A FACTS Based Static Switched Filter Compensator for Voltage Control and Power Quality Improvement in Wind Smart Grid

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Abstract: The renewable energy sources, which have been expected to be a promising alternative energy source, can bring new challenges when it is connected to the power grid. This paper presents a novel FACTS based Static Switched Filter Compensation (SSFC) scheme. This FACTS SSFC scheme is an effective power quality mitigation, voltage stabilization, power losses reduction and power factor enhancement tool for wind schemes interfaced with Smart Grid-Distribution Networks. The FACTS SSFC-device is controlled by two regulators based on a tri-loop dynamic error driven inter-coupled input to a weighted modified PID controller. The FACTS filter compensation scheme has been fully validated for effective harmonic mitigation, voltage stabilization, losses reduction and power factor correction using the Matlab Simulink software environment. The proposed FACTS Static Switched Filter Compensator Scheme can be extended to integrate other distributed/dispersed distributed generation schemes for power quality and power factor enhancement and compensation requirements such as voltage stabilization and efficient utilization.

Keywords: FACTS, Static Switched Filter Compensator, Dynamic Controllers, Wind Energy Utilization, Voltage Stabilization.

1. INTRODUCTION

To have sustainable growth and social progress, it is necessary to meet the energy need by utilizing the renewable energy resources like wind, biomass, hydro, co-generation, etc. In sustainable energy system, energy conservation and the use of renewable source are the key paradigm. The need to integrate the renewable energy like wind energy into power
system is to make it possible to minimize the environmental impact on conventional plant [1]. The integration of wind energy into existing power system presents technical challenges and that requires consideration of voltage regulation, stability, power quality problems. The power quality is an essential customer-focused measure and is greatly affected by the operation of a distribution and transmission network. The issue of power quality is of great importance to the wind turbine [2]. There has been an extensive growth and quick development in the exploitation of wind energy in recent years.

Wind energy conversion systems (WECS) is a form of viable and effective renewable green energy sources that convert wind kinetic energy to mechanical energy that can be used to drive different AC and DC type generators [3]. Typically, the WECS comprises a wind turbine, gear box, generator, interconnection converter, and the required control systems. The WECS can be connected as either stand-alone for supplying power to local isolated loads in remote areas, or connected to the electric grid system. Owing to very large wind farms emerging, the dispersed renewable wind energy is required to be fully connected to the electrical distribution networks [4]. However, increased penetration of the dispersed wind energy creates an uncertain and challenging scenario for the electric power grid system. In remote and isolated sites, the power obtained from wind energy integrated with the electric grid can reach the same order of magnitude as grid-power transferred, which means that the mutual impact between wind-energy schemes and the electric grid networks must be taken into account. 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 [5, 6]. In short, it is necessary to provide effective and economical technical solutions for both power quality and security aspects related to the electric grid with distributed and dispersed wind energy schemes. Fortunately, the new emerging FACTS technologies can perform new stabilization and fast power control functions by quickly switching solid-state devices [7].

In general, FACTS devices are used in transmission control whereas custom power devices are used for distribution control. Since the introduction of FACTS and custom power devices such as Unified Power Flow Controller (UPFC), synchronous static compensator (STATCOM), dynamic voltage restorer (DVR), solid-state transfer switch and solid-state fault current limiter have been developed for improving power quality and reliability of a system [8-14]. Advanced
control and improved semiconductor switching of these devices have reached a new era for power quality mitigation.

The FACTS and custom power devices have been developed for mitigating specific power quality problems. For example, UPFC works well for power flow control, DVR which acts as a series compensator is used for voltage sag compensation and STATCOM which is a shunt compensator is used for reactive power and voltage sag compensation. The STATCOM, DVR, UPS and active power conditioner are only useful for compensating a particular type of power quality problems and therefore, it has become necessary to develop a new kind of Unified Series-Shunt Compensator (USSC) which can mitigate a wider range of power quality problems. Many FACTS devices based on Switched filter compensator which used the principle of USSC had been published [15-20].

This paper presents a FACTS based static switched filter compensator (SSFC) scheme for effective voltage stabilization, power quality enhancement, losses reduction and power factor improvement in distribution grid networks with the dispersed wind energy interface. The FACTS SSFC is based on controlled complementary switching process between two capacitor banks to be connected with the classical tuned. The switching process is achieved by novel dynamic control strategies and the pulse width modulation-complementary switching (PWM). Two error dynamic regulation schemes are utilized with a tri-loop dynamic error inter-coupled control strategy and a weighted modified PID controller. The SSFC-FACTS device scheme has been fully validated for effective power quality mitigation, voltage stabilization, losses reduction and power factor correction using Matlab Simulink environment.

2. THE STATIC SWITCHED FILTER COMPENSATOR

The FACTS SSFC scheme, shown in Figure 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.

3. CONTROLLER DESIGN

In order to reduce the harmonics, improve the power factor and stabilize the buses voltage using the FACTS static switched filter compensator, an integrated dynamic control based on two regulators
A and B are proposed. 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 Figure 2. The weighted

Figure 1: The Novel FACTS Static Switched Filter Compensator Scheme

Figure 2: The Weighted Modified PID Control of the FACTS SSFC Scheme
modified PID (WMPID) includes error sequential activation supplementary loops to ensure fast dynamic response and affective damping of large excursion, in addition to conventional PID structure.

3.1. Regulator A
In this regulator, shown in Figure 3, 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.

3.2. Regulator B
This regulator, shown in Figure 4, is used to suppress any voltage and current harmonic ripples and consequently mitigate the harmonics.
4. DIGITAL SIMULATION OF THE STUDIED AC SYSTEM

4.1. The AC System Configuration

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. Figure 3 depicts a single line diagram of the studied AC system. The detail parameters of the system are given in Appendix.

4.2. Simulation Results of Digital Simulation

The Matlab/Simulink digital simulation results for the proposed hybrid FACTS-Switched Filter Compensation Scheme HFCS is validated for two study cases are as follows:
42.1. Case 1: Normal Loading Operation

The two complementary switching pulses ($P_A$, $P_B$) to the hybrid FACTS filter is shown in Figure 6.

The dynamic response of voltage, current, active power, reactive power, apparent power and power factor at the source ($B_s$) and load ($B_l$) buses under normal operation with and without using hybrid FACTS filter are shown in Figures 7-12.

In the previous figures, with using the FACTS filter compensator, the rms value of the voltage waveform at the source and load buses are increased. In addition, the current flow through the source bus is decreased and the load current is increased.

At the infinite bus ($B_i$), the rms value of voltage waveform does not change and the rms value of waveform current increases with using the FACTS filter compensator.
Figure 7: The rms Voltage and Current at the Generator Bus, Bs

Figure 8: The Apparent Power and Power Factor at the Generator Bus, Bs

Figure 9: The rms Voltage and Current at the Load Bus, B_L, 9
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**Figure 10:** The Apparent Power and Power Factor at the Load Bus, $B_L$

**Figure 11:** The rms Voltage and Current at the Infinite bus, $B_i$

**Figure 12:** The Apparent Power and Power Factor at the Infinite bus, $B_{i10}$
The active and reactive power losses are calculated and are shown in Figure 13. As shown in this figure, with using the FACTS static switching filter compensator, the active and reactive power losses in the two feeders (10 & 5 km) are increased.

![Figure 13: The Active and Reactive Power Losses Without and with FACTS SSFC](image)

The frequency spectra of the voltage and current waveforms are shown in Figures 14-19. The voltage and current harmonic analysis in term of the total harmonic distortion (THD) is summarized in Table 1. It is obvious that the voltage harmonics are significantly reduced to a level within the limit set by the IEEE Std. 519-1992 regarding the THD of bus voltage at low voltage system (less than 69 kV) [21]. Also the THD of current waveform at each bus is decreased.

![Figure 14: The Frequency Spectrum of Voltage Waveform at the Generator Bus, Bs, Without and With the FACTS Filter Compensator](image)
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Figure 15: The Frequency Spectrum of Current Waveform at the Generator Bus, Bs, Without and With the FACTS Filter Compensator

Figure 16: The Frequency Spectrum of Voltage Waveform at the Load bus, BL, Without and With the FACTS Filter Compensator

Figure 17: The Frequency Spectrum of Current Waveform at the Load Bus, BL, Without and With the FACTS Filter Compensator
4.2.2. 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 SFC located at load bus for 1.0 second in order to show its performance under the following disturbance sequence:

Table 1

<table>
<thead>
<tr>
<th>Waveform</th>
<th>% THD of Voltage without SSFC</th>
<th>% THD of Voltage with SSFC</th>
<th>% THD of Current without SSFC</th>
<th>% THD of Current with SSFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator bus B₀</td>
<td>8.9</td>
<td>0.44</td>
<td>5.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Load bus B₁</td>
<td>22.7</td>
<td>0.33</td>
<td>18.5</td>
<td>1.3</td>
</tr>
<tr>
<td>Infinite bus Bᵢ</td>
<td>0.05</td>
<td>0.045</td>
<td>11.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Figure 18: The Frequency Spectrum of Voltage Waveform at the Infinite bus, Bᵢ, Without and With the FACTS Filter Compensator

Figure 19: The Frequency Spectrum of Current Waveform at the Infinite Bus, Bᵢ, Without and With the FACTS Filter Compensator
At $t = 0.1$ second, the linear load is removed for a duration of 0.1 seconds;

At $t = 0.3$ second, the nonlinear load is removed for a duration of 0.1 seconds;

At $t = 0.5$ second, wind speed suddenly decreased to 9 m/s for a duration of 0.1 seconds;

At $t = 0.7$ second, wind speed suddenly increased to 21 m/s for a duration of 0.1 seconds;

At $t = 0.8$ the system is recovered to its initial state.

The rms values of voltage and current waveforms at source ($B_s$) and load ($B_L$) buses under load excursions are depicted in Figures 20-21.

Figure 20: The rms Voltage at the Generator Bus, $B_s$ Under Load Excursions Condition

Figure 21: The rms Voltage at the Load Bus, $B_L$ Under Load Excursions Condition
Figure 20 shows, without using the FACTS SSFC scheme, the disconnection of the linear and nonlinear loads have an effect on the value of voltage at the generator and load buses. It causes a voltage swell. While with using the controlled FACTS SSFC scheme, there is no effect on the voltage waveforms. This means that the controlled FACTS SSFC scheme mitigates the swell event of PQ disturbances.

Also, the use of FACTS SSFC scheme mitigates the sag caused in the current waveforms at infinite bus as shown in Figure 21.

From all the previous figures, it can be observed

- The controlled FACTS SSFC scheme mitigates the harmonic distortion that caused by the nonlinear load where all values of THD for voltage and current at all AC buses are decreased to values within allowable limits of IEEE standard.
- The power losses are decreased using the FACTS SSFC scheme
- The short duration PQ disturbances such as sag and swell are mitigated.
- The gradually change in wind speed does not appear on the voltage and active power waveform while the sudden change have a small effect on it.

5. CONCLUSION

This paper presents a FACTS based static switched filter compensator (SSFC) scheme for effective voltage stabilization, power quality enhancement, losses reduction and power factor improvement in distribution grid networks with the dispersed wind energy interface. The FACTS SSFC is based on controlled complementary switching process between two capacitor banks to be connected with the classical tuned. The switching process is achieved by novel dynamic control strategies and the pulse width modulation-complementary switching (PWM). Two error dynamic regulation schemes are utilized with a tri-loop dynamic error inter-coupled control strategy and a weighted modified PID controller. The SSFC-FACTS device scheme has been fully validated for effective power quality mitigation, voltage stabilization, losses reduction and power factor correction using Matlab Simulink environment. FACTS SSFC topology variations and other flexible dynamic control techniques can be utilized in hybrid wind-PV-fuel cell AC-DC renewable energy utilization systems.
References


APPENDIX

1. Wind turbine
   \( P_{\text{out}} = 1.6 \text{ MW}. \)

2. Squirrel cage induction generator
   3 phase, 1 pair of poles, \( V = 1.6 \text{ kV}, 60 \text{ Hz}, S = 1.6 \text{ MVA}, X_{d} = 1.79, \)
   \( X_{d}' = 0.169, X_{d}'' = 0.135, X_{q} = 1.71, X_{q}' = 0.228, X_{q}'' = 0.2, X_{l} = 0.13. \)

3. Local Hybrid AC Load (1.6 MVA, 4.16 kV)
   - linear load: 300 kVA, 0.8 lag pf.
   - non-linear load: 500 kVA.
   - induction motor: 3 phase, 800 kVA, no of poles = 4,
   Stator resistance and leakage inductance (pu)
   \( R_{s} = 0.01965, L_{s} = 0.0397 \)
   Rotor resistance and leakage inductance (pu)
   \( R_{r} = 0.01909, L_{r} = 0.0397 \)
   Mutual inductance \( L_{m} \) (pu) = 1.354 16

4. 10 km & 5 km feeders
   \( V_{\text{L-L}} = 11 \text{ kV}, R/\text{km} = 0.4 \Omega, L/\text{km} = 0.9337 \text{ mH} \)

5. AC Grid: \( V = 138 \text{ kV} \)

6. FACTS SSFC:
   \( C_{S1/\text{phase}} = C_{S2/\text{phase}} = 125 \text{ µF}, C_{m1/\text{phase}} = 7 \text{ µF}, C_{m2/\text{phase}} = 15 \text{ µF}, CF/\text{phase} = 8 \)
   \( \text{µF}, R_{F} = 0.05 \Omega \text{ and } L_{F} = 1 \text{ mH} \).

7. Weighted Modified PID controller Gains: \( K_{p} = 1, K_{i} = 0.5, K_{d} = 0.2, \)
   \( K_{e} = 0.1, K_{e} = 0.4 \).

8. Tri loop Error Gains: \( \gamma_{e} = 1, \gamma_{p} = 0.75, \gamma_{p} = 0.5, \gamma_{e-rip} = 1, \gamma_{p-rip} = 1, \gamma_{p-rip} = 0.5 \)

9. PWM Frequency: \( f_{s} = 1750 \text{ Hz} \).