A Switched Hybrid Filter – DVS/Green Plug for Smart Grid Nonlinear Loads

Adel. M. Sharaf, *Life Senior Member,* Foad. H. Gandoman*, IEEE Student Member*

***Abstract*—The paper presents a Shunt Filter Compensator-FACTS DVS/Green Plug filter/Dynamic Voltage Stabilization device developed by the First Author as a new member of Switched/Modulated Shunt LC Compensation devices for Dynamically Modulating AC Bus Admittance for stabilized and efficient energy transfer utilization, Dynamic Voltage stabilization DVS- for nonlinear loads on smart grid is required as the grid network becomes weak and insecure, especially with new Distributed Generation (DG) interface and use of Wind/Photovoltaic and battery storage systems. The FACTS-DVS/GP is validated using MATLAB-Simulink Digital Simulation Environment varying load and system conditions including open circuit and short circuit fault conditions and load-excursions/ load reductions. The coordinated, multi-regulation, inter coupled dynamic controller scheme ensures the FACTS-DVS/GP device effectiveness in improving system security, energy utilization, power factor, power quality at key AC Buses, while reducing inrush currents and transient over-voltage/switching Recovery Voltage excursions. Hence, improving dynamic voltage stabilization, feeder regulation and power quality/factor enhancement.**

***Index Terms*—Smart grid, FACTS dynamic voltage stabilization, DVS/Green Plug GP, Efficient energy.**

I. INTRODUCTION

During the last two decades, power quality problems are increasing issues in electrical power transmission and distribution systems. Especially increasing renewable energy rescuers as Distributed Generation (DG) in a modern electrical network have changed the operation on the electrical system remarkably [1, 2]. Additionally, FACTS devices are the best solution to improve power quality such as: long and short duration voltage variations, voltage imbalance, waveform distortion, voltage fluctuation and power frequency variations mostly stem from loads connected to electric supply systems [3, 4].

In order to reduce feeder active and reactive power losses as well as increase response on the electrical system to open, short circuit operation and load changing due to faults and load switching, fixed, switched, and modulated capacitor banks have been widely used [5, 6] in modern electrical system. Fixed power filters which have low cost and simple, robust structure are usually installed particularly in industrial utilization networks to improve power quality. However, the fixed parameter power filters and capacitor banks are limited in effectiveness for dynamic type loads and may result in resonance in some cases [7, 8].

In this paper a new Low-Cost Flexible Alternating Current Transmission System FACTS DVS/GP Device is validated using Matlab-Simulink Software Environment with a new Tri-regulation multi loop error driven controller for voltage stabilization and efficient energy secure delivery to the load.. The new FACTS-DVS/GP developed by the First Author utilized an IGBT/GTO switch controlled by the dynamic error driven control strategies using a multi-loop dynamic error driven, coordinated a regulation, control scheme and a Weighted–modified fast to act PID (WMPID) controller with the additional error squared to improve fast response.

This paper is organized as follows. The FACTS scheme is described in section II. In III, study system is explained. Finally, section IV and V present the Matlab/Simulink digital simulation results under fault open circuit, short circuit and load varying conditions and conclusions, respectively.

II. THE FACTS SCHEME

A. FACTS-DVS/GP Scheme

The proposed Low-Cost FACTS-DVS/GP dynamic voltage stabilization device developed by the first author is a member of a family of modulated switched/modulated power filters and switched capacitor compensators [9] -[16].

The proposed FACTS-GP comprises a series filters to mitigate harmonic and reduce total harmonic distortion as well as improve power quality and power factor using a switched shunt capacitor bank and two shunt connected fixed-capacitor banks connected to the AC side. In addition, a tuned arm filter is connected to the ground of the system.

Two modes of operation using a tuned arm filter or a capacitive compensation mode can be performed by FACTS -DVS/GP uses the controlled solid state switch, Sa. Also, the configuration of the proposed FACTS-GP is shown in Fig.1.

A. M. Sharaf, Sharaf Energy Systems, Incorporated, Fredericton, NB, Canada (e-mail: profdramsharaf@yahoo.ca).

F. H. Gandoman is with the Electrical and Computer Engineering Department, University of Kurdistan, Sanandaj, Kurdistan, Iran, (e-mail: f.haidari.elect@gmail.com).

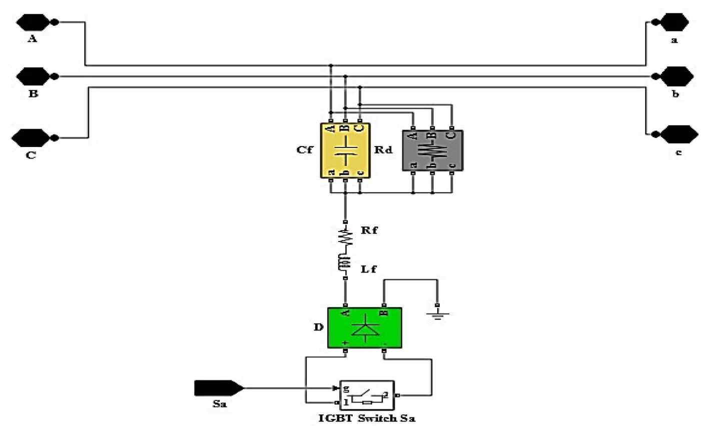

Fig. 1.Low-cost FACTS-DVS/GP device configuration.

B. Control structure

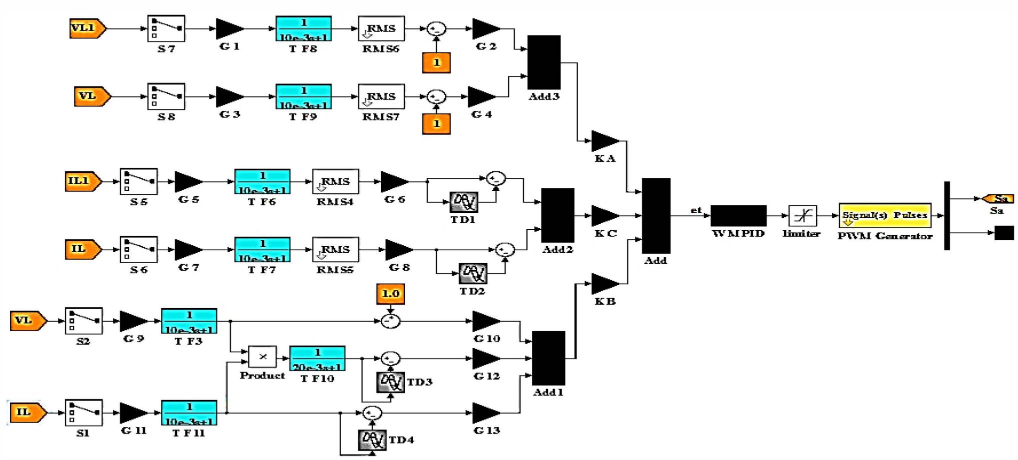

Fig. 2. Dynamic error driven Tri-Regulation controller.

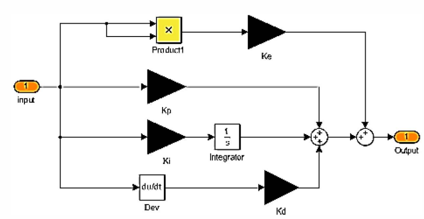

Fig. 3. Weighted-Modified PID controller with error-squared loop.

The global output signal from the dynamic error driven controller is followed by a modified Weighted-Modified PID (WMPID) controller displayed in Fig. 3. WMPID includes an error sequential activation supplementary loop, ensuring fast dynamic response and effective damping of large excursions, in addition to the conventional PID structure. Additionally, the output signal of the Weighted Modified PID controller is used to modulate the PWM signal generator and dynamically control the (On-Off) switching sequences produced by PWM define two operating modes of the FACTS-GP devises

The sample study AC System with additional FACTS-DVS/GP is shown in Fig. 4. It comprises a local hybrid load (linear, nonlinear and induction motor type loads) and is connected to the infinite bus - 138KV, Substation bus through 8 km feeder. The unified AC system, FACTS-DVS/GP and the dynamic control parameters are given in the Appendixes A and B.

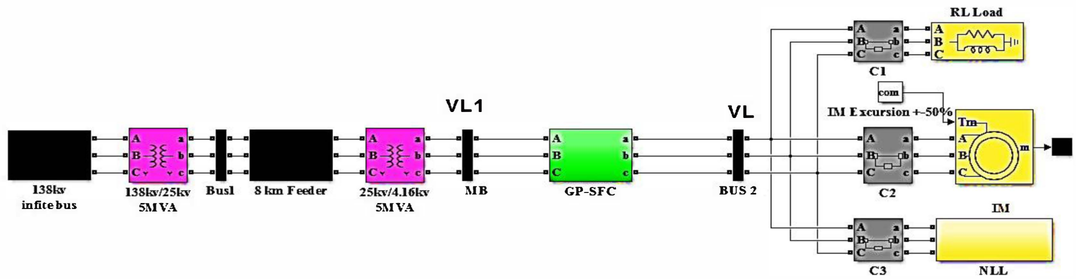

Fig. 4. Radial AC Study system with FACTS-DVS/GP at Load Bus.

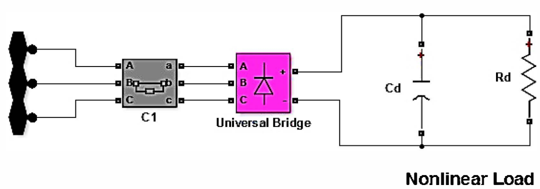

Fig. 5. Nonlinear load.

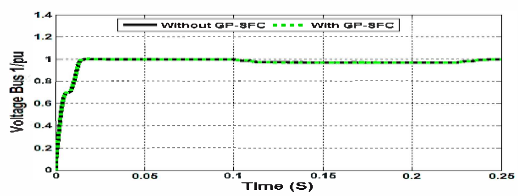

Fig. 6. RMS voltage waveform in bus 1 under short circuit operation.

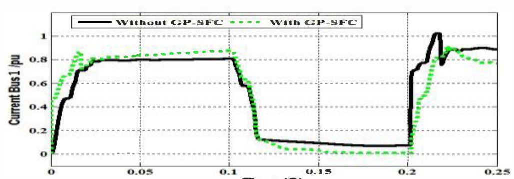

Fig. 7. RMS current waveform in bus 1 under short circuit operation.

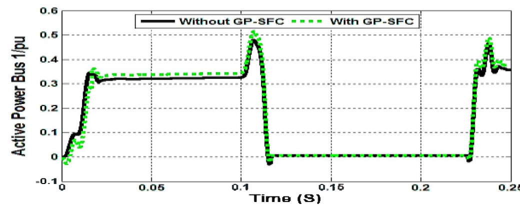

Fig. 8. Active power waveform in bus 1 under short circuit operation.

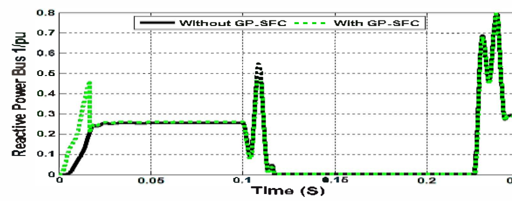

Fig. 9. Reactive power waveform in bus 1 under short circuit operation.

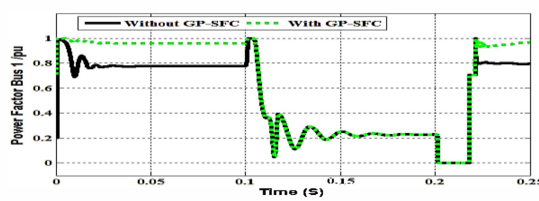

Fig. 10. Power factor waveform in bus 1 under short circuit operation.

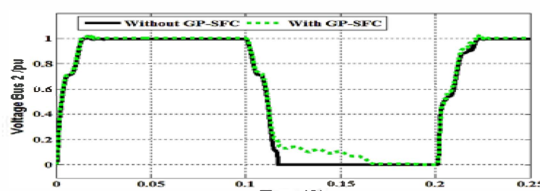

Fig. 11. RMS voltage waveform in bus 2 under short circuit operation.

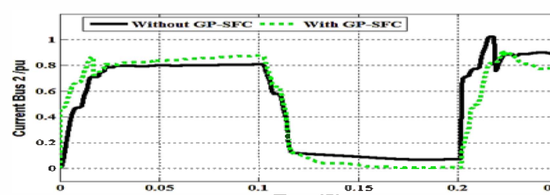

Fig. 12. RMS current waveform in bus 2 under short circuit operation.

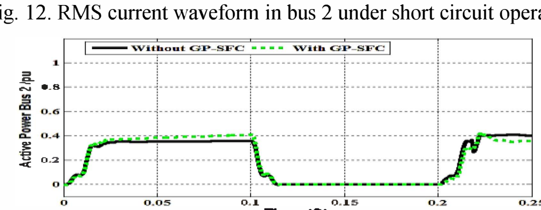

Fig. 13. Active power waveform in bus 2 under short circuit operation.

III. Digital Simulation Results

A. Application Short Circuit Condition

To validate the effectiveness of the low-cost FACTS-DVS/GP Scheme dynamic stabilization and efficient energy utilization with proposed control schemes for stabilization of the host smart grid under short circuit (SC), open circuit (OC) and load changing conditions, the MATLAB/SIMULINK Software Environment was utilized in all digital simulation, a 3-phase short circuit in middle bus (MB) is applied at time 0.02 Sec of the AC grid, and it is cleared after 0.02 Sec. The results of the simulation under short circuit condition have been shown in Figs. 6-15 and Figs 16-25, respectively. Moreover, the FACTS-DVS/GP scheme was validated to be effective in stabilizing bus voltages, improving power factor and reducing inrush currents under short and open circuit faults in the case study.

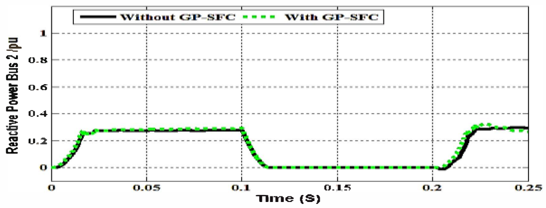

Fig. 14. Reactive power waveform in bus 2 under short circuit operation.

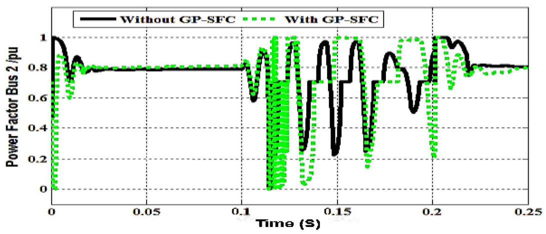

Fig. 15. Power factor waveform in bus 2 under short circuit operation.

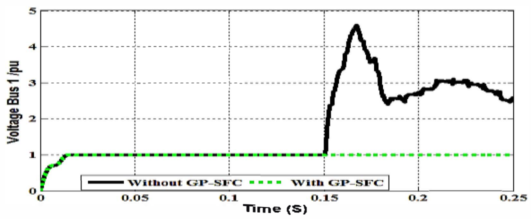

Fig. 16. Voltage waveform in bus 1 under open circuit operation.

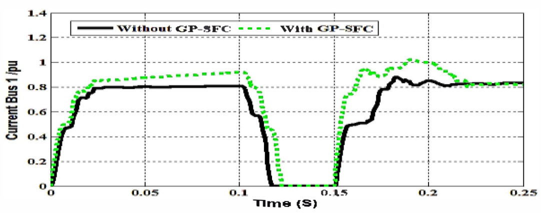

Fig. 17. Current waveform in bus 1 under open circuit operation.

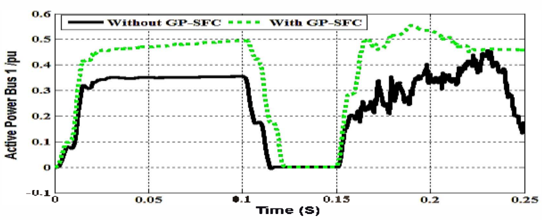

Fig. 18. Active power waveform in bus 1 under open circuit operation.

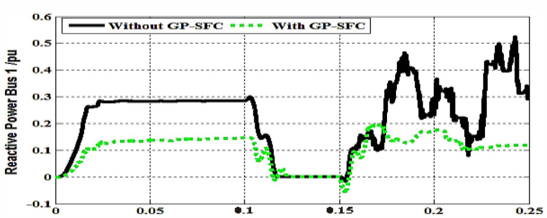

Fig. 19. Reactive power waveform in bus 1 under open circuit operation.

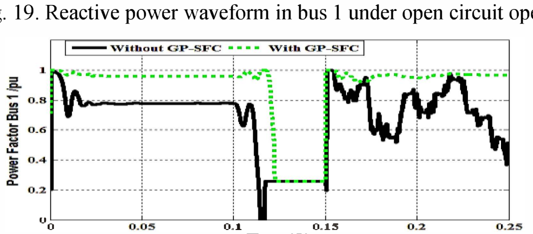

Fig. 20. Power factor waveform in bus 1 under open circuit operation.

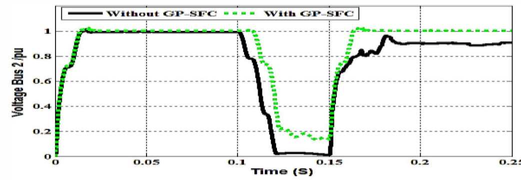

Fig. 21. Voltage waveform in bus 2 under open circuit operation.

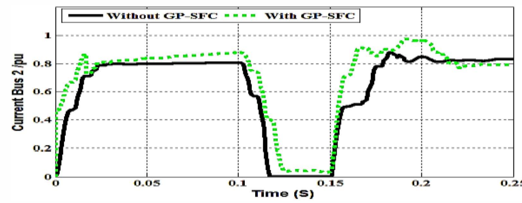

Fig. 22. Current waveform in bus 2 under open circuit operation.

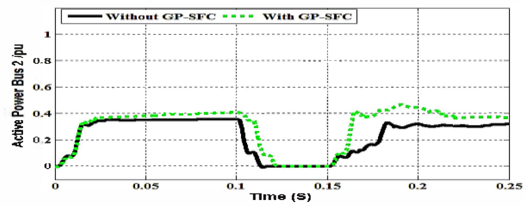

Fig. 23. Active power waveform in bus 2 under open circuit operation.

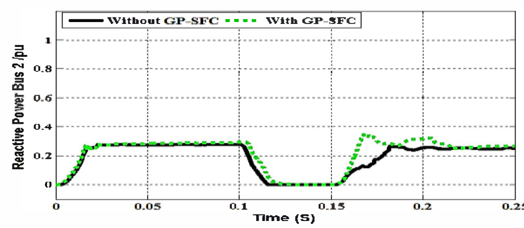

Fig. 24. Reactive power waveform in bus 2 under open circuit operation.

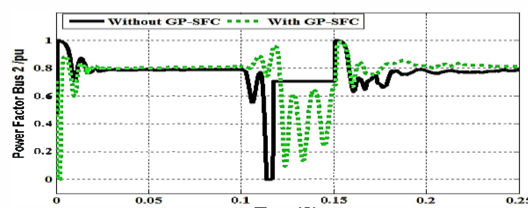

Fig. 25. Power factor waveform in bus 2 under open circuit operation.

B. *Open circuit*

In this part of the paper, an open circuit has been happing near to load and changing of key parameter shown by the following. Additionally, as it can be seen, dynamic response and power quality in buses 1 and 2 have been improved. Also, the power factor during open circuit fault with FACTS-GP in key buses has no many fluctuation, especially in bus 1.

C. *Hybrid Load Variations*

In order to examine the AC grid response to load excursions in the presence of the FACTS-GP and without FACTS-GP, following conditions are dictated to the grid. Figs. 26-35 show the results obtained for voltage and current values. At 0.02 Sec, linear load is disconnected and then reconnected after 0.04 Sec. At 0.1 Sec, nonlinear load is disconnected and reconnected after 0.04 Sec. At 0.18 Sec, motor load's torque decreases by 50% for the duration of 0.04 Sec. At 0.2 Sec, motor load's torque increases by 50% for the duration of 0.04 Sec.

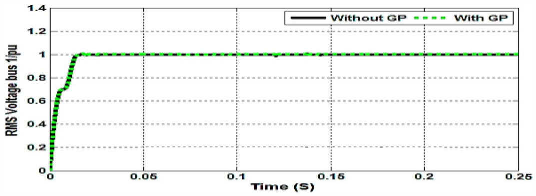

Fig. 26. RMS voltage waveform in infinite bus.

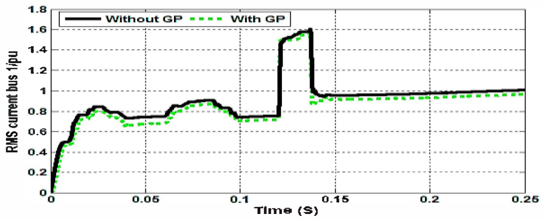

Fig. 27. RMS current waveform in infinite bus.

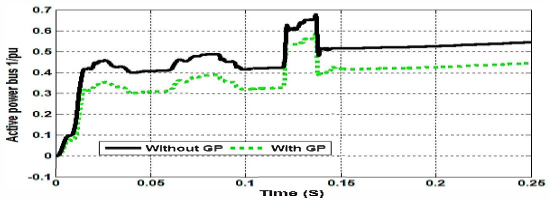

Fig. 28. Active power waveform in infinite bus.

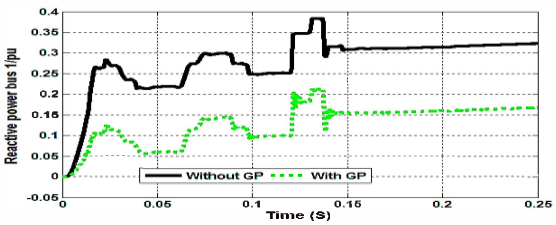

Fig. 29. Reactive power waveform in infinite bus.

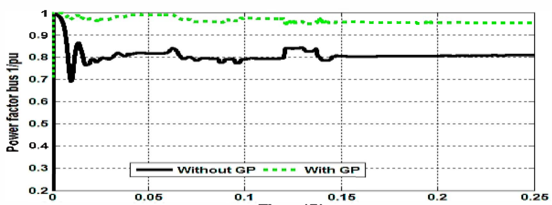

Fig. 30. Power factor waveform in infinite bus.

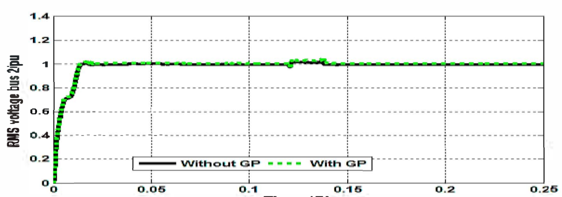

Fig. 31. RMS voltage waveform in load bus.

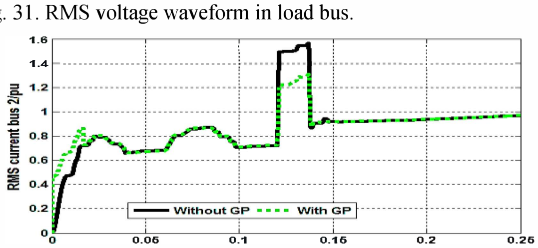

Fig. 32. RMS current waveform in load bus.

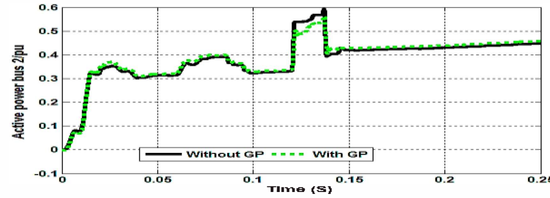

Fig. 33. Active power waveform in load bus.

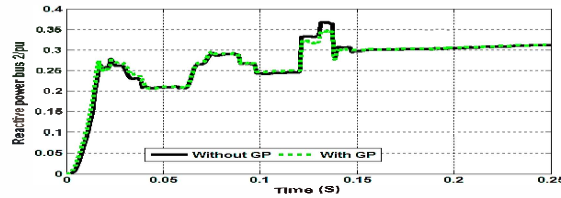

Fig. 34. Reactive power waveform in load bus.

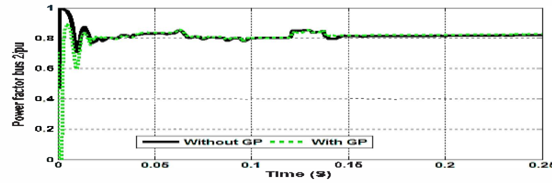

Fig. 35. Power factor waveform in load bus.

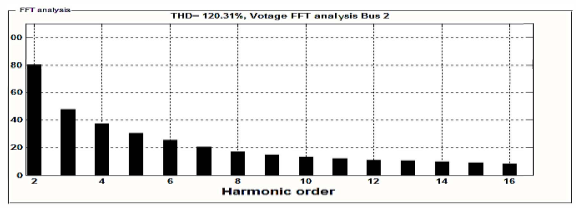

Fig. 36. FFT analysis of voltage at load Bus 2 without FACTS-GP for load changing operation.

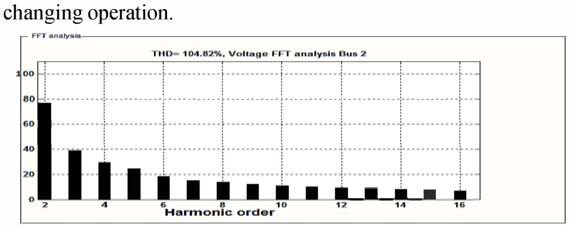

Fig. 37. FFT analysis of current at load Bus 2 without FACTS-GP for load changing operation.

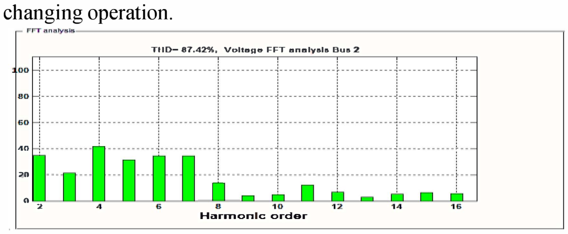

Fig. 38. FFT analysis of voltage at load Bus 2 with FACTS-GP for load changing operation.

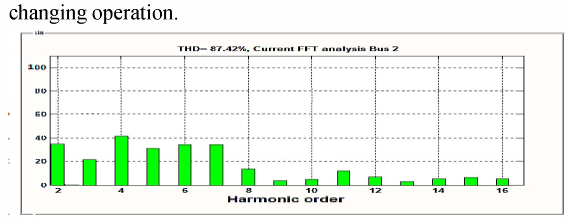

Fig. 39. FFT analysis of current load Bus 2 with FACTS-GP for load changing operation.

D. Power System Harmonic Analysis

The total harmonic distortion (THD) is an important figure of merit used to quantify the level of harmonics in voltage or current waveforms. In this section, the harmonics of the load bus of current and voltage are analyzed.

Figs 36 and 37 show voltage and current the THD of the load bus without FCTS-GP as a function of time, respectively. For constant series compensation, as seen in Figs. 36 and 37, due to using nonlinear load on power system the rate of THD has been increased; however, as seen in Fig. 38 and 39, utilizing the FACTS-GP, the THD of the line current terminal voltage in load bus are improved [17 and 18].

IV. CONCLUSION

This paper presents a low cost FACTS-DVS/GP based switched filter-Capacitor compensation scheme for use in emerging smart grid distribution systems in case of nonlinear loads and Distributed Generation DG with AC-DC interface systems. The low-cost DVS/GP device developed by the First Author is effective in dynamic voltage stabilization at load AC bus and in limiting dynamic transient recovery voltages and inrush current conditions. A tri-regulator coordinated error driven, time-de-scaled dynamic controller is utilized to adjust the Sinusoidal Pulse Width Modulation Switching patterns for the solid state switching to ensure fast dynamic bus voltage stabilization and power factor correction. The same FACTS-DVS/GP device with different control strategies is now being extended for hybrid renewable Wind/Micro hydro green energy systems for robust interfacing to smart AC grid. The digital simulation results validated the fast response and effectiveness of the proposed fast acting FACTS-DVS/GP scheme in improving voltage regulation, limiting inrush current conditions, and modifying power factor.

APPENDIX A

Transmission Line	25 kV (L-L), 8 km	
	R/Km=0. 35 Ω, L/Km=0.4 mh	
Infinite Bus	138 kV, X/R=10	
FACT-GP	C_{sh}=275μf	
	R_f=0.15Ω, L_f=3mh	
Local Hybrid Ac Load	**Induction Motor**	0.2 MW, 4 Poles
		Rs=0.01965pu, Ls=0.0397 Pu
		Rr=0.01909pu, Lr=0.0397 Pu
		Lm=1.354 Pu
	Linear Load	P=1.8 Mw,Q=0.43Mvar
	Nonlinear Load	P=0.9 Mw,Q=0.43Mvar
Power Transformer	**T_1**	138/25kv, 5 MW
	T_2	25/4.16kv, 5 MW

APPENDIX B

Device	Value
FACTS-GP Controller Gains	Ke=1, Kp=25, Ki=2, Kd=1, PWM Frequency Fs=1750 Hz

REFERENCES

[1] A. A. Abdelsalam, H. A. Gabbar, Adel M. Sharaf, "Performance enhancement of hybrid AC/DC microgrid based D-FACTS," International Journal of Electrical Power & Energy Systems., vol. 63, pp. 382-393, 2014.

[2] E. Ozkop, A. M. Sharaf and I. H. Altas. "An Intelligent self ajustable FACTS device for distribution system," International Journal of Power Engineering & Green Technology, vol. 2, no. 1, pp. 11-26, 2011.

[3] A. M. Sharaf, F. H. Gandoman, "A Flexible Facts Based Scheme for Smart Grid-PV-Battery Storage Systems," International Journal of Distributed Energy Resources, vol. 10, no. 4, pp. 261-271, 2014.

[4] P. A. Desale, V. J. Dhawale and R. M. Bandgar, "Brief review paper on the custom power devices for power quality improvement," International Journal of Electronic and Electrical Engineering, vol. 7, no, 7, 2014.

[5] A. M. Sharaf, H. Huang, and L. Chang, "Power quality and nonlinear load voltage stabilization using error driven switched passive power filter," IEEE Proc. on International Symposium on Industrial Electronics, pp. 616-621, 1995.

[6] M. Rastogi, N. Mohan, and A. Edris, "Hybrid active filtering of harmonic currents in power systems," IEEE Trans. On Power Delivery, vol. 10, no. 4, pp. 1994-2000, 2005.

[7] H. Fujita and H. Akagi, "A practical approach to harmonic compensation in power system-series connection of passive, active filters,"IEEE Trans. on Ind. App., vol. 27, no. 6, pp. 1020 -1025, 1991.

[8] A. M. Sharaf and C. Guo "Distributed/utilization system voltage stabilization and power quality enhancement using intelligent smart filter," UPEC'95, England, UK, 1995.

[9] A. M. Sharaf and P. kreidi, "Dynamic compensation using switched/modulated power filters," Canadian Conference on Electrical and Computer Engineering, 2002, IEEE CCECE 2002, vol. 1, pp. 230-235, 2002.

[10] A. M. Sharaf and P. kreidi, "Power quality enhancement using a unified switch capacitor compensator," Canadian Conference on Electrical and Computer Engineering, IEEE CCECE 2003, vol. 1, pp. 331-333, 2003.iversity Science, 1989.

[11] A. M. Sharaf, A. A. Abdelsalam, A. A. Eldesouky, A.A. Sallam, "a novel FACTS based modulated power filter compensation scheme for smart electric grid stabilization and efficient utilization", International Journal of Distributed Energy Resources, vol. 7, no. 4, pp. 311-327, 2011.

[12] A. A. Abdelsalam, Mohammed E. Desouki, Adel M. Sharaf," Power quality improvement using FACTS power filter compensation scheme," J. Electrical Systems, vol. 9, no. 1, pp. 86-96. 2013.

[13] A. M. Sharaf and B. Khaki,"Navel switched capacitor-filter compensator for smart grid-electric vehicle charging scheme" IEEE International conference on Smart grid engineering, pp.1-5 2012.

[14] A. M. Sharaf, A. S. Aljankawey, and I. H. Altas, "Dynamic voltage stabilization of stand-alone wind energy schemes," IEEE Canada Electrical Power Conference, EPC 2007, pp. 14-19, 2007.

[15] M. El. Moursi, A. M. Sharaf , Kh. El-Arroudi, "Optimal control schemes for SSSC for dynamic series compensation," Electric Power Systems Research, vol. 78, no. 4, pp. 646-456, 2008.

[16] A. M. Sharaf and B. Khaki," A navel FACTS hybrid modulated filter/capacitor compensator," Smart grid engineering (SGE), pp.1-6 2012.

[17] IEEE Std. 519-1992, IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, Published by IEEE, 1992.

[18] Electromagnetic Compatibility (EMC)—Part 3–4 Limits— Limitation of Emission of Harmonic Current in Low-Voltage Power Supply Systems for Equipment With Rated Current Greater Than 16 A, IEC Std. 61000-3-4-1998.