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Providing Control Method Using UPQC and Wind Turbine to Reduce Voltage Drop and Harmonics During Distribution Network Faults

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Abstract— *Existing generators used in renewable wind Turbines (WT) that are connected to the power system at the distribution level need a sound power grid for proper operation. The purpose of this article is to simultaneously use Unified Power Quality Conditioner (UPQC), wind turbine and appropriate control system to achieve the lowest harmonic distortion and voltage drop during network faults. Also, in this article, in order to check the efficiency of different fact tools when there is a fault in the network, a comparison between UPQC performance with static VAR compensator (SVC) and distribution synchronous static compensator (D-STATCOM) was made and the obtained results were presented. The performed simulations are based on compensation of voltage decrease and increase as well as compensation of harmonic distortion caused by nonlinear loads. The results obtained in this article show that Using UPQC in the network was able to compensate for 100% of voltage drop and voltage increase in the network, while svc and D-Statcom equipment in the best case compensated for 98% of voltage increase and 90% of voltage decrease. UPQC also can be the best tool to eliminate network flow harmonics. In the previous papers, the best value for harmonic current distortion was 1.67%, but our results showed that the harmonic distortion of the network current when using UPQC is 1.47%. Also the harmonic distortion of network current with SVC and D-Statcom is 5.67 and 4.87 percent, respectively. The capability of the equipment in compensating for short circuit fault current and protection of wind power plant is also evaluated. There was no change in wind turbine voltage during the use of UPQC and faults, and 1 P.U remained constant, but when using svc and D-Statcom equipment, the wind turbine voltage during the fault decreased by 0.3 and 0.5 P.U respectively.*

Keywords— Power Distribution Network, Wind Turbine, UPQC, SVC, D-Statcom.

1. INTRODUCTION

Today, power distribution systems are very complex. Nonlinear loads such as electric welding machines, adjustable speed drives, and switching power supplies are connected to the mains. These times are the most important cause of serious problems in the power distribution system called power quality (PQ) problems. Problems with power adequacy, known as harmonics, voltage drop/increase, flicker, and imbalance, have become serious concerns and overshadow network power quality, so improving power quality is one of the most important issues in the distribution network [1]. To achieve this, custom power devices (CPDs) have been increasingly used in the distribution system because they can compensate for several major power quality problems [2]. Unified power quality devices (UPQCs) are one of the most important CPDs because they can perform various types of compensation such as active filtering, load balancing, power factor correction, and voltage regulation [3]. Therefore, the use of UPQC in the power distribution system to improve the quality of electricity is of interest. UPQC is a combination of two solid state voltage source converters (VSCs): series and shunt converters. Which are connected to a capacitor with a common DC link and each converter is coupled to the AC line through a transformer [4]. In addition, the UPQC can add a series voltage to the common coupling point (PCC), so the device can be used to eliminate any voltage drop or flicker [5]. It is also compatible with both active filter mode and voltage regulation at the same time, which is an advantage for UPQC. [6] Was studied. This single-phase to three-phase converter is called a Unified power quality correction device. In this study, the applicability of this system to rural or remote areas has been investigated. In these areas, for economic reasons, only single-phase electrical power distribution system, such as single-wire ground return system, are available to consumers. Due to the use of active series power filters and parallel active power filters, a Unified power quality correction device is usually used to reduce power quality problems in single-phase distribution systems and four-phase three-wire distribution systems [7]. Three-phase three-wire and Unified integration of Unified power quality correction device, single-phase to the three-phase converter are provided, in [8] complete filter is provided so that several active power filters are combined in series where the converter is with a single-phase full bridge inverter (despite two-pin) And a parallel converter consisting of a three-phase inverter, which together forms a five-phase. In [9] distribution System Analysis with UPQC Allocation Considering Voltage Dependent Time-Variant and Invariant Loads including Load Growth Scenario was studied.

In [10] enhancement of Electric Power Quality using UPQC with Adaptive Neural Network Model Predictive Control was studied. The authors proposed advanced controllers for harmonic

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suppression alongside unified power quality conditioner (UPQC) for the power distribution network. The series converter consists of a half-bridge (single-pin) inverter, while the parallel converter consists of a three-pin capacitive split inverter, which makes up a total of four pins; therefore, it is possible to feed single-phase and three-phase loads. On the other hand, the results are quantitative and presented only using simulation. In addition, no details about the dimensions and control of the converters are properly stated. Unified power quality correction devices are commonly used to control the compensation of series and parallel instruments and to combine non-sinusoidal values of voltage and current. For example, a transducer combines a series of non-sinusoidal voltage values and is used to compensate for grid voltage disturbances, while a parallel converter combines a non-sinusoidal current and is used repeatedly to eliminate harmonic current and compensate for reactive power. To use these compensation strategies, some mathematical methods are used to calculate the reference values of voltage and compensation. On the other hand, some authorities have used the dual compensation strategy to control the series and parallel converters of the Unified power quality correction device [11]. In this strategy, sinusoidal voltage and current are used to control both converters. In this case, the sine series converter generates sine current values and, as a result, acts as a sine current source and provides a high impedance path for the load current harmonics. The parallel converter generates a sine wave voltage, in which case it acts as a sine voltage source and provides a low impedance for the load current harmonics. It is also observed that the performance of controllers using non-sine sources is much better than when using quasi-sine sources. In addition, because they are sinusoidal control references, the controllers that run within the synchronous reference frame have a continuous voltage and current reference and provide even more control. Another advantage of dual compensation in the form of production of control references is that it is done only using a locked phase loop system.

In [12] a study on the best solution to improve power quality in low voltage distribution networks was reviewed, and UPQC was mentioned as the best option [13]. A study was conducted to improve the performance of a distributed generation (DG) system using a Unified power quality modifier. In this article, in addition to the issue of power quality, which is one of the main technical challenges in the distribution system, the issue of compensating for harmonic and voltage drops in distribution networks was discussed and an attempt was made to improve the quality of power. Power quality was evaluated in an independent DG system (including renewable energy sources based on solar, wind, and fuel cell) in the presence of UPQC. The realization of UPQC was performed using conventional synchronous reference frame (SRF) and modified SRF (MSRF) frame generation techniques to generate a reference current with pulse width modulation voltage source inverter technique to produce a pulse for the inverter along with a PI controller for DC tuning. The connection of the voltage reduction compensation capacitor with current and voltage harmonics in different source conditions (ideal and non-ideal) was met with different control schemes such as SRF and MSRF techniques. The result confirms the superiority of the proposed technique in terms of harmonic elimination and compensation. [14] Power fluctuations under asymmetric fault and output power instability, which are the three main problems in the distribution network, were investigated for the network in the presence of distributed generation sources with dual-feed induction generator (DFIG) and a solution was proposed to improve it. To address these issues simultaneously, this paper proposes a Unified power quality device based on the cost-effective energy storage device (ESD-UPQC) to improve low voltage through DFIG capability, reduce voltage fluctuations under unbalanced faults, and adjust DFIG output. The simulation results confirm the feasibility of the proposed controller. The strength of the proposed ESD-UPQC controller is confirmed by a set of comparisons based on the lead-acid battery design and the ESD-DFIG design to power smoothing and increase LVRT, respectively [15]. In [16], the authors examine a grid with a photovoltaic system with a Unified power control system. The photovoltaic (PV) system is used to supply power to the UPQC device through an amplifier converter and improves the Dc link voltage by controlling the pulse width modulation. The inverters in the UPQC are controlled using the Model Predictor Controller (MPC) and improve voltage and power compensation. The results of the proposed system are confirmed using the MATLAB / Simulink environment. This paper describes the most prominent power quality improvements in integrated grid energy systems with solar photovoltaic (SPV) and wind energy (WE) hybrid using Unified power quality controller (UPQC). The control technique for UPQC is implemented through fuzzy logic controllers. The proposed UPQC also helps reduce energy losses that occur in power system components, as well as ensures a safe environment. The new imposed idea is being tested through the PSCAD simulation platform, and the results will certainly justify the proposed UPQC for trapping harmonic agents in distributed renewable energy fields while exposed to nonlinear/sensitive load conditions. The power in the integrated system was investigated using induction UPQC. This paper presents a new method of harmonic voltage and current compensation and voltage reduction using hybrid UPQC. The proposed concurrent reference controller uses the carrier pulse width modulation (CPWM) technique for proper UPQC control. The results of their simulations show that the proposed hybrid UPQC effectively compensates for load current and voltage drop harmonics. Load voltage harmonics decreased from 11.65% to 1.53% and current harmonics from 30.97% to 2.24% [17].

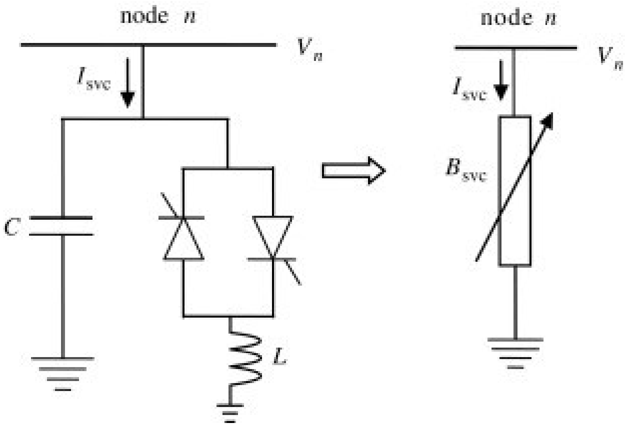


Fig. 1. SVC block diagram [18]

As it is clear from the review of the previous articles, so far many studies have been carried out in the field of FACTS devices in controlling network voltage drop, harmonics and network protection during faults, but the important issue is to provide a suitable method to reduce distortions and voltage drop as much as possible. The continuation of the article is prepared as follows. 2) Introducing the structure of different compensators. 3) Simulations and parameter values. 4) Results and 5) consolations.

2. INTRODUCING THE STRUCTURE OF DIFFERENT COMPENSATORS

2.1. Static VAr Compensator

The static VAr compensator (SVC) is the reactive power in parallel connection mode, first introduced for voltage control in Nebraska and commercially available by GE in 1974 and by Westinghouse in Minnesota in 1975 [18]. Fig. 1 shows the SVC block diagram.

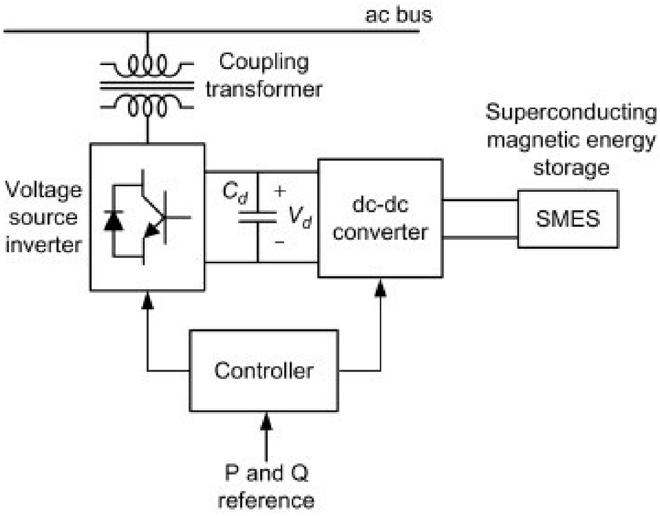


Fig. 2. Single-line diagram of compensator synchronous static distribution [19]

2.2. Distribution Static synchronous compensator

Distribution Static synchronous compensator (D-STATCOM) A solution to improve power quality in distribution systems includes temporary outages, voltage dips, harmonics, and voltage flickers. Typical D-STATCOMs using cascade control. The internal current loop produces reactive power components and harmonics, and the outer loop controls the DC bus voltage. The internal current loop is usually fast enough to produce a PWM pattern, but the response time of the external voltage loop is longer and the capacitor must be able to store enough energy to remain constant at the DC bus voltage. The distribution-synchronous-static-compensator is connected in parallel to the distribution network and, as a fast-current controlled current source, can reduce the reactive power fluctuations and the harmonic current drawn by variable loads and regulate the effective voltage. D-STATCOM regulates the voltage using reactive power absorption. D-STATCOM consists of a DC to AC voltage source converter (inverter), a DC voltage source, an AC filter, a parallel injection transformer (coupling transformer), and a control strategy. The D-STATCOM block diagram is shown in Fig. 2.

2.3. Unified Power Quality Conditioner device

A Unified power quality correction device is equipment that is used to ensure that the delivery power complies with all required standards and specifications at the installation site. The ideal UPQC can be represented as a combination of a voltage converter source (series voltage injection), a current source converter (parallel current injection), and a common DC link (connected to a DC capacitor). There are two possible ways to connect UPQC to a terminal in a PCC:

- UPQC with near-load parallel converter connection as shown in Fig. 3(a). In this structure, the parallel converter is located to the right of the series compensator.
- UPQC by connecting a parallel converter close to the source as shown in Fig. 3(b). In this structure, the parallel converter is located to the left of the series compensator.

These two structures have similar characteristics; however, the general feature of UPQC with a parallel converter on the right is superior (for example, the ability to operate at no-load / power absorption, creating a single power factor at load terminals, and fully compensating for reactive power). Therefore, in this section, the UPQC configuration is analyzed by connecting the parallel converter on the right. References [7] and [21] provide a detailed analysis of the structure of the UPQC with a parallel converter connection on the left. The exact structure of the UPQC with the parallel converter connection on the right is shown in Fig. 4. Assume that the grid has a three-phase, four-wire configuration and that the grid voltage is non-sinusoidal and has perturbations and imbalances. In this case, the UPQC must perform the following tasks:

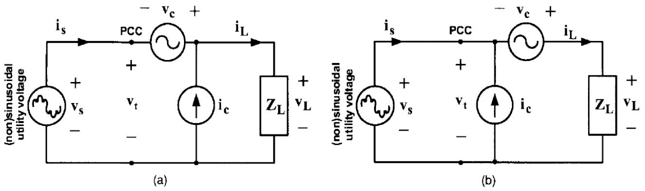


Fig. 3. Types of UPQC connection structure to PCC point [20]

- Convert system currently to balanced sine current through the parallel compensator
- Convert system voltage to balanced sinusoidal voltage through the series compensator
- Reactive power supply

Using Kirchhoff's law in the electrical circuit of Fig. 4, the dynamic model of UPQC in the abc reference frame can be obtained as follows [23–25]:

$$\frac{di_{pa}}{dt} = -\frac{V_{pa}}{L_P} - \frac{R_P}{L_P} i_{pa} - m'_{pa}\left(\frac{V_{dc1}+V_{dc2}}{2L_P}\right) + \frac{V_{dc1}}{2L_P} - \frac{V_{dc2}}{2L_P} \tag{1}$$

$$\frac{di_{pb}}{dt} = -\frac{V_{pb}}{L_P} - \frac{R_P}{L_P} i_{pb} - m'_{pb}\left(\frac{V_{dc1}+V_{dc2}}{2L_P}\right) + \frac{V_{dc1}}{2L_P} - \frac{V_{dc2}}{2L_P} \tag{2}$$

$$\frac{di_{pc}}{dt} = -\frac{V_{pc}}{L_P} - \frac{R_P}{L_P} i_{pc} - m'_{pc}\left(\frac{V_{dc1}+V_{dc2}}{2L_P}\right) + \frac{V_{dc1}}{2L_P} - \frac{V_{dc2}}{2L_P} \tag{3}$$

$$\frac{dV_{dc1}}{dt} = \frac{1}{2C}\Big(-m_{sa}i_{sa} - m_{sb}i_{sb} - m_{sc}i_{sc} + m'_{pa}i_{pa} + m'_{pb}i_{pb} + m'_{pc}i_{pc}\Big) + \frac{1}{2C}\left(i_{sa}+i_{sb}+i_{sc}-i_{pa}-i_{pb}-i_{pc}\right) \tag{4}$$

$$\frac{dV_{dc2}}{dt} = \frac{1}{2C}\left(-m_{sa}i_{sa} - m_{sb}i_{sb} - m_{sc}i_{sc} + m'_{pa}i_{pa} + m'_{pb}i_{pb} + m'_{pc}i_{pc}\right) - \frac{1}{2C}\left(i_{sa}+i_{sb}+i_{sc}-i_{pa}-i_{pb}-i_{pc}\right) \tag{5}$$

$$\frac{di_{pc}}{dt} = \frac{V_{sa}}{L_s} - \frac{R_s}{L_s} i_{sa} + m_{sa}\left(\frac{V_{dc1}+V_{dc2}}{2L_s}\right) - \frac{V_{dc1}}{2L_s} + \frac{V_{dc2}}{2L_s} \tag{6}$$

$$\frac{di_{sb}}{dt} = \frac{V_{sb}}{L_s} - \frac{R_s}{L_s} i_{sb} + m_{sb}\left(\frac{V_{dc1}+V_{dc2}}{2L_s}\right) - \frac{V_{dc1}}{2L_s} + \frac{V_{dc2}}{2L_s} \tag{7}$$

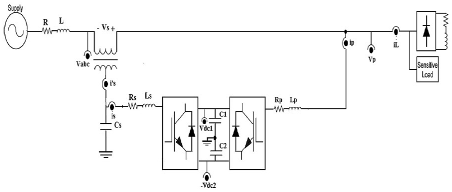


Fig. 4. Example of power system installed with UPQC [22]

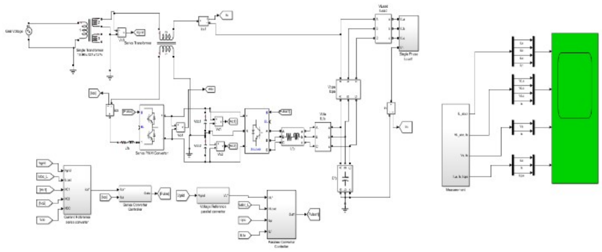


Fig. 5. Power quality modifier integrated with single-phase to three-phase converter

$$\frac{di_{sc}}{dt}=\frac{V_{sc}}{L_s}-\frac{R_s}{L_s}i_{sc}+m_{sc}\left(\frac{V_{dc1}+V_{dc2}}{2L_s}\right)-\frac{V_{dc1}}{2L_s}+\frac{V_{dc2}}{2L_s} \tag{8}$$

The equations (6)–(8) show that the second derivative of the output voltage of the APF series must be calculated to obtain the equations related to the input of the Us(t) control. Thus:

$$\frac{d^2V_{sa}}{dt^2}=\frac{1}{C_s}\frac{di'_{sa}}{dt}+\frac{R_s}{C_sL_s}i_{sa}\frac{-1}{C_sL_s}\left(V_{sa}+\frac{V_{dc1}}{2}+\frac{V_{dc2}}{2}\right)U_{sa}+\frac{V_{dc1}}{2C_sL_s}-\frac{V_{dc2}}{2C_sL_s} \tag{9}$$

$$\frac{d^2V_{sb}}{dt^2}=\frac{1}{C_s}\frac{di'_{sb}}{dt}+\frac{R_s}{C_sL_s}i_{sb}\frac{-1}{C_sL_s}\left(V_{sb}+\frac{V_{dc1}}{2}+\frac{V_{dc2}}{2}\right)U_{sb}+\frac{V_{dc1}}{2C_sL_s}-\frac{V_{dc2}}{2C_sL_s} \tag{10}$$

$$\frac{d^2V_{sc}}{dt^2}=\frac{1}{C_s}\frac{di'_{sc}}{dt}+\frac{R_s}{C_sL_s}i_{sc}\frac{-1}{C_sL_s}\left(V_{sc}+\frac{V_{dc1}}{2}+\frac{V_{dc2}}{2}\right)U_{sc}+\frac{V_{dc1}}{2C_sL_s}-\frac{V_{dc2}}{2C_sL_s} \tag{11}$$

3. SIMULATIONS

3.1. Grid and software simulation parameters

In this section, the simulation on an experimental grid is examined. A view of the simulated model in MATLAB / Simulink software is shown in Fig. 5. Due to the effect of the internal circuit of dual-feed wind turbines and their control system on the network specifications, in this section, the internal circuit of the wind turbine and the internal circuit of the control system, and the dual-feed wind turbine terminals modeled in Fig. 6 are shown. The three-phase terminal of the circuit is connected to the load terminals. To perform the simulation in MATLAB software, network parameters, UPQC and wind turbines are required, which are given in tables 1 to 5 required parameters.

3.2. Check the different modes in the distribution network

- *UPQC capability in recovering weak network voltage compared to SVC and D-STATCOM*

In this section, a DFIG-based wind turbine with a nominal power of 1.5 MW is connected to the system. Under these conditions, by injecting active and reactive power by DFIG, the load compensation conditions are improved to an acceptable extent. In this case, the equipment is examined. Due to the sensitivity of wind turbines to the voltage level in this section, only the voltage waveform diagram is examined.

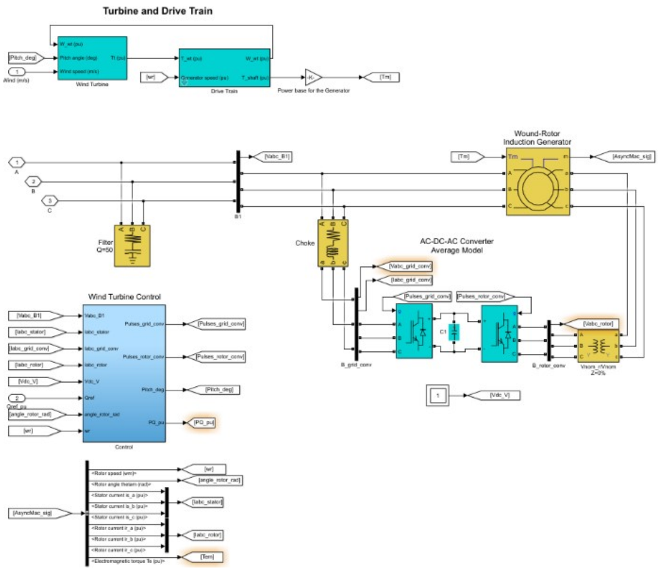


Fig. 6. Double feed wind turbine internal circuit

- *UPQC capability in harmonic elimination of nonlinear loads compared to SVC and D-STATCOM*

In this section, to evaluate the ability of equipment to compensate for network current harmonics, a three-phase nonlinear load is used to inject harmonics into the network. The harmonic distortion (THD) of the load is about 32%, which is unacceptable by international electrical standards.

- *UPQC capability in protecting DFIG-based wind power plant against short circuit failure*

In this part of the simulations, the ability to limit and compensate for short circuit faults by SVC, D-Statcom, and UPQC compensation equipment to protect wind turbines is investigated. The amplitude of the short-circuit fault current depends on the impedance of the feeder from the source location to the fault location. For this purpose, two modes are considered for the location of the fault. The first case is for the time when the short circuit fault occurs before the compensating devices and the proximity of the infinite bus. In the latter case, a short circuit fault occurs at the terminal of one of the wind turbines. Under these conditions, the relevant turbine whose terminals are short-circuited will go out of the circuit depending on the duration of the fault and the time delay of the protection devices. In this case, the compensation equipment should be able to compensate only for the voltage drop caused by this fault and prevent parallel and adjacent power plants connected to the common bus.

4. RESULTS

4.1. Voltage weakness Compensation

The effective load voltage compensated by the equipment in the presence of DFIG is shown in Fig. 7. As can be seen, the compensation rate of the load voltage increase by UPQC and D-Statcom is almost equal to 100%, and in this case, the load voltage is on 1 P.U and the SVC compensation rate is about 86%, and in this case the voltage the load is about 1.03 P.U. Also, the compensation of load voltage reduction by UPQC is almost 100%. The voltage reduction compensation by D-Statcom and SVC is almost 90% and in this case, the load voltage is at 0.98 p.u. Observing the active and reactive powers in Fig. 8, it can be seen that the required power of UPQC is reduced and the necessary

Table 1. Load specifications and parameters and distribution network under simulation

Load and network specifications [26–28]	
Nominal voltage and frequency ($V_s,\ f$)	$25\ kV,\ 60\ Hz$
Source impedance	$0.625\Omega,\ 16.57\ mH$
Short circuit capacity (S_{sc})	$100\ MVA$
Load power and voltage	$1.5\ MW,\ 400\ V$
Line impedance ($R_{Line},\ L_{Line}$)	$2.65\Omega,\ 24\ mH$
Transformer capacity and frequency 25 $kv/400\ V$	$2MVA,\ 60\ Hz$
Resistance and initial inductance of transformer $25kv/400\ V$	$0.00083\ p.u,\ 0.05p.u$
Transformer resistance and secondary inductance25 $kv/400\ v$	$0.00083\ p.u,\ 0p.u$

Table 2. Specifications and control parameters of UPQC series filter

SeAPF Series Active Filter Parameters [29, 30]	
Rated power and frequency of series injection transformers	$1\ MVA,\ 60\ Hz$
Series filter inductance (L_f)	$1.5\ mH$
Parallel capacitive RC filter impedance	$5\Omega,\ 20\mu F$
The conversion ratio of series injection transformers	$240v/120v$
Resistance and inductance of primary winding of series injection transformers	$0.002\ p.u,\ 0.5\ p.u$
Resistance and inductance of secondary winding of series injection transformers	$0.002\ p.u,\ 0.5\ p.u$
High and low bandwidth of the hysteresis controller	$-0.01,\ 0.01$

Table 3. Specifications and control parameters of UPQC shunt filter

Parallel Active Filter Parameters (ShAPF) UPQC [29, 30]	
DC link voltage	$120\ V$
The capacity of DC link capacitors	$1.75\ mF$
the inductance of series coupling (L_{se})	$150\ mH$
DC link voltage regulator gain ($K_p,\ K_I$)	$0.1,\ 0.01$

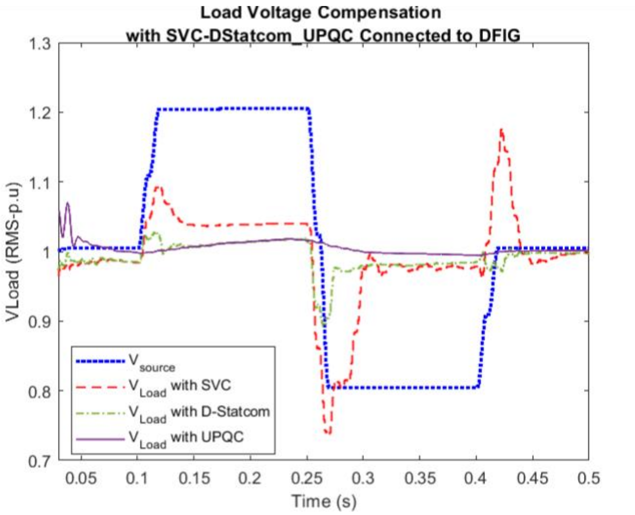
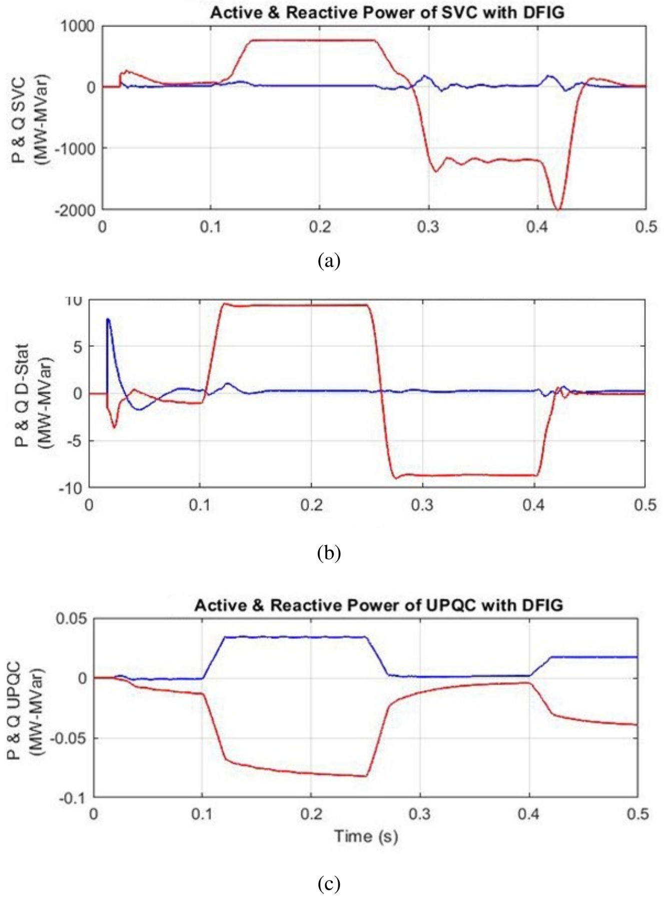


Fig. 7. Comparison of load voltage compensation by each compensation equipment with the presence of wind turbine

power to compensate the load voltage is provided by DFIG. But this is not the case with SVC and D-Statcom. Because to fully compensate for these two equipment, in addition to the power produced by them, DFIG power is also required. A comparison of the active and reactive power generation of wind turbines with compensators is also shown in Fig. 9. In this case, the active power of the wind turbine is positive in all cases. That is, 1.5 MW is injected into the system by a wind turbine. But the wind turbine reactive power works in two modes, which are similar in SVC and D-STATCOM modes. In the first mode, it operates in capacitive mode and injects wind turbine and reactive power into the network. In the next mode, when the voltage drops, the wind turbine operates in Inductive mode and absorbs power from the network. In both cases, it injects active power into the grid. In the case of UPQC, the active power injected into the system is



(a)

(b)

(c)

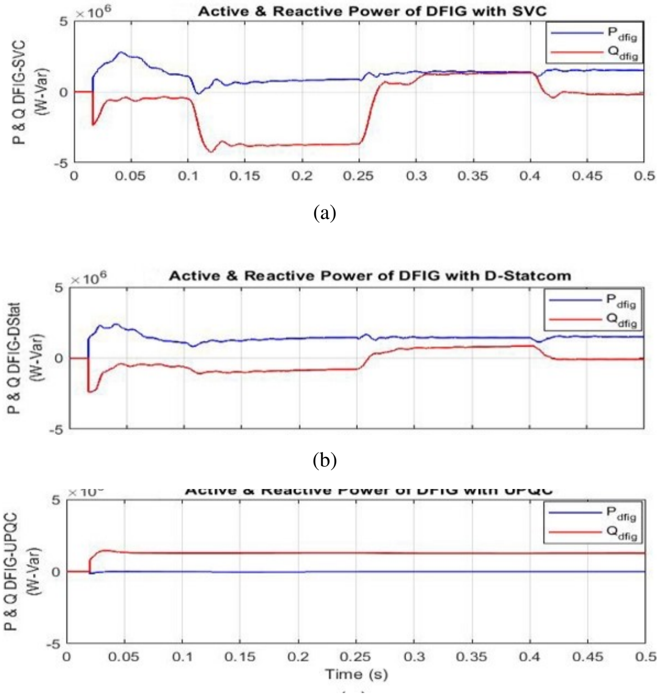
Fig. 8. Injectable active and reactive powers to compensate for voltage decrease and voltage increase with amplitude of 20% in the presence of wind turbine by (a) SVC, (b) D-Statcom, (c) UPQC

Table 4. DFIG Converter Specifications

DFIG generator specifications for each wind turbine unit [28]	
Nominal apparent power (P_n)	1.65 MVA
Nominal effective stator voltage (V_{S_nom})	400 V
Nominal rotor effective voltage (V_{r_nom})	1975 v
Nominal frequency (f_n)	60 Hz
Resistance and stator leakage inductance ($R_s,\ L_{ls}$)	0.023$p.u,$ 0.18$p.u$
Resistance and rotor leakage inductance ($R_{r'},\ R_{lr'}$)	0.016 $p.u,$ 0.16 $p.u$
Magnetic inductance (L_m)	2.9 $p.u$
Constant inertia (H)	0.685 s
Number of pole pairs (p)	3

Table 5. DFIG Converter Specifications

Converter specifications of each wind turbine unit [28]	
Nominal current side of the converter network (I_{sn})	0.8 $p.u$
Network side filter resistance and inductance ($R_f,\ L_f$)	0.003 $p.u,$ 0.3 $p.u$
The nominal voltage of DC link (V_{dc})	1150 V
DC link capacitor capacity (C_{dc})	10000 μF
Network side capacitive filter capacity (C_f)	120 $kVAR$



(a)

(b)

(c)

Fig. 9. Active and reactive power generated by DFIG with compensators (a) SVC, (b) D-Statcom, (c) UPQC

zero because no active power is required and UPQC has made full compensation. The amount of load voltage compensation under voltage increase and decrease voltage with an amplitude of 20% by each compensation device in the presence and absence of DFIG is shown in Table 6.

4.2. Harmonic disturbance

According to Fig. 10 of sections A to C, it can be seen that UPQC can be the best tool to eliminate network flow harmonics. So that the harmonic distortion of network current, in this case, is 1.47%. While the harmonic distortion of network current by compensation of D-Statcom and SVC is 4.87 and 5.67 percent, respectively.

4.3. Short Circuit Protection

A) *Simulation of short circuit fault upstream of compensating devices*

In this case, it is assumed that a three-phase short-circuit fault occurs on the infinite and upstream bus side of the compensation equipment at t = 0.25s and disappears at t = 0.35s. Under these conditions, the amount of fault compensation and load voltage is checked by each of the three mentioned types of equipment.

- **Performance of SVC**

Fig. 11 shows the three-phase to ground fault on the grid side. It should be noted that SVC is not able to compensate for the voltage on the DFIG side despite the injection of reactive current, and the generator of this wind turbine will inevitably trip.

Also, the effective DFIG and source voltages when a fault occurs are shown (Fig. 12). It can be seen that in the event of an SVC fault in voltage compensation mode, no power can be injected. This is because the SVC acts as a current source and in the event of a fault the entire output current passes through the short circuit path, so the voltage across the two ends is zero and the reactive power of the injection is zero.

1) **Performance of D-STATCOM**

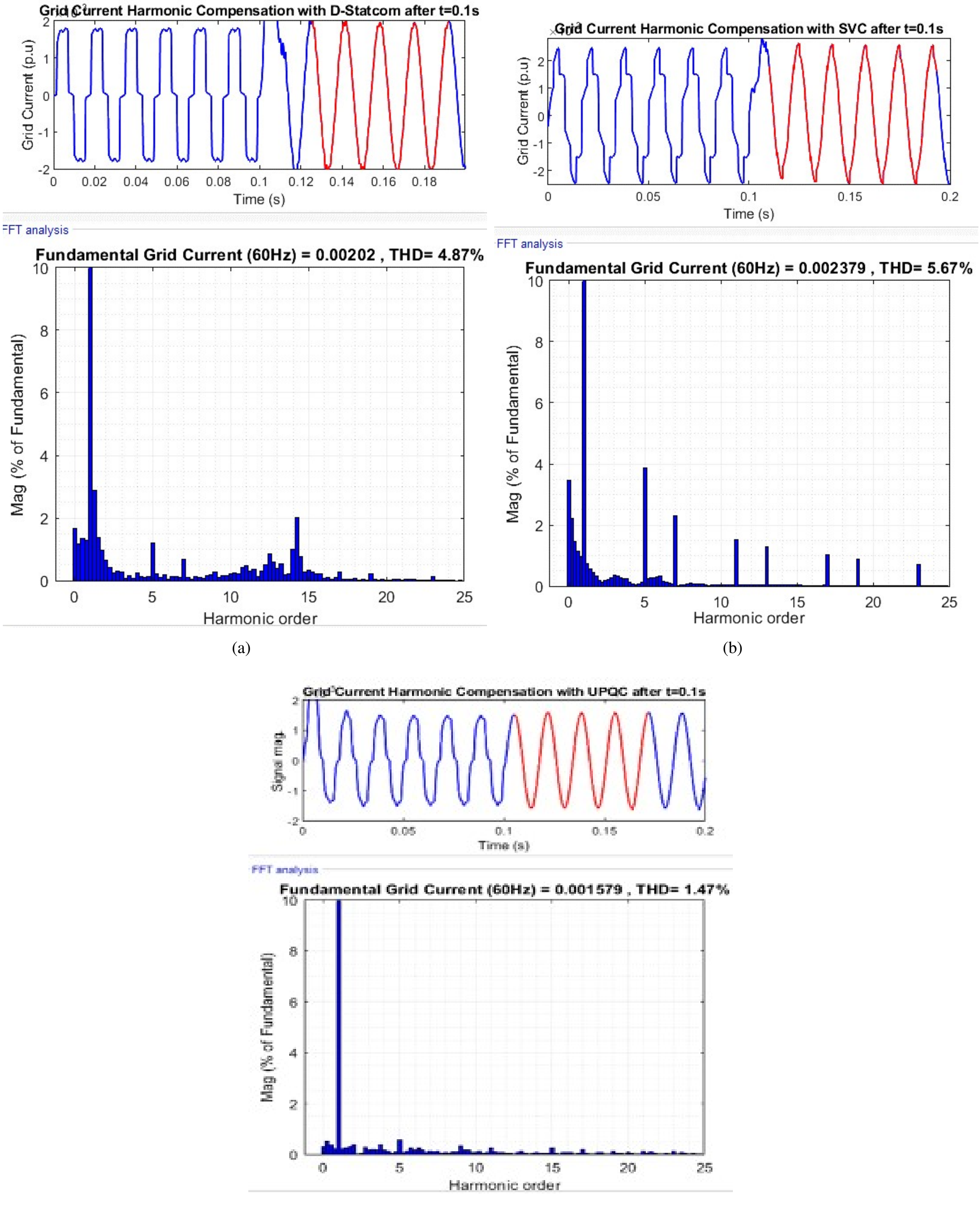
Fig. 13 shows the three-phase fault compensation by D-Statcom. It can be seen that despite the injection of reactive power at the rate of 1 P.U, no compensation is provided.

Fig. 14 also shows the effective source and DFIG voltages along with the D-Statcom injection powers. It can be seen that the source voltage drop is less than the DFIG voltage drop. Because the fault impedance to the source is higher than the fault impedance to D-Statcom. It is also observed that the voltage of D-Statcom and its injection power are zero. Because of the short-circuit voltage of D-Statcom and the fact that it acts as a current source like SVC, it does not inject any power into the load. In addition, due to the zero voltage of DFIG terminals, the voltage of its DC link also increases sharply, which in itself can cause DFIG trip.

1) **Performance of UPQC**

Fig. 15 shows the simulation of the three-phase fault and its compensation by UPQC. It can be seen that UPQC can compensate for any type of fault with any current range. Of course, to fully compensate for the load voltage, the nominal value of the injection voltage must also be high, which will increase the rating and capacity of the UPQC.

According to Fig. 15, it can be seen that UPQC can compensate the DFIG voltage under 100% three-phase short circuit fault and prevent tripping. To better understand this, the effective source and



(a) (b)

(c)

Fig. 10. Branch-node (Graph) model of network in (a) normal operation, (b) self-healing operation

Table 6. The amount of load voltage compensation under voltage decrease and voltage increase with an amplitude of 20% by each of the compensation devices in the presence and absence of DFIG

Compensating devices	Compensation rate of voltage increase with amplitude of 20% (in percentage)		Voltage reduction compensation with amplitude of 20% (in percentage)	
	With DFIG	With DFIG	Without DFIG	Without DFIG
SVC	80	90	72.5	35
D-Statcom	98	90	65	75
UPQC	100	100	100	100

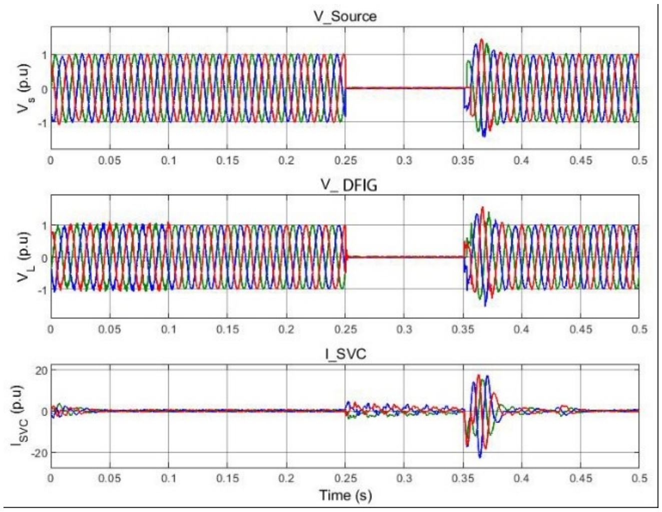


Fig. 11. Three-phase short circuit to ground fault and compensation by SVC

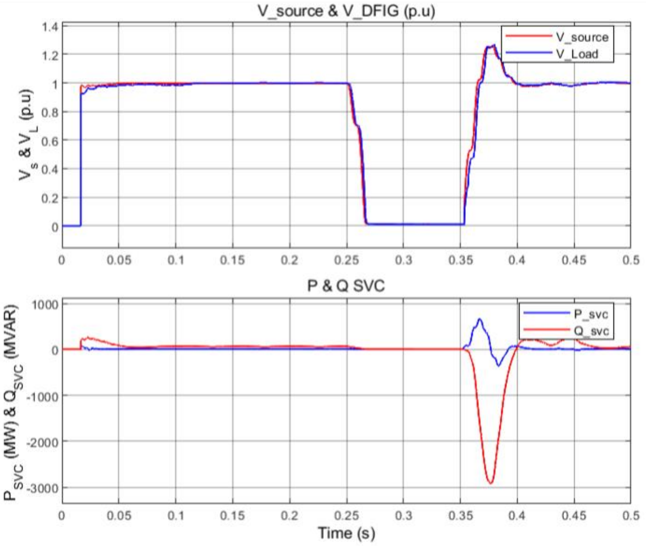


Fig. 12. Effective Source and DFIG Voltages - Active and Reactive Power Injection by SVC When Three Phase Fault Occurs

DFIG voltages along with the UPQC injection and reactive powers are shown in Fig. 16.

B) *Simulation of short circuit fault at the terminal of one of the wind turbines*

In this part, it is assumed that a three-phase symmetrical short circuit fault occurs on the side of one of the two installed wind turbines. Under these conditions, the desired wind turbine, whose terminals are directly short-circuited, is tripled a few milliseconds later to avoid dangerous consequences. It is assumed that adjacent wind turbines connected to a common bus have fault compensation devices. Under these conditions, the voltage of the terminals of adjacent generators must be controlled so as not to decrease or increase the voltage or overcurrent. In the following, all three mentioned types of equipment will be examined under these conditions.

- **Performance of SVC**

Fig. 17 shows that despite the injection of reactive current by the SVC, no improvement in DFIG voltage is observed. It can be seen in Fig. 18 that despite the considerable reactive power injection by the SVC, it does not generate any voltage compensation at the DFIG terminal.

- **Performance of D-STATCOM**

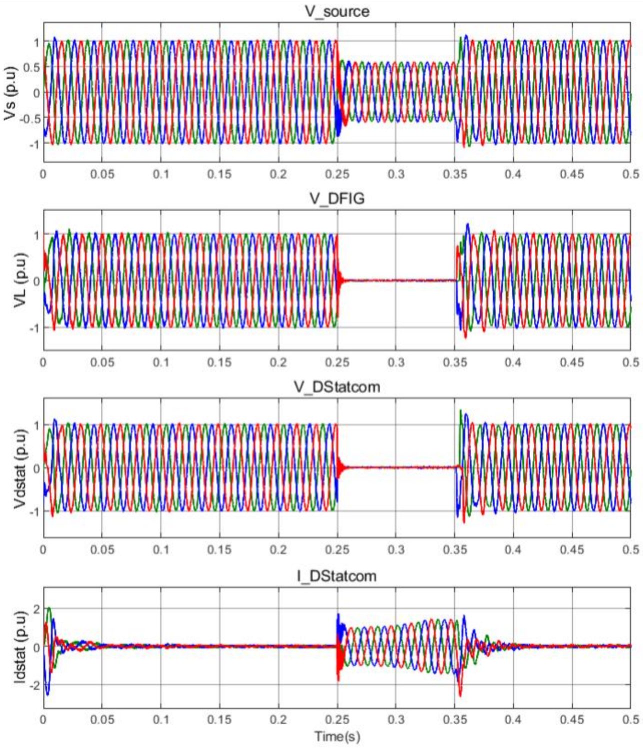


Fig. 13. Source and DFIG voltages when a short circuit occurs on the source side

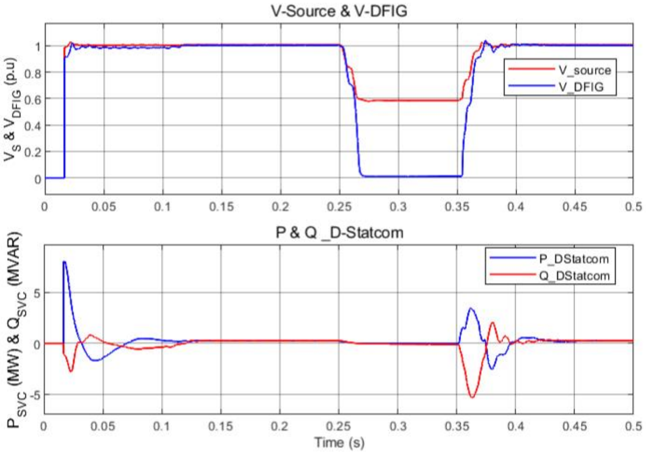


Fig. 14. Three-phase fault compensation by D-STATCOM - effective source voltage and DFIG with D-STATCOM injection power

Fig. 19 shows how to compensate for a three-phase fault in the terminal of one of the DFIGs. Despite the low amplitude of the fault current and the injection of reactive current by D-Statcom, no compensation is provided by D-Statcom. Also, Fig. 20 shows how to compensate for the effective voltage of DFIG along with active and reactive injection powers. Despite D-Statcom's injection of nominal reactive power of 6 MW, there is no voltage compensation, and as a result, both turbines will trip and go out of the circuit immediately after the fault occurs.

1) **Performance of UPQC**

Finally, to demonstrate the ability of UPQC to compensate for short circuit faults at the terminals of one of the DFIGs, a similar simulation is presented in Fig. 21. Under these conditions, it can be seen that despite the maximum voltage drop on the grid side due to a severe short circuit fault, the DFIG voltage equipped with UPQC is within its allowable value and therefore this turbine will

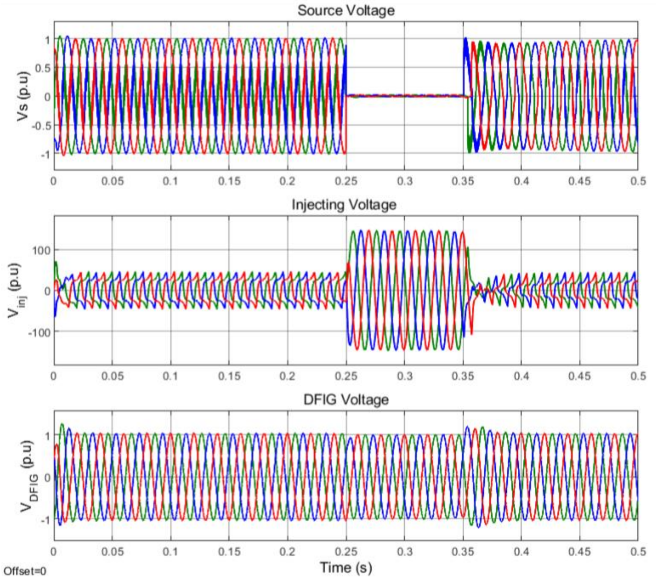


Fig. 15. Power loss minimizations in 3-phase PI lines power system network

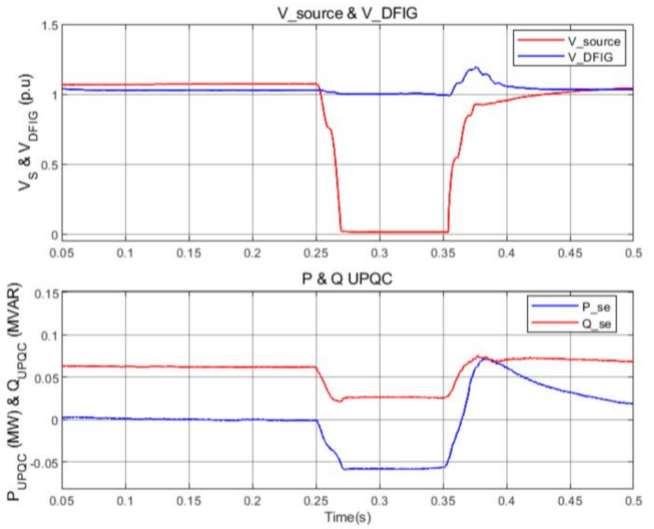


Fig. 16. Power loss minimizations in 3-phase CP lines power system network

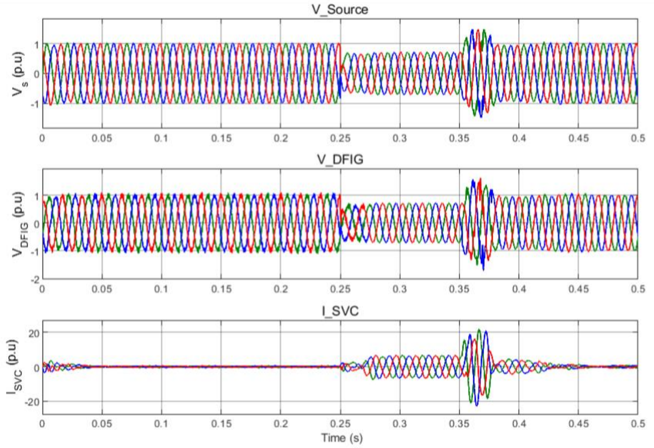


Fig. 17. Three-phase fault compensation at one of the two DFIG terminals by SVC - source voltage, DFIG voltage, and SVC current

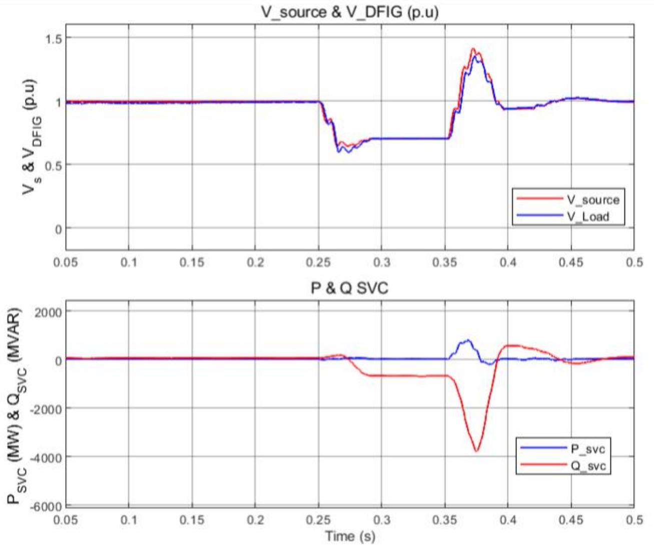


Fig. 18. Effective source and DFIG voltages with SVC injection power to compensate for a three-phase fault in one of the wind turbine terminals

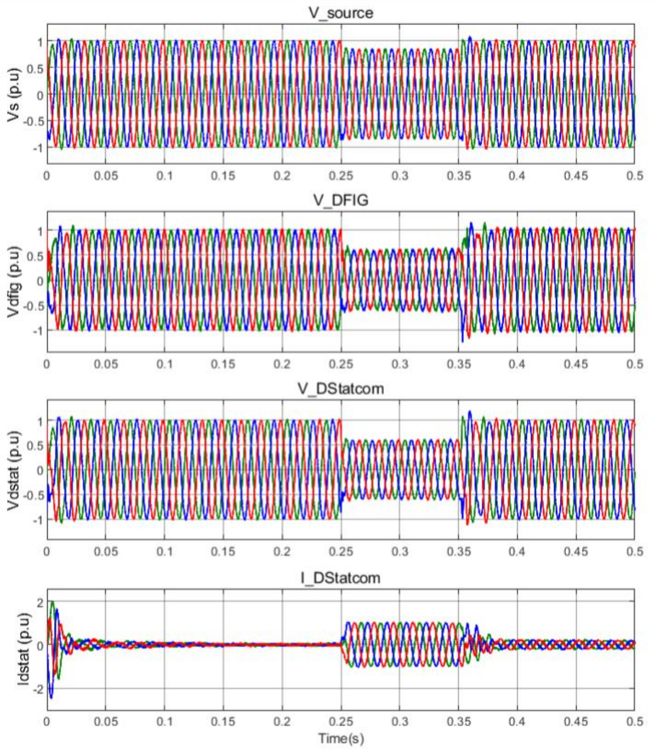


Fig. 19. Three-phase fault compensation at one of the two DFIG terminals by D-Statcom - source voltage, DFIG, and D-STATCOM voltage and D-STATCOM injection current

not be tripped. The power required to compensate for the fault current is absorbed by the UPQC parallel filter from the network and will be provided to the series filter by DC link capacitors. The high currents of the active shunt filter may enter the network with some harmonic.

Fig. 22 presented to better understand the amount of DFIG voltage compensation and the amount of active and reactive power injection by UPQC. It is observed that the effective voltage of DFIG during a severe fault in the adjacent turbine remains in the amount of 1 P.U, while the active power absorbed by the system is about 50 kW and the reactive power is about 10 kW. Under these conditions, the wind turbine is not tripped and continues to

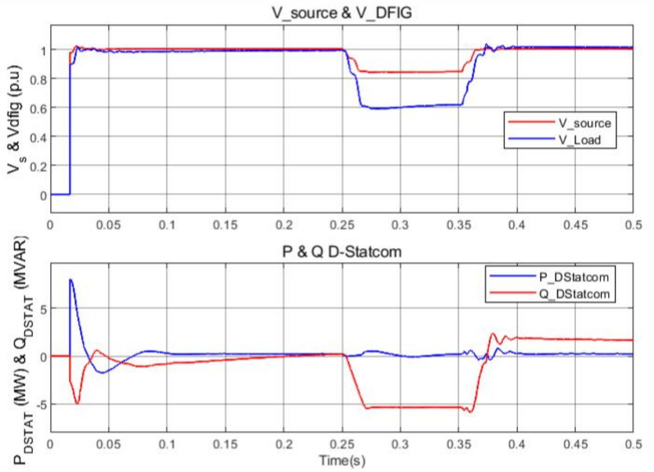


Fig. 20. DFIG and source effective voltage waveforms with active and reactive power injections when compensating for three-phase fault by D-STATCOM

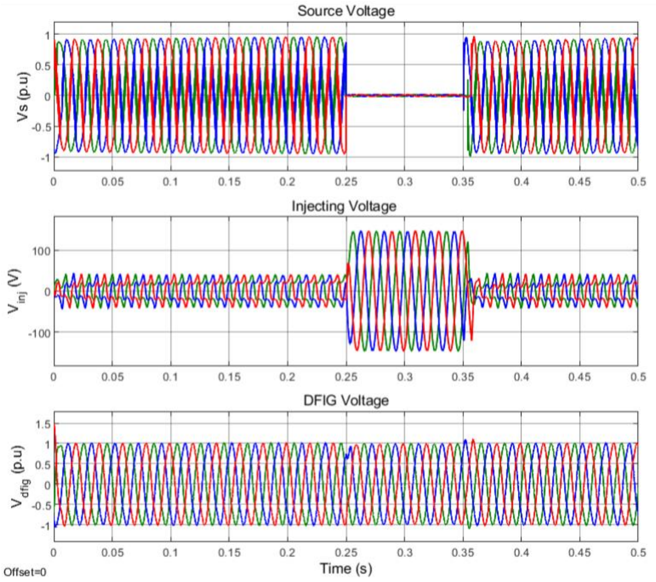


Fig. 21. How to compensate for a three-phase fault in the terminal of one of the DFIGs by UPQC - Source voltage, DFIG series filter injection voltage, and DFIG voltage compensated

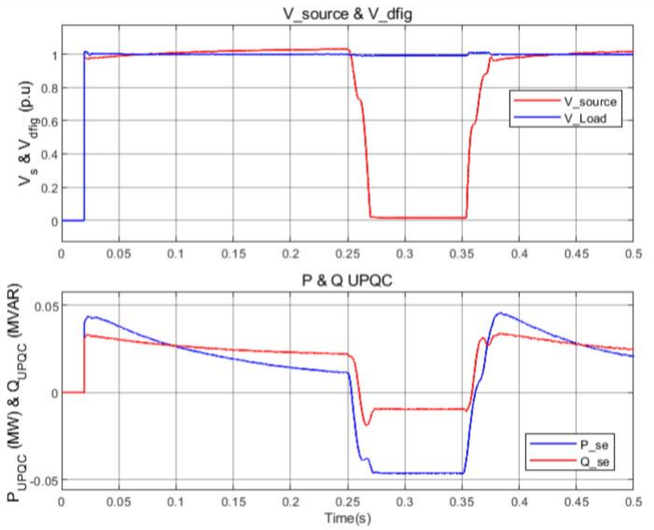


Fig. 22. How to compensate for three-phase faults by UPQC by providing effective source and UPQC voltages and injectable active and reactive powers during compensation

Table 7. Summary of the obtained results

Reference	Compensation of voltage increase/decrease) with amplitude 20%	Compensation of harmonic (%)
Jyothirmai et al [31]	90	4.53
Vinothkumar and Kanimozhi [32]	98.3	1.67
Amini and Jalilian [33]	96	-
Dheeban and Muthu Selvan [34]	100	2.74
Results in this study	100	1.47

operate normally.

The summary of the results obtained in this research and other authors is given in the Table 7. As can be seen, the results of the voltage drop and harmonic compensator have been presented in previous studies. With a comparison, it can be seen that the results of this research were more effective in compensating the voltage drop and removing harmonics and obtained better results.

5. CONCLUSIONS

In this paper, the performance of electric power quality compensators to compensate for power quality phenomena such as decreasing and increasing voltage and harmonics was introduced and analyzed through time domain simulations. Three compensators including static reactive power compensator (SVC), reactive power synchronous compensator for distribution system (D-Statcom), and Unified power quality modifier (UPQC) were studied. In order to investigate and analyze the compensation devices to compensate for voltage disturbances, various simulations were performed with the presence of DFIG-based wind turbines.

The simulation results showed that with the presence of DFIG, the amplitude of the compensation voltage by the mentioned devices is improved to an acceptable level. Also, using UPQC compared to SVC and D-Statcom to compensate for voltage disturbances as well as limiting and compensating for short circuit faults in the network is more useful and effective. Some important results obtained in time domain simulations are presented:

- Compared to SVC and D-Statcom, UPQC has a very good performance in compensating for voltage drop and gain. Also compensates for relatively deep voltage drops and increases, and maintains a load voltage of 1 P.U in the event of a fault. Using UPQC in the network was able to compensate for 100% of voltage drop and voltage increase in the network, while svc and D-Statcom equipment in the best case compensated for 98% of voltage increase and 90% of voltage decrease.
- By using network-connected DFIG due to DFIG's involvement in injecting or absorbing active and reactive power with the network, the compensation capacity of SVC and D-Statcom can be somewhat improved. Therefore, the load voltage and even the voltage of the DFIG terminals themselves are almost completely compensated by SVC and D-Statcom.
- The simultaneous use of UPQC and DFIG has little effect on compensating the load voltage and voltage of DFIG terminals because UPQC can maintain the voltage of load terminals and DFIG at 1 P.U with or without DFIG. However, the presence of DFIG reduces the injection power of UPQC and reduces the capacity.
- To compensate for harmonic current distortion due to

nonlinear loads, UPQC is much more efficient than SVC and D-Statcom and can reduce the THD current and voltage of the network and source to the standard value. The simulation results showed that the harmonic distortion of the network current when using UPQC is 1.47%. While the harmonic distortion of network current with SVC and D-Statcom is 5.67 and 4.87 percent, respectively.

- The results showed that UPQC has a very high ability to protect wind turbines in the event of an error compared to compensating svc and D-Statcom instruments. There was no change in wind turbine voltage during the use of UPQC and faults, and 1 P.U remained constant, but when using svc and D-Statcom equipment, the wind turbine voltage during the fault decreased by 0.3 and 0.5 P.U respectively.

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