Electronic Voltage and frequency Controller (EVFC) for an Isolated Asynchronous Generator (IAG) for low power applications

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Abstract: - In this paper, an electronic voltage and frequency (EVFC) controller has been implemented and simulated in MATLAB/SIMULINK Simpower System Blockset to regulate voltage and frequency of a IAG feeding three-phase balanced and unbalanced linear and non-linear consumer load for constant power applications such as uncontrolled turbine in Pico hydro power generation (<10kW). The EVFC consists of a diode bridge rectifier, IGBT based chopper switch, dc filtering capacitor, PI controller and a resistive Dump load. The steady state and transient behaviour of IAG-EVFC system is examined and studied under different operating conditions to demonstrate the capabilities and effectiveness of electronic voltage and frequency controller (EVFC). The switching ON and OFF like operating condition of balanced and unbalanced load of consumer are obtained by adding circuit breakers in the Simulink model of the system under study.

Key-Words: - Isolated Asynchronous Generator, linear and non-linear load, diode bridge rectifier, MATLAB/SIMULINK, THD

1 Introduction

Distributed or on-site power generation has proven to be more reliable and economical in recent years than the off-site generation due to its cost, complexity of national grid system, reduced reliability and transmission losses. Thus, a distributed power generation system is an alternative or an enhancement of the existing traditional electric power system. Thus a suitable self-excited or stand alone system using locally available energy sources like small hydro, wind, biomass become a preferred option. As these energy sources systems are located in remote areas they must be reliable, robust, economical and manageable by local communities. The unskilled community must handle the complete system comprises of prime mover, generator and its associated controller. Micro turbines or pumps as a turbine are used as a prime mover. The Asynchronous generator in stand-alone mode is the most preferred and suitable option due to low cost, simple construction, ruggedness, brushless rotor, absence of DC source, maintenance-free nature, self-protection against short-circuit and its off-the shelf availability. Due to the latest research on non conventional energy sources and grid OFF systems, the GIAG becomes one of the most important and favoured renewable sources of energy [1-14]. For low power rating (less than 100kW) uncontrolled turbines driving Grid Isolated Asynchronous Generator are preferred which maintain the hydropower constant, thus requiring the generator output power to be held constant at varying consumer loads. This requires Electronics based load controller where a dump load is connected in shunt or across the consumer load so that the total power consumed is held constant.

Various types of electronics based controllers (EVFC) for IAG have been developed and are reported in literature along-with its advantages and disadvantages [4-14]. The IAG can be used for constant power applications and for constant speed variable power application. In constant power applications, prime mover speed, value of excitation capacitor and the consumer load are kept constant and thus known as a single point operation. In constant speed variable power applications, speed of the prime mover is kept constant but the value of excitation capacitance increases with load. For constant power application, generated power and consumer output power must be fixed for stable operation of three-phase IAG. Input power remains constant with uncontrolled pico-hydro turbine but output power may not be constant due to varying consumer load. In this paper, a simple EVFC is developed which maintain the IAG output power constant.

2 Schematic diagram description

The complete Schematic diagram of the three-phase EVFC-IAG system is shown in Fig. 1. The whole system is a combination of Asynchronous machine, delta connected capacitor bank, three-phase load and an electronic voltage and frequency controller (EVFC). The value of excitation capacitor is selected in such a way that it generates the rated voltage at no load. It consists of six-pulse diode bridge rectifier, the IGBT operated chopper switch, a filtering capacitor(C), dump load resistance (Rd). The diode bridge rectifier is used to convert input three-phase ac terminal voltage of IAG to dc output voltage. The output dc voltage has the ripples, which should be filtered and therefore a filtering capacitor is used to smoothen the dc voltage. An IGBT is used as a chopper switch providing the variable dc voltage across the dump load. Initially the consumer load and the electronics based dump load controller are kept OFF and the generator is self-excited at no-load. After successful voltage build-up, the electronics based dump load controller consumes the whole of the generated power. When both the consumer load and the chopper is switched ON, the current flows through the dump load and consumes the difference between the generated power and consumer load power and this result in a constant load on the IAG and hence constant voltage and frequency at the balanced consumer load. Thus the generator maintains the power balance in the system.

The duty cycle of the chopper is varied by a discrete PI controller. The output of the PI controller is compared with the saw tooth wave to generate switching signal of varying duty cycle for the chopper switch. According to the principle of operation of the system, the suitable value of capacitors is connected to generate rated voltage at desired power [5-14].

The input power of the IAG is held constant at varying consumer loads. Thus IAG supplies power to consumer load and dump load in parallel such that the total power is constant. The power balance equation for the system is

$$P_{gen} = P_{eload} + P_{cload}$$

Where, P_{gen} is the power generated by the Isolated Asynchronous Generator (IAG) (which should remain constant). P_{cload} is the consumer power and P_{eload} is the electronic dump load power to be dumped in dump load resistance R_D. The electronic dump load power (P_{eload}) may be used for various applications like water heating, charging of batteries, cooking purpose, baking, space heating etc.

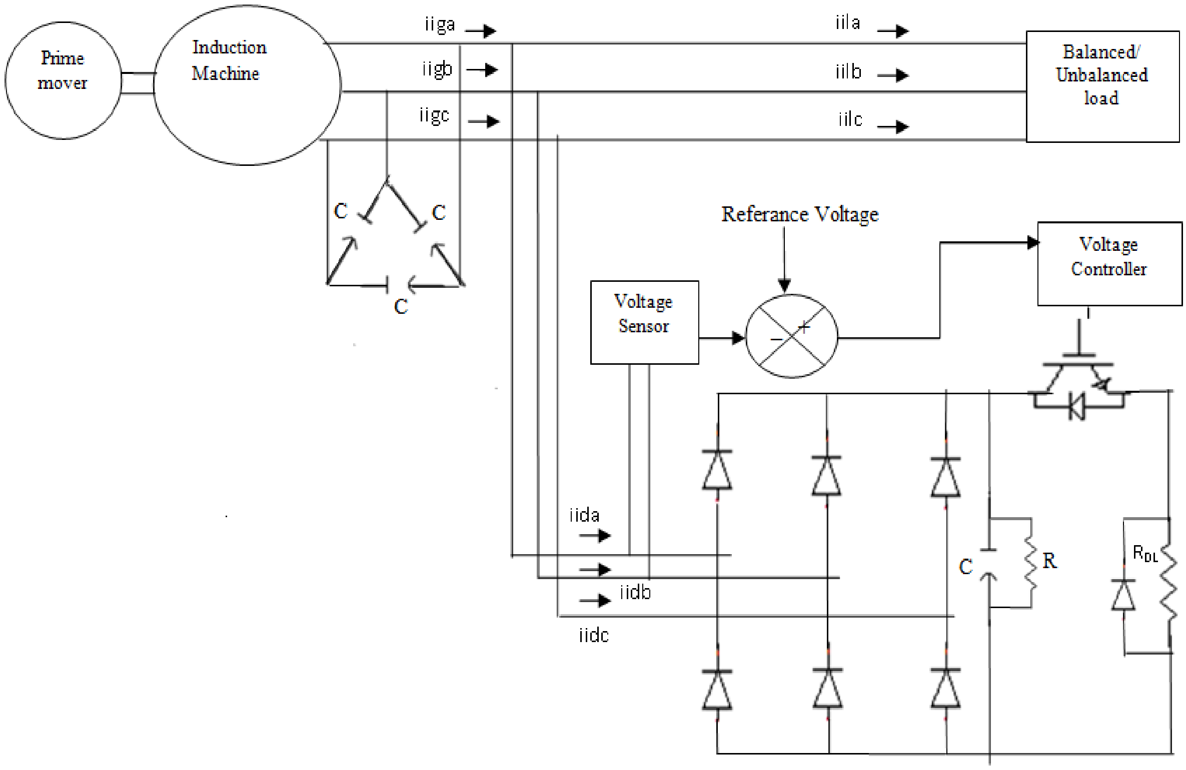


Fig. 1 Simulink model diagram of the whole generating system along with EVFC

3 Control Strategy

The control circuit of electronics voltage and frequency controller (EVFC) consists of a voltage sensor for sensing the three-phase ac voltage of IAG, a comparator for comparing the sensed ac voltage with the reference voltage, a discrete PI controller for processing the error voltage. The output of PI controller is compared with a saw tooth carrier waveform of 1 kHz frequency to generate the PWM switching signal for IGBT operated chopper switch.

4 Simulated results details and its findings

All the simulations have been carried out in MATLAB software package on a 3730 W Squirrel cage Asynchronous motor with Simulation type (Discrete), Sample time (50e-6), Discrete solver mode (Forward Euler), Simulation time (2 seconds), Relative tolerance (1e-3), Time tolerance (10*128*eps) and ode45 (Stiff/TR-BDF2) solver A three-phase electronics voltage and frequency (EVFC) controller for a three-phase IAG is implemented. The dump load resistance and DC link capacitor are selected to 103 Ω and 151 µF for the simulation study under balanced/unbalanced three phase linear and non-linear consumer load [11]. A three-phase star-connected Asynchronous machine of 3.73 kW, 460 V, 60 Hz, 4 poles is used as IAG. The IAG is driven by a three-phase alternator. To generate rated voltage i.e. 460 V at no-load, three-phase capacitor of appropriate value is connected across the machine stator terminals.

4.1 Performance of IAG-EVFC system feeding three-phase balanced/unbalanced resistive load

Fig. 2 shows the transient waveforms of three-phase generator voltages (V_{abcg}), three- phase generator currents (I_{abcg}), three-phase resistive load currents (I_{abcl}), per-phase EVFC currents (I_{ac}, I_{bc}, I_{cc}), generated power (P_{gen}), consumer load power (P_{cload}) and electronic load power (P_{eload})

It is observed from the simulated results [Fig. 2] that when the three-phase balanced delta connected resistive load of 2 kW is switched ON between each phase to phase at 0.7 sec, consumers load current increases and the EVFC currents decreases.

It indicates that transfer of power takes place from three-phase EVFC to the balanced three-phase

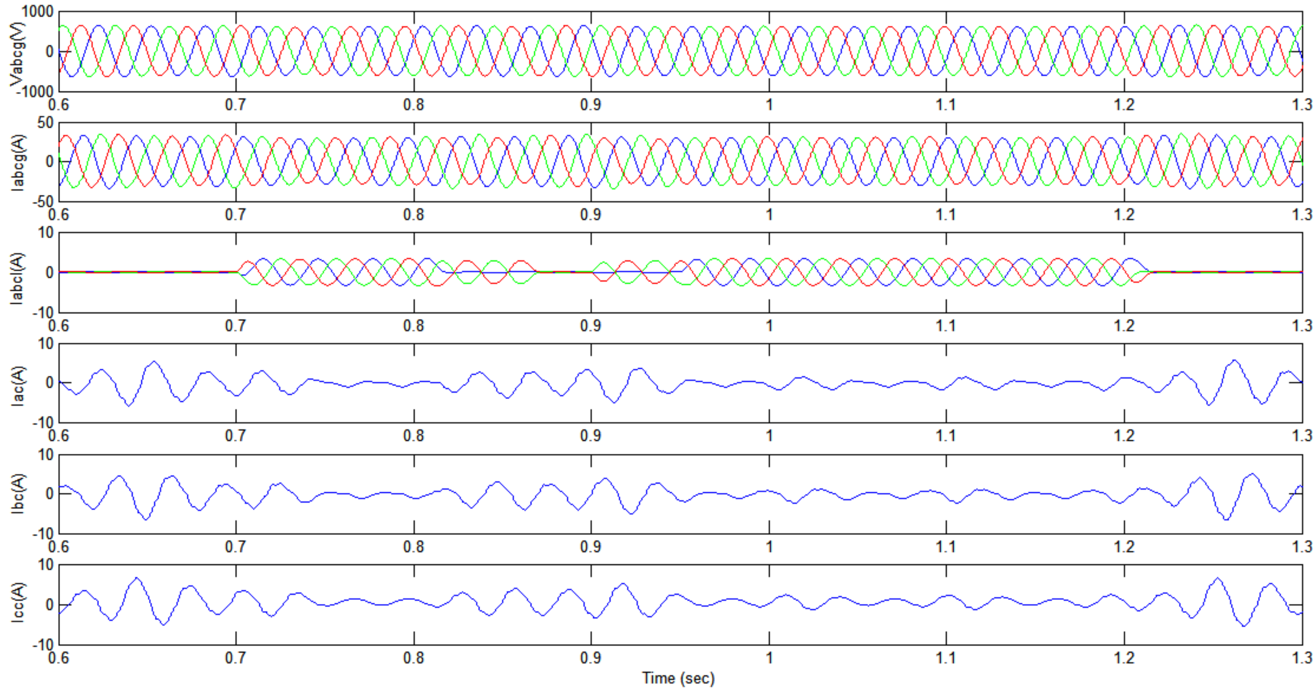


Fig. 2 Simulated transient characteristics waveforms of voltage generated by three-phase IAG (V_{abcg}), three-phase IAG currents (I_{abcg}), three-phase resistive load currents (I_{abcl}), per-phase EVFC currents (I_{ac}, I_{bc}, I_{cc}) under unbalanced resistive load

consumer load and IAG experiences constant load on it and hence maintain constant voltage and frequency [Fig. 3 and Fig. 4]. It is also observed that at this time power grabbed by the dump load (P_{eload}) is nearly zero. With the switching OFF of one phase at 0.8 sec and another phase of load at 0.85 sec, the load becomes unbalanced. Under these operating conditions, consumer load current decreases and the EVFC currents increases. It indicates that transfer of power takes place from three-phase consumer load to the three-phase EVFC and IAG experiences constant load on it and hence maintains constant voltage and frequency.

At 0.9 sec one-phase and at 0.95 sec another phase of load is reconnected on IAG and the system becomes balanced once again. At the instant of switching OFF the three-phase balanced resistive consumer load at 1.2 sec, load current becomes zero and EVFC current increase which gives an indication of transfer of power from consumer load to EVFC such that IAG experiences a constant load on it and maintain constant voltage and frequency [Fig. 3 and Fig. 4]. It is observed from Fig. 4 that electronic load power decreases whereas the consumer load power increases with increase in balanced /unbalanced consumer load so that the load on the IAG remains constant.

Fig. 5 to Fig. 8 shows that the EVFC is capable of reducing the harmonics generated by the load and maintain the THD of the generated voltage at 2.23% under balanced and at 2.42% under unbalanced load conditions .The THD of the generated current is at 4.14% under balanced and at 4.22% under unbalanced load. The THD of both the generated voltage and current are within the limit as specified by IEEE 519 standards.

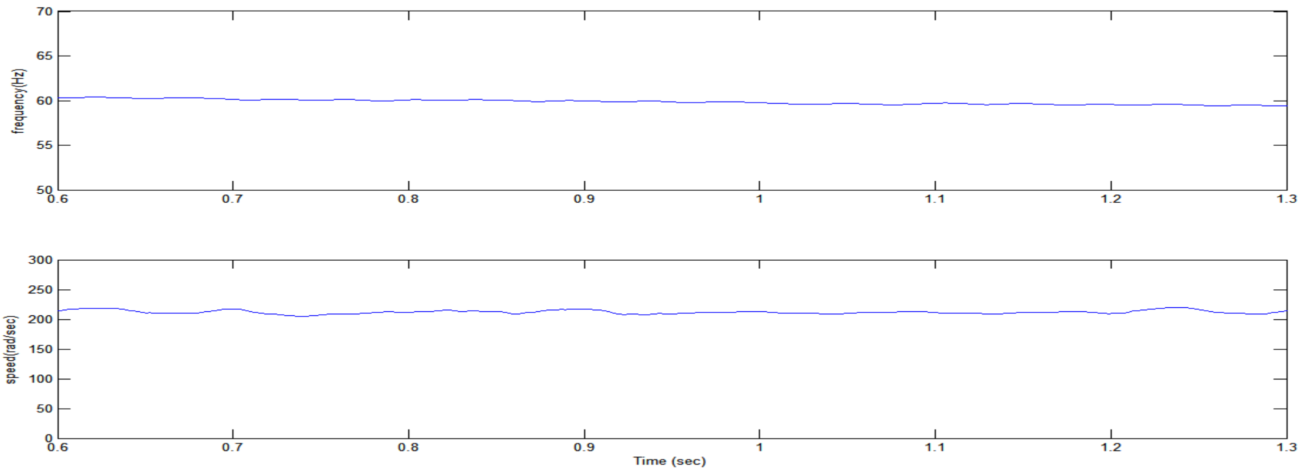


Fig.3 Generated frequency and speed of IAG

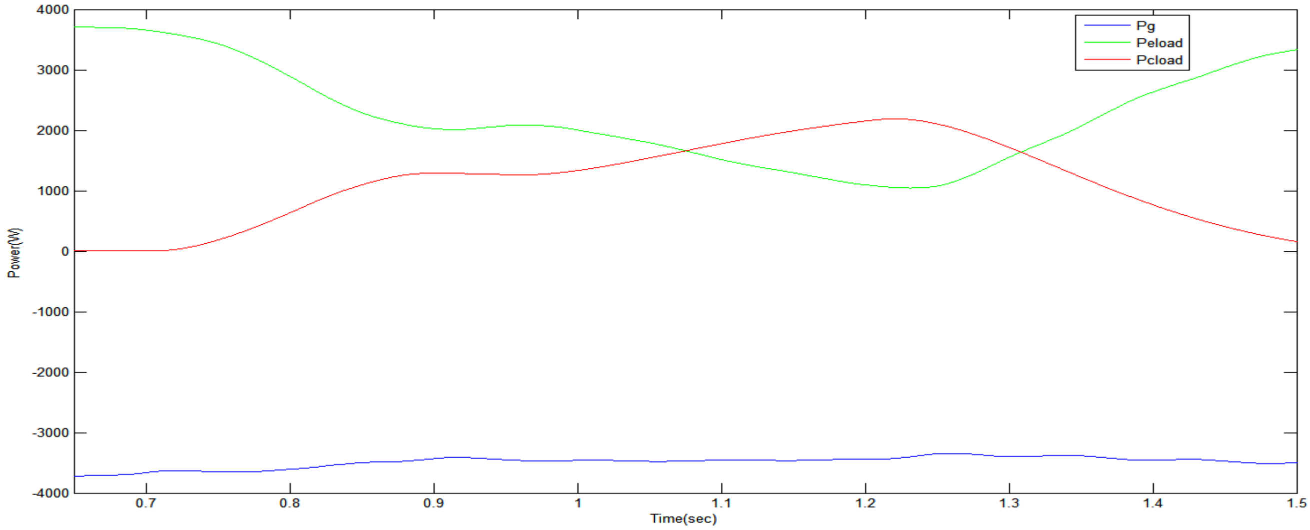


Fig. 4 Variation of power generated by IAG (P_{gen}), consumer power (P_{cload}) and electronic load power (P_{eload}).

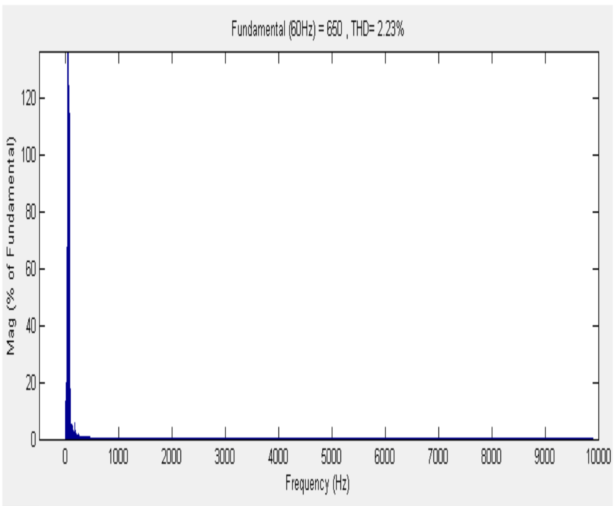


Fig. 5 FFT window for generated voltage with balanced resistive load

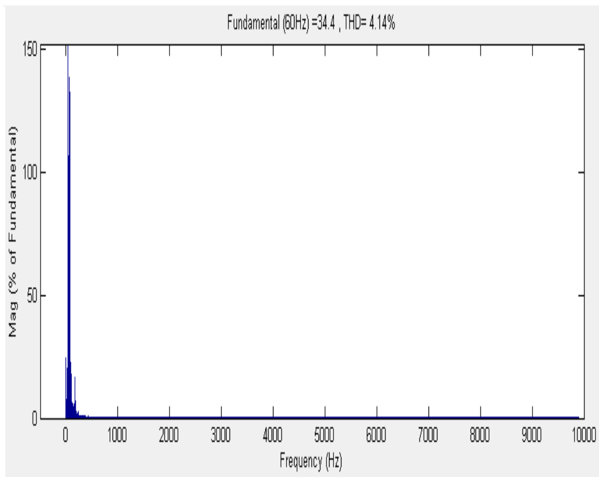


Fig. 6 FFT window for generated current with balanced resistive load

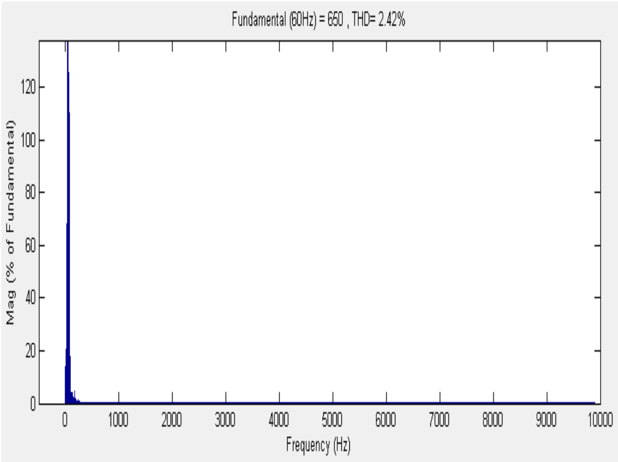


Fig. 7 FFT window for generated voltage with unbalanced resistive load

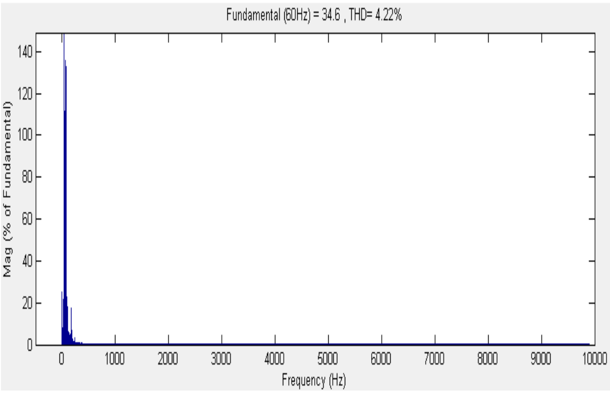


Fig. 8 FFT window for generated current with unbalanced resistive load

4.2 Performance of IAG-EVFC system feeding three-phase balanced/unbalanced reactive load

Fig. 9 represents the transient performance characteristics of three-phase IAG-EVFC system supplying reactive load (0.8 p.f lagging). With the switching ON of three-phase balanced reactive load at 0.7 sec, load current increases and EVFC current of the three -phases decreases to balance the IAG system. With the switching OFF of one phase at 0.8 sec and another phase of load at 0.85 sec, the load becomes unbalanced and hence EVFC currents of two phases increase for balancing the IAG system. At 0.9 sec one-phase and at 0.95 sec another phase of load is reconnected on IAG. Under such situation, EVFC currents decrease to make IAG system balanced. It means that the controller current increases and decreases when the consumer load decreases and increases respectively. It means that the generated power of the IAG remains constant even at varying load conditions. In reactive load situation, generator voltage is constant and is perfectly sinusoidal which shows that EVFC is acting as a voltage regulator and load balancer. The speed of the IAG is constant throughout the whole process which shows that the IAG is generating constant voltage, frequency and power [Fig. 3 and Fig. 4].

Fig. 10 to Fig. 13 shows that the EVFC is capable of reducing the harmonics generated by the load and maintain the THD of the generated voltage at 2.84% under balanced and at 2.94% under unbalanced load conditions .The THD of the generated current is at 4.53% under balanced and at 4.62% under unbalanced load. The THD of both the generated voltage and current are within the limit as specified by IEEE 519 standards.

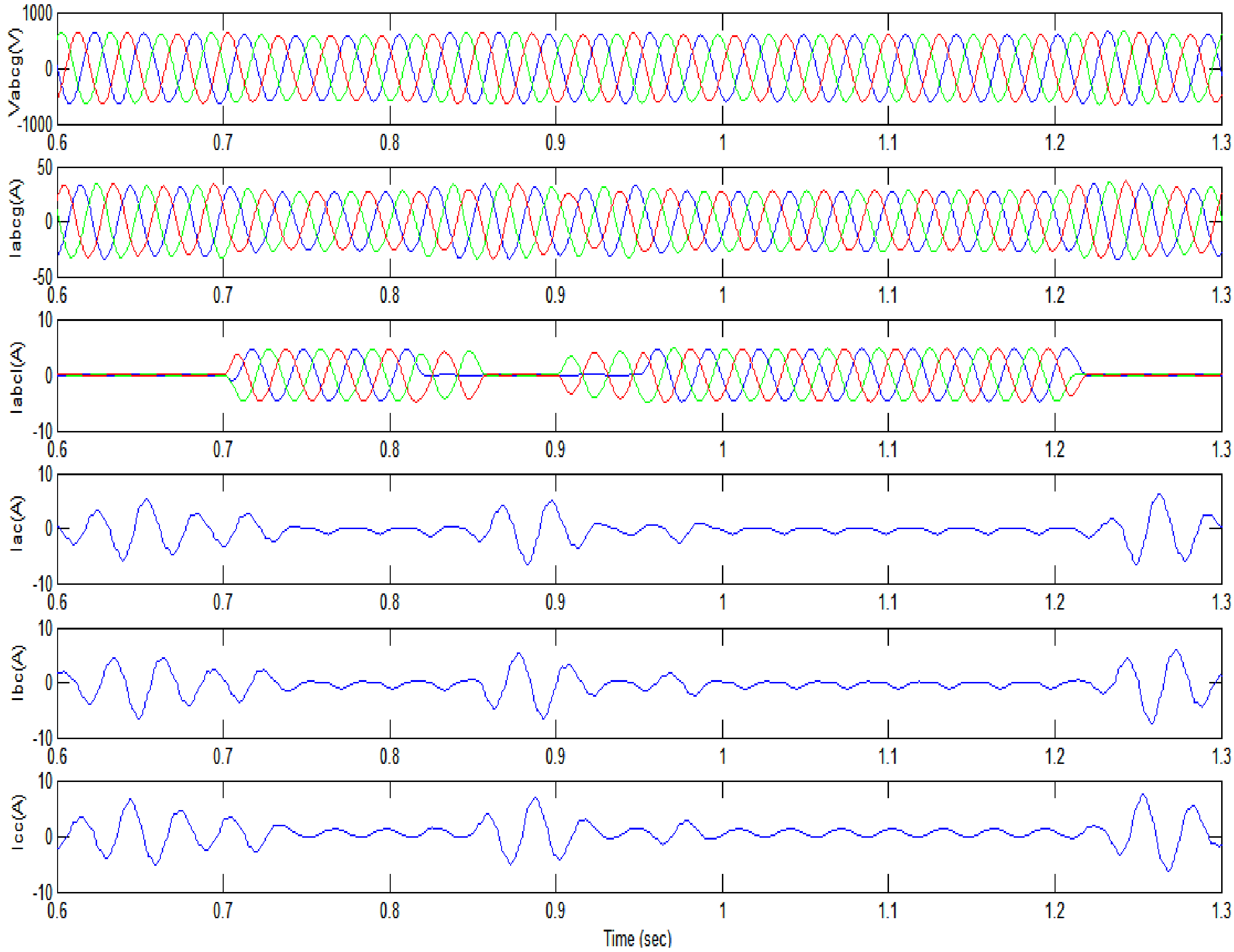


Fig. 9 Simulated transient characteristics waveforms of voltage generated by three-phase IAG (V_{abcg}), three-phase IAG currents (I_{abcg}), three-phase reactive load currents (I_{abcl}), per-phase EVFC currents (I_{ac}, I_{bc}, I_{cc}) under unbalanced reactive load.

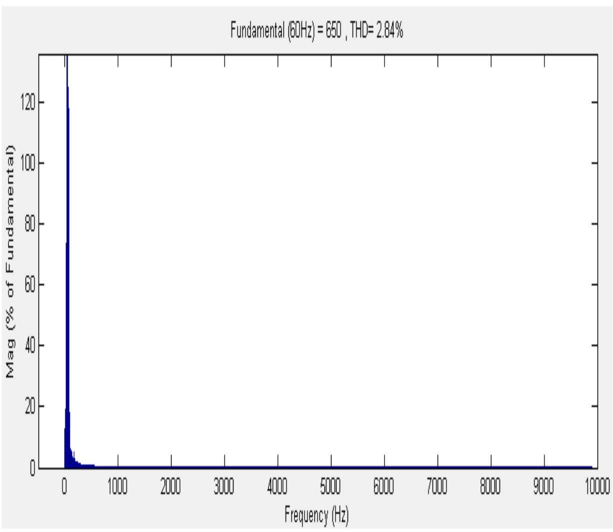


Fig. 10 FFT window for generated voltage with balanced reactive load

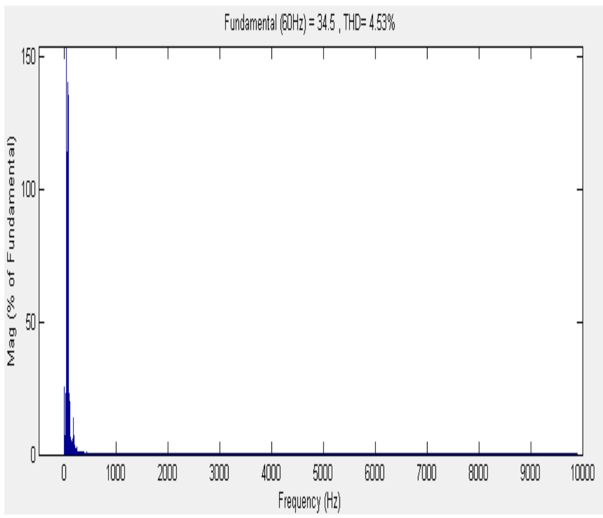


Fig. 11 FFT window for generated current with balanced reactive load

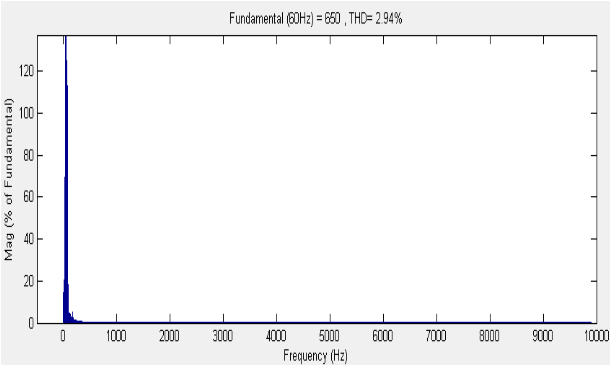


Fig. 12 FFT window for generated voltage with unbalanced reactive load

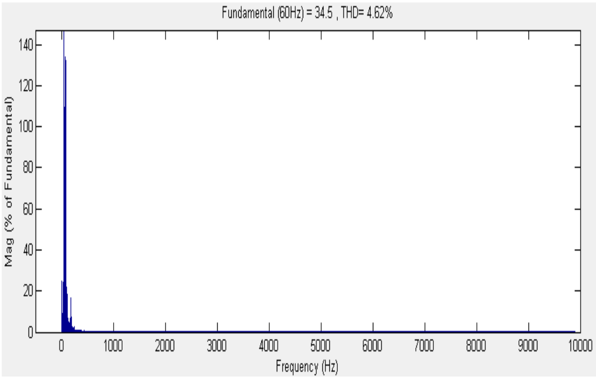


Fig. 13 FFT window for generated current with unbalanced reactive load

4.3 Performance of IAG-EVFC system feeding three-phase balanced/unbalanced non-linear load

Fig. 14 represents the performance characteristics of EVFC Controller system feeding balanced/unbalanced non-linear loads using three-phase diode rectifier with resistive load and C filter at its DC side. At 0.7 sec, a balanced non-linear load is applied then the controller currents are reduced within a cycle for regulating the power, frequency and these becomes non-linear for eliminating harmonic currents. On removal of one phase of the load at 0.8 sec, the load becomes unbalanced but the generator currents remain balanced, which shows the load balancing aspect of the controller. The speed of the IAG is constant throughout the whole process which shows that the IAG is generating constant voltage, frequency and power [Fig. 3 and Fig. 4].

Fig. 15 to Fig. 18 shows that the EVFC is capable of reducing the harmonics generated by the non-linear load and maintain the THD of the generated voltage at 3.66% under balanced and at 4.64% under unbalanced load conditions .The THD of the generated current is at 4.83% under balanced and at 4.93% under unbalanced load. The THD of both the generated voltage and current are within the limit as specified by IEEE 519 standards.

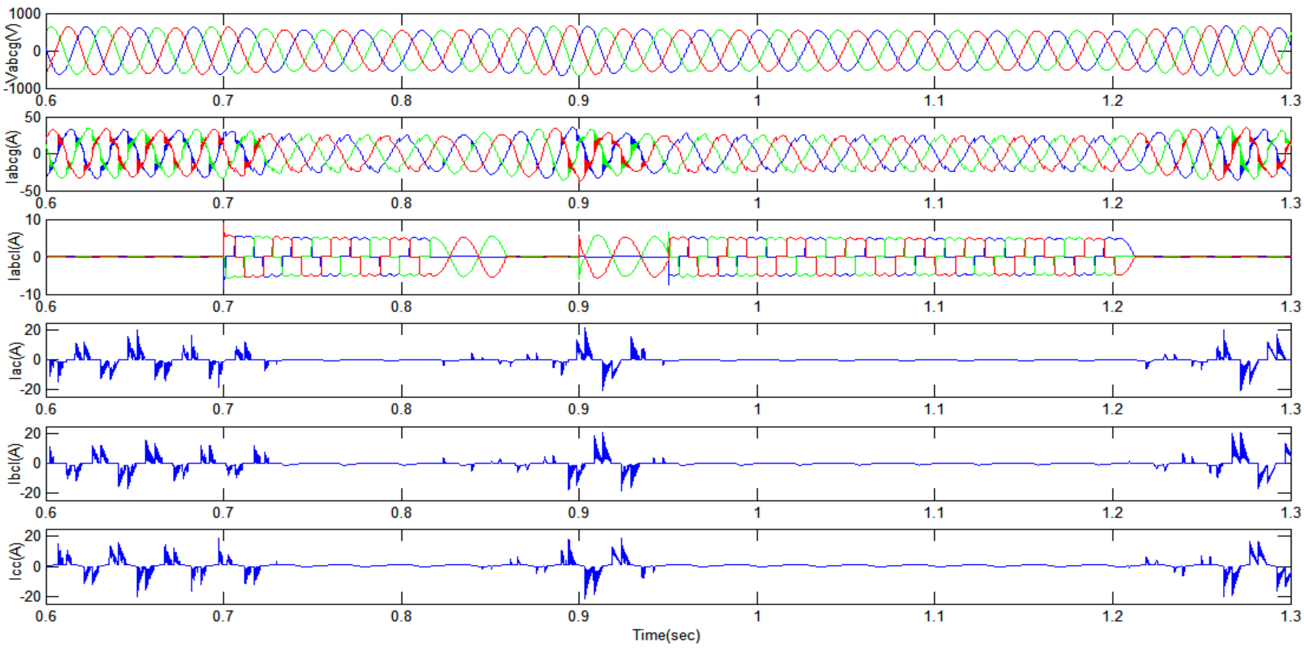


Fig.14 Simulated transient characteristics waveforms of voltage generated by three-phase IAG (V_{abcg}), three-phase IAG currents (I_{abcg}), three-phase non-linear load currents (I_{abcl}), per-phase EVFC currents (I_{ac}, I_{bc}, I_{cc}) under unbalanced non-linear load.

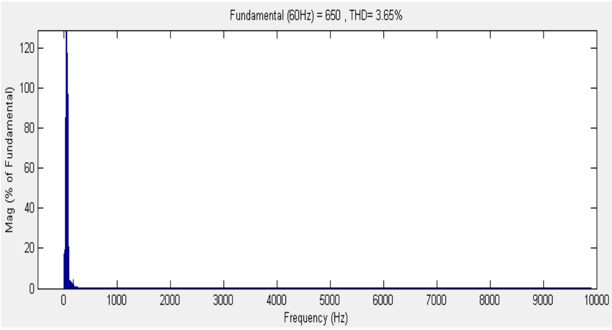


Fig. 15 FFT window for generated voltage with balanced non-linear load

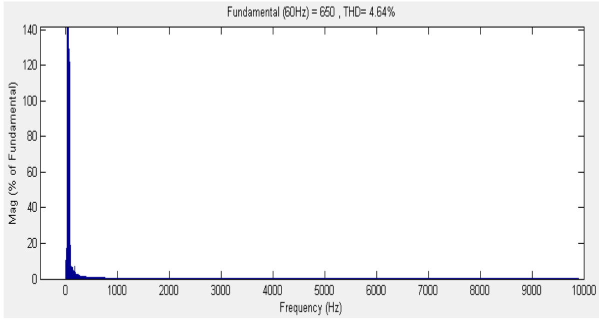


Fig. 17 FFT window for generated voltage with unbalanced non-linear load

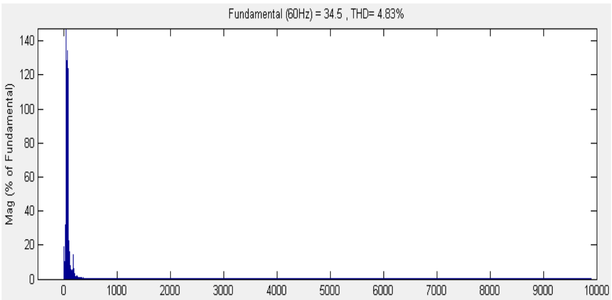


Fig. 16 FFT window for generated current with balanced non-linear load

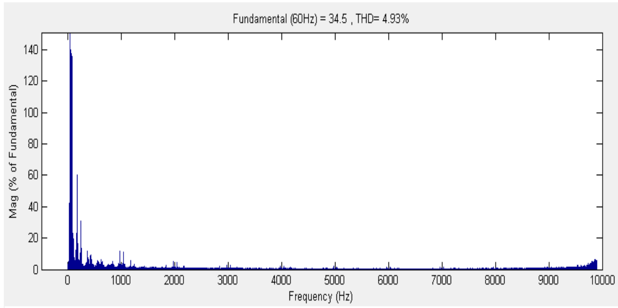
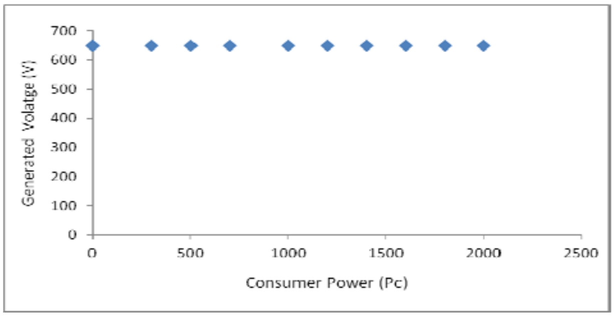
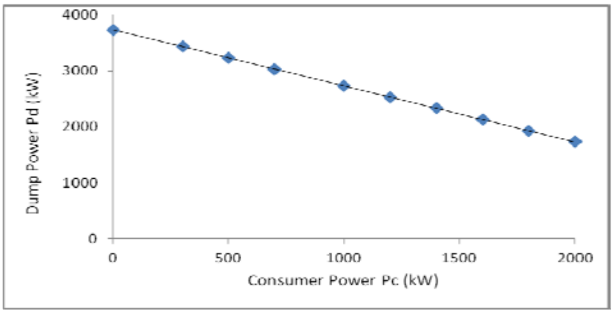


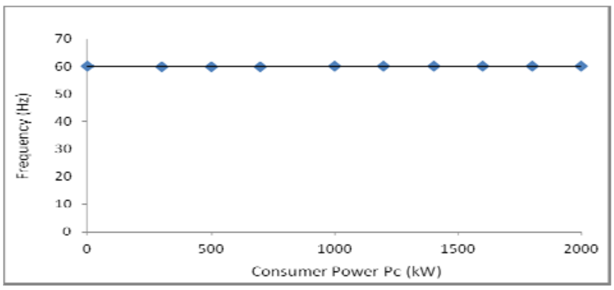
Fig. 18 FFT window for generated current with unbalanced nonlinear load



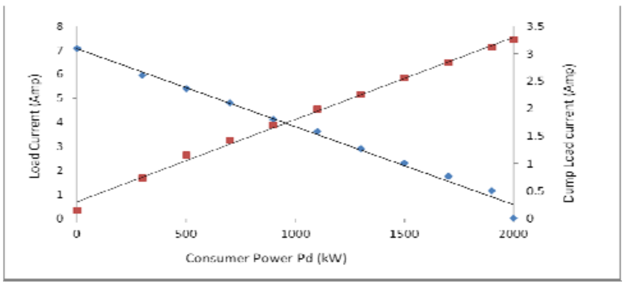
(a)



(c)



(b)



(d)

Fig. 19 Variation of Steady state performance characteristics of three-phase IAG with an increase in consumer load (a) IAG voltage (b) IAG currents (c) frequency (d) Load current and dump load currents

Fig. 19 shows the steady state performance characteristics of IAG voltage, Dump power, frequency, load current and dump load current with variation in Consumer load for the three-phase EVFC. It is noticed [Fig.19 (a), Fig.19 (b)] that IAG voltage and frequency remains constant when the consumer load is varying from 0 to 2 kW. At 0kW consumer power, the dump load power is equal to the rated power of IAG. Further, the dump power decreases with an increase in consumer power [Fig.19 (c)]. With increase in consumer power, the load current decreases whereas the dump loads current increases to make the load constant on the generator [Fig.19 (d)].

5 Conclusions

The steady state and transient state analysis results showed that the developed EVFC for GIAG is capable to maintain both voltage and frequency constant despite the variation in balanced and unbalanced consumer resistive/reactive/non-linear load. The THD of the generated voltage and current are within the limits specified by IEEE 519 standard. Such type of developed system can be used for electrical power production in pico-hydro based applications.

APPENIX-I

1. MACHINE DATA

3.730 kW, 460 V, 60 Hz, Y-connected, 4-pole Asynchronous machine

Rs =0.01965 p.u, Rr' = 0.01909 p.u, L_{ls} = 0.0397 p.u L_{lr}' = 0.0397 p.u, L_m=1.354, J = 0.089 Kg-m^2

2. CONTROLLER PARAMETERS

C_{dc} = 151μF
R_d = 103Ω
K_p = 32.4
Ki = 1.24

3. CONSUMER LOADS

Resistive load	2kW
Reactive load	2kW 1.5kVAR 0.8 power factor lagging
Non-linear load	2kW with a 2000μF capacitor and a 5mH inductor at the DC end

References:

[1] R. C. Bansal, Three-Phase Self-Excited Induction Generators: An Overview, *IEEE transactions on Energy Conversion,* Vol. 20, No. 2, 2005, pp. 292-299.

[2] J.M. Elder, J.T. Boys and J.L. Woodward, Integral cycle control of stand-alone generators , *IEE Proc.,* Vol. 132 , No. 2, 1985, pp. 57-66.

[3] R. Bonert and S. Rajakaruna, Self-excited induction generator with excellent voltage and frequency control, *IEE Proc. Gener Transm. Distrib.,* Vol. 145 , No. 1, 1998, pp. 33-39.

[4] Chandra, T.S, Bishnu, P.M., Voltage regulators for self excited induction generator, *IEEE Transactions on Energy Conversion*, Vol. 20 , No. 4, 2004, pp. 460-463.

[5] S.C Kuo and L Wang , P.M., Analysis of voltage control for a self-excited induction generator using a current-controlled voltage source inverter (CC-VSI), *Proc. Inst. Elect. Eng., Transm. Distrib,* Vol. 148, No. 5, 2001, pp. 431-438.

[6] E.Suarez and G.Bortolotto, Voltage frequency control of a self-excited induction Generator, *IEEE Trans. Energy Convers* , Vol. 14, No. 3, 1999, pp. 394-401.

[7] B. Singh, S.S. Murthy and S. Gupta, Analysis and implementation of an electronic load controller for a self-excited induction generator, *IEE Proc. Gener. Transm. Distrib,* Vol. 151, No. 7, 2004, pp. 51-60.

[8] B. Singh, S.S. Murthy and S. Gupta, Analysis and design of an electronic load controller for a self-excited induction generator, *IEEE Trans. On Energy Conversion,* Vol. 21, No. 1, 2006, pp. 285-293.

[9] Sarsing Gao, S.S Murthy, G. Bhubaneswar and M. Sree Lalitha Gayathri, Design of microcontroller based electronic load controller for a self-excited induction generator supplying single-phase loads, *Journal of Power Electronics, Vol.* 10, No. 4, 2010, pp. 444-449.

[10] Juan M. Ramirez and Emmanuel Torres M., An Electronic load controller for self-excited induction generators, *IEEE PES General Meeting*, June, 2007.

[11] Shakuntla Boora, S.K Agarwal, K.S Sandhu, Electronics based dump load controller for an grid isolated Asynchronous Generator, *International Journal on emerging Technologies,* Vol. 6, No. 2, 2015, pp. 9-14.

[12] M.H.Rashid, *Power Electronics: Circuits, Devices and Applications,, 3rd ed.*, Singapore: Pearson/Prentice-Hall, 2004.

[13] IEEE Guide for harmonic Control and Reactive Compensation of Static Power Converters, *IEEE Standard* 519-1992.

[14] E.G. Marra and J.A. Promilo, Induction-Generator- based system providing regulated voltage with frequency constant, *IEEE Trans. Ind. Electron,* Vol. 47, No. 4, 2010, pp. 908-914.