Load Current Observer and Adaptive Voltage Controller for Standalone Wind Energy System with Linear and Non-linear Loads

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Abstract: The Wind Energy Conversion System (WECS) is one of the most important renewable energy systems in the existing power network, which can be operated in either grid connected or standalone mode. In the standalone WECS, voltage and frequency variations are more due to the wind speed variations, load changes and switching surges. In this paper, space vector pulse width modulation based adaptive voltage controller with load current observer is used to control the voltage and frequency, for the standalone or isolated WECS. The isolated system is simulated using MATLAB/Simulink and the results are analysed when three-phase non-linear and linear (Resistive and Inductive) balanced and unbalanced loads are connected.

Keywords: Isolated Wind Energy conversion system, Space Vector Pulse Width Modulation, Adaptive Voltage Controller, Load Current Observer, Total Harmonic Distortion .

I. INTRODUCTION

The electrical load demand is increasing due to the raise of world population, expansion of industries and raise of commercial loads etc. The required large amount of power is generated at large scale power plants from non-renewable energy sources (fossil fuels) such as coal, oil, and natural gas etc. (Source: Department of Energy 2017 Power Statistics). When the power is generating from the fossil fuels, they can release carbon dioxide, sulphur dioxide, nitrogen oxides and toxic chemicals. It leads to global warming, polluting air and water. Therefore, people suffer from asthma, cancer, heart and other health problems. To reduce all these effects and per unit cost of electricity and to reach the increasing electrical load demand, all the countries looking towards the renewable energy sources such as solar energy, wind energy, geothermal energy, tidal energy and bio fuel energy. The renewable energy sources are freely available in nature and they are environmental friendly. The renewable energy based power plants installation, operation and maintenance costs are less compared to the conventional. They require less installation time because ready made parts are available in the market and are less complex.

The wind energy is one of the most prominent renewable energy sources to generate electrical energy. The wind energy conversion systems (WECS) are not only used to meet the load demand on interconnected power system network but also for electrification of some isolated areas from the power system network such as islands, rural villages, ships and military requirements [1-2].

The functional block diagram of an isolated WECS is shown in Fig.1. The system has wind turbine-generator which is to convert kinetic energy of the wind to electrical energy. AC to DC converter is to convert variable AC to variable DC voltage, three-phase DC to AC converter is used to convert DC to regulated three-phase AC voltages. The regulated three-phase power supply is connected to isolated load through LC filter. The LC filter components are used to reduce the voltage and current ripples. The energy storage system is connected through DC-DC converter. The power flow directions are represented by continuous line arrows and the control signals from controller to converters/inverter are represented by dotted line arrows as shown in the Fig.1.

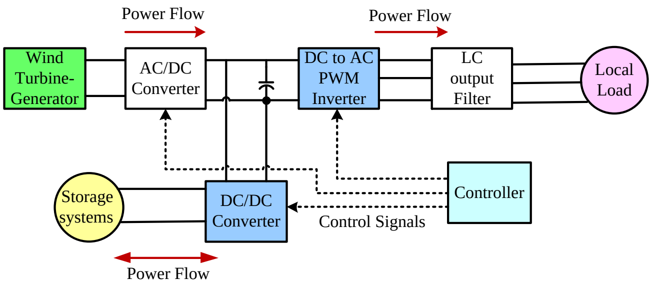

Fig.1. Functional block diagram of an isolated WECS.

As per the literature, various control schemes have been proposed for the regulation of inverter output voltage. A hybrid iterative learning controller (parallel connection of direct iterative learning controller and PD controller) has been designed to improve the dynamic response of the system during the sudden change of loads [3]. But, the controller proposed in [3] uses many loops which increases the complexity of the system and response time. A predictive controller has been designed to forecast the behavior of output voltage and load current at each sampling period [4], where switching states depends on the cost function. This controller forecast the voltage and current under linear load variations but it is not suitable for the sudden and large change of loads.

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A load side converter controller has been designed for load side voltage and frequency control in standalone wind energy conversion systems [5]. In this system a dummy load is connected to stabilize the frequency and it leads to continuous power loss.

A flatness-based controller has been designed for better steady-state and transient behavior of renewable energy conversion systems [6]. It is suitable only for the large rating isolated and / or grid connected systems.

All the above discussed systems were tested with either linear loads or non-linear loads. The most practical scenario is the use of linear and non-linear loads together, this paper considers the same. In this paper, an adaptive voltage controller is used for the performance analysis of an isolated WECS connected to the combination of linear and non linear loads. The adaptive voltage controller operation and performance depending on the reference adaptive control theory [7].

II. SYSTEM DESCRIPTION

In the Functional block diagram of an isolated WECS shown in Fig. 1, the generated voltage and frequency are not constant because of load and wind speed changes. The variable power is converted in to DC power using AC to DC converter and it is fed to the DC link. If the generated power is greater than the load, the excessive power is stored in the energy storage system through DC-DC converter and when the power is less than the load the required power is supplied by the energy storage system. It shows that the energy storage system regulate the voltage and frequency variations and improve the system stability. It shows that the DC link voltage is maintained as constant and it is represented by DC voltage source as shown in the Fig. 2.

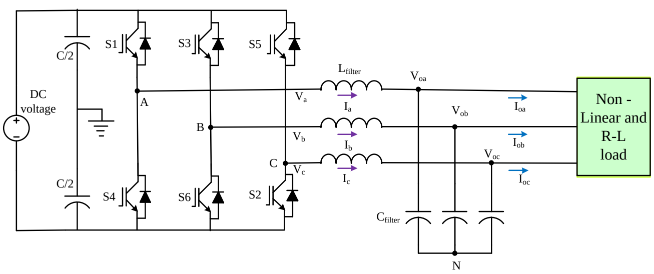

Fig.2. Schematic circuit diagram of wind energy conversion system connected to an isolated linear and non-linear load.

The DC link has voltage ripples because instantaneous voltage at DC link has DC voltage component, high frequency voltage component and low frequency voltage component. The low frequency components are neglected under balanced loads but they should be considered under unbalanced loads. The DC link capacitors are used in the power electronic converters to reduce the voltage ripples. The capacitor is also used for balancing the power between source and load [8].

The three-phase inverter is a converter which converts a DC voltage or current to three-phase AC voltages or currents with variable magnitudes and/or frequency. It has three legs and each leg has two switches. In any leg, if one switch is turned ON, in the same leg another switch is turned OFF. The switching possibilities are 8 (i.e., 2^3) since the three-phase inverter has three legs. The variable magnitudes and/or frequency of voltages or currents of inverter are obtained by Pulse Width Modulation (PWM) technique. The switching frequency of IGBT based inverters can be used in between 3 kHz to 15 kHz and for MOSFET based inverters it is in between 10 kHz to 100 kHz [9].

Now-a-days, inverter with low pass LC filter is used in many applications such as Isolated and/or grid connecter renewable energy conversion systems, uninterruptible power supply (UPS), active filters, dynamic voltage restorers and many more applications. The low pass LC filter is used to attenuate the output voltage ripples and control the high frequency current ripples of the inverter switches.

The output of the inverter is connected to the load through the passive filter. In the isolated power system the types of loads are residential, commercial, agriculture and small scale industrial loads. It shows that the load may be linear and / or non-linear, balanced and / or unbalanced load. The loads may be suddenly connected to the WECS or may be suddenly disconnected from the system as per the requirements. Therefore, the inverter output voltages and currents have more harmonics. The effect of these harmonics could be minimized by using suitable controller.

In this paper, an adaptive voltage controller along with the load current observer is used to reduce the voltage, current ripples and total harmonic distortion at various loads. The explanation about the controller is detailed in the next section.

III. PROPOSED CONTROLLER

The schematic block diagram of WECS controller is shown in Fig. 3. The proposed controller consists of three parts *viz.* load current observer, adaptive voltage controller and the space vector PWM (SVPWM). The load side phase currents are sensed and are supplied to the controller. The measured load currents are fed to the load current observer, it gives stationary d-axis and q-axis currents (I_{dqo}). Depending on the currents (I_{dqo}), the adaptive voltage controller produce time variant voltage signals ($V_{\alpha\beta 0}$). The voltage signals ($V_{\alpha\beta 0}$) are fed to the space vector pulse width modulator to generate the modulated pulses. The pulses are then given to the three-phase inverter switches. A brief explanation is given about the load current observer, adaptive voltage controller and space vector pulse width modulator in the following subsections.

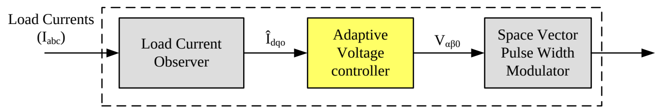

Fig. 3. Proposed controller block diagram

A. Load Current Observer

The optimal load current observer (LCO) is shown in the Fig. 4. In the controller, direct and quadrature axis voltages (V_{od}, V_{oq}), currents (I_{od}, I_{oq}), initial estimations of the voltages ($\hat{V}_{od}$, $\hat{V}_{oq}$) and currents($\hat{I}_{od}$, $\hat{I}_{oq}$) are the inputs. From the controller, final estimated currents are obtained based on the load variations using the state equation [7].

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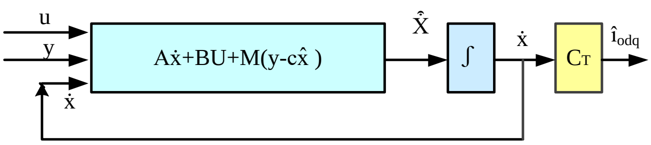

Fig. 4. Block diagram of load current observer (LCO).

The dynamic modeling of the load current observer is as follows:

$$\dot{x} = Ax + Bu \quad (1)$$

$$\text{Where } x = \begin{bmatrix} I_{od} \\ I_{oq} \\ V_{od} \\ V_{oq} \end{bmatrix} \quad A = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -1/C_{filter} & 0 & 0 & -\omega \\ 0 & -1/C_{filter} & -\omega & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 1/C_{filter} & 0 \\ 0 & 1/C_{filter} \end{bmatrix} \quad u = \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix}$$

The load current observer output current represented as

$$\dot{\hat{x}} = A\hat{x} + My - M\hat{C}x + Bu \quad (2)$$

$$Y = CX \quad (3)$$

$$\hat{I}_{odq} = \begin{bmatrix} \hat{I}_{od} \\ \hat{I}_{oq} \end{bmatrix} = C_T \hat{x} \quad (4)$$

(4)

Where $\hat{I}_{od}$, $\hat{I}_{oq}$ are estimations of I_{od}, I_{oq}

$$\hat{x} = \begin{bmatrix} \hat{V}_{od} \\ \hat{V}_{oq} \\ \hat{I}_{od} \\ \hat{I}_{oq} \end{bmatrix} \quad C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad C_T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}$$

B. Adaptive Voltage Controller

The voltage controller performance can be decided by the reference parameters [6]. In the conventional adaptive voltage controller, the reference parameters considered are inverter output voltages sensed before and after the filter, inverter or load currents. However, the proposed adaptive voltage controller in conjunction with the load current observer does not need any voltage sensors, which could reduce the complexity and cost of the system. The values of inverter output or load currents are crucial in the considered system, because of the linear and non-linear loads connected together. The estimated parameters from the load current observer are compared with the reference parameters and the error signal is generated which is compensated using below given procedure.

The compensation and the feedback control parameters say y_{cd} & y_{cq} and y_{fd} & y_{fq} respectively are used as adaptive control laws for the considered WECS. These control parameters can be represented in terms of adaptive gains g_{id} and g_{iq}.

$$y_{cd} = \sum_{i=1}^{4} g_{di} P_{di} + V_{ld}, y_{fd} = -\partial_d \gamma_d \quad (5)$$

$$y_{cq} = \sum_{m=1}^{4} g_{qi} P_{qi} + V_{lq}, y_{fq} = -\partial_q \gamma q \quad (6)$$

The adaptive gains g_{id} and g_{iq} can be defined as follows:

$$g_{id} = -\frac{1}{\theta_{id}} \int_0^t P_{di} \gamma_d \, d\tau \quad (7)$$

$$g_{iq} = -\frac{1}{\theta_{iq}} \int_0^t P_{qi} \gamma_q \, d\tau \quad (8)$$

And the functions γ_d and γ_q can be defined as:

$$\gamma_d = \bar{V}_{ld} + \beta_d \bar{I}_{id} \quad (9)$$

$$\gamma_q = \bar{V}_{lq} + \beta_q \bar{I}_{iq} \quad (10)$$

where, β_d and β_q are positive design constants, g_{id} and g_{iq} are the estimated values for g^*_{id} and g^*_{iq}, δ_d is greater than 0, δ_q is greater than 0, Θ_{di} is greater than 0, and Θ_{qi} is greater than 0.

The adaptive gains given in equations (7) and (8) can be tuned to larger values so as to realize the quicker convergence and better transient response. Hence, the values selected for Θ_{di} and Θ_{qi} must be smaller values as per the relation between adaptive gains and Θ_{di} and Θ_{qi} which is inverse relation. In addition, the control parameters β_d, β_q, δ_d, and δ_q can be calculated with respect to the tuning rule. All the above mentioned parameters are calculated as shown in Fig. 5. These calculations are continued till the desired transient response is obtained and the solution is converged.

C. Space Vector Pulse Width Modulator

The DC-link voltage ripples can be analyzed by Space Vector Pulse Width Modulator (SVPWM). In SVPWM, there exist eight switching combinations, from these switching combinations, six are active and remaining two are zero voltage switching combinations. The reference voltage vector (V_{ref}) is generated by two active and two zero switching voltages in every switching time (T_s). The reference voltage vector is obtained by using the estimated values of voltages from the adaptive voltage controller. The space vector diagram has six sectors and each sector is divided into 'N' equal switching intervals. If T is the time duration for complete cycle of output voltage, each switching interval time is T /N seconds. Consider T_1 is the time period of space vector voltage V_1 and T_2 is the time period of space vector voltage V_2 [10].

From the Fig.6 the following equations can be derived.

Magnitudes of voltage vectors represented as

$$|V_1| = |V_2| = \frac{2}{3} V_{in}$$

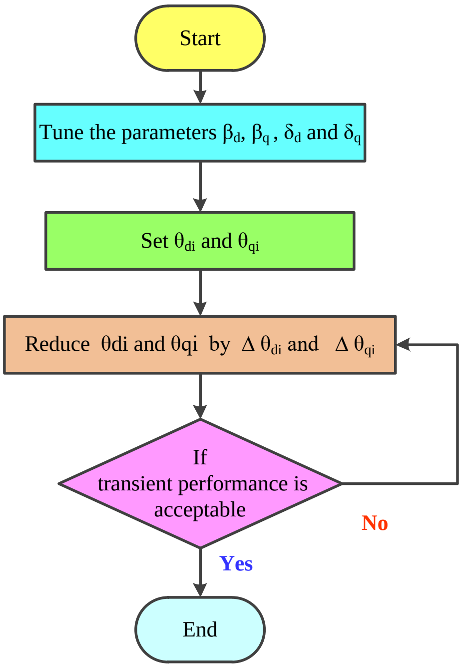

Fig.5: Flow chart of operation of the adaptive controller

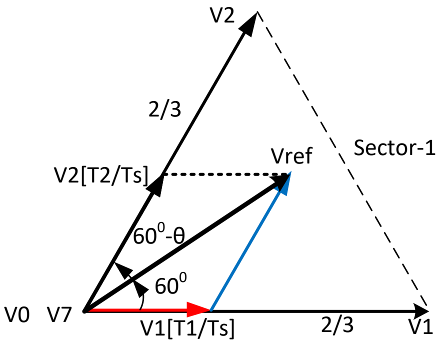

Fig. 6. Sector-1 of space vector diagram.

The time interval of voltage vector V_1 is represented as

$$T_1 = \frac{\frac{2}{\sqrt{3}}\left|V_{ref}\right|\sin(60^0-\theta)}{\frac{2}{3}V_{in}}T_s = T_s m_a \sin(60^0-\theta) \quad (11)$$

The time interval of voltage vector V_2 is represented as

$$T_2 = \frac{\frac{2}{\sqrt{3}}\left|V_{ref}\right|\sin\theta}{\frac{2}{3}V_{in}}T_s = T_s m_a \sin(60^0) \quad (12)$$

Where amplitude modulation factor = $m_a = \frac{\sqrt{3}\left|V_{ref}\right|}{V_{in}}$

If the reference voltage vector located in any sector, the following equations give the time intervals.

$$T_1 = T_s m_a \sin(60^0-\theta-(\frac{n-1}{3})\Pi) \quad (13)$$

$$T_2 = T_s m_a \sin(60^0-(\frac{n-1}{3})\Pi) \quad (14)$$

Where n is sector number = 1, 2, 3, 4, 5, 6

IV. RESULTS AND DISCUSSION

The isolated wind energy conversion system which is shown in Fig. 2 is simulated with the combination of linear and non-linear three-phase loads under balanced and unbalanced load conditions using MATLAB/Simulink. The simulation results and corresponding output voltages, currents and total harmonic distortion (THD) are shown in the Fig.7 to Fig.12. The simulated system parameters are shown in Appendix.

i. Balanced three-phase non-linear and linear (R-L) load in case of circuit breaker set to close at t=0.1 seconds.

The simulation results of isolated wind energy conversion system with controller (Shown in Fig.2) are shown in Fig. 7 for balanced non-linear load and R-L load. The Fig.7 consists of 3-phase load voltages (V_{oabc}), 3-phase load currents(I_{oabc}), source side d and q-axis voltages (V_{sdq}), 3-phase source currents (I_{sabc}) and transformed controller currents (I_{tran}) from dqo to abc reference frame.

For the simulation results analysis, the circuit breaker set to close at t=0.1 seconds it means that the circuit breaker initially kept open. From the results it is observed that before switching (i.e. circuit breaker kept opened), the output load currents and controller transformed currents are equal to zero. After switching (i.e. circuit breaker is closed), controller transformed currents are balanced but load currents are non-linear because non-linear loads. The output voltage Total Harmonic Distortion (THD) is determined as 2.63% shown in Fig.8 and the load current THD is determined as 18.99% shown in Fig. 9. The value of THD for load current is higher because of the combined use of linear and non-linear load.

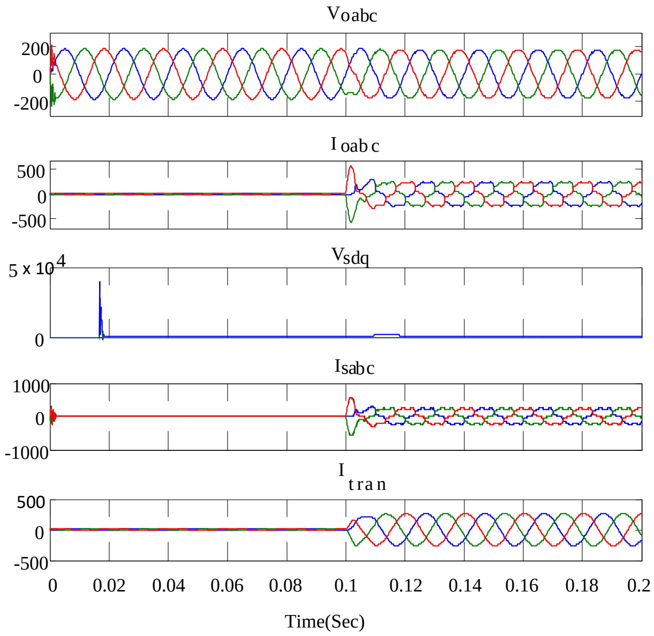

Fig. 7. Simulation results of WECS with the proposed controller in case of non-linear and R-L balanced load, the circuit breaker closed at t=0.1 seconds.

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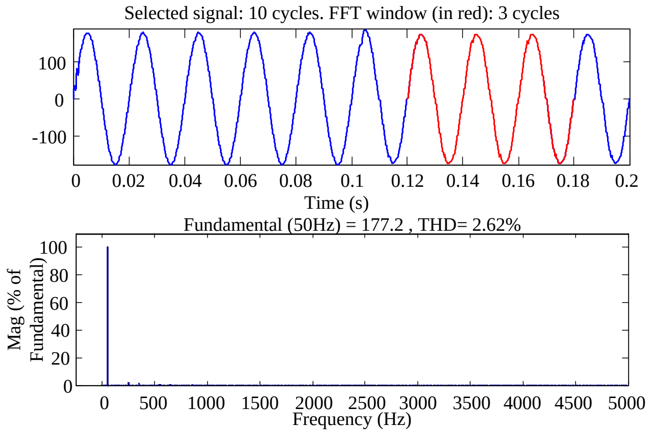

Fig. 8. THD of output voltage (Phase-A) of WECS with the proposed controller in case of non-linear and R-L balanced load , the circuit breaker closed at t=0.1 seconds.

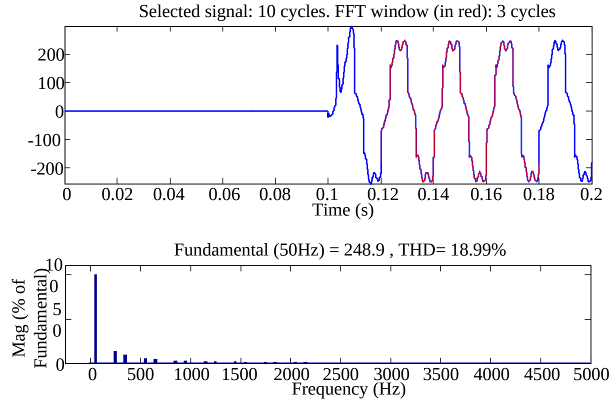

Fig.9. THD of output current (Phase-A) of WECS with the proposed controller in case of non-linear and R-L balanced load, the circuit breaker is closed at t=0.1 seconds.

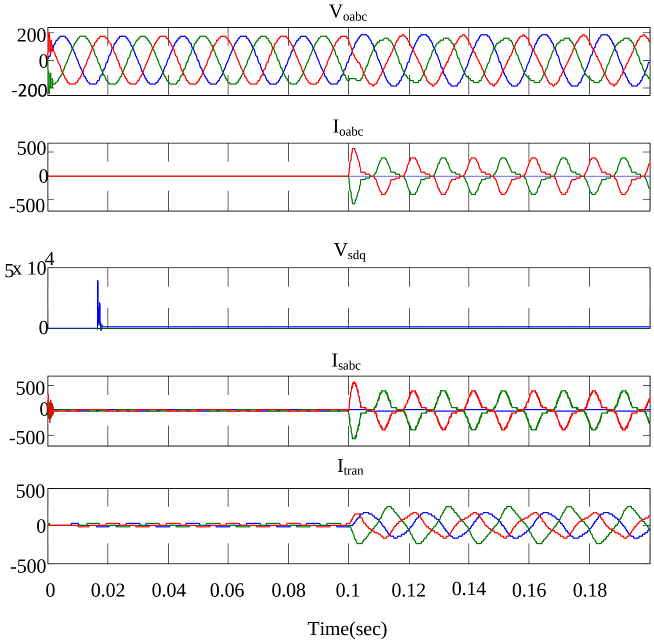

Fig.10. Simulation results of WECS with the proposed controller in case of non-linear and R-L unbalanced load (Phase-A is open), the circuit breaker closed at t=0.1 seconds

ii. Unbalanced three-phase non-linear and linear (R-L) load in case of circuit breaker set to close at t=0.1 seconds

For the unbalanced WECS analysis, the phase-A of three-phase load is kept open. The simulation results of the WECS with adaptive voltage controller with unbalanced load are shown in Fig.10 when the circuit breaker set to close at t=0.1seconds. The THD of output voltage is obtained as 0.41% shown in Fig.11 and load current (either Phase-B or Phase-C) obtained as 31.19% shown in Fig.12.

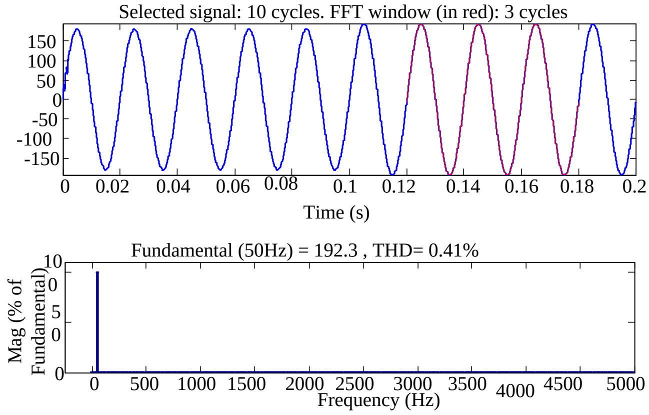

Fig.11. THD of output voltage (Phase-A) of WECS with the proposed controller in case of non-linear and R-L unbalanced load, the circuit breaker is closed at t=0.1 seconds

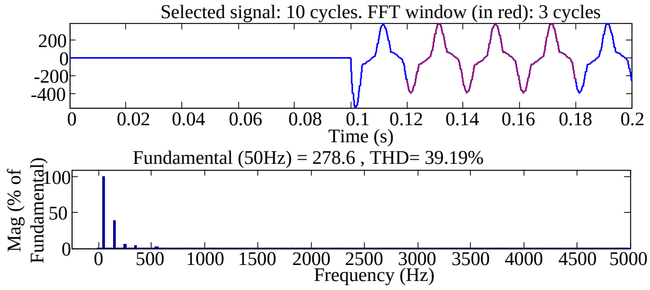

Fig.12. THD of output current (Phase-B) of WECS with the proposed controller in case of non-linear and R-L unbalanced load, the circuit breaker is closed at t=0.1 seconds.

V. CONCLUSION

An adaptive voltage controller in conjunction with the load current observer and the space vector modulator is proposed in this paper for a standalone wind energy conversion system. The load current observer is used to observe the variations in load and the supply, hence estimating the d-q axis load current using state space model. Later, the adaptive voltage controller regulates the output voltage using the data attained from the load current observer. The adaptive controller drives the space vector PWM to operate the inverter. The proposed controller is tested and the results are presented for linear and non-linear load conditions under balanced and unbalanced conditions. The obtained results are satisfactory and depict the working of the proposed controller.

APPENDIX

DC Supply Voltage (VDC) = 564 Volts
Filter Inductance (L filter) = 0.3 mH
Filter Capacitance (C filter) = 500 µF
Inverter Output frequency (f) = 50Hz
Non-linear load:

Full-bridge diode rectifier connected to
Resistor(R) =1.2 Ohms
Inductor(L) = 0.3mH
Capacitor(C) = 4000µF load.
R-L Load:
Resistor(R_L) = 0.726 Ω Ohms
Inductor(L_L) = 0.3mH

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