Enhancement of Power Quality of PMSG Based DG Set Feeding Three-Phase Loads using Fuzzy Controller

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ABSTRACT: This Project presents power quality improvement of PMSG (Permanent Magnet Synchronous Generator) based DG (Diesel Generator) set feeding three-phase loads using STATCOM (Static Compensator). A 3-leg VSC (Voltage Source Converter) with a capacitor on the DC link is used as STATCOM. The reference source currents for the system are estimated using an Adaline based control algorithm. A PWM (Pulse Width Modulation) current controller is using for generation of gating pulses of IGBTs (Insulated Gate Bipolar Transistors) of three leg VSC of the STATCOM. The STATCOM is able to provide voltage control, harmonics elimination, power factor improvement, load balancing and load compensation. The performance of the system is experimentally tested on various types of loads under steady state and dynamic conditions. A 3-phase induction motor with variable frequency drive is used as a prototype of diesel engine with the speed regulation. Therefore, the DG set is run at constant speed so that the frequency of supply remains constant irrespective of loading condition.

Keywords- STATCOM, VSC, IGBTs, PMSG, PWM, DG Set, Power Quality.

I. INTRODUCTION

PMSGs have gained popularity in recent years because of their potential use in WECS (Wind Energy Conversion Systems) [1-4]. The advancement in the field of rare earth permanent magnet with high field intensity such as neodymium–iron–boron (Nd–Fe–B) has also shown great opportunities in the field of automobile industry [5-7]. These generators offer many advantages over wound field type synchronous generators such as brushless operation, no rotor winding, small size, no rotor copper losses, less maintenance and high efficiency. Because of these advantages PMSG are also being used in turbofan jet engine electrical power generation [8]. The main challenges in PMSG are voltage and frequency control under varying load conditions. These challenges can be easily addressed with advancement in power converters. In WECS, the voltage and frequency of PMSG can be controlled using AC-DC-AC power converters [9,10]. PMSG is compact in size so these generators have potential applications in DG (Diesel Generator) set based isolated supply systems. The diesel generator sets are run at a constant speed with the diesel engine as a prime mover. There is no issue of frequency control in these supply systems. The main task in DG sets based supply systems is to maintain the constant terminal voltage. There are consistent efforts of researchers to develop methods to improve voltage regulation of PMSG based isolated supply systems. Suitable design of rotor with Nd–Fe–B magnet can reduce the voltage regulation of PMSG.Chanet.al. have presented the analysis of PMSG with Nd-Fe-B permanent-magnet rotor feeding isolated resistive load to achieve zero voltage regulation. They have presented that the inverse saliency effect of PMSG helps in improvement of voltage regulation of the generator. Chen et. al. have reported use of fixed capacitor for assisting excitation of PMSG to improve the voltage regulation and useful capacity of the generator. Rahman et.al. have regulated the terminal voltage of diesel engine drive PMSG for isolated supply system using fixed capacitor-thyristor controlled reactor.Erramiet.al. have proposed variable structure direct torque control scheme for PMSG based WECS. In the research work on DG sets, very little attention has been paid to potential used of PMSG in DG sets standalone supply systems. The voltage of PMSG based DG set in isolated supply systems can be controlled using STATCOM (Static Compensator). STATCOM is widely used in grid connected and isolated supply systems such for voltage and frequency control. In addition, it can be used for load balancing, harmonics elimination, load compensation and reactive power compensation. In the proposed system with PMSG driven by diesel engine, STATCOM is used for voltage control of the PMSG. Many control algorithms are available for generation of reference source currents. Proposed system uses an Adaline based control algorithm because of its simplicity and suitability under varying load conditions.

II SYSTEM CONFIGURATION

PMSGs have gained popularity in recent years because of their potential use in WECS (Wind Energy Conversion Systems). The advancement in the field of rare earth permanent magnet with high field intensity such as neodymium–iron–boron (Nd–Fe–B) has also shown great opportunities in the field of automobile industry. These generators offer many advantages over wound field type synchronous generators such as brushless operation, no rotor winding, small size, no rotor copper losses, less maintenance and high efficiency. Because of these advantages PMSG are also being used in turbofan jet engine electrical power generation. The main challenges in PMSG are voltage and frequency control under varying load conditions. These challenges can be easily addressed with advancement in power converters. In WECS, the voltage and frequency of PMSG can be controlled using AC-DC-AC power converters. PMSG is compact in size so these generators have potential applications in DG (Diesel Generator) set based isolated supply systems. The diesel generator sets are run at a constant speed with the diesel engine as a prime mover. There is no issue of frequency control in these supply systems. The main task in DG sets based supply systems is to maintain the constant terminal voltage.

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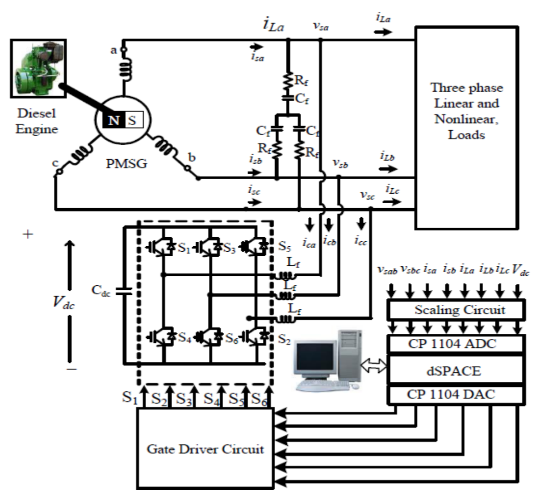

Fig1 Configuration of PMSG based DG set feeding three phase loads

In addition, it can be used for load balancing, harmonics elimination, load compensation and reactive power compensation. In the proposed system with PMSG driven by diesel engine, STATCOM is used for voltage control of the PMSG.

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Many control algorithms are available for generation of reference source currents. Proposed system uses an Adaline based control algorithm because of its simplicity and suitability under varying load conditions.

III CONTROL ALGORITHM

The proposed system consisting of a PMSG based DG set, a three leg VSC, and linear/nonlinear loads, is shown in Fig.1. A RC filter is used for filtering high frequency ripple from voltage at PCC (Point of Common Coupling). A 3-leg VSC is used a STATCOM. The VSC is connected to PCC through three interfacing inductors. The interfacing inductors connected between three legs of VSC and PCC are used to filter the high frequency ripples from current. The proposed system uses a specially designed PMSM of 3.7 kW, 50 Hz, 4-pole, 230 V. The values of interfacing inductors, components of RC filter, DC link capacitor and detailed data of PMSG are given in Appendix.

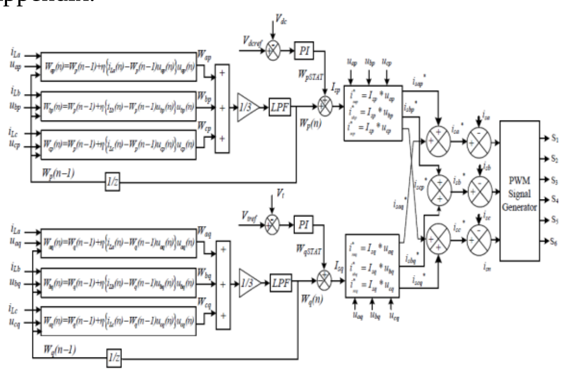

Fig2 Adaline based control algorithm for PMSG Based DG set feeding three-phase loads.

IV PROPOSED CONTROL STRATEGY

The control block diagram is shown in Fig. 1. The unit signals cos(wt) and sin(wt) are generated from the phase-locked loop (PLL) using three-phase supply voltages (v_a'v_b'v_c'). The converter currents are transformed to the synchronous rotating reference frame using the unit signals. The switching frequency ripple in the converter current components is eliminated using a low-pass filter (LPF). From (V_{dc1}^*+V_{dc2}^*) and iq* loops, the controller generates d–q axes reference voltages ed* and eq* for the cascaded inverter. With these reference voltages, the inverter supplies the desired reactive current (iq*) and draws required active current (iq') to regulate total dc-link voltageV_{dc1}^*+V_{dc2}^*. However, this will not ensure that individual dc-link voltages are controlled at their respective reference values. Hence, additional control is required to regulate individual dc-link voltages of the inverters.

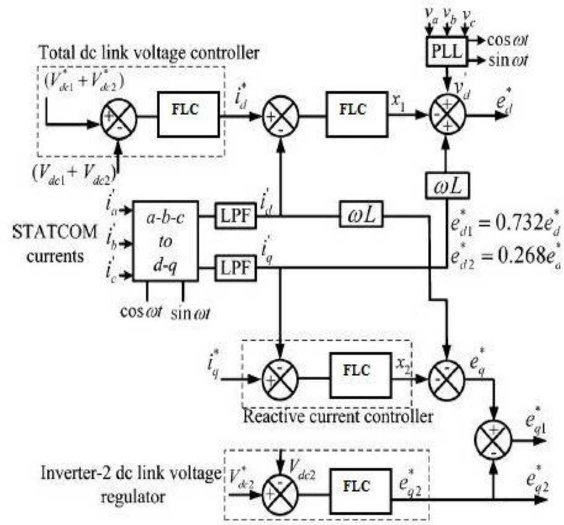

Fig.3 control block diagram

The fuzzy logic controller unlike conventional controllers does not require a mathematical model of the system process being controlled. However, an understanding of the system process and the control requirements is necessary. The fuzzy controller designs must define what information data flows into the system (control input variable), how the information data is processed (control strategy and decision) and what information data flows out of the system (solution output variables).

In this study, a fuzzy logic based feedback controller is employed for controlling the voltage injection of the proposed STATCOM. Fuzzy logic controller is preferred over the conventional PI controller because of its robustness to system parameter variations during operation and its simplicity of implementation. The proposed FLC scheme exploits the simplicity of the Mamdani type fuzzy systems that are used in the design of the controller and adaptation mechanism.

The fuzzy logic control scheme is shown in figure3. That can be divided into four main functional blocks namely Knowledge base, Fuzzification, inference mechanism and defuzzification.

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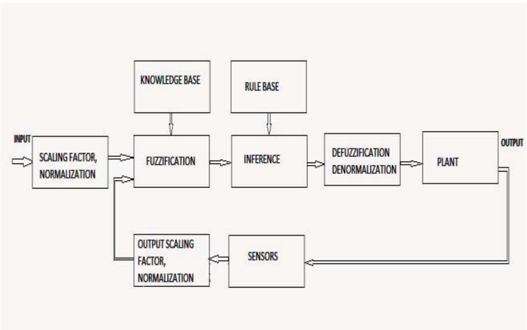

Fig.4 Fuzzy logic controller

The knowledge base is composed of database and rule base. Data base consists of input and output membership functions and provides information for appropriate fuzzification and defuzzification operations. The rule base consists of a set of linguistic rules relating the fuzzified input variables to the desired control actions. Fuzzification converts a crisp input voltage signals, error voltage signal (e) and change in error voltage signal (ce) into fuzzified signals that can be identified by level of memberships in the fuzzy sets. The inference mechanism uses the collection of linguistic rules to convert the input conditions of fuzzified outputs to crisp control conditions using the output membership function, which in the system acts as the changes in the control input (u).

ΔACE →

ACE ↓	NB	NS	ZZ	PS	PB
NB	ZZ	PS	PB	PB	PB
NS	NS	ZZ	PS	PB	PB
ZZ	NB	NS	ZZ	PS	PB
PS	NB	NB	NS	ZZ	PS
PB	NB	NB	NB	NS	ZZ

Table 1: Rule base for fuzzy logic controller

The set of fuzzy control linguistic rules is given in table 1. The inference mechanism in fuzzy logic controller utilizes these rules to generate the required output. The SIMULINK model of the proposed fuzzy logic controller is shown in figure 4.

The resulting voltage of the cascaded converter can be given as, $e_I \angle \delta$ where

$$e_I = \sqrt{e_d^2 + e_q^2} A = \pi r^2$$

And

$$\delta = \tan^{-1}((e_q)/(e_d))$$

The active power transfer between the source and inverter depends on δ and is usually small in the inverters supplying var to the grid[1]. Hence, δ can be assumed to be proportional to e_q. Therefore, the q-axis reference voltage component of inverter-2is derived to control the dc-link voltage of inverter-2 and is derived by means of FLC controller as shown in fig 3. The dc-link voltage of inverter-2v_{dc2} is controlled at 0.366 times the dc-link voltage of inverter-1v_{dc1} [9]. It results in four-level operation in the output voltage and improves the harmonic spectrum. Expressing dc-link voltages of inverter-1 and inverter-2 in terms of total dc-link voltage v_{dc} as

$$Vdc1 = 0.732Vdc$$

$$Vdc2 = 0.268Vdc$$

Since the dc-link voltages of the two inverters are regulated, the reference d-axis voltage component e_d^* is divided in between the two inverters in proportion to their respective dc-link voltage as

$$e_{d1}^* = 0.732 e_d^*$$
$$e_{d2}^* = 0.268 e_d^*.$$

For a given power, if $v_{dc\ 2} < v_{dc2}*$ then δ2 increases and δ1 decreases. Therefore, power transfer to inverter-2 increases, while it decreases for inverter-1. The power transfer to inverter-2 is directly controlled, while for inverter-1, it is controlled indirectly. Therefore, during disturbances, the dc-link voltage of inverter-2 is restored to its reference quickly compared to that of inverter-1. The reference voltages generated for inverter-2 are in phase opposition to that of inverter-1. From the reference voltages, gate signals are generated using the sinusoidal pulse-width modulation (PWM) technique as shown in fig 3.

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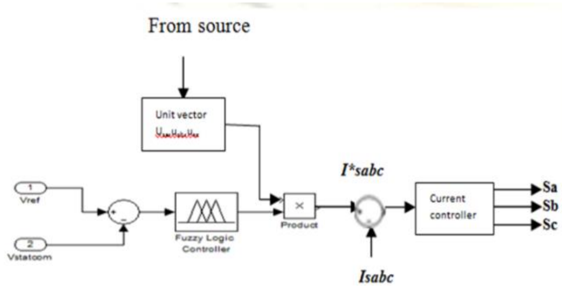


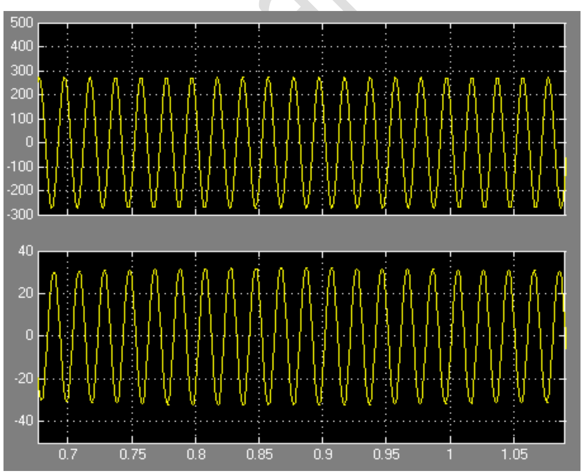
Fig.4 STATCOM model with FLC- Voltage Regulator block diagram

V. RESULTS AND DISCUSSION

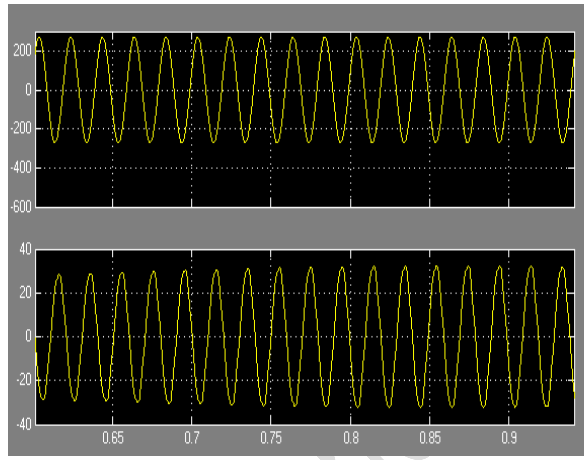
Performance of the system is analyzed under linear and nonlinear loads at steady state and transient conditions. Linear load is a simple RL type load. The nonlinear load is realized by using a three phase rectifier with a resistance on DC link. An inductor is also connected in series with resistance to inject harmonics in current on ac input. The performance at linear and nonlinear loads is also given here.

Performance of DG System under Non-Linear Loads

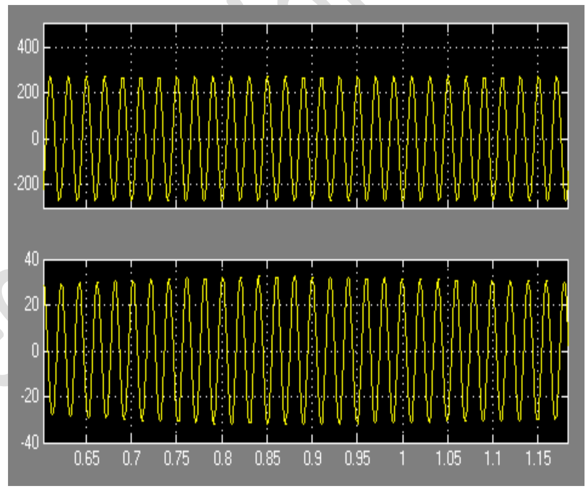
The performance of the PMSG based DG set under linear load is demonstrated in Fig. 3. The system is subjected to three phase load of 2.62 kW at displacement power factor of 0.99. Figs. 3(a)-(c) demonstrate the source voltages (*vsab*) and source currents (*isa, isb, isc*). Figs. 3(d)-(f) show the source voltage (*vsab*) and load currents (*iLa,iLb,iLc*). Figs. 3(g)-(i) demonstrate the source voltage (*vsab*) and STATCOM currents (*iCa,iCb,iCc*).



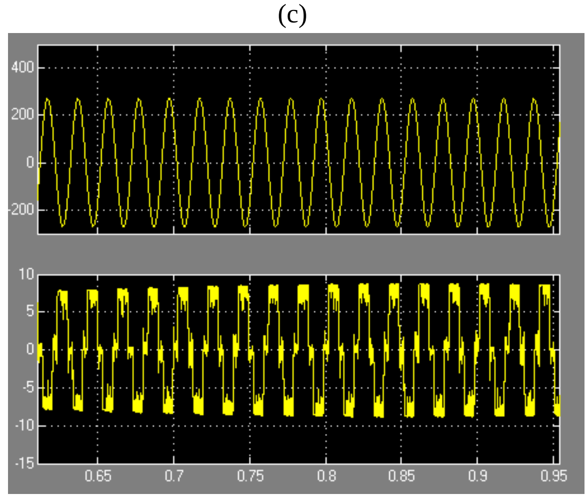
(a) *vsab* and *isa*



(b) *vsab* and *isb*



(c)



(d)

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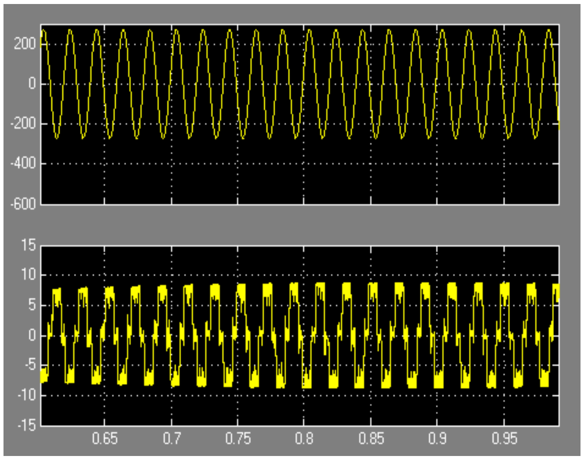
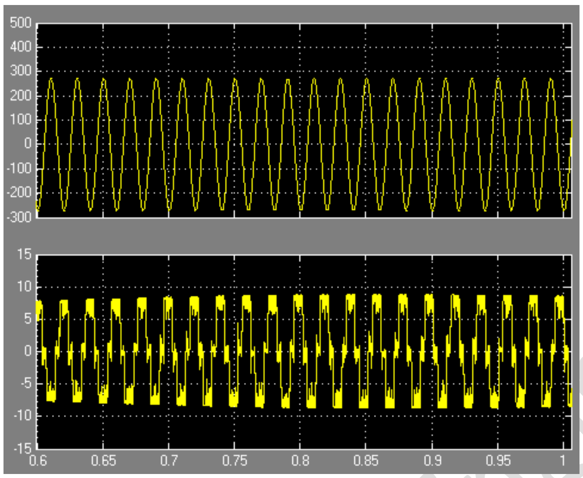
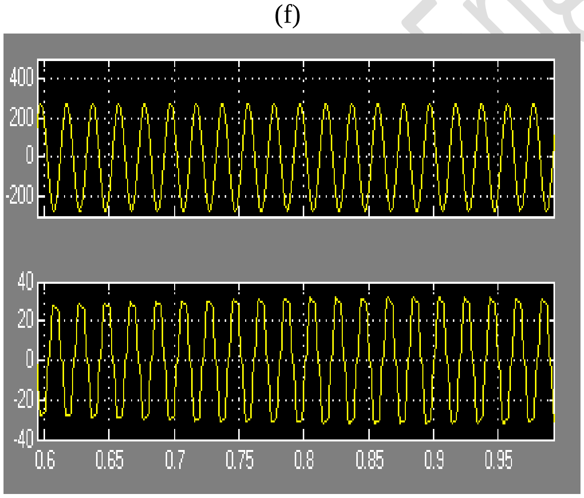


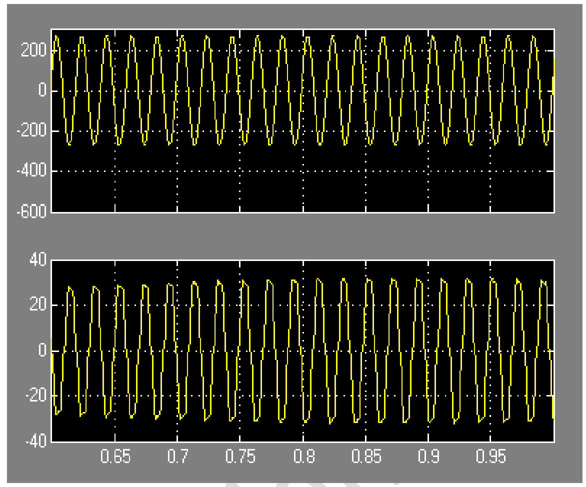
(e)



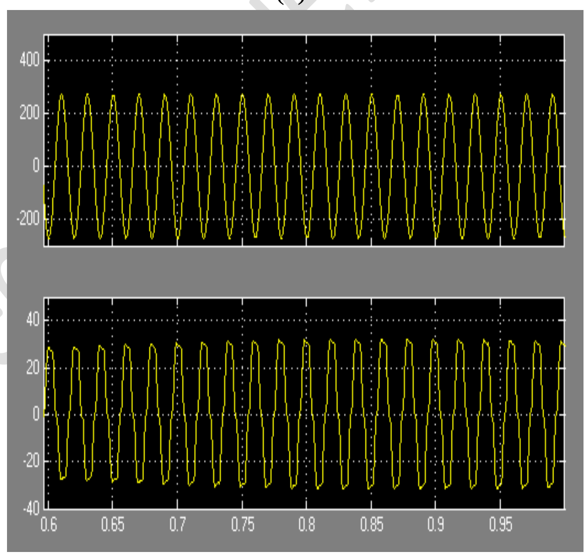
(f)



(g)



(h)



(i)

Fig.5. Performance under balanced nonlinear loads (a)*vsab* and *isa* (b)*vsab* and *isb* (c)*vsab* and *isc* (d)*vsab* and *iLa* (e)*vsab* and *iLb*(f) *vsab* and *iLc* (g)*vsab* and *iCa* (h)*vsab*and *iCb* .

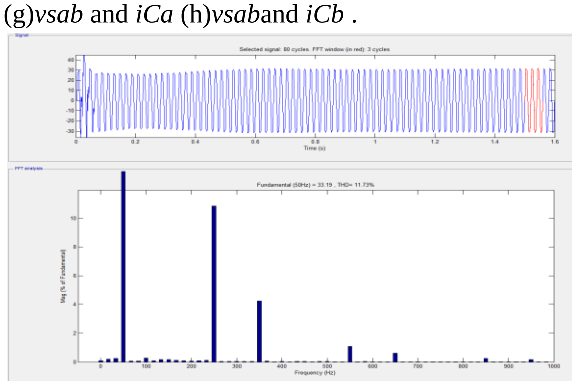


Fig6. THD value of PI controller

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Voltage almost at 220V under a load of 2.62 kW. The STATCOM supplies leading 2.37 KVAR to maintain terminal voltage at fixed level. The STATCOM draws a power of 150W to meet losses in IGBTs and interfacing inductors. The supply frequency is also maintained at 50 Hz by speed regulating system of prototype of diesel engine.

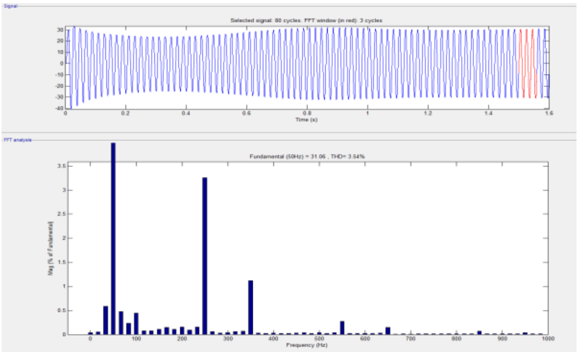

Fig7. THD value of Fuzzy controller

Table 1

THD Comparison for Conventional & Proposed Methods

	PI	Fuzzy
THDi(%)	11.73	3.54

The system is subjected to three phase load of 3.16 kW at displacement power factor of 0.90. Initially, the system is subjected to unbalanced load by removing the load from phase‘c’. The dynamic performance of system is tested by changing the load from unbalanced to balanced by inserting the load in phase ‘c’. It can be observed from these waveforms that system is able to overcome the transient within couple of cycles. It is also observed the DC link voltage has slight oscillatory under unbalanced condition and has under shoot during transient. The DC link capacitor supplies the energy stored to meet the additional load demand during the transient period.

VI CONCLUSIONS

The STATCOM has improved the power quality of the PMSG based DG set in terms voltage control, harmonics elimination and load balancing. Under linear loads, there has been negligible voltage variation (From 219.1 V to 220.9 V) and in case of nonlinear load, the voltage increases to 221 V. Thus, the STATCOM has been found capable to maintain the terminal voltage of DG set within 0.5% (220 V) under different linear and nonlinear loads. Under nonlinear loads, the load current of DG set is a quasi square with a THD of 24.4 %. The STATCOM has been found capable to eliminate these harmonics and thus the THD of source currents has been limited to 3.9 % and the THD of terminal voltage has been observed of the order of 1.8%.Therefore, the THDs of source voltage and currents have been maintained well within limits of IEEE-519 standard under non linear load. It has also been found that the STATCOM maintains balanced source currents when the load is highly unbalanced due to removal of load from phase ‘c’. The load balancing has also been achieved by proposed system with reduced stress on the winding of the generator. The proposed system is a constant speed DG set so there is no provision of frequency control in the control algorithm.

APPENDIX

PMSG	3.7 kW, 230 V, 3-phase, star connected , 1500 rpm, 50 Hz, X_d=4.669 Ω, X_q=5.573 Ω,R_s= 0.2747 Ω
STATCOM	R_f= 5Ω, C_f= 5.25 µF, L_f= 3.5 mH, C_{dc}= 1650 µF
PI controller	k_{pv} = 1.5, k_{iv} = 0.1, k_{pdc}= 0.3, k_{idc} = 0

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