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Supercapacitor energy storage based-UPQC to enhance ride-through capability of wind turbine generators

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Abstract: The recent advancement in electric energy storage technologies provides an opportunity of using energy storage systems to address the issues of grid-integrated wind energy conversion systems. This paper proposes a novel configuration of a unified power quality conditioner (UPQC) with a supercapacitor-based short-term energy storage system for managing wind power intermittency during grid faults. The STATCOM-like compensation device can compensate only current related issues. The dynamic voltage restorer can compensate voltage-related issues but it can contribute only 50% voltage due to converter rating limitations. Moreover, real power handling capabilities of these devices are very poor. This new UPQC scheme can compensate voltage sag, negative sequence current, and real and reactive powers from 0.1 pu to 0.9 pu. The proposed system improves fault ride-through capability of the wind turbine generators and satisfies the grid code requirement. A synchronous reference frame-based control method is employed for the UPQC. The energy storage system is controlled using a two-quadrant DC/DC converter. The proposed model was developed and tested in the MATLAB/SIMULINK environment.

Key words: Wind energy conversion system, unified power quality conditioner, power quality, DC/DC converter, supercapacitor, energy storage system

1. Introduction

The penetration of wind energy into power grids is increasing significantly. As per the RenewableEnergyWorld.com BTM Forecasts 340-GW of Wind Energy 2013 report, the global wind energy's contribution is estimated as 3.2% in 2013 and is expected to reach 8% by 2018. This situation tends to revise the grid code with demanding standards to guarantee the stability and reliability of the power system [1]. The wind farms constructed with induction generators have poor fault ride-through capability; they get tripped out during severe grid faults. The tripping of wind farms during a fault will exacerbate the situation and lead to system instability [2]. It becomes necessary to require wind turbine generators (WTGs) to stay connected to the grid for reliable power system operation.

An important issue to be addressed during fault is the intermittent power in the wind farm terminals, because it causes severe impact on wind power generation and power system balance. Several studies were carried out using the Static synchronous compensator (STATCOM) and dynamic voltage restorer (DVR) for fault ride-through of wind farms [3–6], but no proper investigation was done to handle the energy that the grid cannot absorb during severe fault. Ramirez et al. [7] discussed this issue and provided a solution by connecting a resistor across the DC link of the voltage source inverter to dissipate a part of the active power generated in

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the wind farm; the remaining power is fed to the faulted network. This method cannot give a complete solution for the aforementioned problem and cannot be applied to large-scale wind farms. The only solution is to absorb the power using energy storage devices, but the storage device increases the expense of the compensation device greatly. In [8], various economical energy storage techniques were investigated for handling intermittent power but their round-trip efficiency is very poor. Compared to other storage equipment, the supercapacitor bank is found to be a suitable energy storage system (ESS). The supercapacitors have advantageous features like higher power density, higher round-trip efficiency, long life, and low cost per cycle. Since the energy density is low and self-discharge current is greater, it is suitable only for short-term power exchange. In [9,10], a supercapacitor-based ESS was used to deliver active power to the critical loads during fault and to improve power quality at a common connection point. The supercapacitor-based storage system was used in the literature [11,12] to regulate and balance the power generated in DFIG-based wind farms. The new installations of wind farms are tending to use DFIG-based wind energy conversion systems (WECSs). Nevertheless, a considerable percentage of squirrel cage induction generator (SCIG)-based wind farms are still in use. Hence, extensive investigation is required to provide a solution for intermittent power management of the SCIG-based wind farms.

This paper presents a new configuration of a supercapacitor-aided ESS-based UPQC for managing intermittent power and improving fault ride-through capability of a SCIG-based WECS. The supercapacitor used here is a dedicated ESS only to operate during grid fault and voltage variation. It utilizes a DC to DC converter to handle the intermittent power at wind farms during grid fault. The control scheme uses the synchronous dq rotating reference frame to achieve dynamic compensation. MATLAB/SIMULINK is used to develop a grid-integrated wind farm model and to realize the proposed strategy.

2. UPQC

A UPQC is a combination of shunt active and series active filters and is capable of solving multiple power quality problems at the point of connection. The application of UPQC for wind power integration has gained interest, since it provides a unified solution to mitigate the disturbance propagated from the grid side and wind generator side issues. The UPQC is a viable device that ensures all required standards and specifications at the point of installation. The grid-connected wind farm equipped with a UPQC is shown in Figure 1.

There are two possible shunt connection configurations available for a UPQC; one is a right-shunted and the other is a left-shunted connection. Among these two configurations, the right-shunted configuration is preferred. The absolute reactive power compensation of the wind generator is accomplished and the DC link voltage almost remains constant.

3. Control strategy of UPQC

The UPQC is a unified device that can provide compensation and solutions for both current- and voltage-related issues. The series-connected converter in the UPQC compensates voltage-related issues such as sag, swell, and voltage harmonics. It also eliminates negative and zero-sequence components during voltage unbalance. The shunt compensator exchanges reactive power and maintains the power factor at unity. The shunt converter charges the DC link capacitor and regulates DC link voltage. This DC link voltage supports the active power exchange between the series converter and the system.

The grid-tied wind generator with converter configuration and system specifications is illustrated in Figure 2. The series converter uses 12 active switches and always has two power switches per phase in the current path. With a unipolar switching scheme the converter can generate two voltage levels and the effective

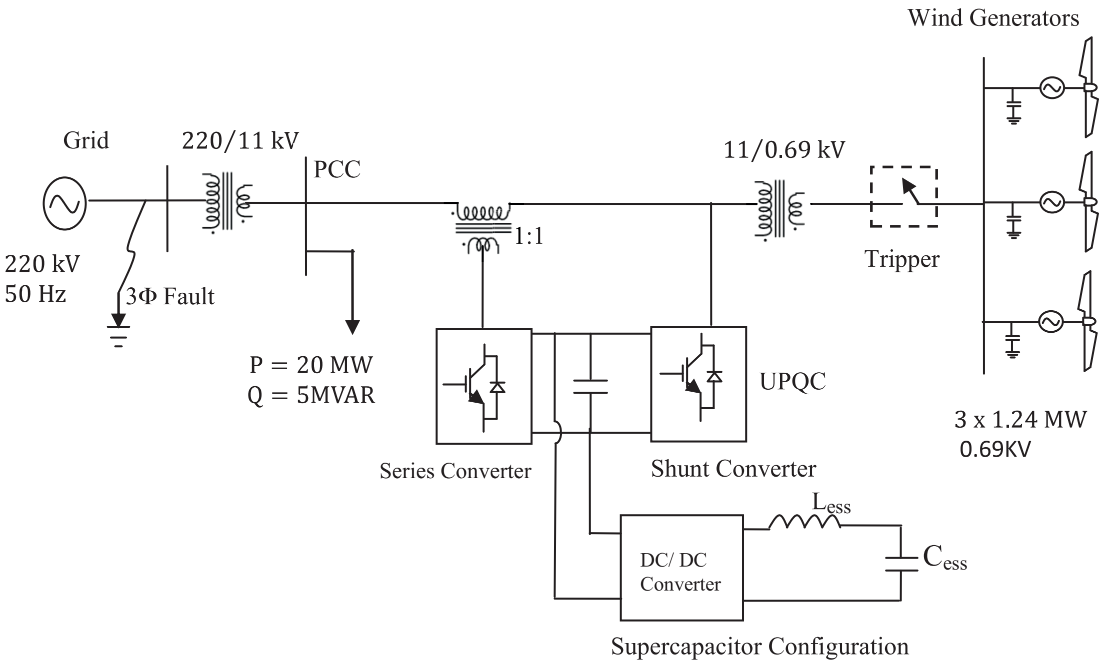

Figure 1. Block diagram of grid-integrated wind farm equipped with UPQC.

switching frequency is selected as 3970 Hz (50 Hz × 79) to suppress up to the 79th harmonic [13]. This gives less voltage distortion and the size of the line filter can be decreased. In an 11-kV line switching frequency of more than this would cause higher switching loss and heat generation. The full bridge converter can inject zero sequence voltage components and it does not need a split DC-link. The shunt converter consists of six switches and is always in the current path, and the DC-link voltage is simple to control. An IGBT is used as a switch. The series-connected IGBT module of rating 6.5 kV is shown in Figure 3. A mechanical bypass switch is used for protection; it serves as a bypass path to drain high current rush during fault.

A widely used transformation is the Park (dq0) transformation. It is used to decouple variables, to facilitate the solution of time-varying equations, and to refer variables to a common reference frame. It can be applied to any arbitrary (sinusoidal or distorted) three-phase, time-dependent signals. The main advantage of the dq0 transformation is that the fundamental (positive-sequence) component of the waveform will be transferred to a constant DC term under steady-state conditions. The dq0 transformation-based synchronous reference frame control scheme employed is shown in Figure 4. It controls both the shunt and series converter simultaneously. In shunt compensation the actual current of the system is transformed into the synchronous dq0 reference frame. In this scheme the positive-sequence component is taken in the d axis, and the negative- and zero-sequence components are taken in the q and 0 axes of the system current, respectively. The following expressions are derived based on the literature [14, 15].

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_d & \cos\left(\theta_d - {}^{2\pi}/_{3}\right) & \cos\left(\theta_d + {}^{2\pi}/_{3}\right) \\ -\sin\theta_d & -\sin\left(\theta_d - {}^{2\pi}/_{3}\right) & -\sin\left(\theta_d + {}^{2\pi}/_{3}\right) \\ {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} & {}^{1}/_{\sqrt{2}} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{1}$$

In this equation, $\theta_d = \omega_d + \varphi$, where ω_d is the angular velocity of signals and φ is the initial angle.

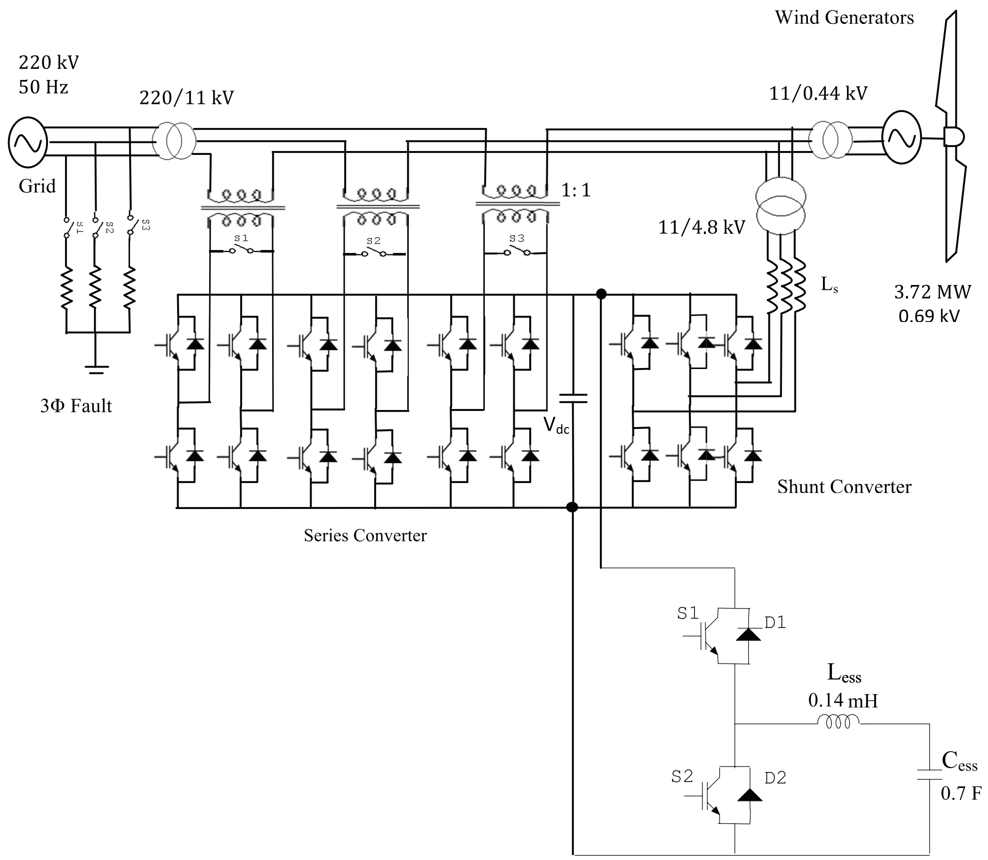

Figure 2. Grid-tied wind generator with converter configuration and system specification.

Figure 3. Series-connected IGBT module.

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \sqrt{3/2}\left\{\begin{bmatrix} I_P\, \cos\theta_p \\ I_P \sin\theta_p \\ 0 \end{bmatrix} + \begin{bmatrix} I_n \cos\left(2\omega t+\theta_n\right) \\ -\ I_n \sin\left(2\omega t+\theta_n\right) \\ 0 \end{bmatrix}\right\} \tag{2}$$

The expected compensation current required for voltage recovery is obtained by setting the d coordinate current to the rated peak current. The reactive power compensation is obtained by setting the negative- and zero-sequence components to zero.

$$\begin{bmatrix} I_d \\ I_q \\ I_0 \end{bmatrix} = \begin{bmatrix} I_p \cos\theta_p \\ 0 \\ 0 \end{bmatrix} \tag{3}$$

The current reference is calculated by adding active current loss with average current component, as shown below.

$$I_d^{'} = I_d + I_{dloss} \tag{4}$$

The resulting dq0 current reference is then transformed into abc reference components.

$$\begin{bmatrix} I_a^{'} \\ I_b^{'} \\ I_c^{'} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_d & -sin\theta_d & {}^1\!/\!\sqrt{2} \\ \cos\left(\theta_d - {}^{2\pi}\!/_3\right) & -sin\left(\theta_d - {}^{2\pi}\!/_3\right) & {}^1\!/\!\sqrt{2} \\ \cos\left(\theta_d + {}^{2\pi}\!/_3\right) & -sin\left(\theta_d + {}^{2\pi}\!/_3\right) & {}^1\!/\!\sqrt{2} \end{bmatrix} \begin{bmatrix} I_d^{'} \\ 0 \\ 0 \end{bmatrix} \tag{5}$$

These reference currents are compared with actual measured system currents using hysteresis current controller for producing converter switching signals. Using this shunt compensation, current-related issues are compensated.

In series compensation the voltage is transformed into the dq0 axis using the Park transformation, resulting in the following equations.

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_d & \cos(\theta_d - 2\pi/3) & \cos(\theta_d + 2\pi/3) \\ -\sin\theta_d & -\sin(\theta_d - 2\pi/3) & -\sin(\theta_d + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{6}$$

$$= \sqrt{\frac{3}{2}} \left\{ \begin{bmatrix} V_p cos\phi_p \\ V_p sin\phi_p \\ 0 \end{bmatrix} + \begin{bmatrix} V_n cos(2\omega t + \phi_n) \\ V_n sin(2\omega t + \phi_n) \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_0 cos(2\omega t + \phi_0) \end{bmatrix} \right\} = \begin{bmatrix} V_{dp} \\ V_{qp} \\ 0 \end{bmatrix} + \begin{bmatrix} V_{dn} \\ V_{qn} \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_{00} \end{bmatrix} \tag{7}$$

Here, ϕ_p is the phase difference between the positive-sequence component and the reference voltage. Hence, for a small phase difference, U_d yields an estimation of the input voltage amplitude and U_q gives the phase error information.

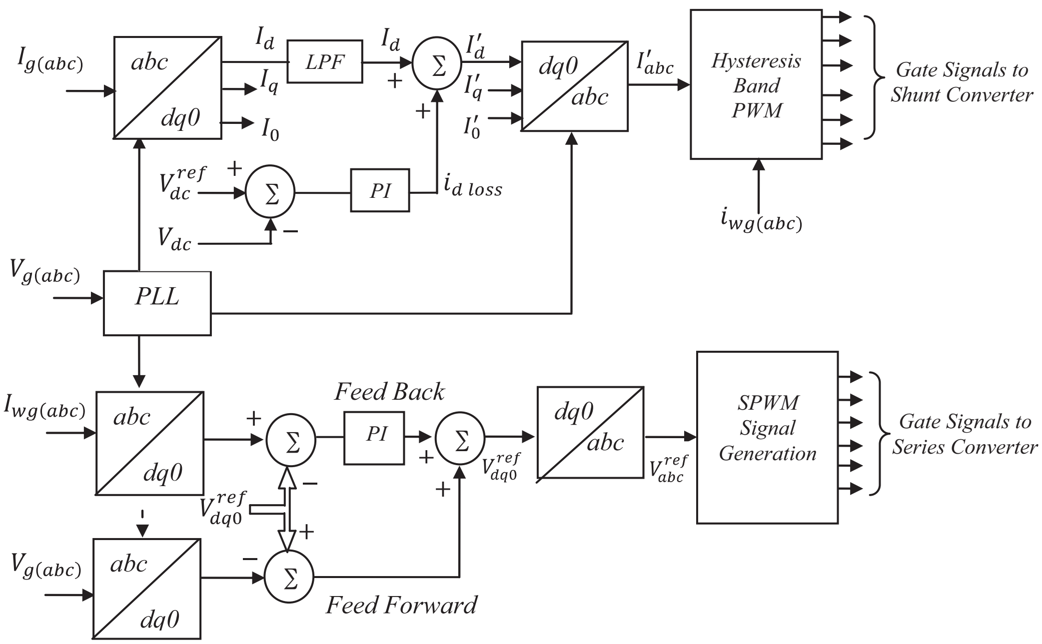

Figure 4. Synchronous reference frame control strategies.

Then, according to Eq. (7), the DC components ($V_{gp}cos\phi_p$ and $V_{gp}sin\phi_p$) are obtained from the positive sequence component of the *dq0* reference frame. Hence, the V_{dp} of Eq. (7) is maintained at V_M and all other components are eliminated by the compensation voltage. As a result the reference voltage is obtained as shown below.

$$\begin{bmatrix} V_d \\ V_q \\ V_o \end{bmatrix} = \begin{bmatrix} V_m \\ 0 \\ 0 \end{bmatrix} \tag{8}$$

The control of injection voltage is done by the combination of grid voltage feedforward and wind generator voltage feedback. Due to the inverter's output filter, there is a difference between the voltage generated with the inverter and the voltage actually injected in series with the line, so a PI regulator is used for equalization. The regulator output is added to the DVR reference, serving as feedforward to improve the system response speed, and it uses the DC-link voltage to calculate the required modulation depth to inject the difference between grid voltage and the reference voltage.

$$V_d^{'} = V_d + \Delta V \tag{9}$$

The $U_d^{'}$ reference voltage is then inversely transformed into the abc reference frame.

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\theta_d & -sin\theta_d & {}^1/\sqrt{2} \\ \cos\left(\theta_d - {}^{2\pi}/{}_3\right) & -sin\left(\theta_d - {}^{2\pi}/{}_3\right) & {}^1/\sqrt{2} \\ \cos\left(\theta_d + {}^{2\pi}/{}_3\right) & -sin\left(\theta_d + {}^{2\pi}/{}_3\right) & {}^1/\sqrt{2} \end{bmatrix} \begin{bmatrix} V_d^{'} \\ 0 \\ 0 \end{bmatrix} \tag{10}$$

These reference values are compared with actual measured voltage of PCC and, finally, series converter switching signals are obtained using the sinusoidal pulse width modulation (SPWM) technique.

4. ESS configuration and control

The supercapacitor is used to build the ESS. The supercapacitor, also known as an ultracapacitor or double-layer capacitor, differs from a regular capacitor in that it has a very high capacitance. A capacitor stores energy by means of a static charge as opposed to an electrochemical reaction. Applying a voltage differential on the positive and negative plates charges the capacitor. The supercapacitor, rated in farads, is again thousands of times higher than the electrolytic capacitor. The supercapacitor is ideal for energy storage that undergoes frequent charge and discharge cycles at high current and short duration. All capacitors have voltage limits. While the electrostatic capacitor can be made to withstand high volts, the supercapacitor is confined to 2.5–2.7 V. Voltages of 2.8 V and higher are possible but they would reduce the service life. To achieve higher voltages, several supercapacitors are connected in series.

The ESS is controlled by a DC/DC converter with two IGBT switches, S_1 and S_2. The duty cycles are controlled using the PWM control scheme shown in Figure 5. The control signal is generated by comparing the actual voltage at the PCC with the reference voltage (0.9 V_{rated}). Hence, the switches are activated only when the system voltage is reduced below the tolerance limit of 90% of the rated value during fault. When switch S_1 is activated the converter operates in buck mode. During this mode, the ESS acts as a sink to absorb the power generated at the wind generator terminal. The duty ratio of switch S_1 is calculated as $D_1 = V_{sc}/V_{dc}$. In normal operating conditions, the converter is operated in boost mode by activating S_2. The duty ratio D_2 is obtained as $D_2 = 1 - D_1$. In this mode the current reversal takes place and the ESS operates as a source; the energy is released and fed to the system using a series inverter. With the aid of the ESS the UPQC is facilitated to handle the energy generated in the wind generator terminal during the grid fault and reduces the stress.

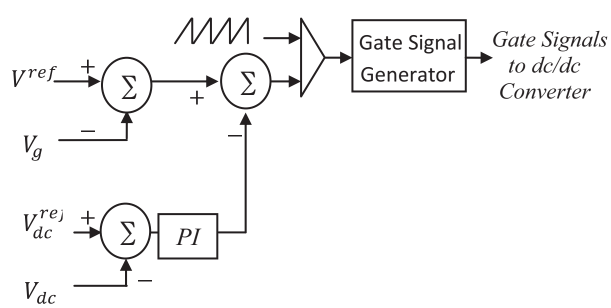

Figure 5. Energy storage system control scheme.

5. Design and specification

A simulation model of the SCIG-based wind farm operating at a power of 3.72 MW is considered for analysis. The specifications of the WTG are given in Table 1. The total capacity of the wind farm is given in Table 2. The wind farm operated at 690 V is integrated with a grid of 220 kV by stepping up the voltage using step-up transformers. A phase-to-phase ground fault is considered for fault ride-through analysis. The UPQC has to exchange both real and reactive power; hence, it is designed for 4.4 MVA. The compensation device is not connected to the wind farm side because the line current is 5.4 kA and the converter switches are not available for this rating. Hence, the UPQC is connected to the 11-kV side where the current rating is reduced by the transformer to 340 A.

Table 1. Wind turbine generator specifications.

Type	Asynchronous
Nominal power	1.24 MW
Power factor	0.85
Synchronous speed	1500 rpm
Voltage	690 V
Current	1.8 kA

Table 2. Wind plant capacity.

Power rating of a single wind plant	1.24 MW
Total number of units	3
Total power generation capacity	3.72 MW
Voltage	690 V
Current	5.4 kA

5.1. Series converter design

The series converter of the UPQC is connected to the line using a series-connected 1:1 transformer. The series converter of the UPQC is switched at 3970 Hz frequency. The voltage is generated as three single-phase outputs to compensate each phase independently. Hence, the converter uses four IGBT switches for each phase with a voltage rating of 6.5 kV. The IGBT has a current rating of 750 A. The IGBT ratings are given in Table 3.

Table 3. IGBT rating.

Parameters	Specification
IGBT module	Make - Infineon
Model number	FZ750R65KE3
Collector-emitter voltage V_{CES}	6.5 kV
Continuous DC collector current $I_{C\,nom}$	750 A
Repetitive peak collector current I_{CRM}	1500 A

The LCL filter design for series compensation is done using [13].

The source impendence Z_e is matched with the impedance of the filter Z_C and is given as

$$|Z_e| = K_f\,|Z_c|\ , \tag{11}$$

where $Z_e = R_e + j\omega L_e$ & $Z_C = -j/m\omega_0 C$,

Using Eq. (11) the capacitance value is determined. From the literature the K_f value is chosen as 485.

$$V_{wg} = K_n V_s \tag{12}$$

$$K_n = 1\Big/\left((n\omega_0)^2 LC - 1\right) \tag{13}$$

K_n is considered as 0.0391.

The inductance value is determined using the relation given in Eq. (14).

$$L = \frac{1+\frac{1}{K_n}}{C\,(n\omega_0)^2} \tag{14}$$

The series converter ratings and specifications are given in Table 4.

Table 4. UPQC series converter ratings.

Devices	Description	Real value
Series converter	Power rating	4.4 MVA
	Voltage rating	11 kV
	Current rating	340 A
Series filter	Frequency F_s	3970 Hz
	m = n is the order of the highest harmonics to be attenuated	100
	Impedance proportionality constant K_f	485
	Voltage proportionality constant K_n	0.0391
	Wind farm resistance R_e	0.0274 Ω
	Wind farm inductance L_e	0.00105 H
	Filter capacitor	74 μF
	Filter inductor	36.37 mH
Series injection transformer	Nominal power	4.4 MVA
	Primary & secondary voltage	11 kV
	Primary & secondary current	340 A
	Injection capability	1 pu
	Turns ratio	1

5.2. Shunt converter design

In the following sections, compensation for obtaining unity power factor is considered for design with reference to [16]. The current rating of the STATCOM corresponds to active and reactive power required from no load to full load at the UPF. During transients the energy transfer from the capacitor to the SEIG to provide the net power requirement is calculated as

$$E_t = 3V_{ph} i_{st} t\,, \tag{15}$$

where t is time in seconds.

A sag in DC bus voltage means that it varies from V_{DC} to V_{DC1}. Then the energy transfer is given as

$$C_{dc}\left[(V_{DC})^2 - (V_{DC1})^2\right] = 3V_{ph} i_{st} t. \tag{16}$$

From Eq. (16) the capacitance value is obtained.

The STATCOM converter ratings are designed according to the wind generator ratings and reactive power requirement. The shunt connection consists of the 11/4.8-kV transformer and the average voltage across the DC link capacitor is maintained at 6.5 kV, which is calculated using Eq. (17):

$$V_{DC} = \frac{3V_m}{\pi}\,, \tag{17}$$

where U_m is the maximum of the rated voltage $(\sqrt{2}V_r)$.

The energy stored in the capacitor is derived as

$$E_{DC} = \frac{1}{2} C_{DC} V_{DC}^2\,, \tag{18}$$

where C_{DC} is the DC link capacitor.

A slightly higher round-off value is considered as the DC voltage. If current ripple through the AC inductor is allowed to be 5%, the inductance can be calculated as

$$L_{in}=\frac{\left(\frac{\sqrt{3}}{2}\right)m_a V_{dc}}{6af_s i_{cr(p-p)}}\ . \tag{19}$$

Here, m_a is the modulation index with a maximum value of 1, and f_s is the switching frequency, which is taken as 5 kHz in this case. During transients, the current is likely to vary from 120% to 180% of the steady-state value. In inductance calculation $i_{cr(p-p)}$ ripple current rating of 120% (a = 1.2) of steady-state current is taken during transients. The shunt converter ratings and specifications are given in Table 5.

Table 5. UPQC shunt converter design.

Devices	Description	Real value
Shunt converter	Power rating	1.2 MVA
	Voltage rating	11 kV
	Current rating	340 A
	Frequency F_s	5 kHz
	Filter inductor L_s	5.86 mH
DC link	DC voltage V_{dc}	6.5 kV
	DC link capacitor C_{dc}	30 mF
	Energy storage E_{dc}	0.6 MJ
Shunt transformer	Nominal power	1.2 MVA
	Primary/secondary voltage	11/4.8 kV
	Primary/secondary current	340/780 A
	Injection capability	1 pu
	Turns ratio	2.3

5.3. DC/DC converter design

The configuration of the UPQC with ESS has a DC/DC converter and supercapacitor bank. The supercapacitor specifications are given in Table 6. The DC/DC converter is operated at 6.5 kV and 750 A. The voltage across the supercapacitor is maintained at 3.25 kV, which is 50% of the DC link voltage. This voltage reduction is done by buck mode of the DC/DC converter for storing energy during grid disturbances. The energy can be retrieved by operating the converter in boost mode. The converter is switched at 5 KHz. The energy storage capacity of the supercapacitor can be determined by calculating the area covered under the ride-through requirement part of the LVRT characteristics shown in Figure 6. The energy storage capacity E_{ess} and other parameters are chosen according to [11,12].

$$E_{ess} = P_{base}\ \{(V_{pf} - V_f)\,T + 0.5\,(3 - T)\,(V_{pf} - V_f)\} \tag{20}$$

Here, E_{ess} is the energy storage capacity of the storage system, P_{base} is the base power of the system under consideration, V_f = 15% of nominal voltage in pu, and V_{pf} = minimum required voltage in pu mentioned as per IWGC. T is the maximum permissible time the system can recover from fault without tripping. The values of V_f and V_{pf} and fault recovery time for various voltage levels are shown in Table 7.

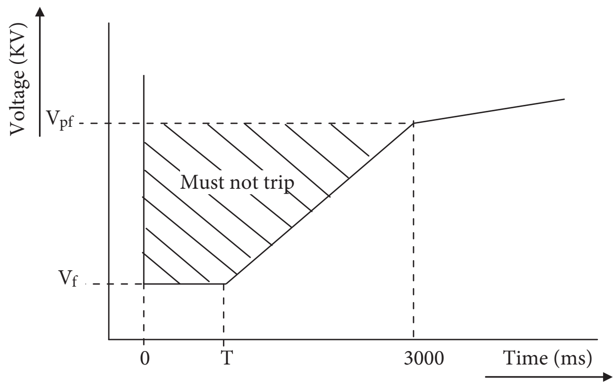

Figure 6. LVRT characteristic of Indian wind grid code.

Table 6. Supercapacitor specifications.

Function	Supercapacitor
Charge time	1–10 s
Cycle life	1 million or 30,000 h
Cell voltage	2.3 to 2.75 V
Specific energy (Wh/kg)	5 (typical)
Specific power (W/kg)	Up to 10,000
Service life (in vehicle)	10 to 15 years
Charge temperature	–40 to 65 °C
Discharge temperature	–40 to 65 °C
Enhanced insulation voltage	10.2 KV AC 1 min
Extended storage temperature Tstg	55 °C

Table 7. Fault clearing time and voltage limits as per IWGC.

Nominal system voltage (kV)	Fault clearing time, T (ms)	V_{pf} (KV)	V_f (KV)
400	100	360	60.0
220	160	200	33.0
132	160	120	19.8
110	160	96.25	16.5
66	300	60	9.9

The capacitance rating of the supercapacitor bank can be determined by

$$C_{ess} = \frac{2E_{ess}}{V_{SC}^2}, \tag{21}$$

where V_{sc} is the supercapacitor's rated voltage. The supercapacitor is maintained at 50% of DC link voltage for storing the energy. The DC link voltage V_{DC} is maintained at 6.5 kV and the supercapacitor voltage V_{SC} is maintained at 3.25 kV.

The inductor used in the energy storage system can be calculated using

$$L_{ess} = \frac{V_{SC}^2\left(V_{DC} - V_{SC}\right)}{2fV_{dc}P_{base}} \tag{22}$$

The designed ESS values are given in Table 8.

Table 8. Energy storage system design ratings.

Energy storage capacity E_{ess}	3.7 MJ
DC link voltage V_{dc}	6.5 kV
Super capacitor voltage Vsc	3.25 kV
Frequency F_s	5 kHz
Energy storage system inductor L_{ess}	0.14 mH
Energy storage system capacitor C_{ess}	0.7 F
Current in the DC/DC converter I_{dc}	750 A

6. Results and discussion

The model is tested by applying an unbalanced fault (phase to phase asymmetrical fault) for a duration of 100 ms. SCIGs used in fixed-speed turbines can cause local voltage collapse after voltage dip. During a fault (and consequent network voltage depression), they accelerate due to the imbalance between the mechanical power from the wind and the electrical power that can be supplied to the grid. Figure 7 shows the voltage, currents, and current sequence component values at wind generator terminals during fault. An unbalance in voltage and current overshoots are observed during the fault. It is found that the transient current reaches 3.6 pu during fault. The real power contributed by the wind farm to the grid undergoes a huge variation due to the fault and the reactive power also get disturbed, as shown in Figure 8. When the fault is cleared, high reactive power is absorbed, further depressing the network voltage. If the voltage does not recover quickly, the wind turbines continue to accelerate and to consume large amounts of reactive power. The reactive power exchange is hindered by the fault and hence induction generators struggle to recover the voltage after clearance of fault. This eventually leads to voltage and rotor speed instability.

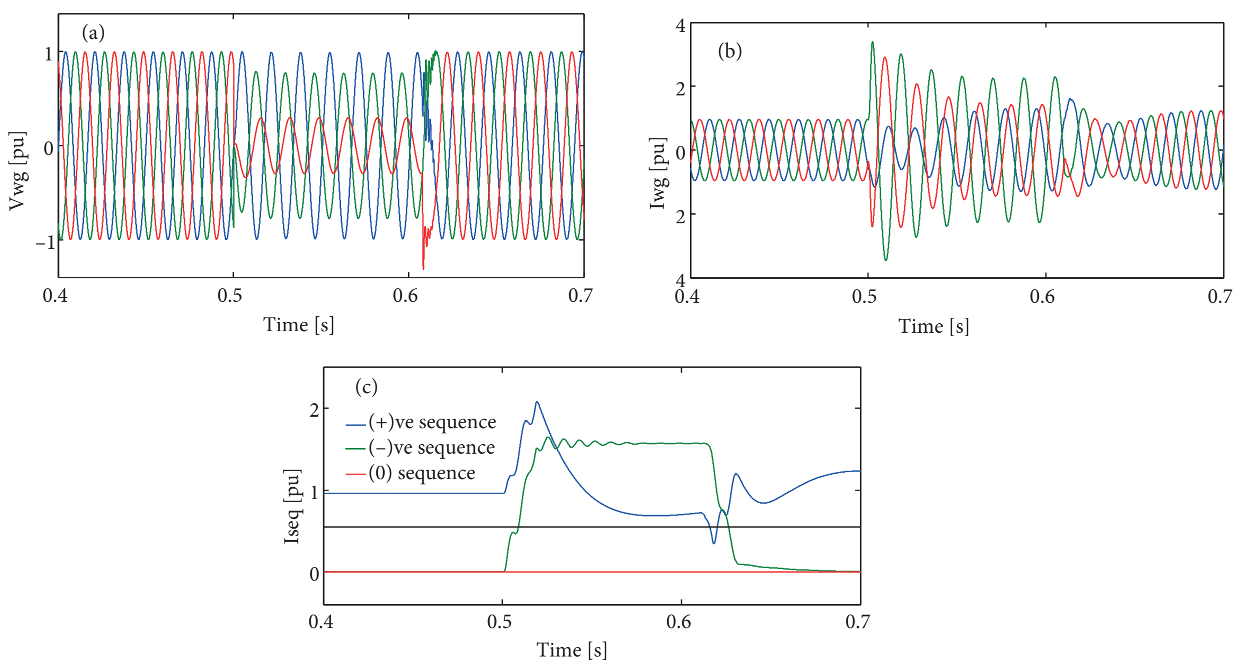

Figure 7. Effect of phase-to-phase ground fault on wind generator: a) voltage dip during fault, b) transient current, c) sequence components of the current.

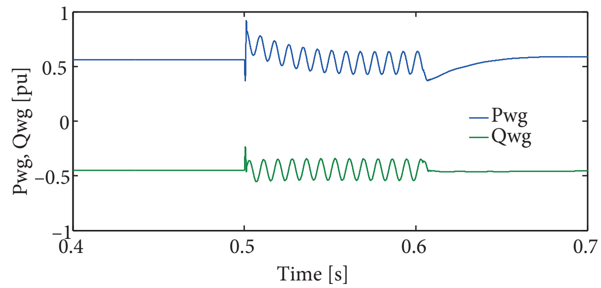

Figure 8. Real and reactive power during the fault.

The wind farms cannot contribute power to the grid fault and hence oscillations are observed in the waveform, which is termed as intermittent power. This intermittent power harms the wind generator by affecting the electromechanical torque, which puts stress on the turbine. On the other hand, when the grid provides unbalanced voltages to SCIG-based WECSs, several drawbacks appear. First, due to the low negative-sequence impedance of the SCIG, high currents of negative sequence flow in the stator. These currents produce overheating, loss of performance, and decrease in the generator's useful life. Second, the interaction of negative-sequence voltages with positive-sequence currents produces a 2ω pulsation in the mechanical torque, which generates high stress in the turbine mechanical system, especially in the gearbox. These electrical and mechanical problems can activate SCIG protection and disconnect the wind farm. In such cases, dip mitigation is the only solution to avoid the aforementioned problem and to make the generator stay connected to the system. The proposed UPQC scheme can provide excellent compensation for aforementioned problem for SCIG-based wind farms.

The voltage dip is compensated by series voltage injection and the reference signal consists of two sequence parameters; one is an in-phase positive sequence and the other is in-phase opposition to the negative sequence. With the combination of the two sequence components the UPQC inserts a voltage in series to restore the balance of the wind generator, as shown in Figure 9. Figure 10 shows the voltage and current wave forms at the wind generator terminals after compensation. The negative-sequence components are nullified. The intermittent power is dealt with by the aid of the ESS. The supercapacitor current, voltage, and voltage at the DC link capacitor are depicted in Figure 11. The power at the wind generator terminal after compensation is shown in Figure 12.

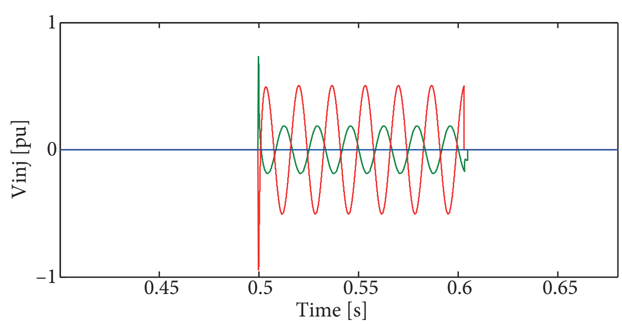

Figure 9. Series injection voltage.

7. Conclusion

The new proposed UPQC configuration with supercapacitor-based ESS has the ability to manage wind power intermittency. The supercapacitor has high round-trip efficiency and is more economical compared to other storage devices. It serves as a sink/source to manage wind energy during a fault and supports the power balance between the WTG and the grid. The proposed system provides an efficient solution for multiple issues such as voltage sag, negative-sequence current, and real and reactive power oscillations. Hence, the fault ride-through capability of the WECS is improved and satisfies the grid code requirement. The simulated results show the viability of the proposed scheme.

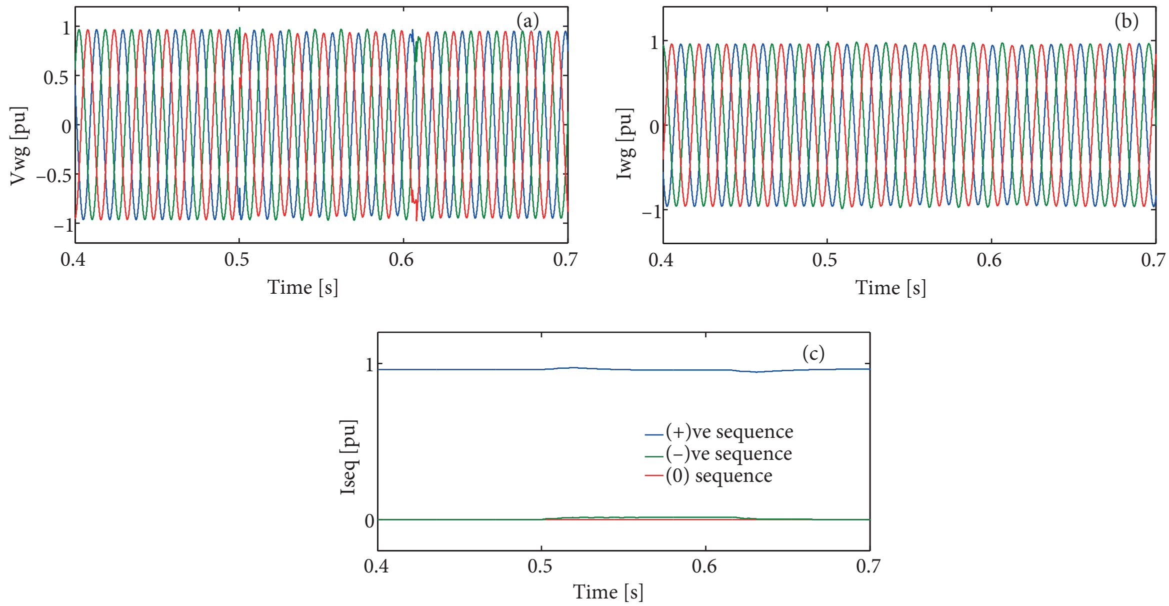

Figure 10. Wind generator terminals after UPQC compensation: a) voltage, b) current, c) sequence component of current.

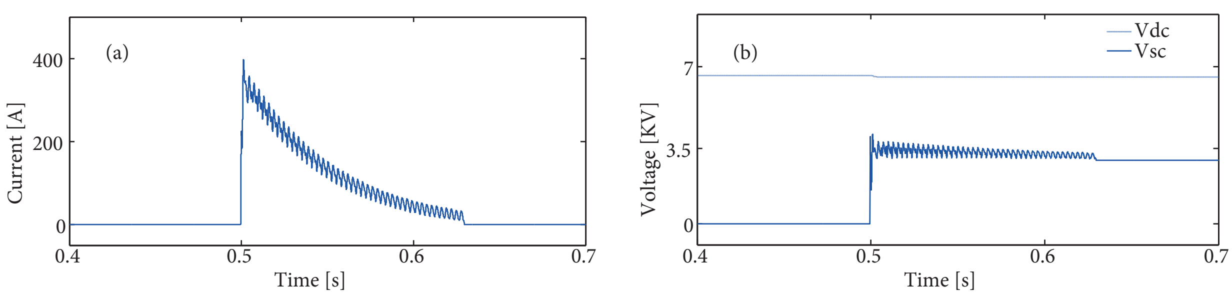

Figure 11. Energy storage system: a) charging current, b) DC link voltage and supercapacitor voltage.

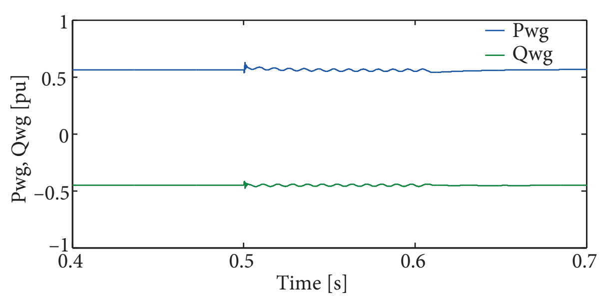

Figure 12. Real and reactive power after compensation.

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