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Voltage And Frequency Controller for Self-Excited Induction Generator with Combined p-q And I_d-I_q Control Strategies

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Abstract - **This paper deals with voltage and frequency controller for three phase self-excited induction generator in constant power operation. When the self-excited induction generator (SEIG) attains steady state condition, an increase in load causes decrease in magnitude of generated voltage and frequency. Moreover, a generator work under non-linear conditions, the voltage and stator current get unbalanced, flows a current in the neutral conductor and harmonics occurred. The proposed controller used to control both frequency and voltage in the generator terminal. The proposed controllers consist of static synchronous compensator (STATCOM) which regulates the voltage and electronic load controller (ELC), which control the power which will maintain the constant frequency. The STATCOM consist of a 4-leg insulated gate bipolar transistor (IGBT)-based current controlled voltage-sourced converter (CC-VSC) and a self-supporting dc bus, while the ELC consists of a converter, a switch and an auxiliary load.The instantaneous real active and reactive power method (p-q) and active and reactive current method (id-iq) are two control methods which are used in both STATCOM and ELC. The simulations are carried out by using PI controller for both p-q and i_d-i_q and adequate results was found. The proposed generating system is simulated in MATLAB along with Simulink.**

***KEYWORDS*–Induction Generator, Electronic Load Controller, STATCOM, Neutral Current Compensation, Harmonic Compensation, p-q Control Strategy, I_d-I_qControl Strategy.**

I. INTRODUCTION

Asynchronous cage machines (AMs) are robust,inexpensive compared with DC and wound field synchronous machines, require little maintenance, and have high power weight ratio. Despite these favorable features, commercialization of an asynchronous machine as an isolated asynchronous generator (IAG) is still a bottleneck because of its unsatisfactory voltage and frequency regulation, even when driven at constant speed and feeding varying loads. In these applications, the micro hydro turbine isgenerally uncontrolled and hence provides constant power. Thus IAG has to operate at constant power at varying consumer loads, called “single point” operation, as the power, excitation capacitance and the speed are maintained nearly constant. Therefore for constant power at the generator terminals, ELCs are used regulating which in turn regulate voltage and frequency of the isolated generation. The basic principle of operation is that total generated power should be absorbed by consumer loads and ELCs to regulate power constant at the generator terminals. In the reported literature for micro hydro generation, variable VAR compensators are used to regulate the voltage with allowable frequency variation.In later stage, the developments of electronic load controllers have been reported for maintaining constant power at the terminal of the generator.

However, in variable power application like biogas, gasoline, and diesel engines driven asynchronous generator where speed is almost constant, a reactive power compensator like STATCOM serves the purpose of voltage regulation while the frequency is maintained constant due to constant speed of the prime mover. Therefore, it cannot be used alone in micro hydro applications where the frequency varies due to variation in consumer loads as it is a constant power prime mover. However, no controller is reported so far which takes care of voltage and frequency control without derating of the machine and provides an option for feeding single-phase as well as three-phase loads simultaneously in micro hydro applications.

In this paper, a new VF controller is proposed which is having capability of controlling the voltage and frequency in decoupled manner. For controlling the voltage, a static compensator (STATCOM) is used as a reactive power compensator along with harmonic eliminator and a load balancer while for controlling the frequency; an electronic load controller (ELC) is used to regulate the total active power at the terminals of generator. The STATCOM is realized using IGBTs (Insulated gate bipolar junction transistors) based voltage source converter (VSC), and a capacitor as an energy storage element at its DC link, while an ELC consists of a diode bridge rectifier, a switch and an auxiliary load resistance.of installation on power distribution systems or industrial power systems.

II. PROPOSED SYSTEM

Fig.1 shows the system configuration ofcapacitor excited asynchronous generator, VFC (voltage and frequency controller) (consisting 3leg IGBT based VSC and diode bridge rectifier based ELC) and the consumer loads. The delta connected 3-phase capacitor bank is used for the generator excitation and value of an excitation capacitor is selected to generate the rated voltage at no load. The CEAG generates constant power and when consumer load power changes; the DC chopper of an ELC absorbs the difference in power (generated-consumed) into an auxiliary load, while STATCOM is used to regulate the voltage due to load changes. Thus generated voltage and frequency are not affected and remain constant during the changes in consumer loads.

The VFC is an arrangement of a STATCOM with an ELC.STATCOM consists of IGBT based current controlled 4-leg VSC, DC bus capacitor and AC inductors. The output of the VSC is connected through the AC filtering inductors to the CEAG terminals. The DC bus capacitor is used to filter voltage ripples and provides self-supporting DC bus. A DC chopper in an ELC is used to control the extra power in the controller auxiliary load due to change in consumer loads, so that generated power at the generator remains constant.

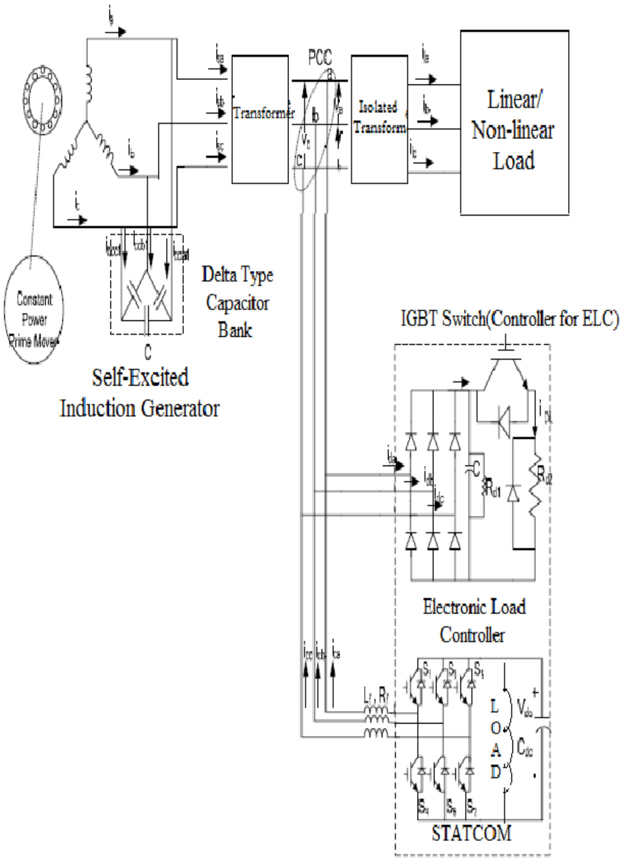

Fig.1. Block diagram for voltage and frequency controller for SEIG

III. CONTROL STRATEGY

The control strategy for the proposed voltage and frequency controller for asynchronous generator has been shown in the baseofcombined p-q and I_d-$I_q$frame. The STATCOM and Electronic load controller whose pulse is controlled by using combined two control method p-q and I_d-I_q .

A. *Control model for Electronic load controller using p-q(Active and Reactive Power method)*

Fig. 1 shows the block diagram to attain reference currents from load. Transformation of the phase voltages v_a, v_b, and $v_c$and the load currents i_La, i_Lb, and $i_L c$into the α - β orthogonal coordinates are given in Equation (1-2). The compensation objectives of ELC are the harmonics present in the input currents. Present architecture represents three phase four wire and it is realized with constant power controls strategy. Fig. 2 illustrates control block diagram and Inputs to the system are phase voltages and line currents of the load. It was recognized that resonance at relatively high frequency might appear between the source impedance. So a small high pass filter is incorporaterated in the system. The power calculation is given in detail form in Equation (3).

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} (1)$$

$$\begin{bmatrix} i_o \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} (2)$$

$$\begin{bmatrix} p_o \\ p \\ q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} v_o & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} (3)$$

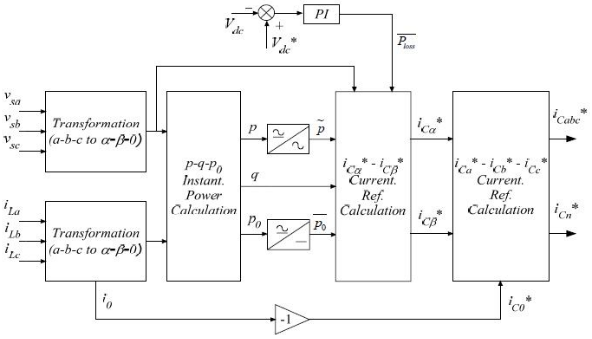

Fig.2. Reference current extraction with *p-q* method

Each of these powers has dc component (1st component) and ac component (2nd component) as shown in (4):

$$p = \bar{p} + \tilde{p} \qquad (4)$$

$$q = \bar{q} + \tilde{q}$$

For reactive and harmonic compensation, the entirereactive power and ac component of active power are utilized as the reference power. The reference currents in α-β coordinates are calculated by using (5),

$$\begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} = \frac{1}{v^2_{\alpha}+v^2_{\beta}} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i^*_{c\alpha} \\ i^*_{c\beta} \end{bmatrix} \qquad (6)$$

In addition PLL (Phase locked loop) employed in shunt filter tracks automatically, the system frequency and fundamental positive-sequence component of three phase generic input signal. Appropriate design of PLL allows proper operation under distorted and unbalanced voltage conditions. Controller includes small changes in positive sequence detector as harmonic compensation is mainly concentrated on three phase four wire [9]. As we know in three-phase three wire, V_a,V_b,$V_c$are used in transformations which resemble absence of zero sequence component and it is given in Equation (7). Thus in three phase four wires it was modified as v'_α , v'_β,and it is given in Equation (8).

$$\begin{bmatrix} v'_a \\ v'_b \\ v'_c \end{bmatrix} = \frac{\sqrt{2}}{3} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} \qquad (7)$$

$$\begin{bmatrix} v'_\alpha \\ v'_\beta \end{bmatrix} = \frac{1}{i^2_{\alpha}+i^2_{\beta}} \begin{bmatrix} i'_\alpha & -i'_\beta \\ i'_\alpha & i'_\beta \end{bmatrix} \begin{bmatrix} \overline{p'} \\ \overline{q'} \end{bmatrix} (8)$$

B. Control model for STATCOM using i_d-i_q method (Active and Reactive Current method)

In Fig. 5, the entire reference current generation scheme has been illustrated. The load currents i_{La}, $i_{Lb}$and $i_{Lc}$are tracked upon which Park's transformation is per-formed to obtain corresponding *d-q* axes currents $i_{Ld}$and i_{Lq}as given, where w is rotational speed of synchronously rotating *d-q* frame. According to *id-iq*control strategy, only the average value of d-axis component of load current should be drawn from supply. Here $i_{Ld1h}$and i_{Lq1h}indicate the fundamental frequency component of $i_{Ld}$and i_{Lq}. The oscillating components $i_{Ld}$and i_{Lq}, *i.e.*, $i_{Ldnh}$and $i_{Lqnh}$are filtered out using low-pass filter.

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} i_{Ld1h} + i_{Ldnh} \\ i_{Lq1h} + i_{Lqnh} \end{bmatrix} \qquad (9)$$

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \end{bmatrix} = \begin{bmatrix} \sin wt & \cos wt \\ -\cos wt & -\sin wt \end{bmatrix} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \quad (10)$$

The currents $i_{Ldnh}$and i_{Lqnh}along with $i_{d1h}$are utilized to generate reference filter currents i_{cd*} and i_{cq}* in *d-q* coordinates, followed by inverse Park transformation giving away the compensation currents i_{ca*}, i_{cb*}, $i_{cc*}$and i_{cn*}in the four wires as described in (10) and (11).

$$\begin{bmatrix} i^*_{ca} \\ i^*_{cb} \\ i^*_{cc} \end{bmatrix} = \begin{bmatrix} \sin wt & \cos wt & 1 \\ \sin(wt - \frac{2\pi}{3}) & \cos(wt - \frac{2\pi}{3}) & 1 \\ \sin(wt + \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) & 1 \end{bmatrix} \qquad (11)$$

$$i_{cn}^* = i^*_{ca} + i^*_{cb} + i^*_{cc} \qquad (12)$$

The reference signals thus obtained are compared with the actual compensating filter currents in a hysteresis comparator, where the actual current is forced to follow the reference and provides instantaneous compensation by the APF on account of its easy implementation and quick prevail over fast current transitions. This consequently provides switching signals to trigger the IGBTs inside the inverter. Ultimately, the filter provides necessary compensation for harmonics in the source cur-rent and reactive power unbalance in the system. Figure 6shows voltage and current vectors in stationary and rotating reference frames. The transformation angle 'θ' is sensible to all voltage harmonics and unbalanced volt-ages; as a result $d\theta / dt$may not be constant.

One of the advantages of this method is that angle θ is calculated directly from main voltages and thus makes this method frequency independent by avoiding the PLL in the control circuit.

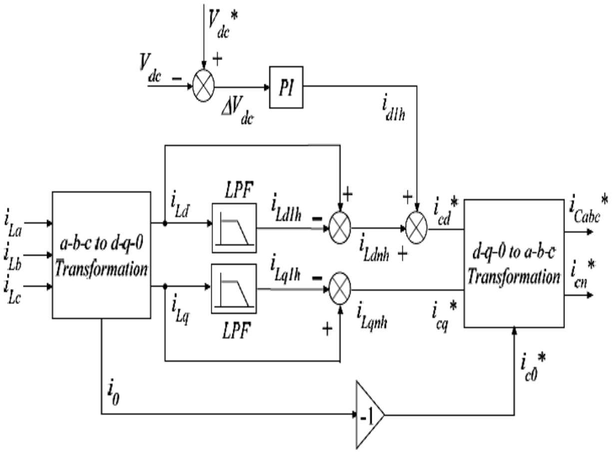

Fig.3. Reference current extraction with i_d -$i_q$method

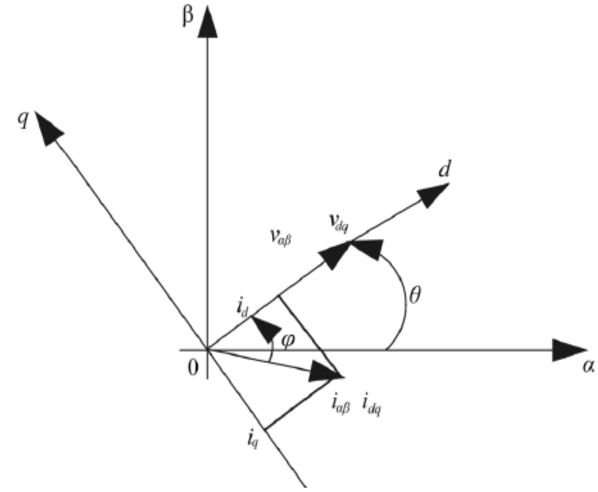

Fig.4. instantaneous current and voltage vector

Consequently synchronizing problems with unbalanced and distorted conditions of main voltages are also evaded. Thus i_d-$i_q$achieves large frequency operating limit essentially by the cut-off frequency of voltage source inverter.

Fig. 5 and 6 show the control diagram for shunt active filter and harmonic injection circuit. On owing load currents *id* and *iq*are obtained from park transformation then they are allowed to pass through the high pass filter to eliminate dc components in the nonlinear load currents. Filters used in the circuit are Butterworth type and to reduce the influence of high pass filter an alternative high pass filter (AHPF) can be used in the circuit. It can be obtained through the low pass filter (LPF) of same order and cut-off frequency simply difference be-tween the input signal and the filtered one, which is clearly shown in Fig. 5. Butterworth filters used in harmonic injecting circuit have cut-off frequency equal to one half of the main frequency ($fc = f/2$), with this a small phase shift in harmonics and sufficiently high transient response can be obtained.

C. Control Scheme for PI Controller

Fig. 7 shows the internal structure of the control circuit. The control scheme consists of PI controller, limiter, and three phase sine wave generator for reference current generation and generation of switching signals. The peak value of reference currents is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value.

The error signal is then processed through a PI controller, which contributes to zero steady error in tracking the reference current signal. The output of the PI controller is considered as peak value of the supply current (*I*max), which is composed of two components:a) fundamental active power component of load current, and b) loss component of APower Factor;to maintain the

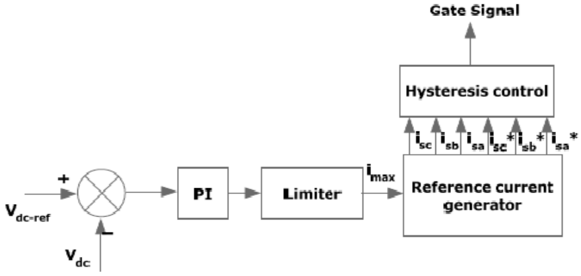

Fig.5. Control diagram for PI Controller

average capacitor voltage to a constant value. Peak value of the current (I_{max}) so obtained, is multiplied by the unit sine vectors in phase with the respective source voltages to obtain the reference compensating currents. These estimated reference currents (I_{sa}*, I_{sb}*, I_{sc}*) and sensed actual currents (I_{sa}, I_{sb}, I_{sc}) are compared at a hysteresis band, which gives the error signal for the modulation technique. This error signal decides the operation of the converter switches. In this current control circuit configuration, the source/supply currents $I_{sabc}$are made to follow the sinusoidal reference current I_{abc}, within a fixed hysteretic band. The width of hysteresis window determines the source current pattern, its harmonic spectrum and the switching frequency of the devices.

The DC link capacitor voltage is kept constant through-out the operating range of the converter. In this scheme, each phase of the converter is controlled independently. To increase the current of a particular phase, the lower switch of the converter associated with that particular phase is turned on while to decrease the current the upper switch of the respective converter phase is turned on. With this one can realize, potential and feasibility of PI controller.

IV MATLAB BASED MODELLING

The MATLAB model of the VFC asynchronous generator system consists of the asynchronous machine with capacitor bank and VFC are realized in MATLAB version 7.3. The modeling of SEIG is carried out using 7.5 kW, 415V, 50Hz, Y-connected cage induction machine and 5kVAR delta-connected excitation capacitor banks. The VF controller is realized with a 3-leg voltage source converter and a diode bridge rectifier based ELC with DC chopper and an auxiliary load. Various loads such as linear, non-linear and dynamic loads are considered here to demonstrate the capability of the VF controller.

V RESULT AND DISCUSSION

The DVFC for IAG system feeding 3-phase 3-wire linear/ non- linear loads are simulated and waveforms of the generator voltage (v_{abc}) and current (i_{abc}), capacitor current (i_{cca}), load current (i_{labc}), STATCOM current (i_{cabc}), ELC current (i_{da}), amplitude of terminal voltage (Vt), DC link voltage(V_{dc}), frequency etcare shown in Figs. 3-6. For the simulation, a 7.5 kW, 415V, 14.8A, 4 pole induction machine is used as an asynchronous generator.

A.1 Performance of IAG-VFCSystem Feeding Balanced/unbalanced Non-linear Loads

Fig. 4 shows the performance of IAG-VFC systemfeeding balanced/unbalanced non-linear loads using a three phase diode bridge with resistive load and capacitor filter at its DC side. At 2.6 sec a balanced non- linear load is applied and then auxiliary load power (P_{dump}) is reduced for regulating the power, and controller currents (i_{cabc}) become non-linear for eliminating harmonic currents. During load unbalancing at 2.8 sec a ripple in DC bus capacitor (v_{dc}) is observed similarly as with linear loads. Table 1 shows the THD (total harmonic distortion) of generator voltage (v_a) and current (i_a) for no-load and for balanced load conditions. It can be observed that total harmonic distortion (THD) is 1.81%, the limit imposed by IEEE-519 standard [22].

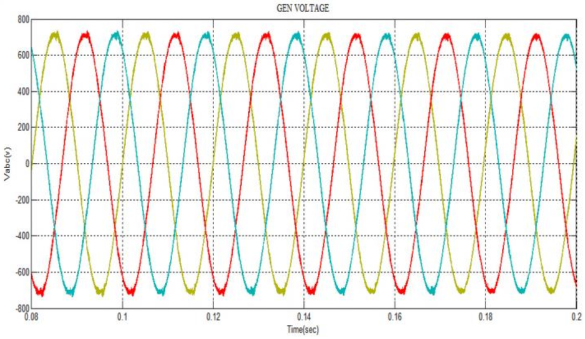

Fig. 6 Generated voltage waveform of 7.5 kW SEIG with VFC feeding Non-linear load

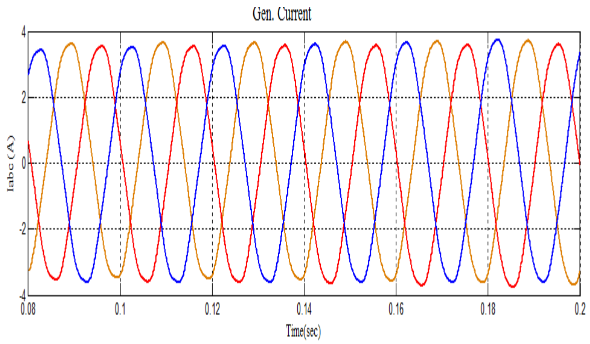

Fig. 7 Generated Current waveform of 7.5 kW SEIG with VFC feeding Non-linear load

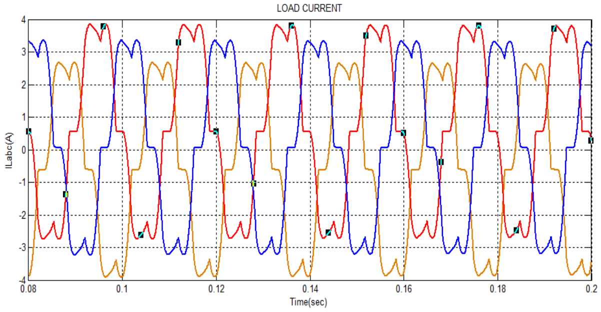

Fig. 8LoadCurrent waveform of 7.5 kW SEIG with VFC feeding Non-linear load

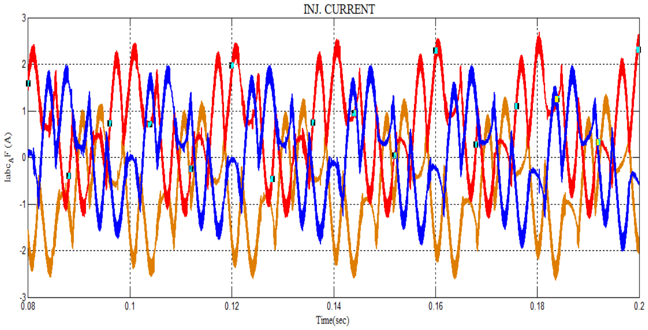

Fig. 9Injected current waveform of 7.5 kW SEIG with VFC feeding Non-linear load

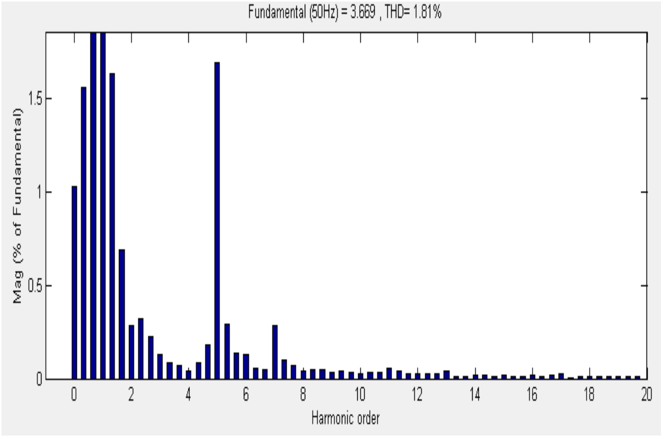

Fig.10THD for *p-q* and *id-iq*control methods with PI Controllers

VI. CONCLUSION

The performance of the proposed voltage and frequency controller has been demonstrated for an isolated power generation system and for feeding various types of consumer loads such as linear/non-linear,Here it is observed that the controller responds in a desired manner and regulates the system voltage and frequency under direct on line starting of the asynchronous motor and application/removal of load torque. In addition, the proposed VF controller also functions as a harmonic eliminator, load balancer for feeding linear/non-linear loads.

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