Integrated Electronic Load Controller with T-Connected Transformer for Isolated Asynchronous Generator

Bhim Singh[1] V. Rajagopal[2]

Abstract – This paper deals with a integrated Electronic Load Controller (IELC) for an isolated asynchronous generator (IAG), used in constant power pico hydro power generation for feeding three-phase four-wire loads. The proposed IELC is used to control the voltage and frequency of IAG in the integrated manner. This IELC is realised using a T-connected transformer and three-leg insulated gate bipolar transistors (IGBTs) based current controlled voltage source converter (VSC) a capacitor, a chopper switch and an auxiliary load on its dc bus. The proposed IELC with an isolated generating system is modeled and simulated in MATLAB along with Simulink and power system blockset (PSB) toolboxes. The simulated results of IAG-IELC system are presented to demonstrate its performance for feeding three-phase four-wire linear/nonlinear (balanced/unbalanced) loads with the neutral current compensation.

Keywords – Integrated electronic load controller, isolated asynchronous generator, voltage source converter, point of common coupling.

I. Introduction

Conventional power generation using fossil fuels such as coal, hydrocarbons etc. cause environmental pollution and degradation. Besides, these sources are limited and at the current rate of their exploitation, are not likely to last very long. Therefore, there is need to give utmost importance to harnessing non-conventional and renewable energy sources such as wind energy, small hydro, bio-mass, solar, geothermal energy etc to reach the consumers in remote and isolated places. This leads to develop small isolated pico hydro generating plants and cost reductions may be obtained by utilizing run of the river schemes [1- 2]. The IELC (integrated electronic load controller) is used to regulate the voltage and frequency constant. Asynchronous machines like a squirrel cage type offers simple and rugged brushless rotor construction with least maintenance requirements over any conventional synchronous machines [3- 4]. As the induction machine is isolated, the reactive power for its operation may be supplied by a VAR generating unit connected across its terminals, which is generally realized in the form of capacitor banks. The capacitor banks are such selected that when driven at rated speed should produce the rated voltage at no load operating under the magnetic saturation at some stable point [5]. These IAGs have inherent voltage and frequency regulation problems in constant power applications, along with these poor voltage and frequency problems it has poor power quality [6]. Therefore, use of an IELC with a suitable scheme becomes necessary for uncontrolled pico hydro turbine driven IAG based power generation.

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In this paper, a synchronous reference frame theory [7-8] based control of an IELC is proposed which is having capability of controlling the voltage and frequency in integrated manner. The dc bus with this type of controller is more stable as compared to other controllers. The control scheme is fast in response as compared to any other control scheme. For controlling the voltage and frequency of IAG system, an IELC with a chopper switch and an auxiliary load at its dc bus is used. The active power of the IAG system is controlled by the chopper switch and an auxiliary load on the dc link of IELC and the reactive power is compensated by the VSC with a capacitor on the dc link. IELC acts as a reactive power compensator along with a harmonic eliminator and a load balancer a chopper switch with an auxiliary load at its DC link to absorb surplus active power not used by consumer loads. For the neutral current compensation a T-connected transformer neutral terminal can be used for non linear and unbalanced linear loads where the neutral current is compensated in primary windings of T-connected transformer keeping the VSC free from circulating currents [9-11].

II. System Configuration and Principle of Operation

Fig. 1 shows the system configuration of IAG, an IELC (consisting a chopper switch and an auxiliary load at its DC link and three-leg VSC with isolation T-connected transformer) and the consumer loads. A three phase capacitor bank is used for the VAR requirement of the asynchronous generator and the value of this capacitor bank is selected to generate the rated voltage at no load. The IAG generates the constant power and when consumer loads power changes, the DC chopper of IELC absorbs the difference in active power into the auxiliary load. The three-leg VSC of IELC regulates the voltage due to changes in consumer loads. Thus the voltage and frequency of IAG system is not affected and remain constant during the frequent changes in consumer loads. The IELC is connected to the IAG terminals (point of common coupling (PCC)) through a T-connected transformer and AC filtering inductors. The DC bus capacitor is used to mitigate voltage ripples and provides self supporting DC bus of VSC.

Fig. 1 also shows the control strategy of an IELC for regulating constant voltage and frequency along with constant excitation capacitor of an IAG driven by uncontrolled pico hydro turbine. The control algorithm for the control of an IELC is based on the generation of reference source currents and a constant generated power of the IAG system. The T-connected transformer is used to change the voltage to an optimum level and for the neutral current compensation.

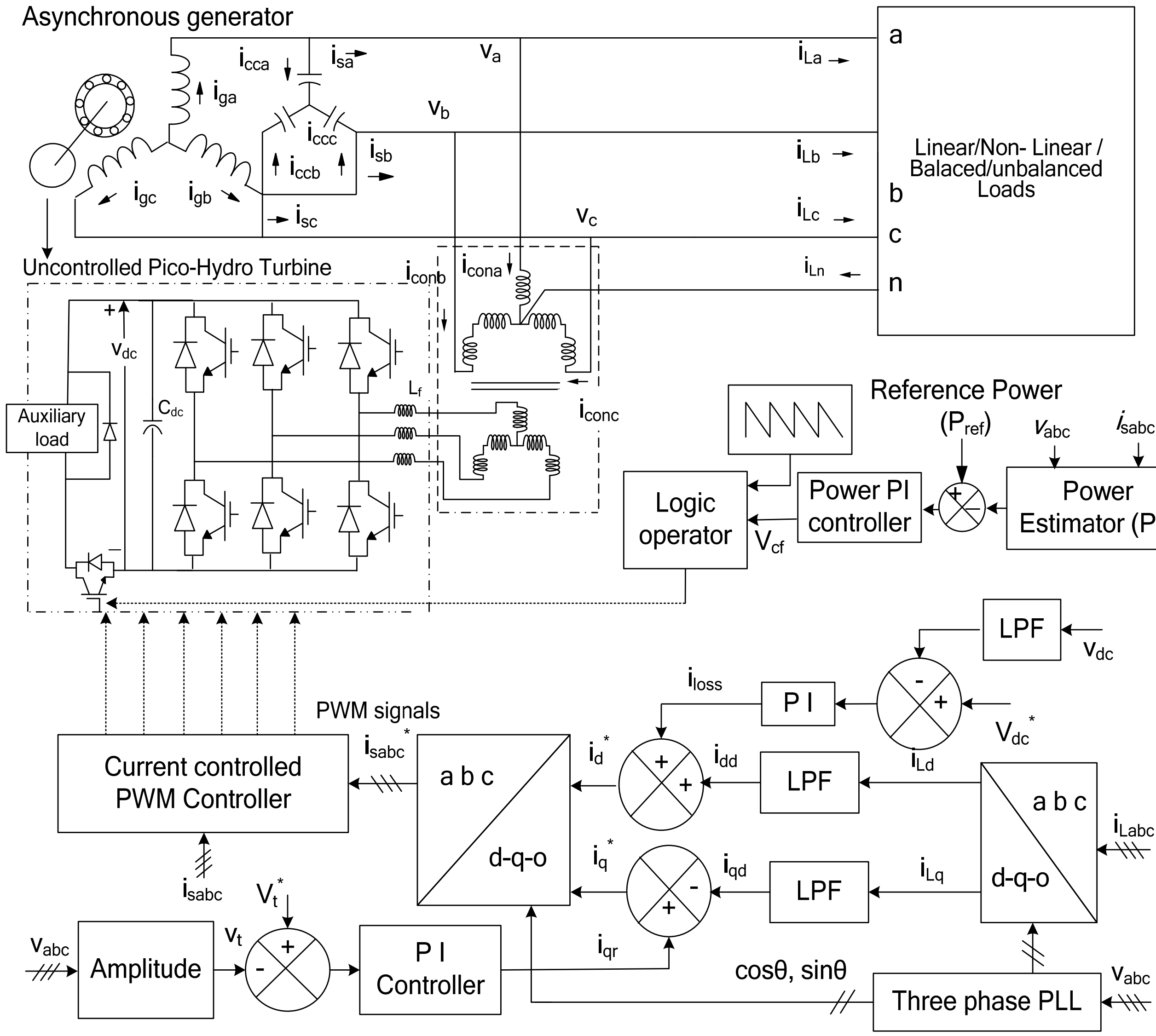

Fig. 1: Schematic diagram of IAG with IELC and its control scheme.

III. Control Strategy

The synchronous reference frame theory [7-8] is used for the control of the voltage and frequency of an IAG in the integrated manner. A block diagram of the control scheme along with generating system and consumer loads is shown in Fig. 1. The load currents (i_{La}, i_{Lb}, i_{Lc}), the terminal voltages (v_a, v_b, v_c) and dc bus voltage (v_{dc}) of VSC are sensed as feedback signals.

A. In-phase and Quadrature Component of Reference Source Currents

The load currents in the three phases are converted into the d-q-0 frame using the Park's transformation as,

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{Lo} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin\theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (1)$$

A three-phase PLL (phase locked loop) is used to synchronize these signals with the terminal voltages. The d-q components are then passed through low pass filters (LPF) to extract the dc component of load currents corresponding to the active power i_{dd} and reactive power i_{qd}. The fundamental active power component of the generator current for constant power operation can be calculated as

$$i_d^* = i_{dd} + i_{loss} \quad (2)$$

This i_d^* is considered amplitude of an active power component of the source current of an IAG system.

The error in DC bus voltage of an IELC ($V_{dcer\,(n)}$) of H-bridge at nth sampling instant is as,

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \quad (3)$$

where $V_{dcref\,(n)}$ is the reference DC voltage and $V_{dc(n)}$ is the sensed DC link voltage of the VSC. The output of the PI controller for maintaining DC bus voltage of the VSC at the nth sampling instant is expressed as,

$$I_{loss(n)} = I_{loss(n-1)} + K_{pd}\,\{V_{dcer(n)} - V_{dcer(n-1)}\} + K_{id}\,V_{dcer(n)} \quad (4)$$

where $I_{loss(n)}$ is considered as part of active power component of source current. K_{pd} and K_{id} are the proportional and integral gain constants of the DC bus PI voltage controller. Similarly, a second PI controller is used to regulate the IAG terminal voltage. Three-phase voltages at the IAG terminals (v_a, v_b and v_c) are considered sinusoidal and hence their amplitude is computed as,

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

The amplitude of IAG terminal voltage and its reference value are fed to a PI controller and the output of PI controller is considered as required reactive power component of the system (i_{qr}) is subtracted from the dc component of the load reactive current (i_{qd}). The voltage error V_{er} is amplitude of AC voltage at the n^{th} sampling instant is as,

$$V_{er(n)} = V_{tref(n)} - V_{t(n)} \quad (6)$$

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

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

$$I^*_{qr(n)} = I^*_{qr(n-1)} + K_{pa}\,\{V_{er(n)} - V_{er(n-1)}\} + K_{ia}\,V_{er(n)} \quad (7)$$

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

Thus the reactive power component of the source current is as,

$$i_q^* = i_{qr} - i_{qd} \quad (8)$$

This control strategy is to regulate the IAG terminal voltage, elimination of harmonics in load currents and the load balancing. The resultant reference source d-q currents (i_d^*, i_q^*) are again converted into the reference source currents in abc frame (i^*_{sa}, i^*_{sb}, i^*_{sc}) using the reverse Park's transformation as,

$$\begin{bmatrix} i^*_{sa} \\ i^*_{sb} \\ i^*_{sc} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \sin\theta & \cos\theta & \frac{1}{\sqrt{2}} \\ \sin(\theta - \frac{2\pi}{3}) & \cos(\theta - \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \\ \sin(\theta + \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i^*_d \\ i^*_q \\ i^*_o \end{bmatrix} \quad (9)$$

These reference source currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with the sensed source currents (i_{sa}, i_{sb} and i_{sc}) in the PWM current controller. These current errors for all the phases are amplified and amplified current errors are compared with fixed frequency triangular carrier wave (10kHz in this case) to generate gating signals using a unipolar PWM switching of IGBTs of IELC.

B. Chopper PWM Controller

The active power error is defined as,

$$P_{er}(n) = P^*_{(n)} - P_{(n)} \quad (10)$$

where P^* is the reference power and "P " is the sensed power of IAG.

At the n^{th} sampling instant, the power PI controller is as,

$$V_{cf(n)} = V_{cf\,(n-1)} + K_{pf}\,\{P_{re(n)} - P_{re(n-1)}\} + K_{if}\,P_{re(n)} \quad (11)$$

This output of frequency controller $V_{cf(n)}$ is compared with fixed frequency triangular carrier wave (3 kHz in this case) to generate gating signal of IGBT of the chopper of IELC..

IV. MATLAB BASED MODELING

A Simulink model of the asynchronous generator system is developed and it consists of an asynchronous machine with a capacitor bank and IELC. The modeling of an IAG is carried out using 7.5 kW, 415V, 50Hz, Y-connected induction machine and a 6 kVAR star-connected excitation capacitor bank. The IELC is realized using three-leg VSC, a T-connected transformer and interfacing inductors, a DC chopper and an auxiliary load. The unbalanced linear and non linear loads are considered here to demonstrate the capability of an IELC. Simulation is carried out in discrete mode at 20e-6 step size with ode23tb (stiff/ TR-BDF-2) solver. A T-connected transformer is used for the neutral current compensation and to reduce the dc bus voltage of voltage regulator to optimum level, which is shown in Fig. 1.

V. RESULTS AND DISCUSSION

The performance of a proposed IELC is studied for a constant power input uncontrolled pico hydro turbine driven isolated asynchronous generator feeding linear/ nonlinear balanced/ unbalanced three-phase four wire loads. Fig 2 shows its performance with unbalanced linear loads and Figs 3 and 4 show its performance with unbalanced nonlinear loads. Figs 2 and 3 show the waveforms of IAG terminal voltages (v_{abc}), source currents (i_{sabc}), capacitor bank current (i_{cca}), load currents (i_{La}, i_{Lb} and i_{Lc} for linear and non linear load), IELC currents (i_{con}), load neutral current (i_{ln}), amplitude of IAG terminal voltage (v_t), reference and DC bus voltage of IELC (v_{dc}^*, v_{dc}), IAG speed (ω), frequency and its reference (f^*,f) and powers for the source (P_G), auxiliary load (P_A) and consumer loads (P_L) during different dynamic load conditions.

A. Performance of IAG with the IELC with Balanced /Unbalanced Linear Loads

Fig. 2 shows the performance of the IELC under the application of balanced/ unbalanced linear loads on an IAG system driven by a constant power uncontrolled pico hydro turbine. All three single phase loads of 2.5 kW each are applied to the IAG terminals. At 4.2 sec one phase load is removed, the IELC starts diverting the excess amount of power into the auxiliary load. At 4.3 sec, second phase load is removed, the IAG is dissipating the extra power into the auxiliary load. At 4.4 sec all the three phase loads are removed, IAG is feeding the total power to the auxiliary load. The T-connected transformer is having the unbalanced currents and it provides the neutral current compensation through circulating current in the primary windings of the transformer with stable neutral terminal of the transformer and IELC and secondary windings are free from circulating currents

B. Performance of IAG with the IELC with Balanced /Unbalanced Non Linear Loads

Fig. 3 shows the performance of an IELC under the application of balanced/ unbalanced nonlinear loads on the IAG system driven by constant power uncontrolled pico hydro turbine. At 4.15 s all three single phase loads each of 2.5 kW are fed by IAG. The IELC is not consuming any active power. At 4.2 s, one phase load is removed, and IAG is feeding the excess amount of the active power to the IELC auxiliary load. At 4.3 s, the second phase of the load is removed, the IAG is diverting the power from consumer loads to auxiliary load. At 4.4 s, the third phase load is removed, the IAG is diverting the total power from consumer loads to auxiliary load. The transformer primary winding is having the unbalanced currents providing the path to the load neutral current with stable neutral terminal leaving the IELC free from the load neutral currents. Fig 4(a) shows the source voltage waveform and its harmonic spectrum, which has a THD (Total Harmonic Distortion) of 2.14 %. Fig 4 (b) shows the source waveform and harmonic spectrum and its THD is 3.23%. Fig 4 (c) shows the nonlinear load current waveform and its harmonic spectrum which has a THD of 77.14%. The THD of the terminal voltage of the generator is well within 5%, the limit imposed by the IEEE-519 standard.

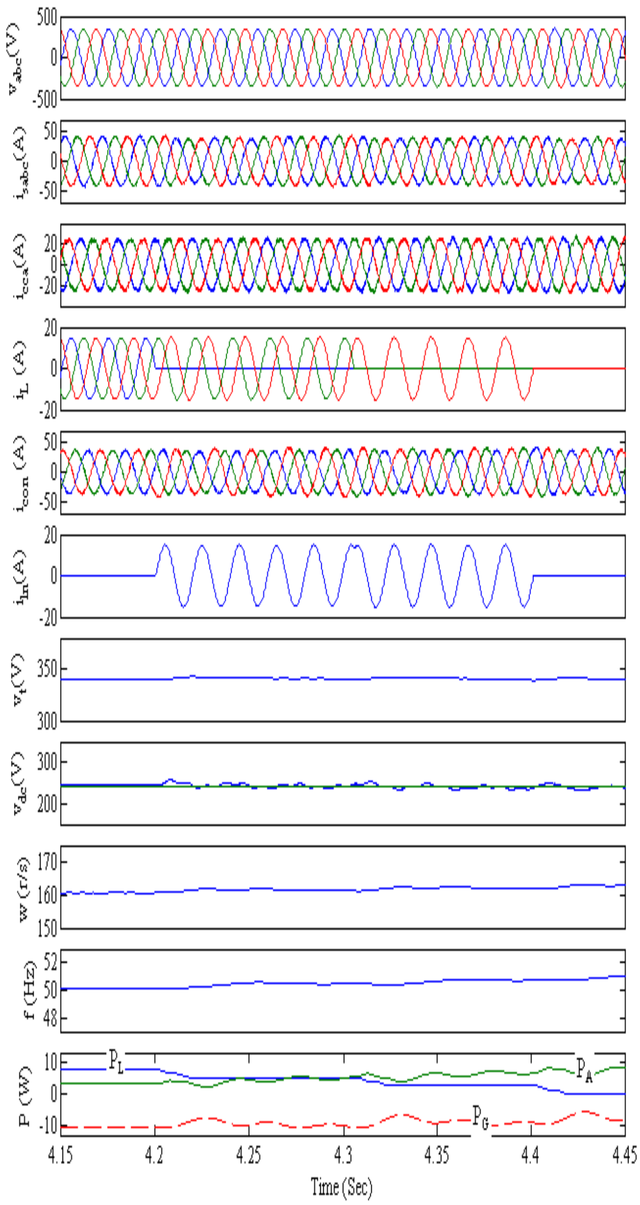

Fig. 2: Performance of IAG with a IELC feeding an three – phase four wire linear loads.

VI. Conclusion

An integrated electronic load controller for standalone pico-hydro based asynchronous generator has been designed, modeled and its performance has been simulated with a SRF based controller. The performance of an IAG has been demonstrated under different loading conditions (balanced/unbalanced linear/nonlinear).

It has been observed that the proposed IELC results in a satisfactory performance under different loading conditions along with the frequency and its voltage control, load balancing and harmonic elimination of three-phase four wire loads. The requirement of PI controllers is reduced to two in the proposed voltage and frequency controller. This type of control scheme has been found simple, quick in response and easy to control.

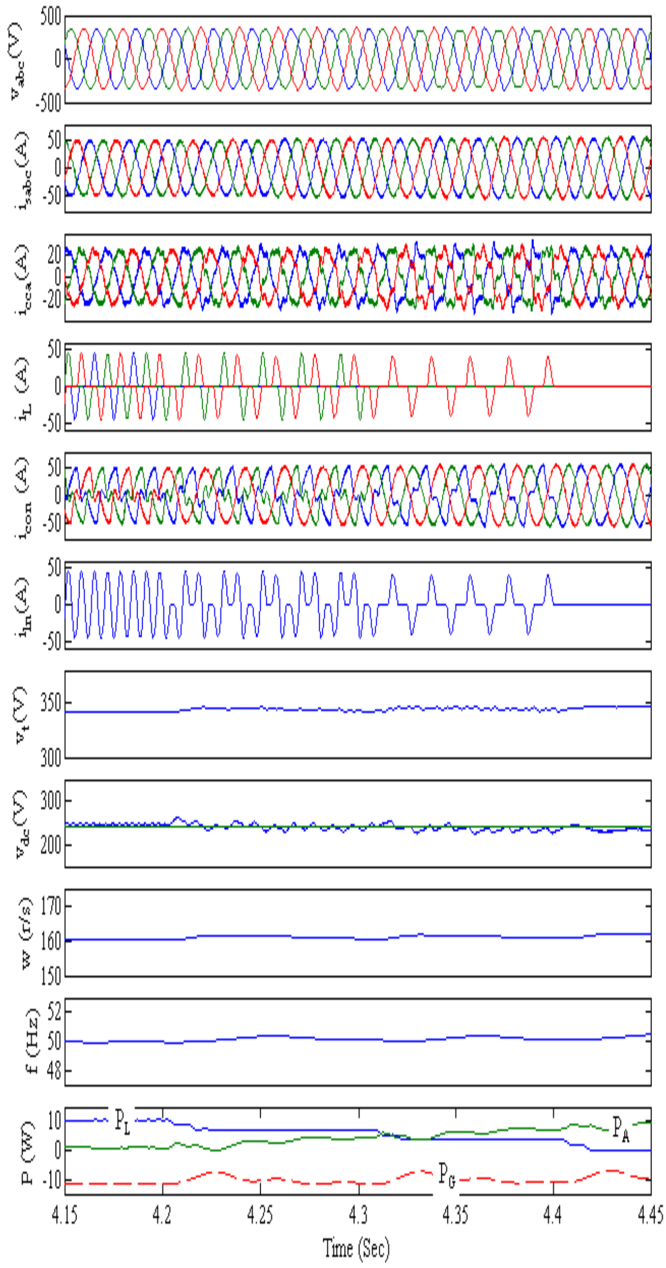

Fig. 3: Performance of IAG with a IELC feeding an three – phase four wire non-linear loads.

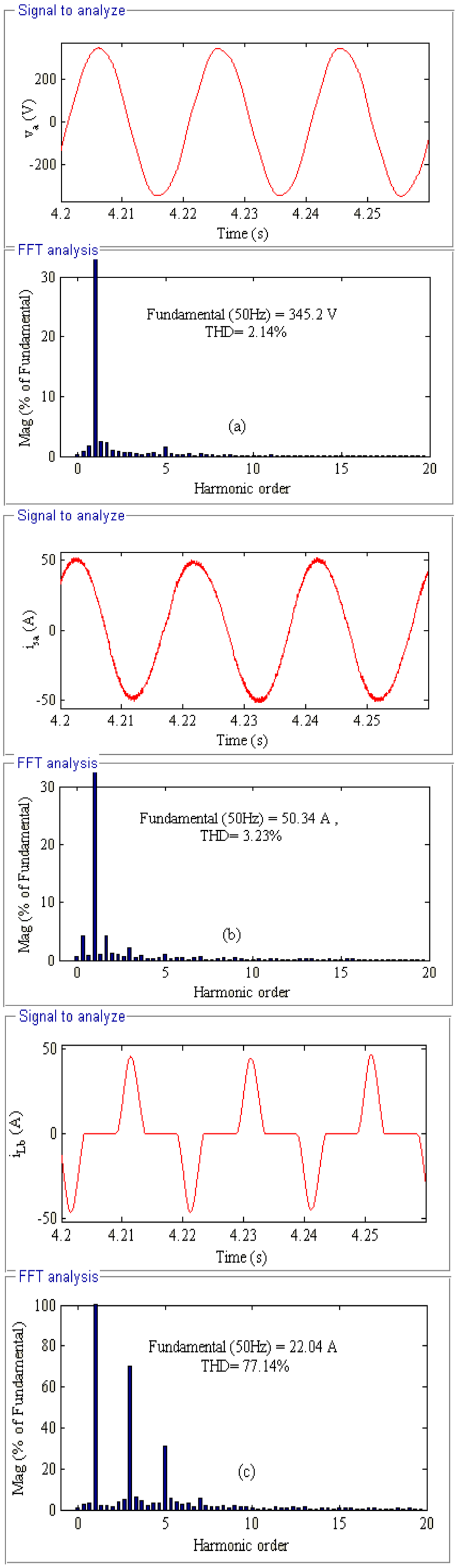

Fig. 4: Harmonic spectra of (a) generator voltage (V_a), (b) generator current (i_{sa}) and (c) load current (i_{lb}) under balanced nonlinear condition.

APPENDICES

A. *Parameters of 7.5 KW, 415 V, 50 Hz, Y connected, 4 - Pole Asynchronous Machine*

R_s=1 Ω, R_r = 0.77 Ω, X_{lr} = X_{ls} =1.5Ω, J= 0.1384 kg – m^2
L_m = 0.134 H (I_m< 3.16)
$L_m = 9e^{-5}\ I_m^{\ 2} – 0.0087\ I_m + 0.1643$ (3.16<I_m<12.72)
L_m = 0.068 H (I_m> 12.72)

B. *Controller parameters*

L_f = 3 mH and C_d = 6000 μF
AC voltage PI controller: K_{pa} =0.05, K_{ia} = 0.07
DC voltage PI controller K_{pd} = 0.1, K_{id} =0.12
Power PI controller K_{pp} = 0.004, K_{ip} =0.001

C. *Prime mover Characteristics*

$T_{shaft} = (K_1 - K_2\ \omega_m)$; K_1= 1465, K_2 = 8.6.

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BIOGRAPHIES

Bhim Singh was born in Rahamapur, India, in 1956. He received the B.E. degree in Electrical Engineering from University of Roorkee (Now IIT Roorkee), Roorkee, India, in 1977, and M.Tech. and Ph.D. degrees in Electrical Engineering from Indian Institute of Technology Delhi (IIT-Delhi), New Delhi, India, in 1979 and 1983, respectively.

In 1983, he joined Department of Electrical Engineering, University of Roorkee, as a Lecturer, and in 1988, became a Reader. In December 1990, he joined the Department of Electrical Engineering, IIT-Delhi, as an Assistant Professor, became an Associate Professor in 1994 and a Professor in 1997. He has received Khosla Research Prize of University of Roorkee in the year 1991. He is recipient of JC Bose and Bimal K Bose awards of The Institution of Electronics and Telecommunication Engineers (IETE) for his contribution in the field of Power Electronics in the year 2000. He is also a recipient of Maharashtra State National Award of Indian Society for Technical Education (ISTE) in recognition of his outstanding research work in the area of Power Quality in the year 2006. He has received PES Delhi Chapter Outstanding Engineer Award for the year 2006. He has been the General Chair of the IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES'2006) held in New Delhi. His current research interests include power electronics, electrical machines and drives, active filters, flexible ac transmission system (FACTS), high-voltage dc (HVDC), and power quality.

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