

Performance Analysis of UPFC and DPFC in a Grid-Integrated Hybrid Solar–Wind System



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Abstract In this work, a relative inspection is performed with distributed power flow controller (DPFC) and unified power flow controller (UPFC) connected to a solar–wind hybrid system. The hybrid system consists of dual sources for renewable energy as solar and wind. Solar generation system followed by a boost converter is useful to raise the level of DC power from the solar energy. On the other hand, wind generation system followed by a diode rectifier and boost converter amplifies the energy received from wind source. Now DC obtained from both the sources is coupled to a common DC bus to get the DC link voltage which eventually is applied as input to the grid side two-level voltage source inverter (VSI). The grid side demands control actions and monitoring perfectly due to the presence of distortions, noise, power losses, etc. Reactive elements reduce these problems up to a certain extent, but it increases the possibility of sub-synchronous resonance phenomenon and extra inductive and capacitive losses. Moreover, the power factor is also affected considerably. Thanks to the emerging FACTS technology, which controls as well as increases the utilization of transmission lines to its full thermal limits. Unified power flow controller (UPFC) is one of the latest FACTS devices available today. It controls the power flow through the lines by varying line inductances, transmission angles and voltage magnitude. The disadvantage of UPFC is its immensely high rated three-phase series–shunt converters and the increased ripple content in output grid voltages and currents. These problems are overcome by a newly invented FACTS device, namely distributed power flow controller (DPFC), which uses small single-phase series and shunt converters. The paper studies the effect of incorporating UPFC and DPFC to hybrid solar–wind system. Additionally, working principle of both the devices was presented. At the end, results from MATLAB simulation are used to support the claim of DPFC being superior to UPFC.

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1 Introduction

It is very well known and well documented that the emissions due to carbon combustions are affecting the environment at a global scale [1]. Global warming and fossil fuel depletion are forcing to change the focus from thermal-based generation to renewable-based generation [2]. It is clearly noted by the International Renewable Energy Agency the increase in production of power by renewables in the twenty-first century. It is also stated that the overall production of wind energy has gone up to 487 GW, which is 7 times the amount it was ten years ago. The overall production of solar system also increased up to 302 GW, which is 43 times as it was ten years ago. Developing countries are also setting up renewable targets to improve their overall power at the grid level. China is one of the leading countries as far as renewable power generation is concerned. In China by the end of the year 2016, the total photovoltaic power and wind power capacity was around 77.42 and 168.69 GW, respectively [3]. European countries are not far behind. European Union (EU) has a target in mind to reach power production using renewables by 20% of its total energy consumption by the year 2025. The European nation Germany has further ideas of reaching renewable use up to 30% by 2020 and 60% by 2050 [4].

Out of all the renewables in market, solar, wind and hydro power are the most dominant ones. With decreasing day-to-day cost of these technologies, it is now easily available with the common people. These renewable technologies, especially solar and wind, are called variable renewable energy (VRE), and in the coming years, these will be dominant over the conventional sources as well. In the past decades, many researches were performed on renewable systems, especially to increase the overall efficiency of the whole system. On view of this, the hybrid generation system came up the market. In [5], the behaviour of hybrid solar–wind generation system is analysed. The authors stated that the complementary nature of these two sources makes them the best choice for co-generation or hybrid generation. Both solar and wind systems completely depend on weather conditions. They are present in abundance, non-polluting and free of cost available, which makes it perfect alternative to the existing conventional sources. The hybrid generation system can feed power to the main grid as a grid-integrated system or it can work independently supplying power to a load. During independent operation, the voltage and current have to be according to the rating of the load. In case of grid integration, the voltage and current should be according to the grid standards [6]. So both the operations deal with challenges. [7] described the issues with grid integration of renewable sources. The authors focused mainly on power quality issues which emerge due to penetration of renewable sources. With arising power quality issues, changes in fault level also occur. Different positioning of renewables at the line results in different fault levels and hence different protection schemes [8]. Another approach performed in

[9] concluded that voltage fluctuations, frequency fluctuations and harmonic distortions are very common problems in grid-connected system. As defined by IEEE std. 929–2000, voltage flicker, frequency fluctuation and harmonic distortion are the major factors to affect the power quality of a grid-connected renewable system. In other words, monitoring of power at the output side is appreciable. In the process, transmission lines have a major role to perform, which opens up ways for flexible AC transmission system (FACTS) to improve the power level and to mitigate some of the problems mentioned above.

The most dominant and popular FACTS device was introduced in [10], namely unified power flow controller (UPFC). The incredible capability of this device was to control all parameters of transmission lines in order to control the power flow through it. It can control the voltage magnitude and angle as well as the transmission angle. The authors also discussed some disadvantages of UPFC, firstly, the complexity. Two high rated three-phase converters are joined using a common DC link. Secondly, the device is not portable; there should always be a connection between the two converters for complete operation. In the year 2010, Yuan et al. [11] introduced yet another FACTS device, namely distributed power flow controller (DPFC), which according to the authors is an advanced version of UPFC. The function and capability of DPFC are same as that of UPFC, but the operation is quite different. It uses small rated single-phase full wave converters. Moreover, the connection between series and shunt converters is not present which makes installation and upgradation very easy. It also uses the third harmonic frequency component for the power flow control operation. The paper starts with the main system model in Sect. 2. The next two Sects. 3 and 4 deal with the operating principles of UPFC and DPFC, respectively. Section 5 presents the results obtained from MATLAB/Simulink and observations. Section 6 consists of the paper conclusion followed by Acknowledgement and References.

2 System Description

2.1 Photovoltaic System

The solar generation system rated at 1000 W consists of a solar panel, followed by perturb and observe (P&O)-based DC–DC boost converter. The solar panel used is Mitsubishi PV with only parallel connected module and five number of series connected module. The detailed specifications are shown in Table 1. The VSI is controlled using state vector pulse width modulation (SVPWM) technique [12]. The VSI controller takes voltage at grid V_g , current at grid I_g and DC link voltage V_{dc} as the inputs and correspondingly generates six pulses to maintain the DC link voltage constant at the given reference quantity.

Table 1 Uncompensated source-side system parameters

Variable	Values
PV OC voltage(V_{oc})	30.8 V
PV SC current(I_{sc})	8.23 A
Maximum power(P_{max})	200 W
DC link reference(V_{dc})	500 V
Transformer rating	440 V/25 kV, 1000VA, 50 Hz
Grid voltage	25 kV
TSR	0.2
Cpmax	0.59
Torque constant (PMSG)	0.912
Wind speed	12 m/s ²
No. of phases (PMSG)	3
Pole pairs (PMSG)	2
Inertia	25 kgm ²
Viscous damping	0.0003035
Vdc link capacitor	4000uF
L filter	0.135 H
R filter	0.001 Ω

2.2 Wind Energy System

Wind energy conversion system consists of direct-driven permanent magnet synchronous generator (PMSG) with a turbine followed by a diode bridge rectifier to convert alternating quantity (AC) into direct quantity (DC) and a DC–DC converter to track the maximum power at an enhanced output voltage level. In order to track maximum power, a simple perturb and observe (P&O) algorithm is utilized due to its simplicity and reduced complexity. The values of PMSG which has been utilized in the system are shown in Table 1. The enhanced DC output of the chopper is directly connected to the main DC link point or the point of common coupling of the solar system, resulting in the hybrid model (Fig. 1).

3 Unified Power Flow Controller

Unified power flow controller abbreviated as UPFC belongs to the category of combined devices. Two three-phase converters make the most part of it. The converters are joined in continuation using a DC link. The series converter injects desired voltage of desired magnitude and angle to the line. The DC link is used to transfer the active power from the shunt converter to the series converter. Subsections explain the detailed working of both the series and shunt controllers.

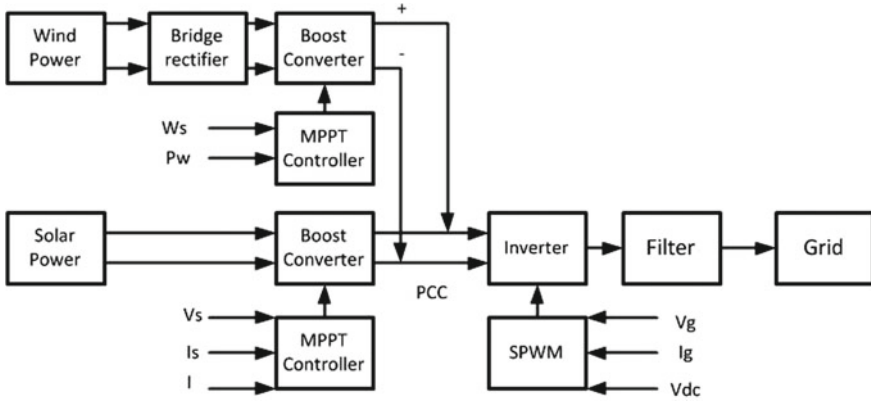


Fig. 1 Block representation of the entire system

3.1 UPFC Shunt Controller

The shunt controller functions like a normal static shunt compensator (STATCOM). Its main function includes charging of the DC link capacitor voltage, which could be utilized by the series converter for its own operation and maintaining constant voltage at the point of connection. It accepts V_{dcref} (desired value for DC capacitor voltage) and V_{lref} (the desired value for line voltage) as references. The error term of V_{dcref} with DC voltage (V_{shdc}) is regulated using PI controller which gives result I_{dref} . Likewise, I_{qref} equals to the output obtained using tuned PI controller, regulating the inaccuracy between desired voltage and grid voltage.

3.2 UPFC Series Controller

The series control utilizes the voltage stored by the capacitor to inject the power quantities in accordance with the references as depicted in Fig. 2. The system provides two references: P_{ref} and Q_{ref} . With the help of conventional PI tuner, I_{dref} and I_{qref}

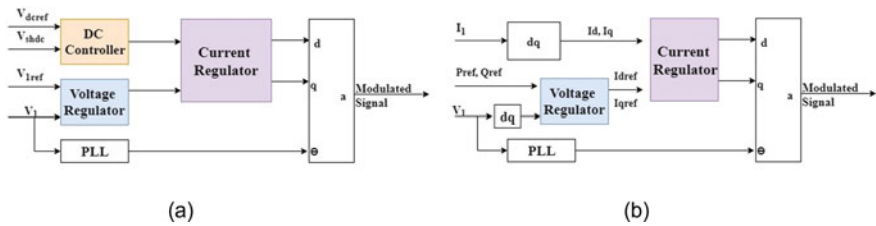


Fig. 2 Controller diagrams of UPFC a series, b shunt

(current references) can be obtained by utilizing values of P_{ref} , $V_{d,g}$, Q_{ref} and $V_{q,g}$ as shown by Eqs. (1) and (2):

$$I_{dref} = \frac{(V_d * P_{ref}) + (V_q * Q_{ref})}{\sqrt{(V_d)^2 + (V_q)^2}} \quad (1)$$

$$I_{qref} = \frac{(V_q * P_{ref}) - (V_d * Q_{ref})}{\sqrt{(V_d)^2 + (V_q)^2}} \quad (2)$$

4 Distributed Power Flow Controller

Distributed power flow controller (DPFC), proposed in [11], is a modified variety of unified power flow controller (UPFC). It is basically the combined result of UPFC and DSSC or distributed static series controller [13]. The idea is to upgrade the UPFC in such a way that the new device overcomes all the disadvantages of UPFC.

The DC link connection between shunt and series converter in UPFC acts as a constraint for further upgradation. Hence, the DC link is eliminated to increase flexibility of the system. The high-voltage transmission line itself is used as the connection path between shunt and series converter. The interesting fact which makes DPFC different from other devices is the use of the third harmonic current component. The DPFC set-up comes with a pair of star–delta transformers. These transformers are used to inject third harmonic component in the line and later reject the harmonic component through it. The reason for using third harmonic and not the other higher harmonics is the fact that it can be easily filtered out from the line using a low-pass filter. The low-pass filter can be eliminated using the star–delta transformer itself. As delta appears to be open for the third harmonic component, joining the neutral of star to ground actually passes the entire third harmonic component to the ground. Moreover, the line inductances are also lowered using third harmonic and not the higher harmonics. Another problem of UPFC is its high rated converters. This problem is solved using multiple small rated series converters. The number of series converters depends on the desired real and reactive power. UPFC faces another problem as if any one of the converters becomes useless, the operation is stopped. In case of DPFC, all the converters have separate control blocks and separate capacitors, that is why the failure of one will not affect the operation of the other converters. The structure of DPFC is shown schematically in Fig. 3.

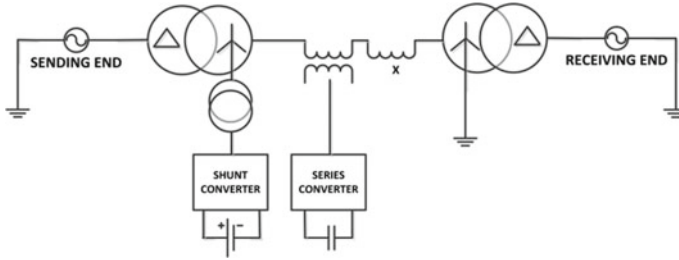


Fig. 3 Schematic diagram of DPFC

4.1 DPFC Shunt Controller

The shunt controller performs at third harmonic frequency. Its main function is to support the working of series converters. The block diagram of shunt control structure is shown in Fig. 4. Its main work is to deliver the third harmonic component, which will be utilized for charging the series capacitors. The controller accepts two references: the third harmonic direct axis reference and third harmonic quadrature axis reference as I_{d3ref} and I_{q3ref} , respectively. A single-phase coupling transformer is also used through which the third harmonic current is injected into the neutral of the star–delta line transformer. The injected current is broken into its corresponding dq parameters (I_{d3} and I_{q3}) using single-phase abc to dq transformation block. The actual dq components I_{d3} and I_{q3} are compared with the references I_{d3ref} and I_{q3ref} for getting the V_{d3}^* and V_{q3}^* . The angle ωt is obtained through a PLL block and is multiplied with a gain of 3 for getting the required $3\omega t$. These three parameters V_{d3}^* , V_{q3}^* and $3\omega t$ give the modulated signal using single-phase dq to abc transformation.

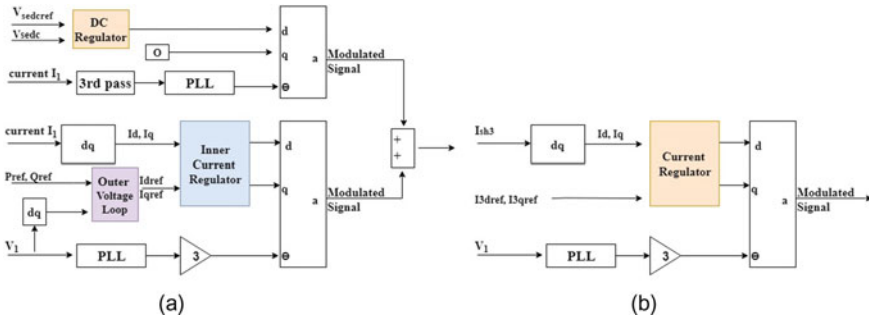


Fig. 4 Schematic diagrams of DPFC controllers **a** series controller, **b** shunt controller

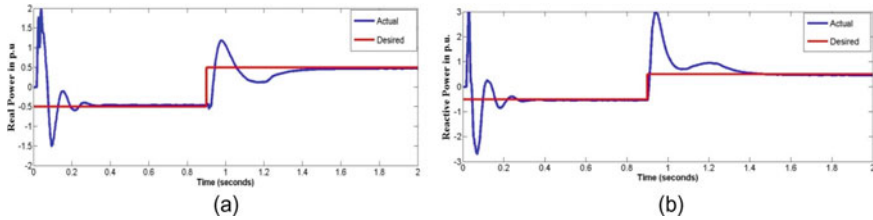


Fig. 5 Power tracking using UPFC **a** real power, **b** reactive power

4.2 DPFC Series Controller

The series converter performs the main function of DPFC, i.e. the control of power flow through the line. The series converter in DPFC is a standard four switch full controlled single-phase converter. The series converter is connected with the transmission line through a single-phase coupling transformer. The converter performs two actions: firstly, it charges its own capacitor, i.e. acts as a rectifier, and secondly, it injects the desired voltage which in turn affects the power parameters, i.e. it also functions as an inverter. The third harmonic content in the line is utilized for charging the capacitor. At the same time, it injects the required voltage at fundamental frequency. As the function is performed at two different frequencies, two different control structures are needed. The modulated signals from both the controllers are added to get the final modulated signal for the series converter. The controller implements vector current control strategy. The control structure of the series converter is shown in Fig. 4.

The third harmonic frequency control charges the capacitor up to the reference voltage value $V_{dc\text{ref}}$ as given by the operator. The actual voltage V_{dc} and reference voltage $V_{dc\text{ref}}$ are compared, which gives the error signal. The error signal is passed through a PI tuner which gives the V_d^* . The V_q^* is kept zero. The line current (i) contains 50 Hz signal as well as 150 Hz signal. As this is the third harmonic frequency control, the line current (i) is filtered out using a high-pass filter, to get the third harmonic content of the line. The output of HPF is passed through a single-phase phase-locked loop (PLL) which gives phase angle $3\omega t$. The three components V_d^* , V_q^* and $3\omega t$ act as the input for single-phase dq to abc transformation block. This transformation block generates the modulating signal for third frequency control. The fundamental frequency control's primary function is to inject required voltage of desired magnitude and angle into the line, which in turn controls the real and reactive power flow through the line. It follows the direct power control (DPC) strategy. The references are given as real power reference (P_{ref}) and reactive power reference (Q_{ref}). The input voltage of DPFC, in this case the output voltage of the inverter, is broken into its corresponding dq parameters [14].

Table 2 Uncompensated grid-side system parameters

Parameters	Values
Vgrid (kV)	25
Igrid (amps)	0.03
Vinv (volts)	440
Iinv (amps)	5.58
Real power (p.u)	0.71
Reactive power (p.u)	0.38
Voltage THD (%)	4.42
Current THD (%)	5.02

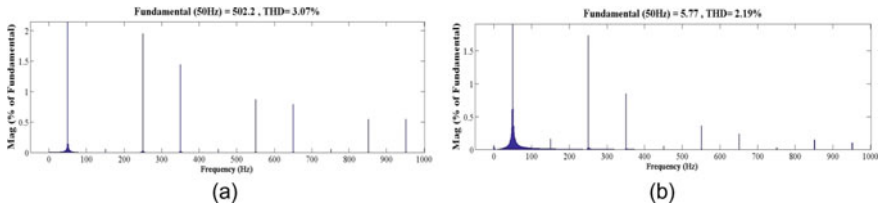


Fig. 6 Total harmonic distortion with UPFC **a** line voltage, **b** line current

5 Results and Discussion

The results for uncompensated system are depicted in Table 2. Uncompensated system means the FACTS devices (UPFC and DPFC) are connected but are not enabled. It is observed that the real power rests at around 0.71 p.u and the reactive power at 0.98 p.u. The voltage and current THD are 4.42% and 5.02%, respectively.

The FACTS is connected after the grid side main inverter. The targets of reactive and real power are taken as -0.5 p.u. and 0.5 p.u. For UPFC shunt controller, $K_P = 1.2$ and $K_I = 400$. For series controller, $K_P = 0.3$ and $K_I = 22$. V_{1ref} is 1 p.u., and V_{dcref} is 500 V. Likewise, DPFC comprises a shunt converter and a set of three series converters. The variables for shunt controller are as follows: $I_{shref3} = 3$ A and K_p , K_I values are 0.05 and 0.5 , respectively. Similarly, for the series controller, $V_{sdcref} = 50$ v, power references V_{ref} and I_{ref} are -0.5 and 0.5 p.u. K_p and K_I values are 0.5 and 20 , respectively. The results are depicted from Figs. 6, 7 and 8.

6 Conclusion

The conclusions of the study are drawn based on the total harmonic distortion and power tracking capabilities of both the devices. Table 3 presents the detailed simulation results obtained through MATLAB/Simulink platform. The uncompensated

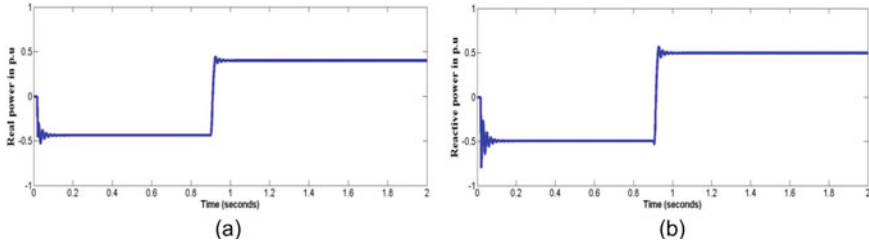


Fig. 7 Power tracking using DPFC a real power, b reactive power

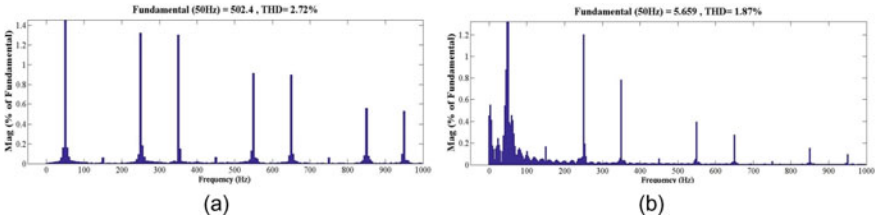


Fig. 8 Total harmonic distortion with DPFC a line voltage, b line current

Table 3 Line powers and THD results

Parameters		UPFC	DPFC
Real power	Ref: -0.5	-0.46	-0.49
	0.5	0.44	0.44
Reactive power	Ref: -0.5	-0.55	-0.48
	0.5	0.46	0.49
Voltage THD (%)		3.07	2.72
Current THD (%)		2.19	1.87

voltage and current THD were 4.42% and 5.02%, which is reduced using UPFC to 3.07% and 2.19%, respectively, and further reduced using DPFC to 2.7% and 1.8%, respectively. In addition, the paper also describes the control structure and working of the power controllers in detail. At the end of the analysis, it is clear that DPFC outperforms UPFC in accuracy as well as robustness.

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