A Hybrid Approach with STATCOM to Enhance Grid Power Quality Associated with Wind Farms

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ABSTRACT

The growing use of renewable energy sources in the production of electric power has certain adverse effects on power quality. A compensation system includes some additional devices, such as capacitors, compensators, or reactive power injection devices. FACTS devices, such as the Static Var Compensator (SVC), Dynamic Voltage Restorer (DVR), and Unified Power Quality Conditioner (UPQC), have become popular as power electronics become more sophisticated. This study investigated the properties of three significant compensating devices: SVC, STATCOM with PI controller, and a hybrid STATCOM with a harmonic filter. Common power quality concerns, such as voltage sags and swells and the percentage of Total Harmonic Distortion (TDH), were taken into account during the initial modeling and performance analysis of the proposed system. The overall results showed that the proposed hybrid STATCOM system enhanced the power quality in wind energy systems more than the other two systems.

Keywords-harmonic filter; hybrid STATCOM; total harmonic distortions; voltage sag/swell; voltage flickers

I. INTRODUCTION

Power quality problems, such as harmonic distortion, unstable voltage from sags and surges, and unreliable operation, are among the most critical problems in a power system [1-2]. Wind Energy Generating Systems (WEGS) with double-fed IG have become popular in power generation because they are cost-effective and can operate at variable speeds with constant frequency [3-5]. However, this is not always the case, as wind power is often located far from the Point of Common Coupling (PCC), also known as load bus, and its end users. When a PCC has a Multi-Terminal Load (MTL) tied to a wind farm, power quality problems such as frequency fluctuations and voltage sag/swell can occur, necessitating the use of shunt compensation [6-7]. Voltage flicker is a phenomenon in which the frequency abruptly varies from the rated frequency for a brief period due to load switching and the integration of compensatory devices [8-10]. Due to this, the voltage stability is affected along with the PCC's demand for reactive power [11-13]. Voltage collapse results from a voltage sag that lasts a long time, and harmonics can be introduced into the system if voltage swell or flickers last for a long time. The fault current generated by sag/swelling or flickers will also affect the PCC's switch gears and protection system [5, 10, 12, 14-15]. Power quality issues can be handled by integrating SVC and STATCOM with a wind farm connected by a transmission line [16-17]. A hybrid structure was introduced to improve STATCOM operation performance while using Active Power Filters (APFs) and Passive Power Filters (PPFs) with lower current ratings [5, 7]. On the other hand, hybrid structures only perform well when subjected to inductive loads and are not good when subjected to capacitive loads [12]. However, due to the higher cost of APF with a multilevel structure, they do not apply to high-voltage transmission lines [18].

Many studies investigated reactive power compensation for the stability of a power system [14]. Improving voltage regulation and voltage stability with shunt FACTS devices is comparable to using SVC or STATCOM [8, 11, 18-19]. The most common application for SVC and STATCOM based on PI can be found in the industry [4]. The performance of STATCOM and SVC is affected as a result of the PI gains k_p and k_i remaining constant and unchanged, regardless of the operating conditions the system experiences [15]. ANN-based SVC and STATCOM, among other fuzzy and diverse computer-based topologies, are better suited to replace PI [5]. However, the real-time implementation with the grid and its integration with the power system requires precise and time-consuming commissioning and testing, creating a very complex system to analyze and control under unforeseen transient conditions [14, 20]. Very few studies addressed these difficulties, particularly when there are power quality issues.

This study investigated a harmonic filter tuned with STATCOM, modeled in MATLAB-Simulink, to address the above issues with the following objectives:

- Modeling and design of a three-phase harmonic filter with STATCOM.
- Using the three-phase harmonic filter to successfully mitigate the harmonic signal from the given power compensated from STATCOM.
- Comprehensive analysis of different power quality issues with the proposed compensator.

II. PROPOSED POWER SYSTEM WITH WIND FARM

MATLAB-Simulink simulations were carried out to evaluate the efficacy of the proposed model and examine the shunt compensator with SVC, STATCOM with PI, and hybrid STATCOM with a harmonic filter. The proposed test system included two generators, 500 kV - 3000 MVA and 500 kV - 2500 MVA, coupled to three buses, designated B1, B2, and B3, as illustrated in Figure 1. Bus B3 is where the multiterminal load system with a 6000 MW load and a 9 MW wind generator are connected. Concerns about power quality were taken into account whenever PCC or load bus B3 connects a wind farm. Power quality analysis was carried out during the time that load bus B3 was connected to an MTL load with a wind generator.

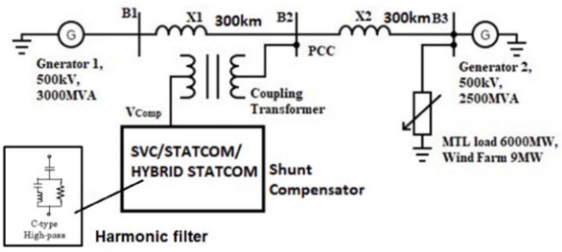

Fig. 1. Test system with the proposed strategy.

Shunt compensators are used more frequently in power systems because of their ability to quickly compensate for power loss while requiring little maintenance. SVC, as shown in Figure 2, is a shunt compensator that dynamically creates static reactive var power to modify reactive impedance in a network and change the characteristics of a transmission line.

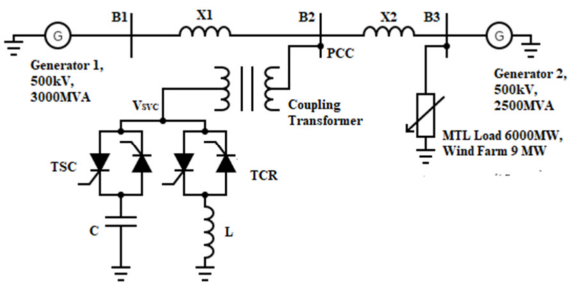

Fig. 2. Test system with SVC.

Adjusting the output of the converter in STATCOM, as depicted in Figure 3, reactive power can be transferred from the converter into the grid.

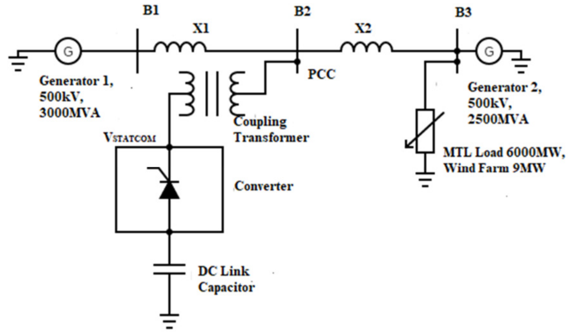

Fig. 3. Test system with STATCOM.

A. *Test System with the Proposed STATCOM*

As shown in Figure 4, the simulated system used three different types of compensators: SVC, STATCOM, and hybrid STATCOM. The proposed hybrid STATCOM was a combination of an active inverter part with a DC link in conjunction with a customized three-phase C-type high-pass harmonic filter connected in line with the inverter part.

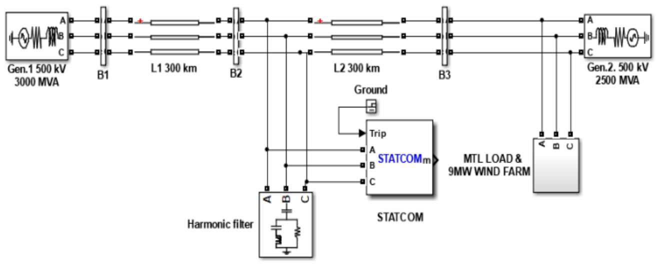

Fig. 4. Hybrid STATCOM.

Figure 5 shows a STATCOM submodel in the phasor model, which was designed in Matlab-Simulink using Simscape in the Simpowersystem toolbox. The STATCOM submodel consists of a power component model, measurement system, STATCOM control block, converter output voltage calculation, and DC-link voltage calculation. The power components model consists of the connection between STATCOM with the grid at bus 2, the measurement system that continuously measures grid voltage, I_d and I_q currents with phase angle theta, as well as a reactive power component. The STATCOM control block continuously monitors the measured values of the system parameters and compares them with the AC output voltage and the DC link voltage of STATCOM. The shunt converter output voltage computation block generates a control signal to control similarly the DC link voltage computation block and the input DC voltage to the active converter part. After obtaining the control parameter from STATCOM, the control signals are fed from the power modeling block through a three-phase harmonic filter via output signals A, B, and C. High-pass filters are used to filter high-order harmonics and are responsible for the filtration of a wide spectrum of frequency ranges. A specific type of high-pass filter, known as a C-type high-pass filter, was used. This filter was used to both provide reactive power and prevent parallel resonances. It is also possible to filter the low-order harmonics, such as the third harmonic, while at the same time ensuring that there are no losses at the fundamental frequency.

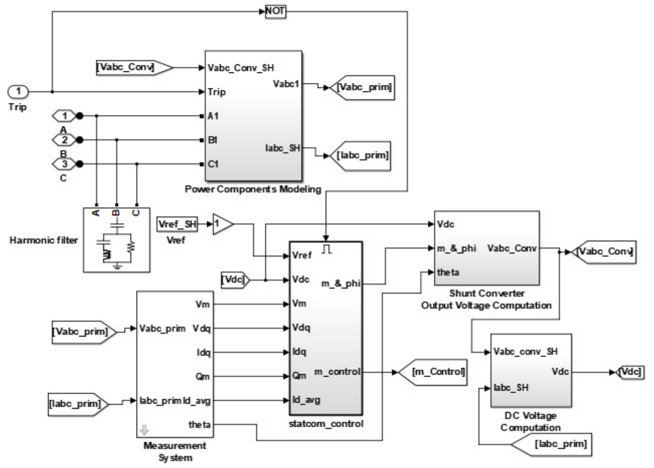

Fig. 5. Harmonic filter in phase with the STATCOM.

III. POWER QUALITY INVESTIGATION

This section describes the performance analysis of the proposed hybrid STATCOM and its effectiveness compared to a similar system consisting of SVC or STATCOM. The effects of voltage sag, swell, voltage distortions, and harmonics were investigated in the respective systems connected to MTL and a 9 MW wind farm. All performance parameters were examined for three different instances: 1-Before fault, 2-During fault, and 3-After fault.

A. Voltage Sag Simulation Result

A voltage drop is a common and serious issue that can occur in transmission line systems as a result of system faults, a sudden increase in load, or the start of powerful motors. Near bus B1, the line-to-line ground fault depicted in Figure 6 has a duration of 0.2 to 0.3 s, a fault resistance of 80 Ω, and a ground resistance of 0.001 Ω. SVC, STATCOM with PI, and hybrid STATCOM with a harmonic filter are shown in the figure, illustrating their respective voltage sag calculations. PCC is equipped with SVC, STATCOM with PI, and STATCOM with a harmonic filter. Table I shows the four parameters examined on the dynamic behavior of the system.

Understanding the effect of transient voltage sag on voltage stability requires testing the PCC RMS voltage with and without a compensator and measuring active, reactive, and harmonic influences before, during, and after a fault occurs. The voltage on the load bus rises in proportion to the reactive power it draws, so compensating for this consumption requires using FACTS controllers. A line-to-line short circuit was simulated on generator bus B1 to examine voltage sag. After a short circuit occurs in a system without a compensator, as shown in Figure 7, the RMS voltage drops to 0.64 p.u. but is kept at 0.77 p.u. by the SVC and PI controllers, 0.84 p.u. by the STATCOM PI controller, and 0.86 p.u. by the proposed hybrid STATCOM controller.

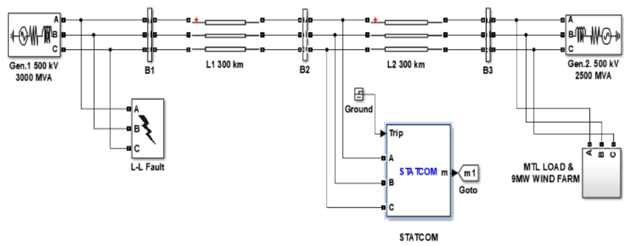

Fig. 6. Test system with LL fault.

TABLE I. VOLTAGE SAG

Parameter		No Compensator	PI-SVC	PI-STATCOM	Hybrid STATCOM
RMS Voltage (PU)	1	0.70	0.88	0.94	0.96
	2	0.64	0.77	0.84	0.86
	3	0.70	0.88	0.94	0.96
Active Power (Watt)	1	825	1040	1100	1130
	2	540	640	670	680
	3	825	1040	1100	1130
Reactive Power (VAR)	1	324	-170	-300	-335
	2	35	-310	-470	-500
	3	326	-170	-300	-335
% THD		484.96	412.43	320.61	283.08

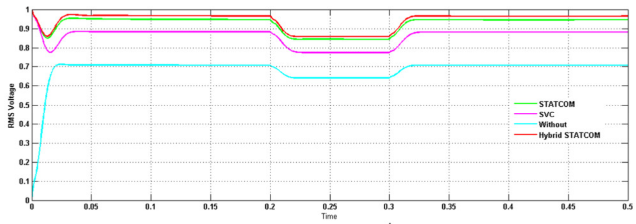

Fig. 7. RMS voltage during L-L Fault.

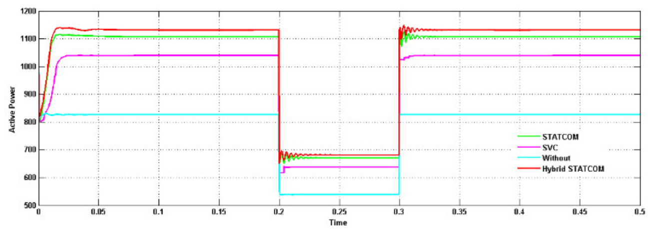

Fig. 8. Active power during a voltage sag.

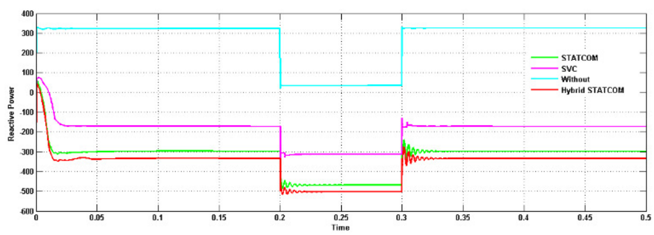

Fig. 9. Reactive power during a voltage sag.

STATCOM efficiently preserves active power in the event of a fault. While the system requires around 35 var of power during faults without a compensator, SVC provides 310 var, STATCOM with PI provides 470, and a hybrid STATCOM provides around 500 var, as shown in Figure 9. The proposed compensation was used by STATCOM to return the system voltage to normal. The installed capacity of the SVC prevents voltage recovery in this case.

B. Voltage Swell Simulation Result

The proposed MTL load system with wind farm featured a parallel load with 500 MW of active power, 100 var of inductive reactive power, and 100 var of capacitive reactive power to produce a voltage swell. The three-phase circuit breaker shown in Figure 10 was responsible for creating the voltage swell test system. Table II shows the results of the proposed system, which consists of STATCOM with a harmonic filter, STATCOM, and SVC with PI control.

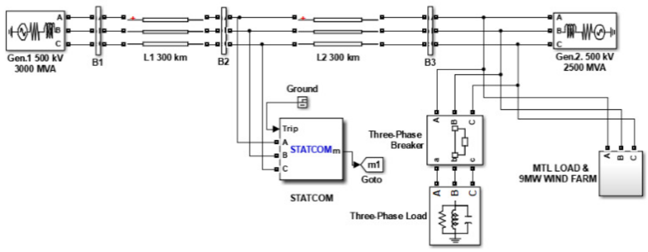

Fig. 10. The proposed system with a sudden load off.

TABLE II. VOLTAGE SWELL

Parameter		No Compensator	PI-SVC	PI-STATCOM	Hybrid STATCOM
RMS Voltage (PU)	1	0.64	0.78	0.86	0.88
	2	0.7	0.88	0.94	0.96
	3	0.64	0.78	0.86	0.88
Active Power (Watt)	1	765	944	1040	1062
	2	825	1040	1105	1130
	3	765	944	1040	1062
Reactive Power (VAR)	1	400	-80	-220	-250
	2	325	-170	-297	-335
	3	400	-80	-220	-250
% THD		484.96	485.68	448.51	406.57

Figures 11-13 show the evaluation of the test system with and without compensation, examining the effects of various compensators while accounting for a brief voltage surge that lasts between 0.2 and 0.3 s. As seen in Table II, without STATCOM, electrical mode instability occurs when a load is suddenly removed from bus B3 as the RMS voltage was 0.7 p.u. The RMS voltage improved to 0.88 with SVC, up to 0.94 with STATCOM, and up to 0.96 with the proposed hybrid STATCOM with a harmonic filter. During load off, the active and reactive power were respectively 825 W and 325 var without a compensator, 1040 W and -170 var with SVC, 1105 W and -297 var with STATCOM, and 1130W and -335 var using the proposed hybrid STATCOM with a harmonic filter. As can be seen, the proposed hybrid model provided the best results.

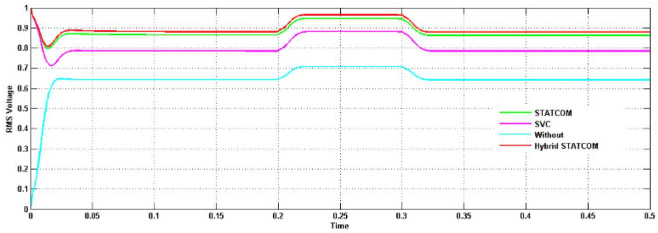

Fig. 11. VRMS during a sudden load off.

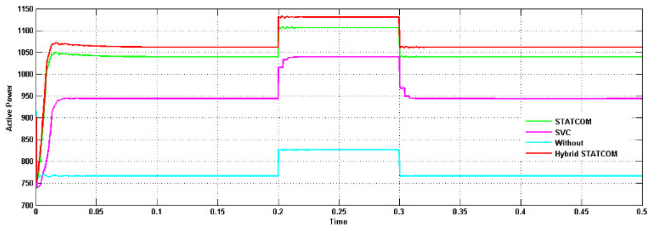

Fig. 12. Active power during a sudden load off.

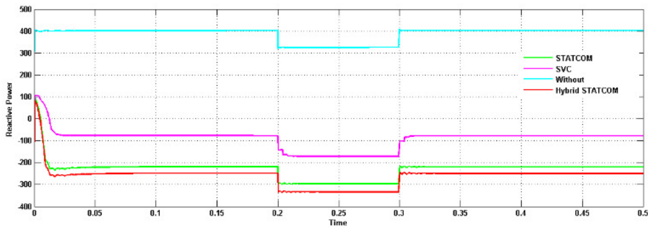

Fig. 13. Reactive power during a sudden load off.

C. Voltage Flickers

Voltage flickers and voltage distortion are the most common power system problems. As seen in Figure 14, capacitor banks were connected to bus B3 by a switch to simulate voltage distortion or flickering. Capacitor banks were used as shunt compensators with the load bus to regulate reactive power fluctuations. Each on/off cycle of capacitor banks distorts the load voltage at the bus. Voltage flickers or distortion occur on the bus when a capacitor operates during steady-state operation or when load compensation is needed. These phenomena were examined at PCC with and without a compensator, as well as with the suggested hybrid STATCOM.

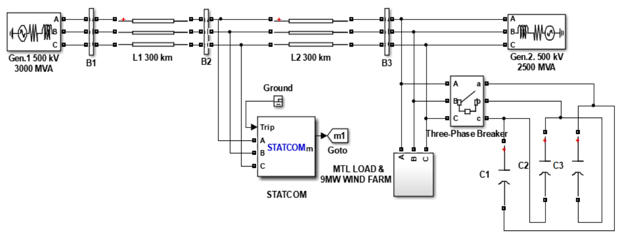

Fig. 14. Test system with a switching capacitor.

Table III shows how different compensators affect transmission line performance characteristics during different transient events. With the help of the proposed hybrid STATCOM, the RMS voltage at the PCC can be raised to a maximum of 0.97 p.u, near 1 p.u, as shown in Figures 15-17.

The proposed hybrid STATCOM with harmonic filter outperformed PI-based SVC and STATCOM in simulations measuring active and reactive power transmission. Table III also shows that the proposed controller improved THD by 20-25%.

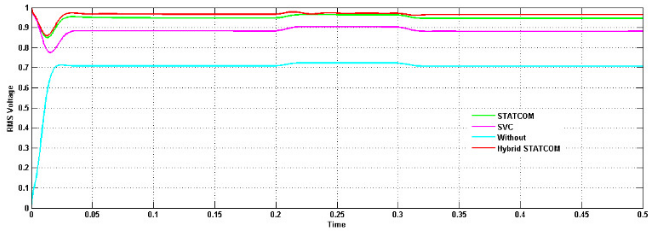

Fig. 15. RMS Voltage during capacitor switching.

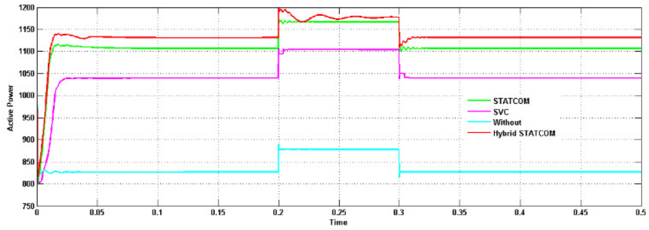

Fig. 16. Active Power during capacitor switching.

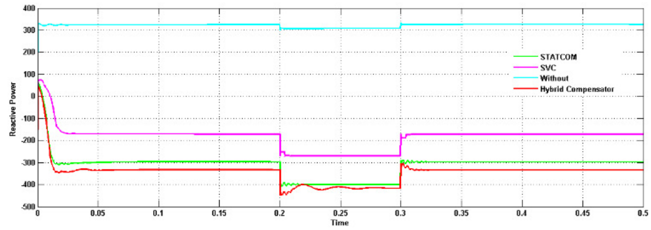

Fig. 17. Reactive Power with capacitor switching.

TABLE III. VOLTAGE FLICKERS

Parameter		No Compensator	PI-SVC	PI-STATCOM	Hybrid STATCOM
RMS Voltage (PU)	1	0.71	0.88	0.95	0.96
	2	0.72	0.90	0.96	0.97
	3	0.71	0.88	0.95	0.96
Active Power (Watt)	1	826	1040	1106	1130
	2	878	1104	1166	1177
	3	826	1040	1106	1130
Reactive Power (VAR)	1	324	-170	-298	-335
	2	311	-270	-400	-420
	3	326	-171	-299	-335
% THD		484.96	485.55	418.53	323.02

IV. DISCUSSION

The paper presented a novel hybrid strategy for STATCOM using a harmonic filter and compared it with a PI-based SVC and STATCOM shunt compensator. Most power industries rely on SVC and STATCOM built on the PI platform. The performance of STATCOM and SVC was negatively affected as a result of the inability of the PI gains k_p and k_i to adapt to changing system operating conditions. One of the distinctive features of this hybrid STATCOM is the three-phase harmonics filter, which lowers the harmonic component produced by the active inverter component of the STATCOM during compensation, and thereby increases the range of compensation. Very few studies have focused on harmonic filters and shunt FACTS devices to improve power quality.

V. CONCLUSION

This study carried out a comprehensive analysis of the proposed hybrid STATCOM with a harmonic filter controller for power quality issues under different transient conditions in Matlab-Simulink. The simulation results showed that STATCOM and SVC using a PI controller can effectively lower voltage sag/swell. Simulations of the same system showed that combining a hybrid controller based on a harmonic filter with STATCOM improved performance. The proposed hybrid STATCOM had RMS voltage values that were significantly more consistent during voltage sags, voltage surges, and switching of capacitor banks compared to SVC, STATCOM with PI, and a system without a compensator. The harmonic filter-based STATCOM immediately provided the system with reactive power during sudden transients. The proposed hybrid STATCOM produced a remarkably stable voltage profile, with only minor transient overshoots caused by sudden events, such as the removal of a heavy load or capacitor switching. Moreover, the proposed hybrid STATCOM showed fewer distortions in load voltage, line active power, and reactive power. The simulation results showed that voltage ripple and distortion can be reduced by 5-10% and 10-20%, respectively, with the proposed hybrid STATCOM. The proposed controller can reduce THD by approximately 20-25% compared to a system with a PI controller.

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