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DSTATCOM Application for Mitigation of Voltage Sag Caused by Dynamic Loads in Autonomous Systems

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ABSTRACT

This paper presents the application of distribution static compensator (DSTATCOM) for mitigating the frequently occurring problems of voltage dips in autonomous systems. Consumer loads are experiencing proliferation of induction motors. The starting of induction motors draws large current causing voltage sag (dip). Autonomous Power system is comparatively less stiff than the grid connected system. Large starting current, causing objectionable voltage drop, is critical for an autonomous system. DSTATCOM has been effectively used to redeem this power quality problem. An asynchronous generator with a motor load having a DSTATCOM connected in shunt is simulated on a MATLAB platform using Simulink and Power System Block set. The simulation establishes the capability of DSTATCOM to mitigate the voltage dip problem for an autonomous system.

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1. INTRODUCTION

Depletion of fossil fuel and its rising cost has forced mankind to look for (1) efficient and proper use of conventional fuel (2) alternative or nonconventional source of energy. Thus improving power quality and use of nonconventional resources has become the thrust area of modern electric power system. Solar wind and hydro are some of the sources of energy which get renewed in nature and have not been fully exploited. Focus has now shifted to these untapped sources of energy. Small hydro generation potential exists in quite large number in the remote locations of the hills. These have the capability to feed local loads and with improved quality of power at comparatively less investments. Further reaching the grid power to these isolated areas using overhead conductors or cables is not feasible due to prohibitive cost of transmission system. The small hydro generation calls for a generator which is easy to install, cost less, easy to maintain, rugged and reliable. One generator which met all of the requirements is the induction generator [1]. Thus autonomous asynchronous generator (AAG) with its excitation requirement being met by a capacitor bank connected across its terminals [2]-[7], has become the most suitable option.

Among the consumer loads induction motor loads are quite predominant. They draw large starting current (5- 6 times of full load current) and produce a sag in the power system voltage [8]. This may cause the autonomous generator to be used at de-rated level if many induction loads are started simultaneously. An effective solution can be the use of a DSTATCOM with the induction generator. This shall provide fast control on the voltage variations & sags (dips) and shall also provide adequate reactive power supply to the system [9]-[16]. Further the static excitation requirement of AAG provided by the capacitor bank can be reduced to no-load level and additional reactive power requirement of the AAG on load and that of the load itself can be provided by the DSTATCOM. Thyristor based reactive power compensation has been initially provided for reduction of voltage flicker due to arc furnace loads [9]-[10]. However, due to the drawbacks of passive devices like large size, fixed & step compensation, possibility of resonance etc. and the fact that dynamic compensation is possible with DSTATCOM, it has become the state or art means for power quality improvement. Use of STATCOM & DSTATCOM for power quality improvement has been reported by many authors [11]-[16]. Akagi et al [17] proposed instantaneous reactive power compensator using switching devices without energy storage components. However this was proposed for grid connected systems. Ghosh and Joshi [18] proposed use of DSTATCOM for compensation of distribution systems. Larsson et al, Schauder, Blazic & Papic, and Zhang et al [12]-[15] proposed the use of STATCOM for the mitigation of flickers produced by arc furnace and other loads. J. Sun, et al [16] proposed the use of DSTATCOM for the mitigation of flickers produced by arc furnace.

This paper presents the application of DSTATCOM for compensation of dynamic loads of an autonomous asynchronous generator system. Autonomous Power system is comparatively less stiff than the grid connected system and voltage sag produced may be more severe. The DSTATCOM is used for providing dynamic voltage regulation during short duration of induction motor starting and thereby avoiding large voltage dips. Further its use reduces the size of the static capacitor bank, which is now used to provide only the no load excitation. B. Singh and J. Solanki [19] presented a comparative study of the control algorithms used with DSTATCOMs for load compensation. Kazmierkowski and Malesani [20] made a survey of the current control Techniques of PWM voltage source converters. Many of the reported use of DSTATCOMs with asynchronous generators in autonomous generation systems are based on hysteresis control or carrier less control [21]. Hyteresis based switching of the converters, depending on the dynamics of load, may cause excessive switching losses. However a linear control, SPWM, is used in this paper for control of DSTATCOM. The switching is done at a fixed frequency, allowing the switching losses to be limited within the rating of the converter. This type of control is inherently linear & robust and uses PI or PID controls, which are very easy to implement in real time and are less complex in hardware than the above control.

2. POWER SYSTEM CONFIGURATION

Fig. 1 shows the schematic of the autonomous power system. A three phase squirrel cage induction motor 4kW, 400V, 50Hz, 1430 rpm has been used as induction generator and feeds power to an isolated distribution system. A micro hydro turbine provides constant power to the induction generator. The AAG system feeds a load comprising of an induction motor. The current and voltage of the asynchronous generator and the load are used as feedback to the control system of the DSTATCOM.

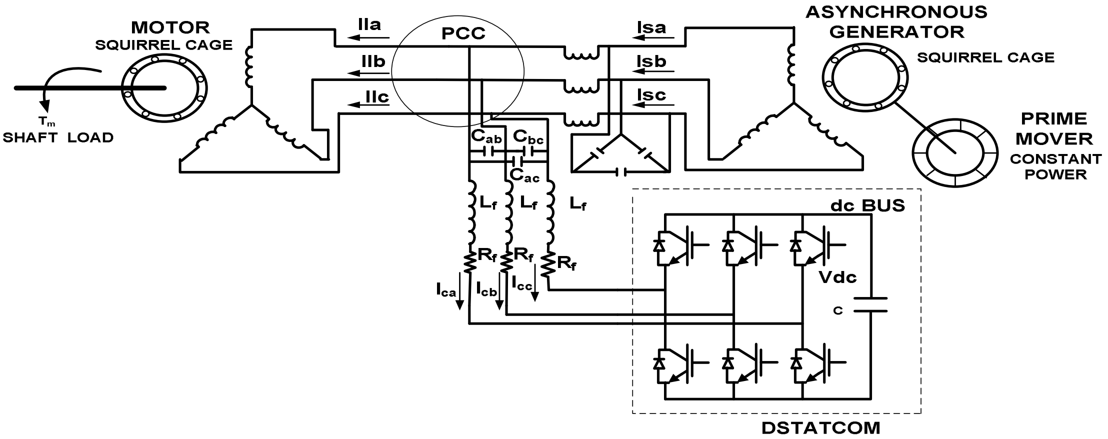

Fig. 1. Schematic of the autonomous power system.

The DSTATCOM is connected in shunt to the AAG and load system. It is made up of three phase current controlled voltage sourced converter (CC-VSC). The VSC is made up of a three phase two level IGBT bridge converter. A capacitor is connected to its DC bus to make it self-supporting. The AC output terminals of the DSTATCOM are connected to the point of common connection (PCC) through a series filter

(LR filter). It represents the resistance and the reactance of the connecting transformer of a practical system. A SPWM control circuit, which gets feedback information about the generator and load voltages and currents, is used to provide triggering pulses to the IGBTs of the VSC.

3. DSTATCOM CONTROL SCHEME

Fig. 2 shows the schematic diagram of DSTATCOM control for the voltage regulation. The DSTATCOM regulates voltages at its terminal by controlling the amount of reactive power injected into or absorbed from the power system. When PCC voltage is low, the DSTATCOM generates reactive (DSTATCOM capacitive). When the PCC voltage is high, it absorbs reactive power (DSTATCOM inductive).

The VSC is an IGBT based PWM converter. It uses PWM technique to synthesize a sinusoidal waveform from a DC source voltage with a typical chopping frequency of a few kilohertz. Harmonics are removed by connecting filters at the AC side of the VSC. It uses a fixed DC voltage. The AC output voltage of the VSC is varied by changing the modulation index of the PWM modulator. A phase- locked loop (PLL) synchronizes on the positive sequence component of the three phase supply voltage or voltage of PCC. The output of the PLL is used to compute the direct-axis and the quadrature-axis components of the AC three phase voltage and currents (labled ac V_d, V_q or I_d, I_q on the diagram).

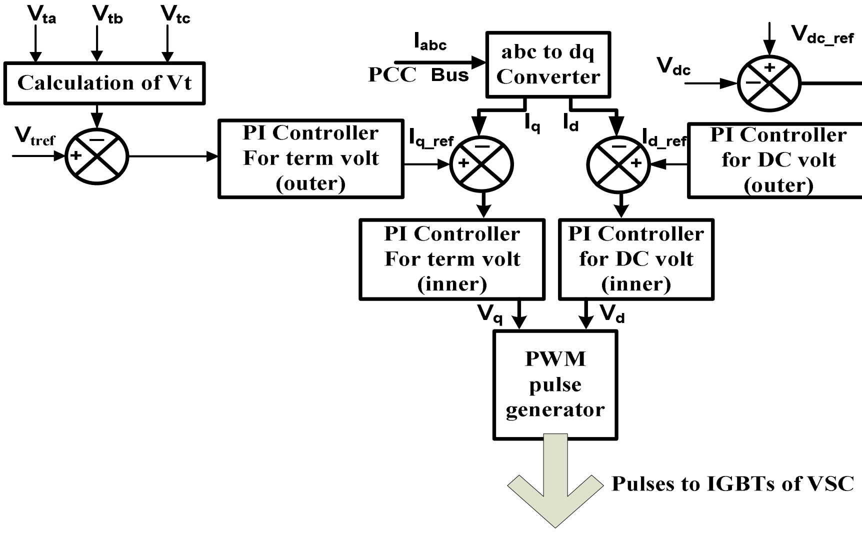

Fig. 2. Schematic diagram for control of DSTATCOM

The control of the output voltage of VSC is controlled by control of the firing pulses of the IGBTs, which in turn is done by two regulation loops namely the outer voltage regulation loop and the inner current regulation loop.

The outer regulation loop consists of an AC voltage regulator and a DC voltage regulator. The output of the AC voltage is the reference current I_{qref} for the current regulator. The output of the DC voltage regulator is the reference current I_{dref} for the current regulator. The inner current regulation loop consists of in-phase current regulator and quadrature current regulator. The output of in-phase current regulator generates V_d and output of quadrature current regulator generates V_q which are then used by PWM converter to generate the gate pulses of the IGBTs.

4. ALGORITHM FOR MODELLING OF CARRIER BASED CONTROL OF DSTATCOM

MATLAB platform [22] is used to design the model of autonomous power system shown in Fig. 1. The discrete mode using ode23tb is used for the model. For the control of VSC, shown in Fig. 2, the discrete-time integrator block [23] is used to implement the PI controller. Forward Euler method is used for integration. The discrete-time integrator block approximates 1/s by T/(Z-1), which results in the following expression for the output Y(n) at the n^{th} step .

$$Y(n) = Y(n-1) + KT^{*}\,U(n-1) \qquad (1)$$

Where U(n-1) is the input to the controller at the $(n-1)^{th}$ step. T is the discretization time interval.

4.1. PCC Voltage Control

The amplitude of the three phase sinusoidal supply voltage (v_{sa} v_{sb} and v_{sc}) can be computed as:

$$V_t = \sqrt{\{(2/3)\ (v^2_{sa} + v^2_{sb} + v^2_{sc})\}} \qquad (2)$$

Comparing the desired terminal voltage V_{tref} with the amplitude V_t computed above gives the ac voltage error $V_{er(n)}$ at the *n*th sampling instant

$$V_{er(n)} = (V_{tref} - V_{t(n)}) \qquad (3)$$

Where $V_{t(n)}$ is the amplitude of the sensed three phase ac voltage at the PCC terminal at the *n*th instant.

The outer PI controller, using discrete time integration, generate the I_{qref} using the error $V_{er(n)}$ fed to its input.

$$I_{qref\,(n)} = I_{qref\,(n-1)} + K_{a\,p}\,\{V_{er(n)} - V_{er(n-1)}\} + K_{ai}\,V_{er(n)} \qquad (4)$$

Where the proportional and integral gain constants of the outer PI controller for the ac terminal voltage control at the PCC are K_{ap} and K_{ai} respectively.

An ‘abc to dq convertor using parks transformation over the load current generate the actual I_q. The I_{qref} and I_q are compared and the error is fed to an inner PI current controller to generate V_q .

$$I_{qer(n)} = (I_{qref\,(n)} - I_{q(n)}) \qquad (5)$$

$$V_{q(n)} = V_{q(n-1)} + K_{bp}\,\{I_{qer(n)} - I_{qer(n-1)}\} + K_{bi}\,I_{qer(n)} \qquad (6)$$

Where the proportional and integral gain constants of the inner PI controller for the ac terminal voltage at the PCC are K_{bp} and K_{bi} respectively.

4.2 DC bus Voltage Control of the VFC

The desired dc bus voltage V_{dc_ref} is compared with the sensed dc voltage $V_{dc(n)}$ at the *n*th sampling instant to arrive at the dc voltage error $V_{der(n)}$

$$V_{dcer(n)} = (V_{dc\_ref} - V_{dc(n)}) \qquad (7)$$

The outer PI controller uses the dc voltage error $V_{der(n)}$ to generate the I_{dref} .

$$I_{dref\,(n)} = I_{dref\,(n-1)} + K_{a\,p}\,\{V_{dcer(n)} - V_{dcer(n-1)}\} + K_{ai}\,V_{dcer(n)} \qquad (8)$$

Where the proportional and integral gain constants of the outer PI controller of the dc bus voltage are K_{ap} and K_{ai} respectively.

An ‘abc to dq convertor using parks transformation over the load current generate the actual I_d . The I_{dref} and I_d are compared and the error is fed to an inner PI current controller to generate V_d

$$I_{der(n)} = (I_{dref\,(n)} - I_{d(n)}) \qquad (9)$$

$$V_{d(n)} = V_{d(n-1)} + K_{bp}\,\{I_{der(n)} - I_{der(n-1)}\} + K_{bi}\,I_{der(n)} \qquad (10)$$

Where the proportional and integral gain constants of the inner PI controller of the dc bus voltage are K_{bp} and K_{bi} respectively.

4.3. PWM Controller

Modulation index ‘m’ and phase ‘Φ’ are then generated using the V_d and V_q signals generated above, which are then used by the standard PWM modulator block of power system library for producing the required pulses for firing the IGBTs of the VSC. This causes the VSC to maintain the terminal voltage of the generator by generating / absorbing the required reactive current and supplying / absorbing active power from the generator to charge the battery and maintain the dc side voltage of the converter.

5. MATLAB BASED MODELING OF THE SYSTEM

Fig. 3 shows the MATLAB based simulation model of the AAG along with DSTATCOM and the motor load. A 4kW, 400V, 50Hz, 4-pole, Y-connected asynchronous machine is used for autonomous generation. Data for characteristics of the machines are obtained by simulation of saturation. They are given in the Appendix and are used in the model. A 4kW, 400V, 50Hz induction motor is connected as load to the generator. An IGBT based PWM voltage sourced converter, as DSTATCOM, is implemented using Universal Bridge Block from the Power Electronics subset of Power System Block-set. It is connected in shunt to the main system through the transformer impedance L_c, R_c. The simulation is performed on MATLAB platform (version 7.1) in discrete mode at 0.5 μsec step size with ode 23tb (stiff/TR-BDF-2) solver.

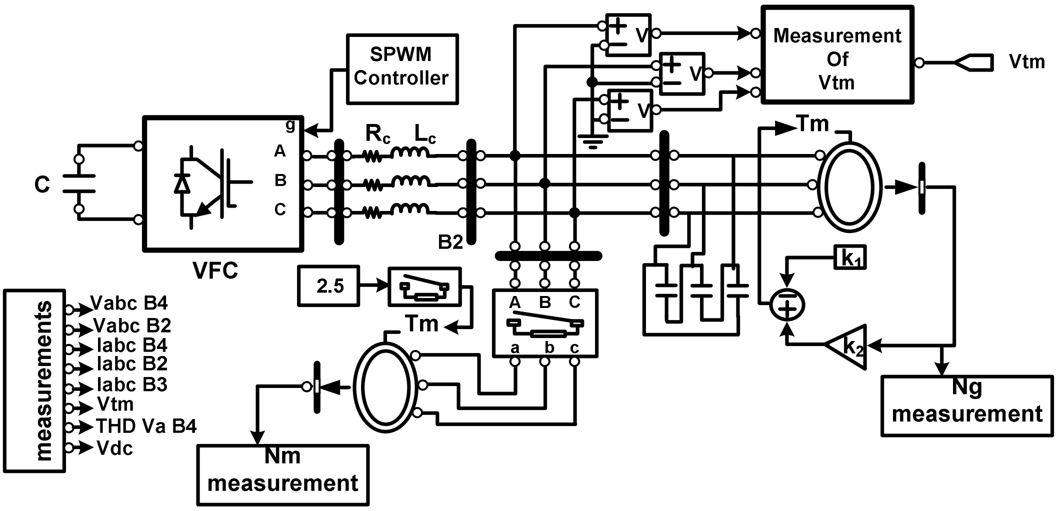

Fig. 3. MATLAB based model of the autonomous power system.

6. RESULTS AND DISCUSSIONS

The performance of the proposed DSTATCOM for an autonomous asynchronous generator is observed when subjected to dynamic induction motor load. Simulated and transient waveforms of the generator voltage (V_{abc_B4}), controller bus voltage (V_{abc_B2}), generator currents (I_{abc_B4}), controller current (I_{abc_B2}), consumer motor load current (I_{abc_B3}), amplitude of PCC voltage (V_{tm}), asynchronous generator rpm(N_g), consumer motor load rpm (N_m), total harmonic distortion of PCC voltage (THD $V_{a\ B4}$), DC bus voltage (V_{dc}), at different dynamic conditions are shown in Fig. 4 and Fig. 5 for dynamic motor load without and with the DSTATCOM connected to the PCC respectively. The simulation demonstrates the dynamic voltage control aspect and the harmonic elimination aspect of the DSTATCOM at the instant an induction motor is switched on and is drawing 5-7 times the full load motor current. Parameters of the asynchronous generator considered, is presented in Appendix. Fig. 6 and Fig. 9 demonstrate the harmonic spectrum of source voltage and current at the instant of switching on the motor load and at the instant full load is applied.

6.1. Performance of AAG with motor load without DSTATCOM

Fig. 4 shows the response of the AAG system with a dynamic induction motor load without the DSTATCOM connected to the PCC. The autonomous system starts with the DSTATCOM connected to the PCC and without the motor load being connected. At 0.5 sec the DSTATCOM is disconnected from the PCC. The asynchronous generator now runs with excitation provided by only static capacitor bank and no load is connected on its terminal as shown by $I_{abc\ B4}$. As there is no voltage regulation aspect after 0.5 sec the voltage shoots up. At 0.7 sec the Induction motor load is applied on the asynchronous generator terminal. More reactive power is now needed by the asynchronous generator to sustain its terminal voltage and also for the induction motor load. The asynchronous generator terminal voltage collapses as the additional reactive power requirement is not met.

6.2 Performance of DSTATCOM with AAG feeding motor load.

Fig.5 shows the response of DSTATCOM connected in shunt configuration at PCC to the AAG system feeding a dynamic motor load. The autonomous system starts with the DSTATCOM connected to the PCC and without the motor load being connected. The asynchronous generator now runs with excitation provided by static capacitor bank and DSTATCOM and no load are connected on its terminal as shown by $I_{abc\ B3}$. At 0.5 sec the induction motor (with no Load) is connected on the load bus. A starting current of 5 - 6 times of rated current is drawn by the induction motor load as is shown by the $I_{abc\ B3}$ and $I_{abc\ B2}$ plots. However the DSTATCOM dynamically regulates voltage at PCC and very little change is observed on $V_{abc\ B2}$ and $V_{abc\ B4}$ plots. The induction motor acquires the rated speed in about 0.05 sec as shown by the plot of N_m. Further the amplitude of the PCC voltage V_{tm} shows a very small dip of about 30 Volts as is shown by the plot of V_{tm}. The DSTATCOM dynamically provides the additional reactive power requirement and prevents the collapse of the AAG terminal voltage. This establishes the dynamic voltage regulation aspect of the DSTATCOM.

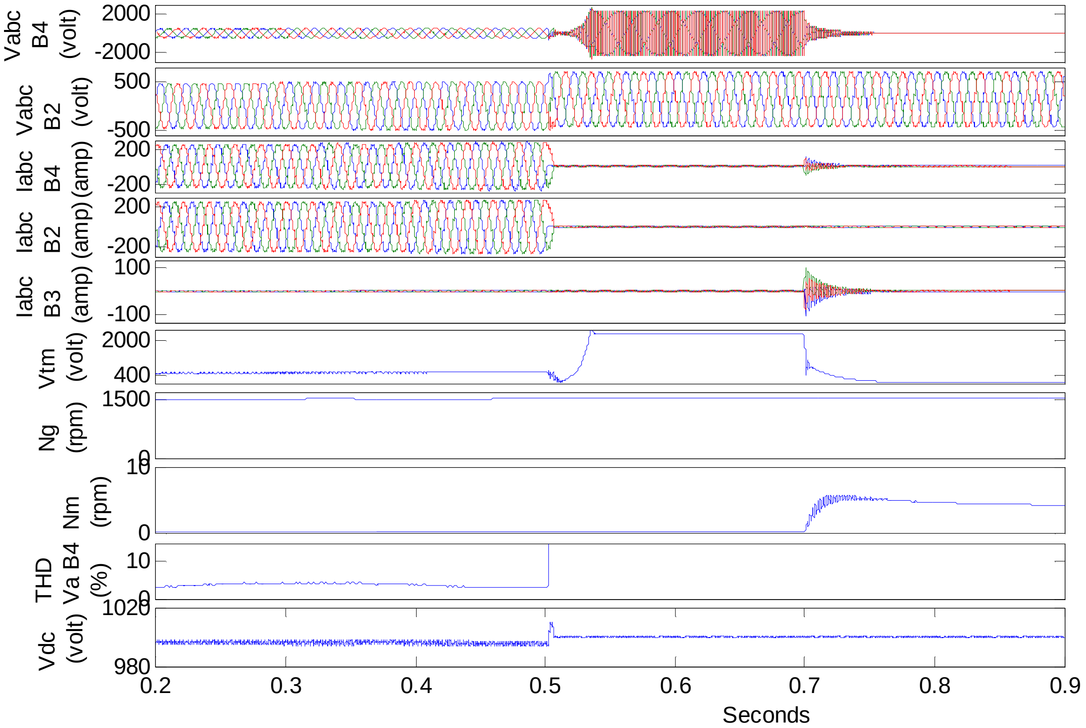

Fig. 4. Performance of AAG system feeding induction motor load without DSTATCOM.

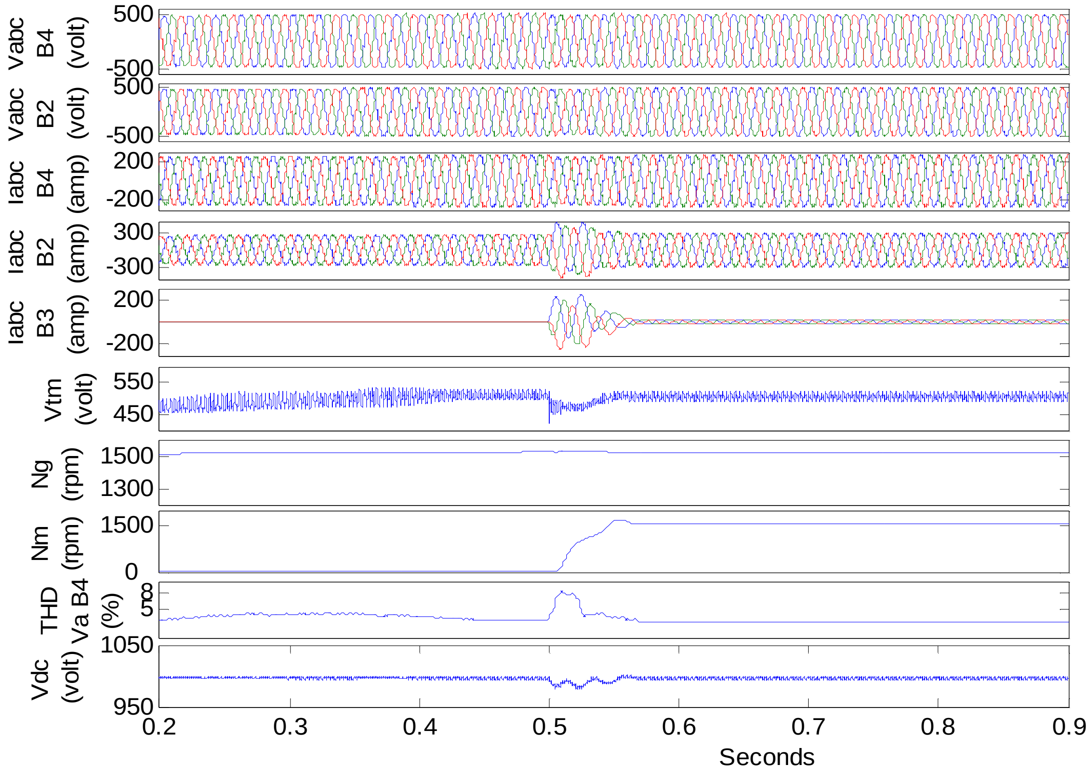

Fig. 5 Performance of AAG system feeding induction motor load with DSTATCOM connected to PCC.

At 0.7 sec rated load is applied on the induction motor. As the induction motor is already connected to the asynchronous generator terminal and is running, large change in load current is not observed and the autonomous system continues to run with the additional reactive power requirement being provided dynamically by the DSTATCOM.

Fig. 6 and Fig. 7 present the harmonic spectrum of the source voltage $V_{abc\ B4}$ and source current I_{abcB4} at the instant of starting the induction motor load (i.e. 0.5 sec). This shows that the DSTATCOM takes care of the harmonic and excess current requirement at this instant and does not allow these currents to be drawn from the asynchronous generator. Fig. 9 and Fig. 10 present the harmonic spectrum of source voltage $Vabc_{\ B4}$ and source current $I_{abc\ B4}$ at the instant of loading the induction motor with full load (i.e. at 0.7 sec).

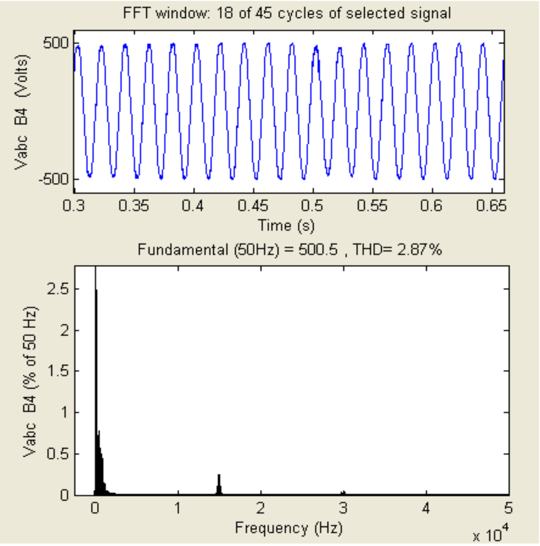

Fig. 6. Harmonic Spectrum of AAG source voltage for starting of induction motor load.

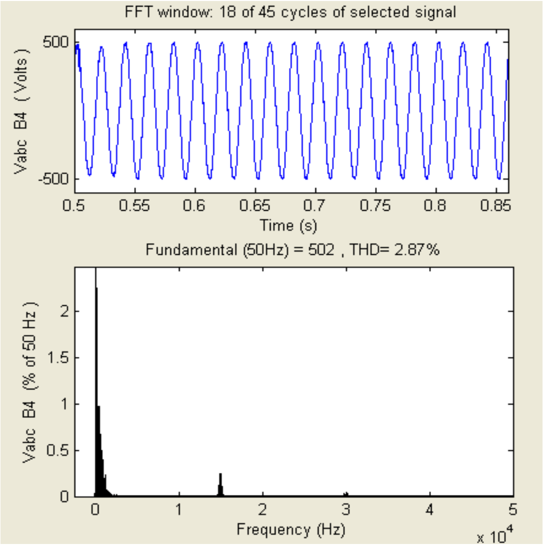

Fig. 8. Harmonic spectrum of AAG source voltage for induction motor being put on full load.

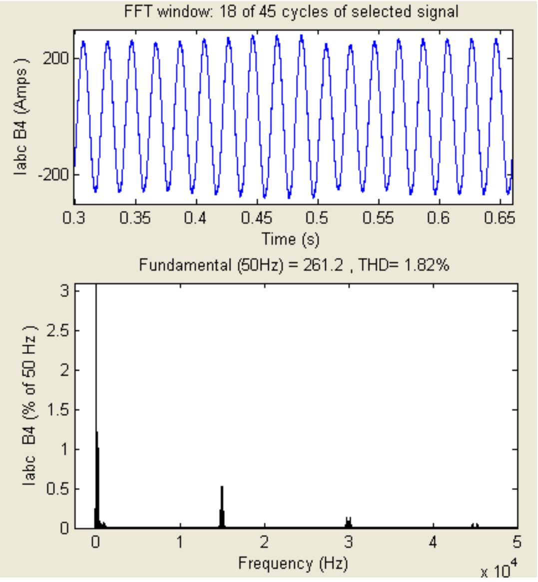

Fig. 7. Harmonic Spectrum of AAG source current for starting of induction motor load.

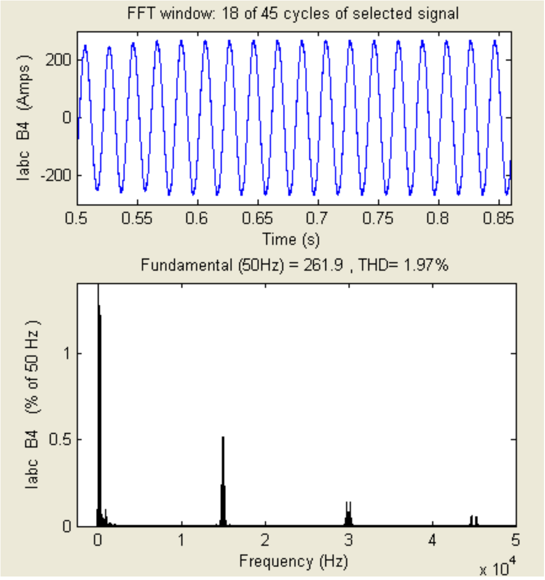

Fig. 9. Harmonic Spectrum of AAG source current for induction motor being put on full load.

7. CONCLUSIONS

The dynamic regulation of the terminal voltage of an autonomous asynchronous generator connected to an induction motor load is presented in this paper. The simulation Fig. 4 shows that without the DSTATCOM the terminal voltage of AAG shoots up being unregulated and then collapses on the application of motor load. The simulations of AAG with DSTATCOM connected, show that on application of the motor load, the DSTATCOM is able to regulate the AAG terminal voltage, allowing only a small dip and prevent the AAG terminal voltage collapse. Further on the application of full load on the motor there is no disturbance of the voltage at PCC as the motor is running at full speed and the dynamic requirement of reactive power is met by the DSTATCOM. This establishes the dynamic voltage regulation aspect of the DSTATCOM. Further, the control method used in this paper limits the switching losses to that within the rating of the switches and is robust & easy to implement. Thus DSTATCOM, with the control scheme proposed in this paper, can be used to prevent voltage dips and flickers for an autonomous asynchronous generation AAG system.

APPENDIX

ASYNCHRONOUS GENERATOR

4 kW 400V 50Hz 4 poles 1430 rpm, Rs=0.435 Ω, Ls = 4mH, Rr= 0.816 Ω, Lr = 2mH, Lm= 69.31 mH, J= 0.089 kg-m^2. Prime Mover Characteristic: $T_{sh} = K_1 - K_2\omega_r$, $K_1 = 3100$, $K_2 = 2$. Where $\omega_r = N_g$

INDUCTION MOTOR

4 kW 400V 50Hz 4 poles 1430 rpm, Rs=0.435 Ω, Ls = 4mH, Rr= 0.816 Ω, Lr = 2mH, Lm= 69.31 mH, J= 0.089 kg-m^2.

DSTATCOM

VSC 3 arm 6 IGBT with anti parallel diode bridge. C= 1500µF 15 kHz SPWM control, Kap= 0.01, Kai = 3, Kbp= 0.05, Kbi= 2. Rc=0.004 Ω, Lc= 800µH

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His fields of interest are static power conversion, electrical drives, power semiconductor applications, magnetics and applied electronics. He has authored 35 research publications in refereed journals [of which 8 are in IEEE Transactions and 3 in IEE Proceedings (now IET Journals)] and 62 papers in National and International Conferences (of which 48 are in IEEE Conferences) and about 42 circuit ideas/popular electronics articles. He also holds two patents on Semiconductor Power Converter Circuits and has applied for a patent on a special generator.

He has been a member of several National and International Committees and has served as an External Expert to several Government of India organizations. He has been associated as a consultant with several major industries in India to develop indigenous technologies in the area of Power Electronics and Drives.

Dr. Biswas received several awards, amongst which the most prestigious are the Indian National Science Academy Medal for young Scientists in 1987 and the IETE-Bimal Bose Award for “Outstanding contribution in the field of Power Electronics” in 2004.

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