H-Bridge VSC Based Voltage Controller for an Isolated Asynchronous Generator Supplying Three-Phase Four-Wire Loads

Gaurav Kumar Kasal[1] Bhim Singh[1]

Abstract – This paper presents a new configuration of a STATCOM based voltage controller for an isolated asynchronous generator (IAG) driven by bio-gas, diesel and gasoline engines and feeding 3-phase 4-wire consumer loads. The proposed controller consists of a two-leg IGBT (Insulated Gate Bipolar junction Transistor) based voltage source converter with an equal voltage distributed mid point capacitors at its DC link. The neutral point for the consumer loads is created using a tertiary winding zig-zag transformer. The tertiary winding allows the selection of the optimum voltage level of the DC link. The complete system is modeled and simulated using Simulink and PSB toolboxes. Extensive simulation results are presented to demonstrate the capability of the controller as a harmonic eliminator, a load balancer, alongwith as a voltage controller.

Keywords – Stand-alone power generation, two leg voltage source converter, mid point capacitors, voltage control, zig-zag transformer.

I. INTRODUCTION

Continuous depletion of fossil fuels and concern about the global warming, an importance of the locally available natural sources has increased such as hydro, biogas etc. In isolated applications for harnessing renewable energy from available non- conventional energy sources such hydro, and bio-mass, an asynchronous machine driven by a constant speed prime mover operated as an isolated asynchronous generator (IAG) with its excitation requirement being met by a capacitor bank connected across its terminals [1-3], has become the compatible option since last two decades. The increased emphasis on renewable energy sources has accelerated research and development of the IAG for autonomous power generation due to its simplicity, ruggedness and low cost. The fundamental problems with the IAG are its inability to control the terminal voltage under varying load conditions. Hence the limitations of an induction generator system with capacitor self excitation are poor voltage regulation, which results in under utilization of the machine. In order to regulate its terminal voltage with the load and to utilize the machine to its rated capacity an external source of the reactive current is required. A number of methods have been proposed in the literature for regulating the voltage of IAG for 3-phase 3-wire [3-5] constant speed, variable power applications. However here an attempt is made to investigate a voltage regulator for the 3-phase 4-wire loads on IAG in constant speed variable power isolated applications where consumer loads are distributed as single phase loads. Therefore, a need of 3-phase 4-wire system is essential and more effective than other configurations. In constant speed operation (prime mover such as diesel, gasoline and bio-mass engines) the drop in speed from no load to full load is almost negligible therefore variation in frequency is only because of slip which in turn depends on the amount of power required by the electrical loads. However, it needs the variable reactive power of the machine for regulating the voltage of IAG. Moreover, in such applications, the load balancing is also an essential requirement.

In this paper, a new configuration of the controller is proposed which is based on the two leg IGBT (Insulated Gate Bipolar Junction Transistor) based voltage source converter (VSC) with a mid point capacitors [6-8] at its DC bus. The neutral terminal for the loads is created using a zigzag transformer and its additional secondary windings. An advantage of a two leg voltage source converter is that number of IGBT switches are reduced compared to four leg VSC topology and compared to three single phase VSC with transformer topology and three leg VSC with mid point capacitors topology. In addition, the proposed novel voltage controller with an additional secondary winding in zig-zag transformer has facilitated the selection of suitable voltage rating of the DC bus capacitor and a zigzag transformer provides the path for the load neutral current [9,10]. The proposed voltage controller also functions as a harmonic eliminator and a load balancer [11].

II. SYSTEM CONFIGURATION

Fig. 1 shows a stand alone generating system along with the proposed voltage controller. The system consists of a constant speed prime mover (such as diesel, gasoline and biogas engines) driven squirrel cage asynchronous generator and its controller is connected at the point of common coupling through interfacing transformers. Two leg of the VSC are connected to the two phases while third phase is connected at the mid point of the DC bus capacitors. A zig-zag transformer is used to solve the problem of the neutral conductor and compared to other four wire topology system becomes less complex. The zig-zag transformer acts as a path for zero-sequence components of load currents while two leg VSC serves the purpose of harmonic elimination, load balancing and reactive power compensation. The zig-zag transformer consists of three tertiary winding transformers with the turn ratio of 2:2:1. Hence it is regarded as an open-circuit for the positive and negative sequence currents. The tertiary winding of the transformers facilitates to select the optimum voltage level of the DC bus capacitor.

This paper first received 26 June 2008 and in revised form 14 August 2008.
Digital ref: Al70401203

[1] Department of Electrical Engineering, Indian Institute of Technology, New Delhi-110016, India, E-mail: gauravkasal@gmail.com, E-mail: bhimsinghr@gmail.com

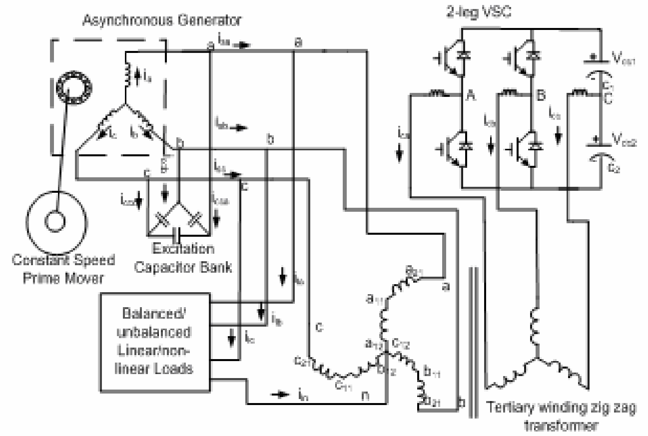


Fig. 1: Schematic diagram of a proposed system configuration.

III. CONTROL STRATEGY

As shown in Fig. 2, the control strategy of the two leg voltage controller is realized through derivation of reference source currents (i^r_{sa}, i^r_{sb}). Reference source currents consist of two components one is in phase or active power component (i^r_{da}, i^r_{db}) for the self supporting DC bus of VSC while other one is in quadrature or reactive power component (i^r_{qa}, i^r_{qb}) for regulating the terminal voltage. The amplitude of active power component of the source current (I_{dm}) is estimated using two PI controllers among which, one is used to control the voltage of DC bus of VSC while another one is used for equal voltage distribution across the DC bus capacitors. The output of the first PI controller is estimated by comparing the reference DC bus voltage (V_{dcref}) with the sensed DC bus voltage (V_{dc}). The output of the second PI controller is estimated by comparing the voltages across both capacitors (V_{dc1}) and (V_{dc2}) and error signal is optimized using a second PI controller. The sum of output of both PI controllers (I_{dm1}) and (I_{dm2}) gives the active power current component (I_{dm}) of the reference source current. The multiplication of I_{dm} with in-phase unit amplitude templates (u_{ad}, u_{bd}) yields the in-phase component of instantaneous reference source currents. These (u_{ad}, u_{bd}) templates are sinusoidal functions, which are derived by unit templates of in phase with line voltages (u_{ab}, u_{bc}, u_{ca}). These templates (u_{ab}, u_{bc}, u_{ca}) are derived by dividing the AC voltages v_{ab}, v_{bc} and v_{ca} by their amplitude V_t. To generate the quadrature component of reference source currents, another set of sinusoidal quadrature unity amplitude templates (u_{aq}, u_{bq}, u_{cq}) is obtained from in-phase unit templates (u_{abd}, u_{bcd}, u_{cad}). The multiplication of these components (u_{aq}, u_{bq}) with output of the PI (Proportional-Integral) AC voltage controller (I_{qm}) 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^r_{sa}, i^r_{sb}), and each phase source current is compared with the corresponding reference source current to generate the PWM switching signals for VSC of the controller.

IV. CONTROL ALGORITHM

Basic equations of the control scheme of the proposed controller are as follows.

Different components of the controller used in an asynchronous generator-system shown in Fig. 1, are modeled as follows. Three line voltages at the generator terminals (v_{ab}, v_{bc} and v_{ca}) are considered sinusoidal and hence their amplitude is computed as

$$V_t = \sqrt{(2/3)}\ (v_{ab}^2 + v_{bc}^2 + v_{ca}^2) \tag{1}$$

The unit template in phase with v_{ab}, v_{bc} and v_{ca} are derived as

$$u_{ab} = v_{ab}/V_t;\ u_{bc} = v_{bc}/V_t;\ u_{ca} = v_{ca}/V_t \tag{2}$$

From these in phase line voltage templates, unit templates in phase with phase voltage can be estimated as:

$$u_{ad} = (\sqrt{3}/2)\ u_{abd} + \{1/(2\sqrt{3})\}\ \{(u_{bcd} - u_{cad})\} \tag{3}$$

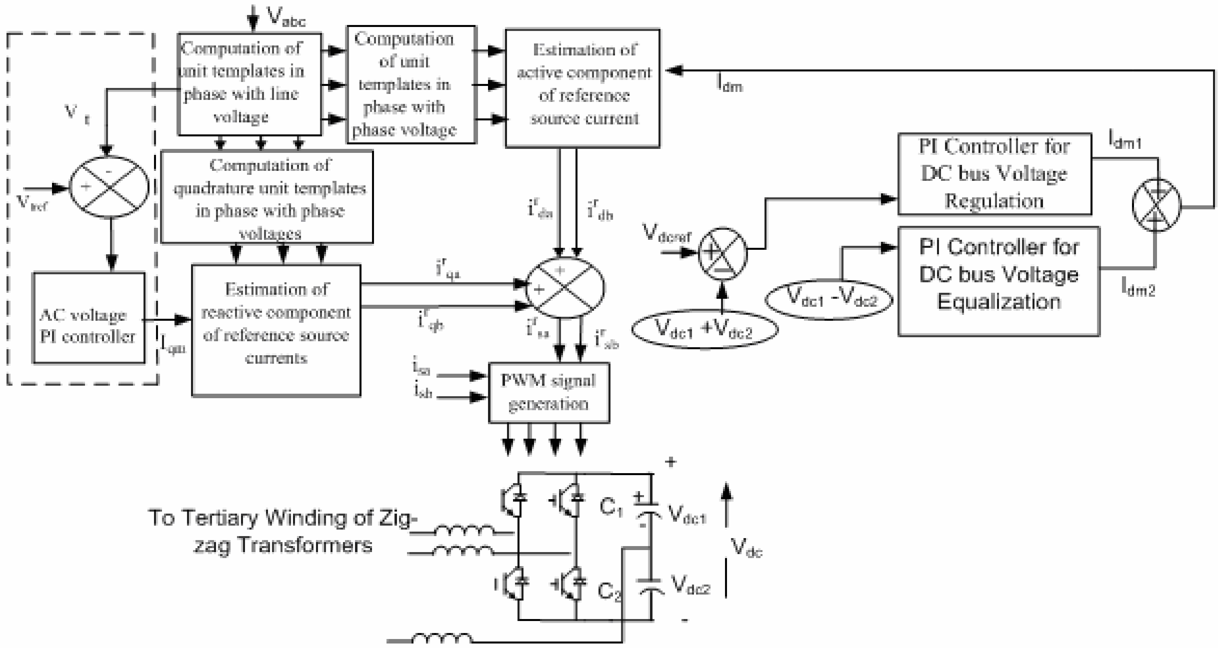


Fig. 2: Control scheme of the proposed controller.

$$u_{bd} = -(\sqrt{3}/2)\, u_{abd} + \{(1/(2\sqrt{3})\}\{(u_{bcd}-u_{cad})\} \quad (4)$$

$$u_{cd} = -(1/\sqrt{3})\{(u_{bcd}-u_{cad})\} \quad (5)$$

and templates in quadrature with phase voltages are

$$u_{aq} = (1/2)\, u_{abd} - \sqrt{3}\,(u_{bcd} - u_{cad}) / (2\sqrt{3}) \quad (6)$$

$$u_{bq} = (1/2)\, u_{abd} + \sqrt{3}\,(u_{bcd} - u_{cad}) / (2\sqrt{3}) \quad (7)$$

$$u_{cq} = -\, u_{abd} \quad (8)$$

A. In-Phase Component of Reference Source Currents

The error in DC bus voltage of STATCOM ($V_{dcer(n)}$) at n^{th} sampling instant is:

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \quad (9)$$

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 DC bus PI controller (I_{dm1}) for maintaining DC bus voltage of the VSC at the n^{th} sampling instant is expressed as:

$$I_{dm1(n)} = I_{dm1(n-1)} + K_{pd1}\{V_{dcer1(n)} - V_{dcer1(n-1)}\} + K_{id1} V_{dcer1(n)} \quad (10)$$

K_{pd1} and K_{id1} are the proportional and integral gain constants of the PI controller.

Then second part of active component of reference source current (I_{dm2}) is calculated for equal voltage distribution across the mid-point capacitor as.

$$V_{dcer(n)} = V_{dc1(n)} - V_{dc2(n)} \quad (11)$$

where $V_{dc1(n)}$ and $V_{dc1(n)}$ are the voltage across the capacitors C_1 and C_2 .

The output of the PI controller ($I_{dm2(n)}$) for maintaining equal capacitors voltages at the n^{th} sampling instant is expressed as

$$I_{dm2(n)} = I_{dm2(n-1)} + K_{pd2}\{V_{dcer2(n)} - V_{dcer2(n-1)}\} + K_{id2} V_{dcer2(n)} \quad (12)$$

Total active component (I_{dm}) of reference source current is estimated as:

$$I_{dm} = I_{dm1} + I_{dm2} \quad (13)$$

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

$$i^{r}_{da} = I_{dm}\, u_{ad}; \quad i^{r}_{db} = I_{dm}\, u_{bd} \quad (14)$$

B. Computation of Reactive Component of Reference Source Current

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

$$V_{er(n)} = V_{tmref(n)} - V_{tm(n)} \quad (15)$$

where $V_{tmref(n)}$ is the amplitude of reference AC terminal voltage and $V_{tm(n)}$ 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 ($I_{qm(n)}$) for maintaining constant AC terminal voltage at the n^{th} sampling instant is expressed as

$$I_{qm(n)} = I_{qm(n-1)} + K_{pa}\,\{V_{er(n)} - V_{er(n-1)}\} + K_{ia} V_{er(n)} \quad (16)$$

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 $I_{qm(n-1)}$ 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

$$i^{r}_{qa} = I_{qm}\, u_{aq}; \; i^{r}_{qb} = I_{qm}\, u_{bq;} \quad (17)$$

C. Computation of Reference Source Current

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

$$i^{r}_{sa} = i^{r}_{qa} + i^{r}_{da} \quad (18)$$

$$i^{r}_{sb} = i^{r}_{qb} + i^{r}_{db} \quad (19)$$

D. PWM Signal Generation

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

$$i_{saerr} = i^{r}_{sa} - i_{sa} \quad (20)$$

$$i_{sberr} = i^{r}_{sb} - i_{sb} \quad (21)$$

These current errors are amplified and amplified signals are compared with fixed frequency triangular wave to generate the gating signals to the IGBTs and similar logic is applied to generate the gating signals for other phase of VSC.

V. MATLAB Based Modeling

The proposed controller is modeled and simulated in MATLAB using Simulink and PSB (Power System Block set) toolboxes. A 7.5 kW, 415V, 50Hz asynchronous machine is used as a generator including the saturation characteristics of the machine, which is determined by synchronous speed test [5]. A delta connected excitation capacitor is used to generate the rated voltage at no-load [5], while an additional demand of the reactive power of the generator during load variation is met by the proposed controller. An in-built universal bridge is used as a two leg voltage source converter. The tertiary winding zig –zag transformer is modeled using transformer blocks. All necessary equations to model the control algorithm such as calculation of terminal voltage, unit vectors etc. are carried out using function blocks. Simulation is carried out in MATLAB version of 7.3 using ode (23tb/stiff/TR-BDF-2) solver in discrete mode at 5e-6 step size.

VI. Results and Discussion

Figs. 3-5 show the performance of the proposed standalone generating system under the dynamic conditions of varying loads. These figures show the performance of the controller for supplying balanced/ unbalanced, linear/ non-linear loads respectively. Fig. 5 demonstrates the waveforms and the total harmonic distortion (THD) of the generator voltage, generator current and load current under the non-linear load condition and it is observed that in all conditions, the controller responds in desirable manner. Simulated transient waveforms of the generator voltage (v_{abc}), generator current (i_{abc}), capacitor current (i_{cca}), load currents (i_{labc}), controller current (i_{cabc}), load neutral current (i_{ln}), terminal voltage (V_t), DC link voltage (V_{dc}) and voltage across both the capacitors (V_{dc1} and V_{dc2}), are given in different dynamic conditions.

A. Performance of the Controller for Feeding 3-Phase 4-Wire 0.8pf Lagging Linear Loads

Fig. 3 demonstrates the controller performance for isolated asynchronous generator for feeding 3-phase 4-wire loads. At 2.5 s, when 0.8pf lagging balanced reactive load of

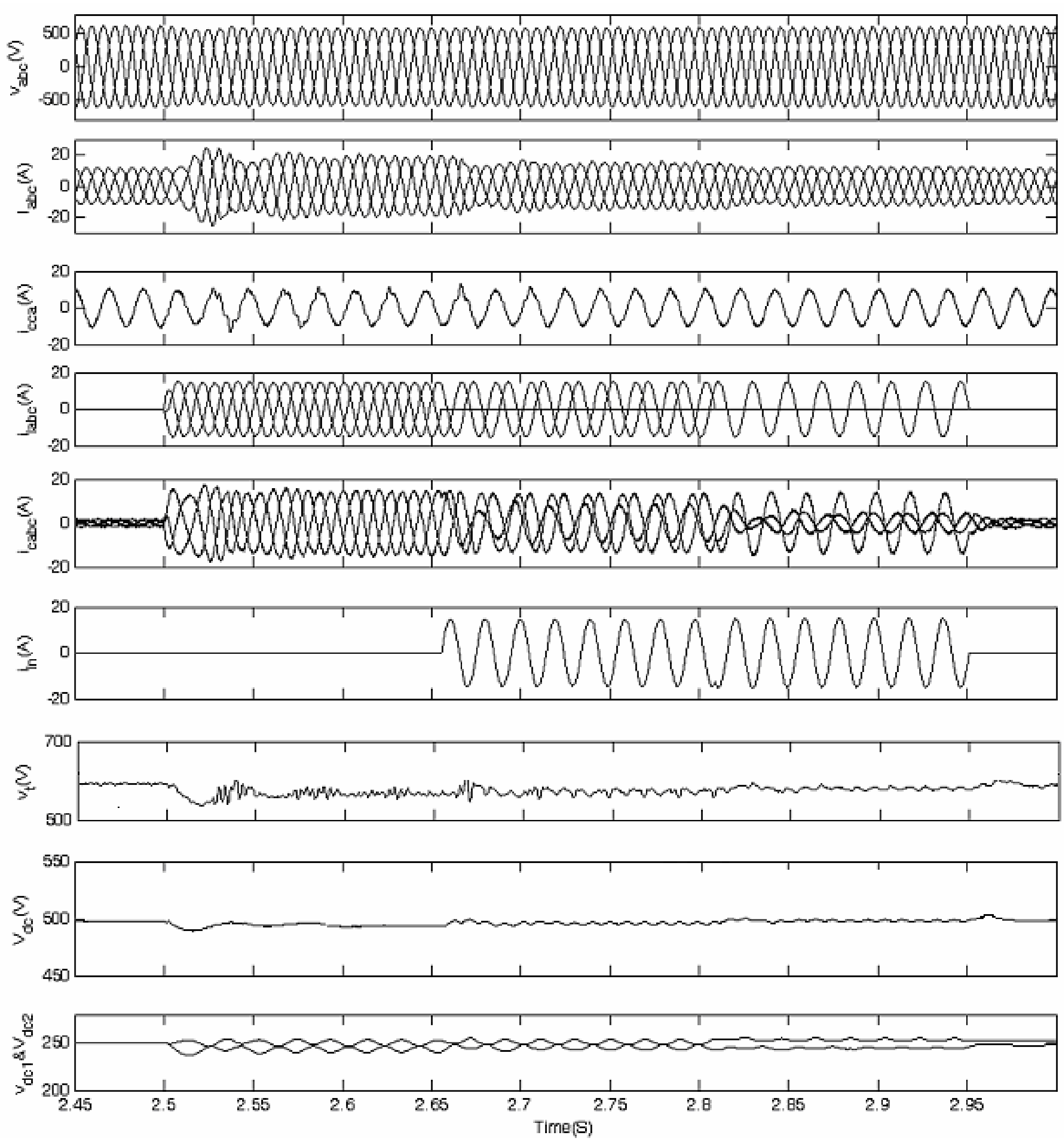


Fig. 3: Performance of the controller under the condition of feeding varying 3-Phase 4-wire 0.8 pf lagging reactive loads

around 6kW is applied at PCC, the compensator is supplying the reactive current to regulate the voltage at its reference value. At 2.65 s, one phase and later on at 2.8 s, other phase of the load is opened, the load becomes unbalanced, which is compensated by the controller as shown in Fig. 3.

A. Performance of the Controller for Feeding 3-Phase 4-Wire Non-linear Loads

In the similar manner, Fig. 4 demonstrates the performance of the controller for isolated asynchronous generators feeding 3-phase 4-wire non-linear loads. At 2.5s, on the application single-phase diode bridge rectifier based 6kW three non-linear loads between each phase and neutral, the voltage is regulated by the controller. At 2.7 s, one phase and later on at 2.9 s, other phase is opened, the load becomes unbalanced on the system while on the generator side source currents remain balanced which demonstrates the load balancing aspects of the controller.

B. Power Quality Aspects

Harmonic spectrum and waveform of the generator voltage, current and the load current are demonstrated in Fig. 5 under balanced conditions of non-linear loads. Under the condition of balanced load currents having THD (total harmonic distortion) of the order of 79.05%, these are compensated by the controller and THD of the voltage and currents of the generator is observed around 1.78% and 2.71% respectively. The THD of generated voltage and generator current is obtained less than 5% and it meets the requirements of IEEE -519 standard [12]. Hence from these results, it is demonstrated that along with voltage regulation, load balancing, and harmonic elimination are achieved using the proposed controller.

VII. CONCLUSION

A novel reduced switch configuration of a voltage controller has been investigated for a stand alone power generating system along with tertiary winding zigzag

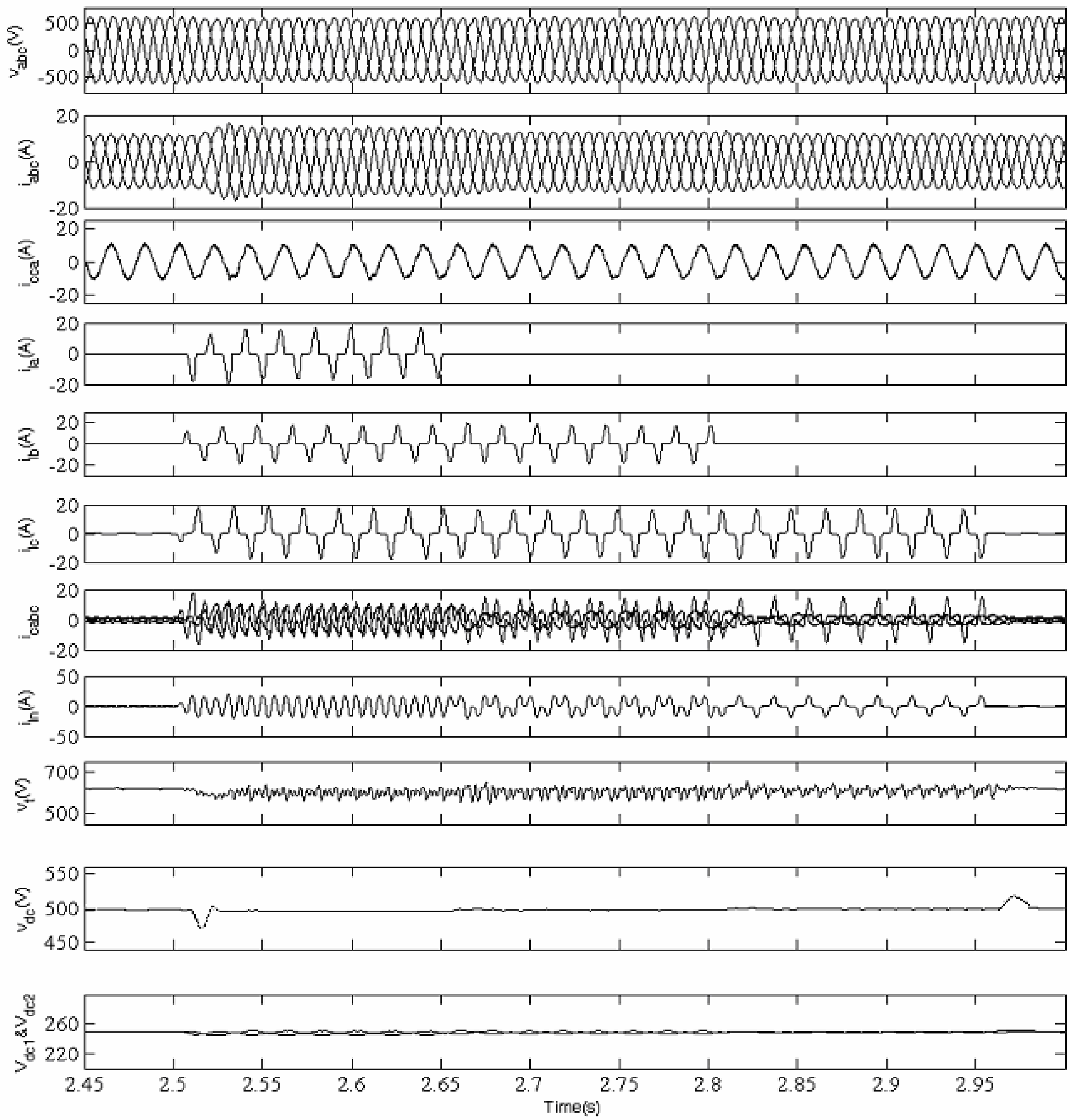


Fig. 4: Performance of the controller at varying 3-Phase 4-wire non-linear loads.

transformer. The size, cost and complexity of the controller have comparatively reduced in comparision to other 3-phase 4-wire topology of the VSC based voltage controller in a stand alone power generation. The simulation results have demonstrated the capability of the controller as a harmonic eliminator, a load balancer along with voltage regulator in a stand-alone power generating system. The performance of the controller has been demonstrated under different dynamic conditions such as varying consumer loads and it has been observed that the proposed controller has given quite satisfactory performance of IAG system.

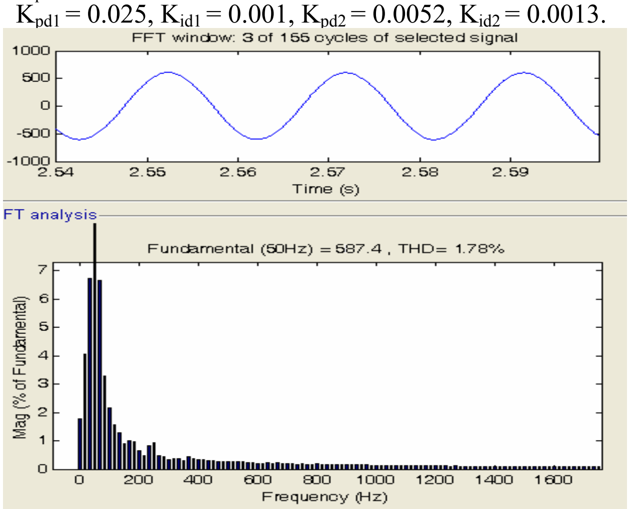
VIII. Appendix

*A. The parameters of 7.5*kW*, 415*V*, 50Hz,* Y*-Connected, 4-Pole asynchronous machine are given below.*

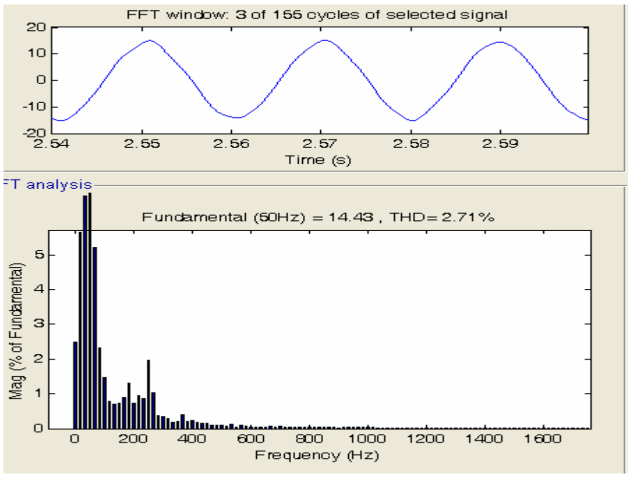
$R_s = 1\ \Omega$, $R_r = 0.77\Omega$, $X_{lr} = X_{ls} = 1.5\Omega$, $J = 0.1384 kg\text{-}m^2$
$L_m = 0.134H$ ($I_m<3.16A$)
$L_m = 9e\text{-}5I_m^2 - 0.0087I_m + 0.1643$ ($3.16<I_m<12.72$)
$L_m = 0.068H$ ($I_m>12.72A$).

B. Controller Parameters

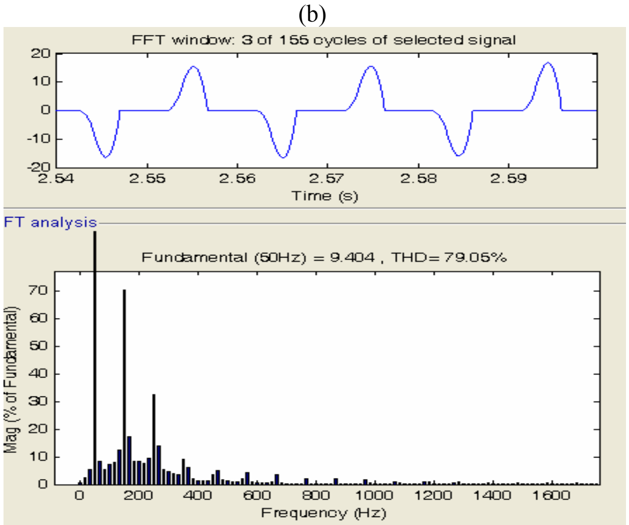
$L_f = 4mH$, $R_f = 0.1\Omega$, and $C_{dc} = 4000\ \mu F$.
$K_{pa} = 0.14$, $K_{ia} = 0.0015$.
$K_{pd1} = 0.025$, $K_{id1} = 0.001$, $K_{pd2} = 0.0052$, $K_{id2} = 0.0013$.



(a)



(b)



(c)

Fig. 5: Waveforms and harmonic spectra of generator voltage (v_a), generator current (i_a) and consumer load current (i_{lc}) feeding balanced non-linear load.

IX. References

[1] Jean-Marc Chapallaz, Dos Ghali Peter Eichenberger, Gehard Fischer, "Manual on induction motors used as generators," Deutsches Zentrum Fur Entwicklingstechnologien- GATE , Germeny, 1992.

[2] M. Godoy Simoes and Felix A. Farret, Renewable Energy Systems, (CRC Press Florida, 2004).

[3] Bhim Singh and Gaurav Kumar Kasal, "Neural network based voltage regulator for an isolated asynchronous generator supplying 3-phase 4-wire loads", Electric Power Systems Research, Vol. 78, No. 6, 2008, pp.985-994.

[4] I. Tamrakar, L. B. Shilpkar, B. G. Fernandes and R. Nilsen, "Voltage and frequency control of parallel operated synchronous generator and induction generator with STATCOM in micro hydro scheme", Proc IET – Gener. Transm. Distrib, Vol. 1, No. 5, Sept 2007, pp 743-750.

[5] Bhim Singh, S.S. Murthy and Sushma Gupta,"STATCOM based voltage regulator for self excited induction generator feeding non-linear loads", IEEE Trans. on Industrial Electronics, Vol. 53, No. 5, Oct 2006, pp 1437-1452.

[6] J.C. Wu, "Novel circuit configuration for compensating for reactive power of the induction generator", IEEE Transactions on Energy Conversion, Vol. 23, No.1, March 2008, pp 156-162.

[7] Antonio Griffo and Davide Lauria, "Two-Leg Three-Phase Inverter Control for STATCOM and SSSC Applications", IEEE Transactions on Power Delivery, Vol. 23, No.1, Jan 2008, pp 361-370.

[8] H. Akagi, E.D. Watanable and M.M. Aredes, Instantaneous Power Theory and Applications to Power Conditioning, (John Willey and Sons Ltd, Hoboken, NJ, 2007).

[9] P. P. Khera, "Application of zigzag transformers for reducing harmonics in the neutral conductor of low voltage distribution system", in Proc. IEEE IAS Conf. Rec, Vol. 2, 1990, pp. 1092.

[10] Sewan Choi and Minsoo Jang, "Analysis and control of a single-phase-inverter–Zigzag-transformer hybrid neutral-current suppressor in three-phase four-wire systems", IEEE Transactions on Industrial Electronics, Vol. 54, No.4, Aug 2007, pp 2201-2208.

[11] Amit Jain, Karan Joshi, Aman Behel and Ned Mohan, "Voltage regulation with STATCOMs: modeling, control and results", IEEE Trans on Power Delivery, Vol. 21, No. 2, April 2006, pp. 726-735.

[12] IEEE Guide for Harmonic Control and Reactive Compensation of Static Power Converters, IEEE Standard 1981, pp. 519.

Biographies

Bhim Singh was born in Rahamapur, India, in 1956. He received the B.E (Electrical) degree from the University of Roorkee, Roorkee, India, in 1977 and the M.Tech and Ph.D. degree from the Indian Institute of Technology (IIT) Delhi, New Delhi, India, in 1979 and 1983, respectively. In 1983, he joined the 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. He became an Associate Professor in 1994 and Professor in 1997. His area of interest includes power electronics, electrical machines and drives, active filters, FACTS, HVDC and power quality
Dr. Singh is a fellow of Indian National Academy of Engineering (INAE), the Institution of Engineers (India) (IE (I)), and the Institution of Electronics and Telecommunication Engineers (IETE), a life member of the Indian Society for Technical Education (ISTE), the System Society of India (SSI), and the National Institution of Quality and Reliability (NIQR) and Senior Member of Institute of Electrical and Electronics Engineers (IEEE).

Gaurav Kumar Kasal was born in Bhopal, India, in Nov, 1978. He received the B.E (Electrical) and M.Tech degree from the National Institute of Technology (NIT) Allahabad and National Institute of Technology (NIT) Bhopal, India respectively in 2002 and 2004. Since Dec 2004, he has been pursuing the Ph. D. degree with the Department of Electrical Engineering, Indian Institute of Technology (IIT) Delhi, New Delhi, India. His field of interest includes power electronics and drives, renewable energy generation and applications, flexible AC transmission system.