Voltage and Frequency Controller for a Small Scale Wind Power Generation

Bhim Singh[1] and Gaurav Kumar Kasal[1]

Abstract – This paper deals with the control of voltage and frequency of a wind turbine driven isolated asynchronous generator (IAG). The proposed voltage and frequency controller consists of an IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter along-with a battery energy storage system at its DC bus. The controller is having bidirectional flow capability of active and reactive powers by which it controls the system voltage and frequency with variation of consumer loads and the speed of a wind turbine. For a constant frequency operation, the asynchronous generator operates at almost constant speed (small range of slip). In addition to voltage and frequency control it is also having capability of harmonic elimination and load balancing. The proposed electro-mechanical system with its controller is modeled and simulated in MATLAB using Simulink and PSB (Power System Block-set) toolboxes.

Key-words – Isolated Asynchronous Generator, Wind Energy Conversion System, Battery Energy Storage System, Voltage and Frequency Controller.

I. INTRODUCTION

There has been an exponential increase in the energy demand during the last few decades, which has accelerated the depletion of the world fossil fuels. Environmental concerns and international policies are supporting new interests and developments of small scale renewable power generation [1, 2]. It is reported in the literature that in small scale wind and hydro power generation, a capacitor excited squirrel cage asynchronous generator (CEAG) which is also known as a self excited induction generator (SEIG) is a most suitable candidate because of its low cost, robustness, less maintenance and high power density (W/kg) and can be used for single phase and three phase power distribution [3, 4]. However the magnitude and frequency of the generated voltage depends upon the rotor speed, the amount of excitation and the load (magnitude and power factor).

As a renewable energy source the wind power is one of the prominent energy sources and various types of electrical generators such as synchronous generator, asynchronous generators in squirrel cage and slip ring rotor construction [3-6], reluctance generators [7] have been reported in stand alone applications. However, because of simplicity of the squirrel cage asynchronous generator it is widely used and recommended for wind power generation. In the literature, various attempts have also been made to develop the mathematical models in steady state, dynamic and during the period of transient for isolated wind energy conversion system using capacitor excited asynchronous generators [8-10].

In this paper, a voltage and frequency (VF) control scheme is proposed for an isolated capacitor excited asynchronous generator (CEAG) driven by wind turbine. The proposed control scheme presented in this paper optimized the cost of the system by requiring reduced number of current sensors along with giving the faster response of the controller compared to scheme presented in ref [10]. The performance of the controller is investigated in different dynamic conditions such as wind speed variation and application of balanced/unbalanced non-linear loads in MATLAB using Simulink and PSB toolboxes. The proposed voltage and frequency controller is realized using IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter (VSC) along with battery energy storage system (BESS) [11-13] at its DC bus and functioning as a load balancer and a harmonic eliminator.

II. SYSTEM CONFIGURATION AND PRINCIPLE OF OPERATION

Fig. 1 shows the schematic diagram of the proposed CEAG system driven by wind turbine along-with its controller, excitation capacitor and consumer loads. The proposed controller consists of an IGBT based voltage.

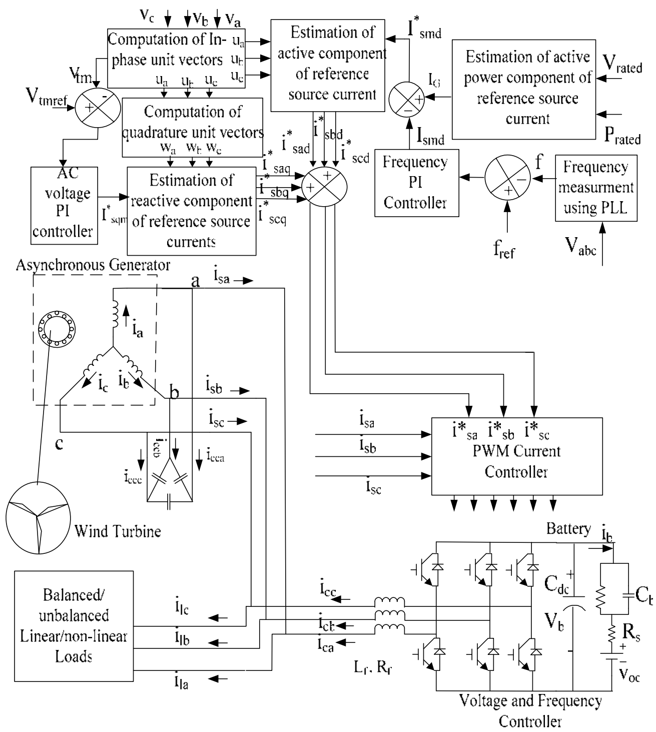

Fig.1:Schematic diagram of VF controller for an isolated asynchronous generator driven by wind turbine

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There is a source converter along-with a battery energy storage system at its DC bus. The delta connected capacitor bank is used to generate the rated voltage at no load while additional demand of the reactive power is met by the controller. The proposed controller is having bidirectional flow capability of active and reactive powers and it controls the voltage by controlling the reactive power while the frequency is controlled by the active power control.

The basic principle of its operation is that at high wind speeds the generated power is also high and accordingly for frequency regulation the total generated power should be consumed otherwise difference of mechanical and electrical power is stored in the revolving components of the generator and by which the speed of the generator and in turn it increases the output frequency. Therefore this additional generated power is used to charge the battery to avoid the frequency variation as stated above. During deficiency of the generated power, when there is an insufficient wind power to meet the consumer demand an additional required active power is supplied by the battery to the consumer loads. In this manner, the battery energy storage system based voltage and frequency controller also provides load leveling and frequency regulation.

III. Control Strategy

As shown in Fig. 1, the control strategy of the proposed voltage and frequency controller is based on the generation of reference source currents. Three-phase reference source currents are having two components one is in phase or active power component (i^*_{sad}, i^*_{sbd}, i^*_{scd}) for regulating the frequency while other one is in quadrature or reactive power component (i^*_{saq}, i^*_{sbq}, i^*_{scq}) for regulating the voltage. For generating the active power component of reference source current, the output of the frequency PI (Proportional-Integral) controller (I_{smd}) is compared with the rated generator current (I_G) and the difference in these two currents is considered as an amplitude of in-phase component of reference current (I^*_{smd}). The multiplication of I^*_{smd} with in-phase unit amplitude templates (u_a, u_b and u_c) yields the in-phase component of reference source currents. These templates (u_a, u_b and u_c) are three-phase sinusoidal functions, which are derived by dividing the filtered AC voltages v_a, v_b and v_c using band pass filter by their amplitude V_t. To generate the quadrature component of reference source currents another set of sinusoidal quadrature unity amplitude templates (w_a, w_b, w_c) is obtained from in-phase unit templates (u_a, u_b and u_c). The multiplication of these components with output of AC voltage PI controller (I^*_{smq}) gives the quadrature or reactive power component of reference source currents. The sum of instantaneous quadrature and in-phase component of source currents is the reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}), and these are compared with the sensed source currents (i_{sa}, i_{sb}, i_{sc}). These current error signals are amplified and amplified signals are compared with fixed frequency triangular carrier wave to generate the PWM signals for switching of the devices of the voltage source converter used in the controller.

Basic equations of the control scheme for BESS based voltage and frequency controller is given as follows.

A. In Phase Component of Reference Source Currents

In-phase component of reference source current is calculated by taking the difference of rated generator current (I_G) and output of the frequency PI controller (I_{smd}). The frequency error is defined as

$$fer(n) = fref(n) – f(n) \tag{1}$$

where f_{ref} is reference frequency (50Hz in present system) and f is the frequency of the voltage of an asynchronous generator. The instantaneous value of 'f' is estimated using PLL (Phase Locked Loop) on the terminal voltage.

At the n^{th} sampling instant, the output of the frequency PI controller (I_{smd}) is as

$$I_{smd(n)} = I_{smd(n-1)} + K_{pf} \{ f_{er(n)} – f_{er(n-1)} \} + K_{if} f_{er(n)} \tag{2}$$

The rated current of the generator is calculated as

$$I_G = \sqrt{2}\, (P_{rated}) / (\sqrt{3}\, V_{rated}) \tag{3}$$

where P_{rated} and V_{rated} are rated power and rated line voltage of the asynchronous generator.

By eqs. (2) and (3) at the n^{th} sampling instant, the amplitude of active current component is

$$I^*_{smd} = I_{G(n)} - I_{smd(n)} \tag{4}$$

The instantaneous line voltages at the asynchronous generators terminals (v_a, v_b and v_c) are filtered using band pass filter (BPF) which has resulted in sinusoidal voltages and their amplitude is computed as

$$V_t = \{(2/3)\, (v_a^2 + v_b^2 + v_c^2)\}^{1/2} \tag{5}$$

The unity amplitude templates are having instantaneous value in phase with instantaneous voltage (v_a, v_b and v_c), which are derived as

$$u_a = v_a/V_t\,;\ u_b = v_b/V_t\,;\ u_c = v_c/V_t \tag{6}$$

Instantaneous values of in-phase components of reference source currents are estimated as

$$i^*_{sad} = I^*_{smd}\, u_a; \quad i^*_{sbd} = I^*_{smd}\, u_b;\ i^*_{scd} = I^*_{smd}\, u_c \tag{7}$$

B. Quadrature Component of Reference Source Currents

The AC voltage error V_{er} at the n^{th} sampling instant is as

$$V_{er(n)} = V_{tref(n)} – V_{t(n)} \tag{8}$$

where $V_{tref(n)}$ is the amplitude of reference AC terminal voltage and $V_{t(n)}$ is the amplitude of the sensed three-phase AC voltage at the terminals of an asynchronous generator at n^{th} instant.

The output of the PI controller ($I^*_{smq(n)}$) for regulating constant AC terminal voltage at the n^{th} sampling instant is expressed as

$$I^*_{smq(n)} = I^*_{smq(n-1)} + K_{pa} \{ V_{er(n)} – V_{er(n-1)} \} + K_{ia} V_{er(n)} \tag{9}$$

where K_{pa} and K_{ia} are the proportional and integral gain constants of the proportional integral (PI) controller (values are given in Appendix). $V_{er\,(n)}$ and $V_{er(n-1)}$ are the voltage errors in n^{th} and $(n-1)^{th}$ instant and $I^*_{smq(n-1)}$ is the amplitude of quadrature component of the reference source current at (n-1)th instant.

The instantaneous quadrature components of reference source currents are estimated as

$$i^*_{saq} = I^*_{smq}\, w_a;\; i^*_{sbq} = I^*_{smq}\, w_b;\; i^*_{scq} = I^*_{smq}\, w_c \qquad (10)$$

where w_a, w_b and w_c are another set of unit templates having a phase shift of 90º leading with the corresponding unit templates u_a, u_b and u_c which are computed as follows

$$w_a = -u_b / \sqrt{3} + u_c / \sqrt{3} \qquad (11)$$
$$w_b = \sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \qquad (12)$$
$$w_c = -\sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \qquad (13)$$

C. Reference Source Currents

Total reference source currents are the sum of in-phase and quadrature components of reference source currents as

$$i^*_{sa} = i^*_{saq} + i^*_{sad} \qquad (14)$$
$$i^*_{sb} = i^*_{sbq} + i^*_{sbd} \qquad (15)$$
$$i^*_{sc} = i^*_{scq} + i^*_{scd} \qquad (16)$$

D. PWM Current Controller

Reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with sensed source currents (i_{sa}, i_{sb} and i_{sc}). The current errors are computed as:

$$i_{saerr} = i^*_{sa} - i_{sa} \qquad (17)$$
$$i_{sberr} = i^*_{sb} - i_{sb} \qquad (18)$$
$$i_{scerr} = i^*_{sc} - i_{sc} \qquad (19)$$

These current errors are amplified and the amplified signals are compared with fixed frequency (10 kHz) triangular carrier wave to generate gating signals for IGBTs of VSC of the controller.

IV. Modeling of the Proposed System

Fig 2 shows the complete MATLAB based simulation model for the proposed isolated electrical power generating system. This model consists of a mechanical system, an electrical system, proposed voltage and frequency controller and consumer loads. Modeling and simulation are carried in MATLAB version 7.1 using Power System Block-set (PSB) toolbox. The detailed modeling description of each part is given in the following sections.

A. Modeling of Mechanical System

The mechanical system consists of a wind turbine along-with gear system. The gear ratio (N) is selected such that the IAG generates the rated voltage at rated frequency and a rated wind speed of 9m/s to extract the maximum power from the wind turbine. The aerodynamic power generated by the wind turbine can be expressed as

$$P = 0.5\, \rho A C_p \upsilon_w^3 \qquad (20)$$

where the aerodynamic power is expressed as a function of the specific density (ρ) of the air, The swept area of the blades (A) and the wind speed (υ_w).

To generate the constant frequency, the additional generated power with increased wind speed is stored into the battery and the speed of the generator is maintained almost constant. Fig. 3 shows the curve between the power coefficient (C_p) and the tip speed ratio (λ) at zero degree

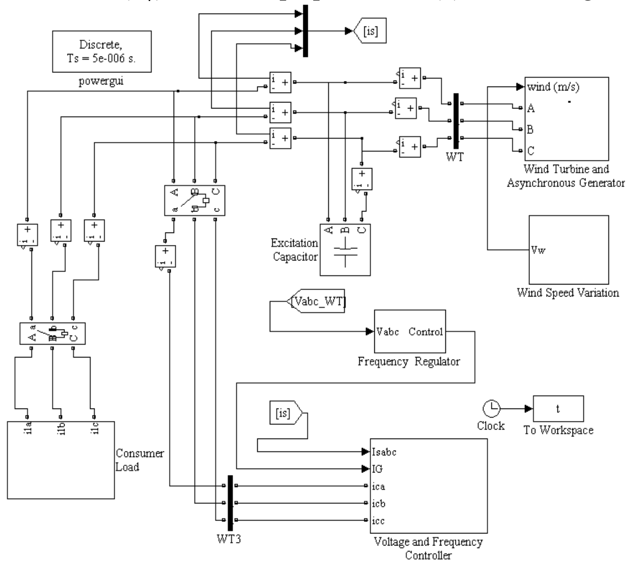

Fig. 2: MATLAB based simulation model of proposed system

pitch angle(β) which shows that C_p reaches a maximum value (0.48) for a maximum tip speed ratio (8.1). It yields the maximum mechanical power available in the wind turbine for a given wind speed. The tip speed ratio (TSR) is defined as the ratio of the linear speed at the tip of the blade ($\omega_T R$) and the wind speed (ν_w), where ω_T being the rotational speed of the wind turbine. The polynomial relation between C_p and λ at particular pitch angle for considered wind turbine [2] is represented as

$$C_p = C_1 \{(C_2/\lambda i)-C_3\,\beta-C_4)\}\, e^{-(C_5/\lambda i)} + C_6\lambda \qquad (21)$$

where $1/\lambda i = \{1/(\lambda+C_7\,\beta)\} - \{C_8/(\beta^3+1)\}$and $\beta = 0°$ and values of all coefficients are given in Appendix.

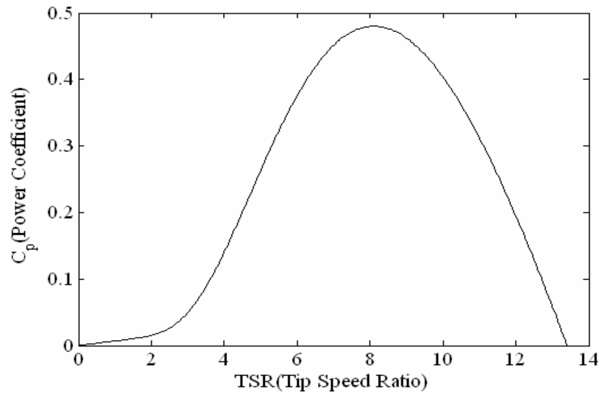

Fig. 3: Curve between power coefficients (C_p) and TSR (λ)

B. Modeling of Electrical System

The electrical system consists of an asynchronous generator with the excitation capacitor. An available model of an asynchronous machine including the saturation characteristics, which is determined by conducting the synchronous speed test on the machine, is considered into the model of the isolated asynchronous generator. A bank of fixed value delta connected excitation capacitor is selected to generate the rated voltage at no-load while additional demand of the reactive power is met by the controller.

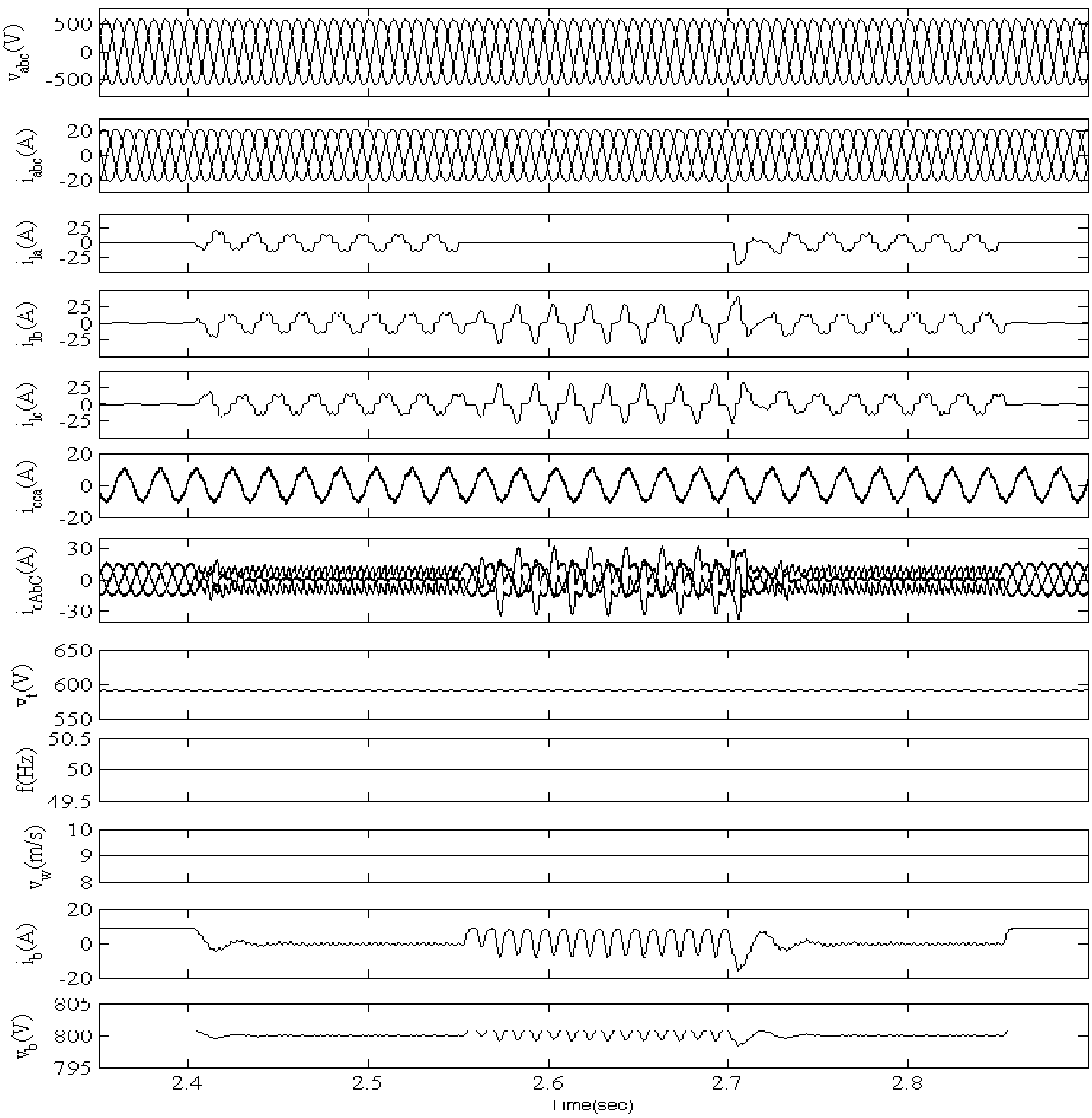

Fig. 4: Transient waveforms under varying balanced/unbalanced non-linear loads at wind speed of 9m/s.

C. Modeling of the Controller

battery at its DC bus. In Fig 1, Thevenin's equivalent circuit of battery based model [11,12] is shown at DC bus of controller. The terminal voltage of the equivalent battery (V_b) is obtained as follows

$$V_b > (2\sqrt{2}/\sqrt{3})\, V_{LL} \tag{22}$$

where V_{LL} is the line rms voltage.

Since the battery is an energy storage unit, its energy is represented in kWh when a capacitor is used to model the battery unit, the capacitance can be determined from

$$C_b = \frac{\text{kWh} * 3600 * 10^3}{0.5(V_{ocmax}{}^2 - V_{ocmin}{}^2)} \tag{23}$$

In the Thevenin's equivalent model of the battery, where

The proposed VF controller consists of CC-VSC with a R_s is the equivalent resistance (external + internal) of parallel/series combination of a battery, which is usually a small value. The parallel circuit of R_b and C_b is used to describe the stored energy and voltage during charging or discharging. R_b in parallel with C_b, represents self discharging of the battery, since the self discharging current of a battery is small, the resistance R_b is large. Here the battery is considered of having 6 kW for 8 Hrs peaking capacity, and with the variation in the voltage of order of 795V-805V.

D. Modeling of the Consumer Loads

Linear and non-linear loads are modeled using resistive element and three phase diode rectifier with resistive element at it DC bus respectively.

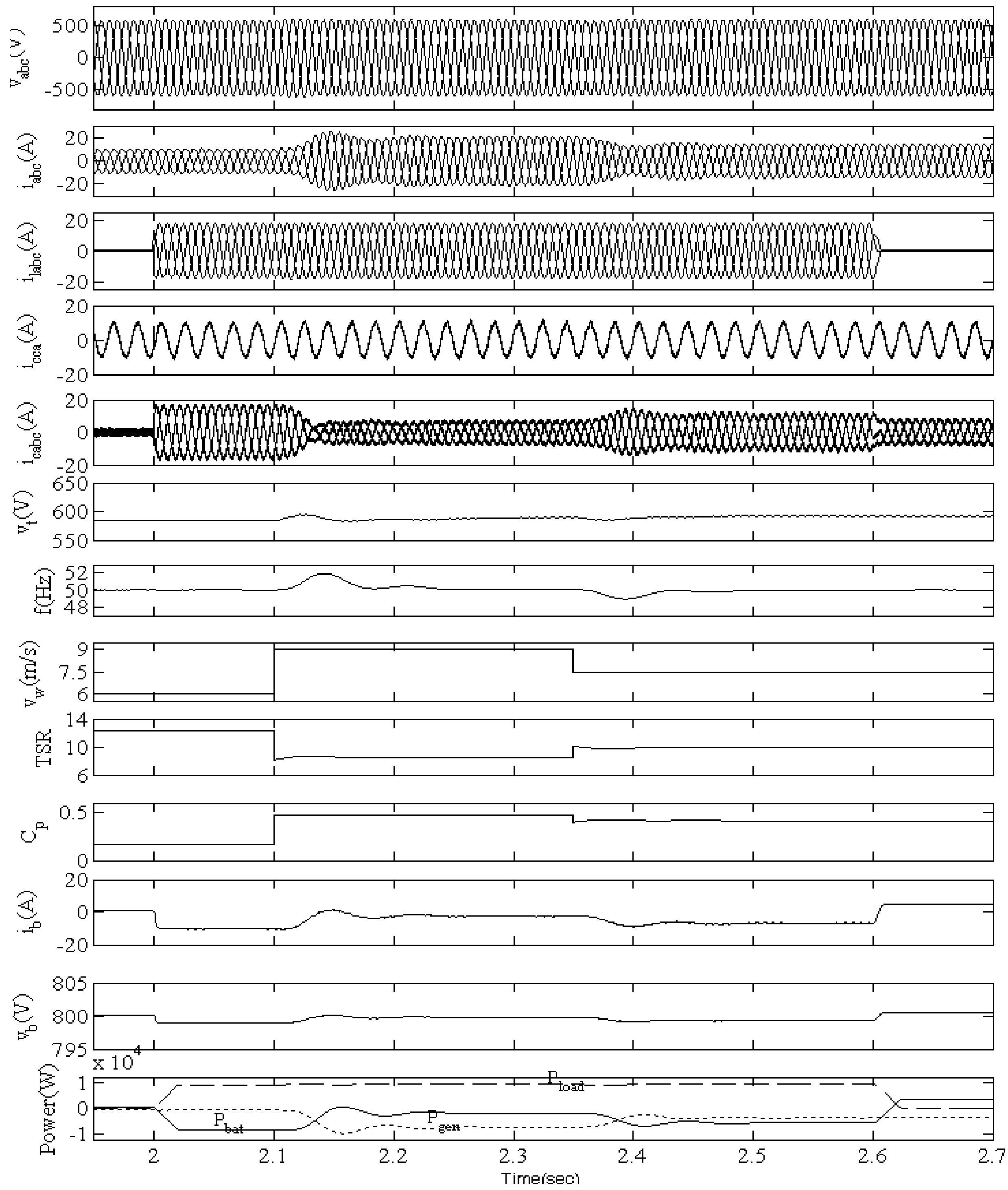

Fig. 4: Transient waveforms under varying balanced/unbalanced non-linear loads at wind speed of 9m/s.

IV. Results and Discussion

The performance of the proposed controller for a wind turbine driven isolated asynchronous generator system feeding non-linear balanced/unbalanced loads under varying wind speeds are shown in Figs 4-5. The waveforms of the generator voltage (v_{abc}), generator current (i_{abc}), load current (i_{labc}), capacitor current (i_{cca}), controller current (i_{cabc}), terminal voltage (v_t), frequency (f), speed of the wind turbine(υ_w), tip speed ratio (TSR), power coefficient (C_p), battery current (i_b), battery voltage (v_b), and the variation in power (P_{load}, P_{bat}, P_{gen}) are shown during different dynamic conditions.

A. Performance of the Controller with Balance/ Unbalanced Non-linear Loads

The performance of the controller with balanced-unbalanced non-linear loads is demonstrated in Fig. 4 at wind speed of 9m/s. A three phase diode bridge rectifier with L-C filter based non-linear load is applied at 2.4 s and after opening of one phase of the load at 2.55 s the load becomes unbalanced. In both of these cases it is observed that the voltage and frequency of the system remain constant.

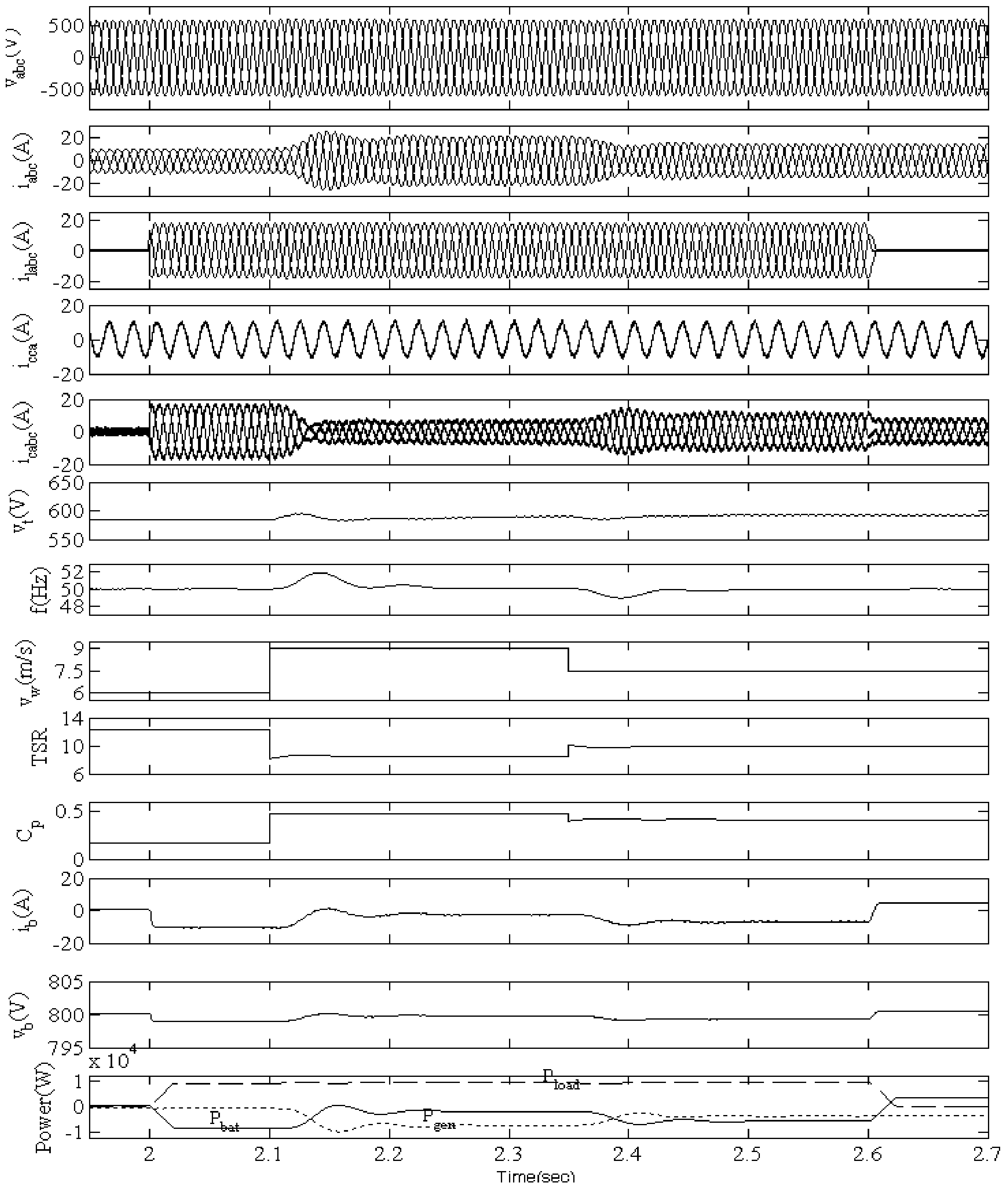

Fig. 5: Transient waveforms during variation of wind speed at particular consumer load.

At 2.7 s, open phase of the load is reconnected and later on at 2.85 s, the load is fully removed from the system and it is observed that the controller responds in desirable manner to regulate the voltage and frequency along-with additional mentioned features of the load balancing and harmonic elimination. Harmonic spectra of the generator voltage (v_a), generator current (i_a) and load current (i_{lb}) are also given in Figs. 6 for balanced non-linear load conditions respectively to demonstrate the harmonic elimination capability of the controller. Total harmonic distortion (THD) of the generator voltage, current is obtained to be an order of 1.87% and 3.99% for the THD of load current of 25.76% under the balanced non-linear load condition. These THD values are well within 5% limit imposed by IEEE-519 standard. In this way it is demonstrated that the proposed voltage and frequency controller is also functioning as a harmonic eliminator.

B. Performance of the Controller with Variation of Wind Speed

Fig. 5 shows the performance of the controller with varying wind speeds at constant applied consumer load. At 2 s when wind speed is 6m/s, a consumer load (9kW) is applied at the generator terminals. It is observed that due to insufficient power generation at low wind speed an additional load power is supplied by the battery to regulate the frequency. At 2.1 s as the wind speed is increased from 6m/s to 9m/s, an output power of the generator (P_{gen}) is increased so that at particular load now the power supplied by the battery (P_{bat}) is reduced because now demand is met by the generator itself and having the availability of enough wind power. For maintaining the constant speed of the generator for constant frequency operation it is shown that tip speed ratio (TSR) is also reduced in same proportion as the wind speed is increased. At 2.35 s, the wind speed is reduced from 9m/s to 7.5m/sec then it is observed that the battery again starts discharging to meet the demand of the consumer loads. At 2.6 s when the load is fully removed it is shown that the battery starts charging to store the total generated power. In this manner, the controller provides the load leveling and regulation of the frequency. Here an interesting observation is also made that the response of the controller under electrical dynamic conditions (load variation) is faster than the mechanical dynamic conditions (wind speed variation) and the frequency regulation under electrical dynamic condition is much faster than the mechanical dynamic condition. It is mainly because mechanical time constant is higher than the electrical time constant of the system.

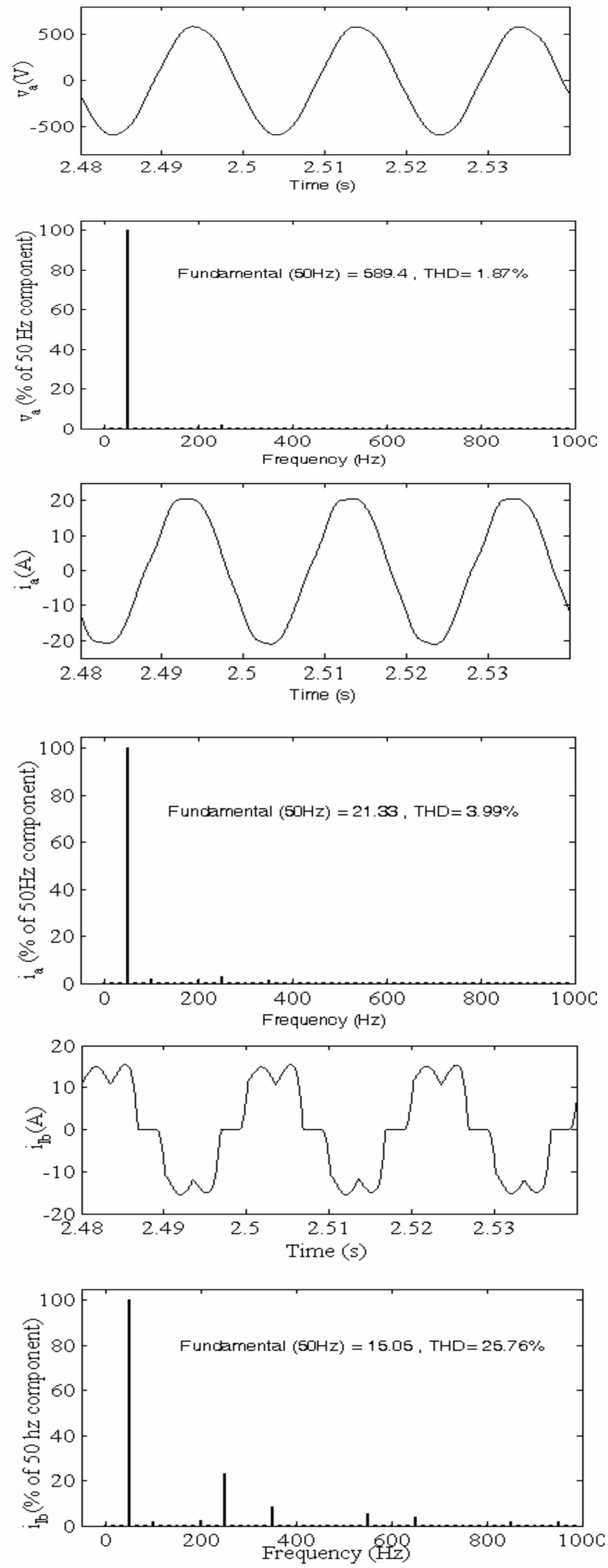

Fig. 6: Harmonic spectra of (a) generator voltage (v_a) (b) generator current (i_a) (c) load current (i_{lb}) under balanced non-linear load condition.

VI. Conclusions

The performance of the proposed voltage and frequency controller has been demonstrated for an isolated asynchronous generator driven by fixed pitch wind turbine. The proposed controller has been found suitable with simple control strategy to regulate the voltage and frequency with variation of the load and under varying wind speeds. The performance of the controller has been investigated with balanced and un-balanced non-linear loads and it has been found that total harmonic distortion of terminal voltage and the generator current in such type of worst load condition is well within the limit of IEEE-519 standard. Therefore it is concluded that proposed voltage and frequency controller is also functioning as a harmonic eliminator, a load balancer and a load leveler.

Appendix

A. *Parameters of 7.5kW, 415V, 50Hz, Y-Connected 4-pole Asynchronous Machine are given below.*

$R_s = 1\Omega$, $R_r = 0.77\Omega$, $X_{lr}= X_{ls}= 1.5\Omega$, $J = 0.1384$ kg-m^2, $C_2 = 5$ kVAR

$L_m = 0.134$ ($I_m<3.16$)

$L_m=9e\text{-}5I_m^2 - 0.0087I_m + 0.1643$ ($3.16<I_m<12.72$)

$L_m = 0.068$ ($I_m>12.72$)

B. *Battery Specification*

$C_b = 21500$F, $R_b = 10k\Omega$, $R_s = 0.01\Omega$, $V_{oc} = 800$V

C. *Controller Pararameters*

$L_f = 3$mH, $R_f = 0.1\Omega$, and $C_{dc} = 8000\mu$F

$K_{pa} = 0.13$, $K_{ia} = 0.012$; $K_{pf} = 6.13$, $K_{if} = 140$

D. *Wind Turbine Specification*

Rating 7.5kW, Gear ratio (N) = 11, Radius of wind urbine (R) = 5m, $C_{pmax} = 0.48$,

$\lambda_m = 8.1$, $C_1= 0.5176$, $C_2= 116$, $C_3=0.4$, $C_4= 5$, $C_5= 21$, $C_6= 0.0068$, $C_7= 0.08$, $C_8= 0.035$.

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BIOGRAPHIES

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