and reactive decoupled power control, grid synchronization.
A simple and efficient current regulator design of grid inverter assures a fast disturbance rejection resulting in low DC-link ripple voltage. Maintaining a constant DC link voltage the DC link current follow the load level requirements.
The grid connected inverter has the advantages like constant DC-link voltage, nearly unity efficiency, zero displacement between voltage and current fundamental component, disturbance compensation capability, fast control response and high quality balanced three-phase output voltages.

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