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Power Quality Enhancement in Wind Connected Grid System Interface Based On Static Switched Filter Compensator (SSFC)

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Abstract -
Wind energy has become one of the significant alternative renewable energy resources because of its abundance and the strong drive for its commercialization. Dynamic electric load variations and wind velocity excursions cause excessive changes in the prime mover kinetic energy and the corresponding electrical power injected into the AC grid utility system. In this paper, a scheme based on the low cost static switched filter compensator (SSFC) is presented for voltage sag/swell compensation, power factor improvement in distribution grid networks with the dispersed wind energy interface. The SSFC scheme is based on an intermittent switching process between two shunt capacitor banks to be one of them in parallel with the capacitor of a tuned arm filter. Two regulators based on a tri- loop dynamic error driven inter-coupled weighted modified proportional-integral-derivative (PID) controller which is used to modulate the PWM.

      The Static Switched Filter Compensation (SSFC) compensation scheme which enhances the system power quality has been fully validated using MATLAB–Simulink. The effectiveness of this compensation scheme approach is demonstrated using a study case of 3 bus system. Simulation results show that there is improvement in harmonics reduction, voltage sag/swell compensation, power factor improvement at generator bus, load bus, and infinite bus respectively
Keywords: FACTS, Static Switched Filter Compensator, Dynamic Controllers, Wind Energy, Power Quality.

I. INTRODUCTION

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, wind mills for mechanical power, wind pumps for water pumping, orsailstopropelships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world's rapid growing source of energy.

The need to utilize the abundant renewable energy sources such as wind is increasing due to massive world energy shortage, economic and environmental pollution concerns. Wind energy has become one of the most significant, alternative renewable energy resources because of its abundance and the strong drive for its commercialization. Most large size wind turbines in the world (50-2000kw) use the three phase asynchronous (squirrel cage) induction generator]. The reason for choosing squirrelcage induction generator is that it is low lost, very reliable, less maintenance. So a self-excited asynchronous induction generator driven by a wind turbine called a standalone Wind Energy Conversion Scheme

(WECS) with self-excited capacitors is studied in this paper.

II. THE STATIC SWITCHED FILTER COMPENSATOR

The FACTS SSFC scheme, shown in Fig. 1, is a combination of two series capacitor banks (C_{S1} and C_{S2}) and two shunt capacitor banks (C_{m1} and C_{m2}) in parallel with the capacitor element (C_F) of a tuned arm filter (R_F, L_F and C_F). An intermittent switching process between the two shunt capacitor banks is achieved by novel dynamic control strategies.
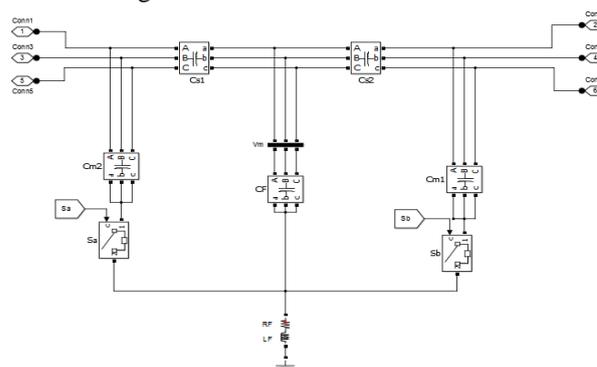

Fig..1   Simulink Model of the Static Switched Filter Compensator (SSFC) Scheme

III. CONTROLLER DESIGN

Integrated inter-coupled regulators dynamic control based on two regulators A and B are proposed to reduce the harmonics, improve the power factor and stabilize the buses voltage using the FACTS static switched filter compensator. Both the regulators will consist of the following three loops. The proposed novel tri-loop dynamic controller is very effective and flexible and can also be modified by adding any other supplementary compensation loops such as dynamic power loop.

A. The Generator Voltage Tracking Main Loop

Any variations of wind speed and loads will be mainly reflected on the generator voltage after some delay due to system and inertia time constants. Therefore, this loop is tracking the error of generator voltage root mean square value and keeping the generator bus voltage V_{grms} to be around per unit. By setting the control signal weight $\gamma_V=l$, the voltage loop is selected to be the domain loop to ensure the voltage stabilization.

B. Generator Current Tracking Main Loop

The other main loop is dynamic current tracking loop which accounts for any sudden generator output current variations due to either wind speed or electric load excursion. The signal weight is set to $\gamma_I=l$.

C. Generator Power Tracking Supplement Loop

This is a supplementary loop which tracks and minimizes any dynamic generator power exchange mismatch. The loop weight is set at $\gamma_P=0.5$.

Regulator A:

In this regulator which is shown in Fig. 2, the voltage and current waveform are used in a tri loop error to provide a stable voltage at all AC buses and to improve the power factor. This is achieved by modulating the admittance of the SSFC.
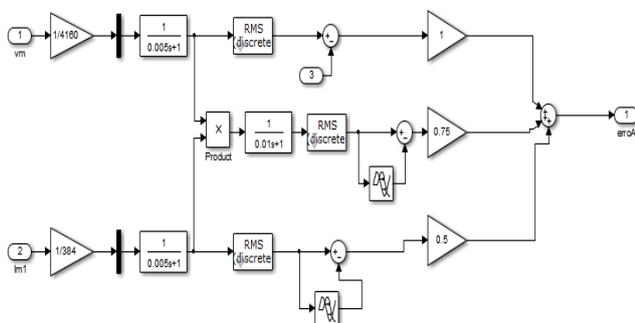

Fig. 2 The Tri Loop Regulator A

Regulator B:

The regulator B which is shown in Fig. 3, used to suppress any voltage and current harmonic ripples and consequently mitigate the harmonics.
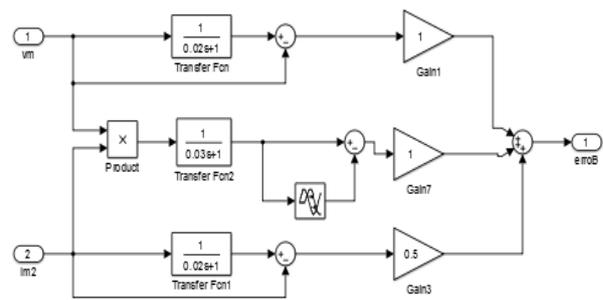

Fig. 3 The Tri Loop Regulator B

The global error is the sum of the two inter-coupled regulators output. The global error signal is an input to the weighted modified PID controller to regulate the modulating control signal to the PWM switching block as shown in Fig. 4.The PWM Carrier frequency for 6 pulse thyristor operation: fs/w=1750 (Hz) for ideal switches. The switching f frequency of ideal switches is s elected by trial to e ensure control objectives and minimum switching loss.
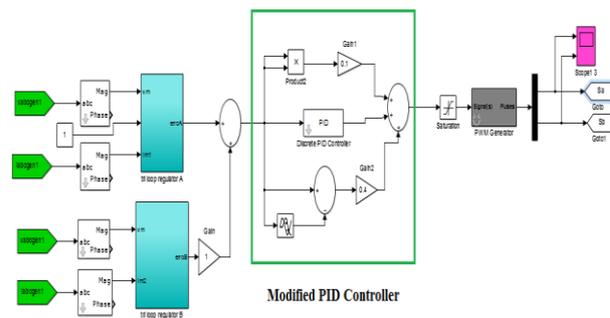

Fig. 4. The Modified PID Control of the FACTS SSFC Scheme

The two ideal switches (S_a and S_b) are controlled by two complementary switching pulses (S_1 and S_2) that are generated by the dynamic tri loop error driven weighted modified PID controller, as shown in Fig. 4. The upper pulse switches while the lower pulse controls. The variable topology of the SSFC can be changed by the complementary PWM pulses as follows:

Case 1: If S_1 is high and S_2 is low, the resistor and inductor will be fully shorted and the combined shunt and series capacitors will provide the required shunt and series capacitive compensation to the AC distribution system

Case 2: If S_1 is low and then S_2 is high, the resistor and inductor will be connected into the circuit as a tuned arm filter.

IV. DIGITAL SIMULATION OF THE STUDIED AC SYSTEM

A. SINGLE LINE DIAGRAM OF 3 – BUS 11KV DISTRIBUTION SYSTEM

The grid connected wind energy system with squirrel cage induction generator, hybrid load and SSFC compensation is depicted in Fig.5.The studied AC system is 11 KV distribution network with a renewable wind energy source and is connected to 138 kV AC grid through 11/138kV step up transformer. A hybrid load comprises a linear load, a
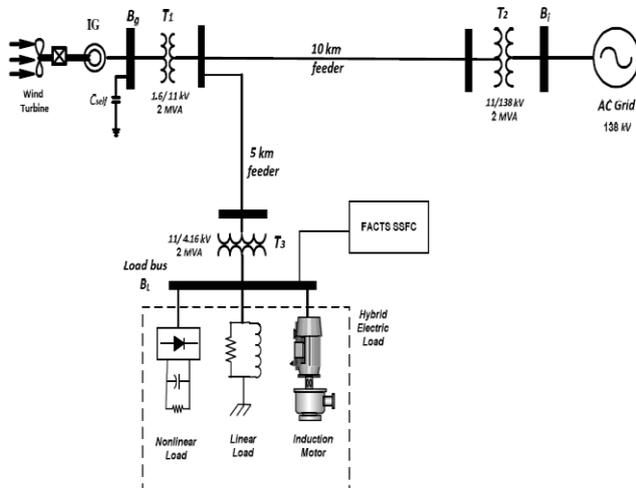
converter type nonlinear load and an induction motor load is connected to the distribution network through 11/4.16kV step down transformer. The detailed parameters of the system are given in [10].

Fig. 5Single Line Diagram of the 3-bus 11 kV Distribution System with the Static Switched Filter Compensation Scheme

V SIMULATION CIRCUITS
A. *Simulink Model of Wind System*
The Simulink model for the Wind Energy Conversion Scheme is shown in Fig. 7. The wind energy conversion scheme consisting of squirrel cage induction generator is developed using the power and torque equations. The novel WECS schemes provide a dynamic level of compensation and electric power/energy exchanges to ensure voltage stability and minimum disturbance/excursion impact on the WECS operation.
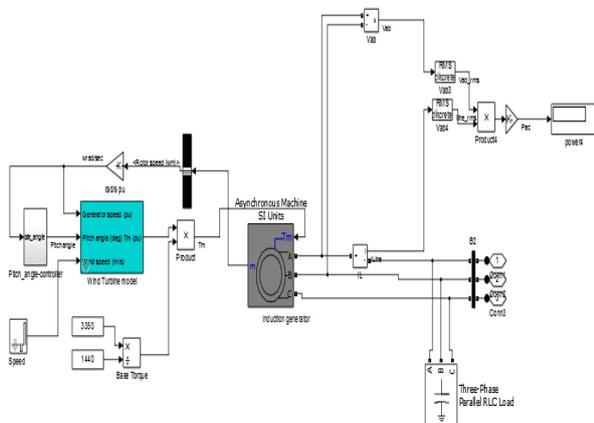

Fig.7 Simulink Model for Wind Energy Conversion Scheme

C. SIMULINK MODEL OF 3 BUS, 11KV WECS WITHOUT SSFC
The grid connected wind energy system with squirrel cage induction generator, hybrid load is simulated and it is shown in Fig.8.The studied AC system is 11 kV distribution network with a renewable wind energy source and is connected to 138 kV AC grid through 11/138kV step up transformer. A hybrid load comprises a linear load, a converter type nonlinear load and an induction motor load is connected to the distribution network through 11/4.16kV step down transformer.
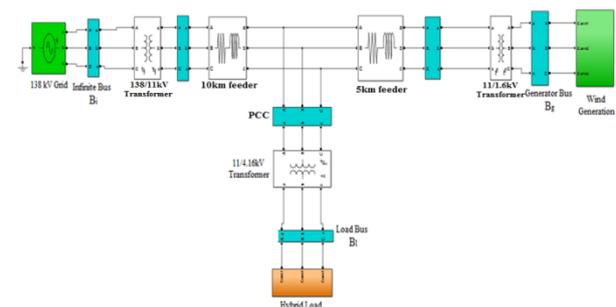

Fig.8 Simulink Model of 3 bus 11 kV WECS Connected to the Grid without SSFC

D. SIMULINK MODEL OF 3 BUS, 11KV WECS WITH SSFC
The grid connected wind energy system with squirrel cage induction generator, hybrid load and Static Switched Filter Compensation scheme is simulated and it is shown in Fig.9.The studied AC system is 11 kV distribution network with a renewable wind energy source and is connected to 138 kV AC grid through 11/138kV step up transformer. A hybrid load comprises a linear load, a converter type nonlinear load and an induction motor load is connected to the distribution network through 11/4.16kV step down transformer.
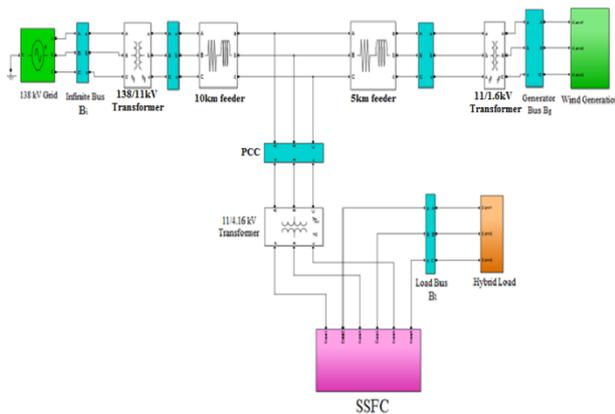
Fig.9Simulink Model of 3 bus 11 kV WECS Connected to the Grid with SSFC

VI SIMULATION RESULTS

A. Case Studies

Case 1: Normal Loading Operation

The digital simulation is carried out with and without the controlled SSFC located at load bus for 1.0 second in order to show its performance in harmonic reduction at normal operating condition. The dynamic response of Voltage, Power factor, THDs for Voltages and THDs for Currents at generator bus (B_g), load bus (B_l) and infinite bus (B_i), with and without SSFC at normal operating conditions are shown.

The RMS voltages of generator bus, load bus and infinite bus are shown in Fig. 10, Fig 11 and Fig. 12 respectively.

The value of the fixed self excitation capacitor bank for wind energy converter schemes is usually sized for the operating range of wind (cut-in) and (cut-off) speeds. Therefore, there will always be an imbalance of reactive power at the generator bus under sudden wind speed variations and electric load excursions. This can cause a dynamic voltage instability problem and possible loss of excitation of induction generator requiring a full shutdown and delayed restarting of the wind energy conversion scheme. The WECS schemes provide a dynamic level of compensation and electric power/energy exchanges to ensure voltage stability and minimum disturbance/excursion impact on the WECS operation.
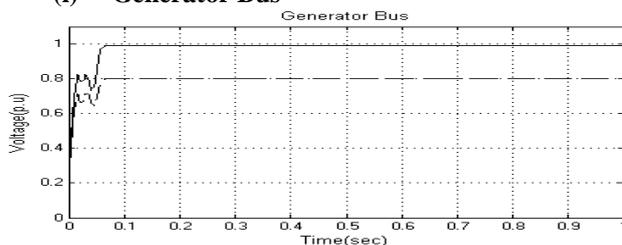
(i)   Generator Bus

Fig.10 The RMS Voltage at the Generator Bus (B_g) with SSFC (solid line) and without SSFC (dashed line)

From Fig. 10 It is observed that due to the presence of hybrid load (i.e., Linear, Non Linear, and Induction Motor) and sag is created between 0 to 0.06sec.Without SSFC device, the RMS Voltage is maintained at 0.8 p.u. after 0.06sec.With SSFC device, the RMS Voltage is improved to 1 p.u. after 0.06sec at the Generator Bus(B_g).
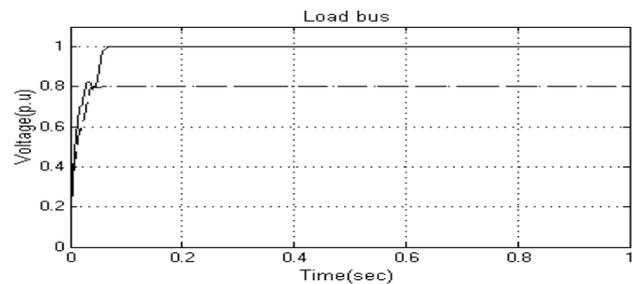
(ii)   Load Bus

Fig.11 The RMS Voltage at the Load bus (B_l) without SSFC (dashed line) and with SSFC (solid line)

From Fig. 11 It is observed that due to the presence of hybrid load (i.e., Linear, Non Linear, and Induction Motor) and sag is created between 0 to 0.06sec.Without SSFC device, the RMS Voltage is maintained at 0.8 p.u. after 0.06sec.With SSFC device, the RMS Voltage is improved to 1 p.u. after 0.06sec at the Load Bus(B_l).
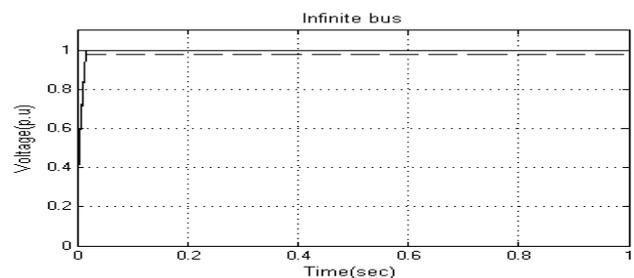
(iii)   Infinite Bus

Fig.12 The RMS Voltage at the Infinite Bus (B_i) with SSFC (solid line) and without SSFC (dashed line)

From Fig. 12, it is observed that infinite bus, the RMS value of voltage waveform does not change. It always maintained at 1p.u at the Infinite Bus (Bi).

In the previous figures, with using the FACTS filter compensator, the RMS value of the voltage waveform at the generator and load buses are increased while the RMS value of voltage waveform at the infinite bus (Bi) does not change.

The RMS voltages of generator bus, load bus and infinite bus are shown in Fig. 13, Fig. 14 and Fig. 15 respectively.
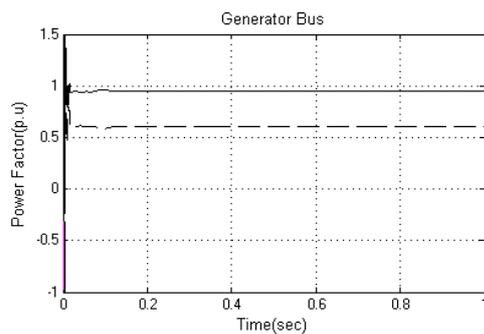
(i)   Generator Bus

Fig. 13 The power factor at the Generator Bus (Bg) without SSFC (dashed line) and with SSFC (solid line)

From Fig. 13, it is observed that the power factor at the generator bus(Bg)is improved from 0.6 p.u to 0.95 p.u in 0.1 sec after connecting SSFC scheme at the load bus.
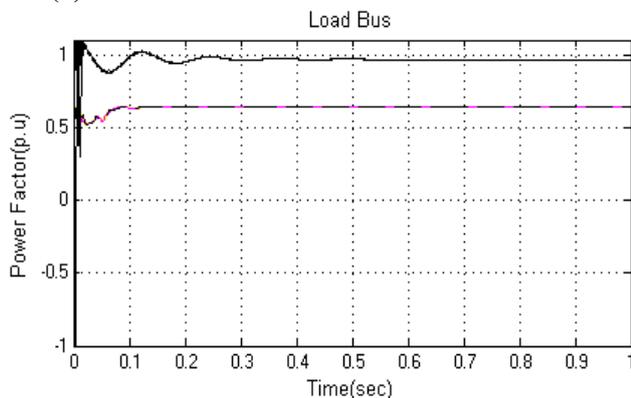
(ii)   Load Bus

Fig.14The Power Factor at the Load Bus (Bl) without SSFC (dashed line) and with SSFC (solid line)

From Fig. 14,it is observed that power factor at the Load Bus(Bl) is improved from 0.6 p.u to 0.95 p.u in 0.1 sec after connecting SSFC scheme at the load bus.
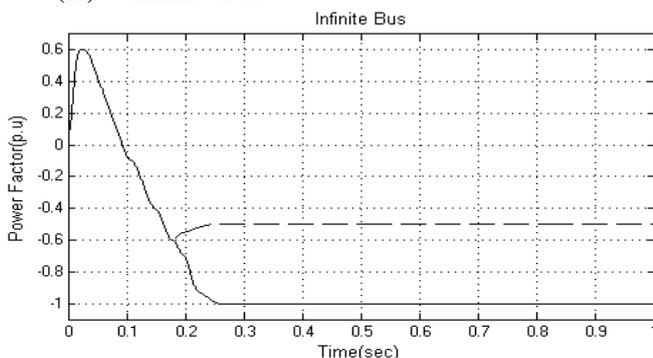
(iii)   Infinite Bus

Fig.15The Power Factor at the Infinite Bus (Bi) without SSFC (dashed line) and with SSFC (solid line)

From Fig. 15, it is observed that power factor at the Infinite Bus (Bi)is improved after connecting SSFC

scheme at the load bus. In the previous figures, with using the FACTS filter compensator, the power factor values at the generator and load bus, infinite bus (Bi} are increased.

Case 2: Sudden change of the Wind Speed and the Load Excursion. In this case study, the digital simulation is carried out with and without the controlled SSFC located at load bus for 1.0 second in order to show its performance under the following disturbance sequence:

1.   At t = 0.1 second, the linear load is removed for a duration of 0.1 seconds
2.   At t = 0.3 second, the nonlinear load is removed for a duration of 0.1 seconds
3.   At t = 0.5 second, wind speed suddenly decreased to 9 m/s for a duration of 0.1 seconds
4.   At t = 0.7 second, wind speed suddenly increased to 21 m/s for a duration of 0.1 seconds
5.   At t = 0.8 the system is recovered to its initial state.
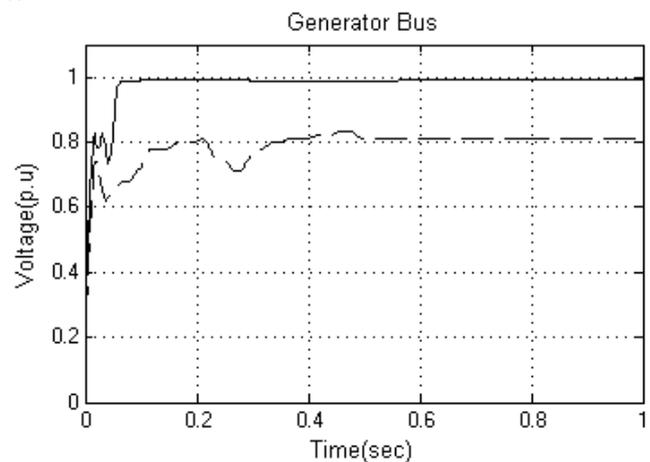
(i)   Generator Bus

Fig.16 The RMS Voltage at the Generator Bus (Bg) without SSFC (dashed line) and with SSFC (solid line)

From Fig. 16, it is observed that without SSFC scheme, the disconnection of the linear and nonlinear loads has an effect on the value of voltage at the generator bus cause a voltage swell. After using SSFC we can observe that there is no effect on the voltage waveforms because it mitigates the swell event of PQ disturbances.
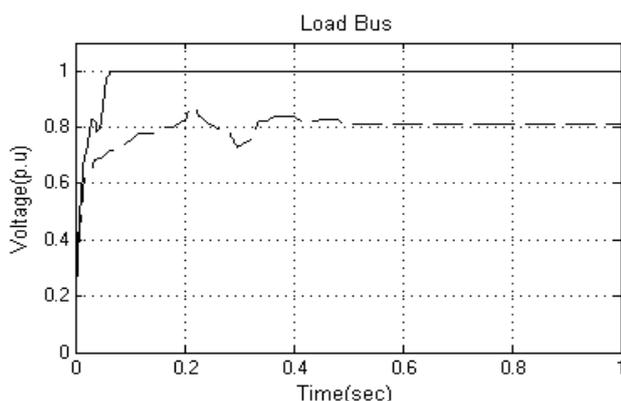
(ii)   Load Bus

***Fig.17 The RMS Voltage at the Load Bus (B_l)
without SSFC (dashed line) and with SSFC (solid
line)***

From Fig. 17, It is observed that without SSFC scheme, the disconnection of the linear and nonlinear loads has an effect on the value of voltage at the load bus cause a voltage swell. After using SSFC it is observed that there is no effect on the voltage waveforms because it mitigates the swell event of PQ disturbances.
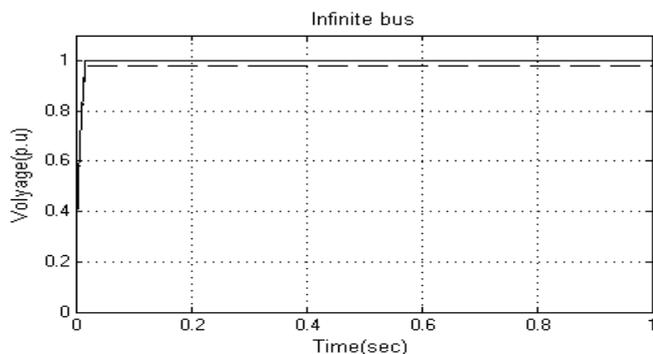
(iii)   Infinite Bus

***Fig. 18 The RMS Voltage at the Infinite Bus (B_i)
without SSFC (dashed line) and with SSFC (solid
line)***

From Fig. 18,it is observed thatat the infinite bus (Bi), the rms value of voltage waveform does not change it always maintained at 1 p.u.

Without SSFC scheme, the disconnection of the linear and nonlinear loads has an effect on the value of voltage at the generator bus and load buses cause a voltage swell. With controlled SSFC scheme, there is no effect on the voltage waveforms because it mitigates the swell event of PQ disturbances. With the controlled SSFC scheme, the gradual change in wind speed does not appear on the voltage waveform while the sudden changes have a small effect on it. At infinite bus, the RMS value of voltage waveform does not change. It always maintained at 1 p.u.

The RMS values of voltage waveforms at generator (Bg), load (Bl)and infinite buses (Bi) under load excursions are depicted in Fig. 16, Fig. 17 and Fig. 18.From Fig. 16, it is observed that without using the

FACTS SSFC scheme, thedisconnection of the linear and nonlinear loads have an effect onthe value of voltage at the generator and load buses.It causes a voltage swell while using the controlled FACTS SSFCscheme, there is no effect on the voltage waveforms. This meansthat the controlled FACTS SSFC scheme mitigates the swell eventof PQ disturbances. Also with the controlled FACTS SSFC scheme, the gradual change in wind speed does not appear on the voltage and active power waveform while the sudden change have a small effect on it.

VI CONCLUSION

The paper illustrates the operation and control of a Static Switched Filter Compensator (SSFC).The SSFC can mitigate significant power quality issues like harmonics, voltage sag/swell, poor power factor, voltage instability problems due to wind speed variations and load excursions. The SSFC is based on controlled complementary switching process between two capacitor banks to be connected with the classical tuned arm filter. The effectiveness of the mentioned compensation approach is demonstrated in a case study using MATLAB-Simulink environment. After connecting SSFC scheme, the RMS value of the voltage waveform at the generator and load buses are increased and maintained at 1p.u. While at the infinite bus (Bi), the RMS value of voltage waveform does not change.

In this paper, the SSFC device scheme has been fully validated for effective harmonics reduction, voltage sag/swell compensation, power factor improvement.

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