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WECS Fed Unified Power Flow Conditioner for Solving PQ Issues with Crow Search Algorithm

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Abstract: As non-linear loads are used in a greater amount, the electric power system faces serious issues affecting the Power Quality (PQ). Among the various PQ issues, this article addresses the issues like voltage, sag, swell and harmonics; UPFC (Unified Power Flow Conditioner) is utilized for solving such issues. In UPFC, the shunt and the series converters are interfaced together with a common dc-link. Integrating renewable energy with UPFC results in clean energy generation and also improvises the load side PQ. Here UPFC is integrated with WECS in which DFIG (Doubly Fed Induction Generator) is used as generator and Crow Search (CS) algorithm is utilized for retaining the WECS output. The shunt and the series converters are regulated with the assistance of cascaded fuzzy, and d-q theory is used for the generation of reference signal. The proposed work is simulated in MATLAB and the results were analysed in two cases; it has been revealed that the proposed work stands good in solving the PQ issues like harmonics, voltage sag and swell along with the compensation of reactive power. The THD is also observed as 2.3% which falls within the IEEE standard.

Keywords: *Power Quality, WECS-UPFC, Shunt Converter, Series Converter, Cascaded Fuzzy, Crow Search Algorithm, DFIG, WECS.*

1. Introduction

In electric utility, the power electronic loads are more prominent due to various developments in semiconductor technology; it is also an important fact that these loads lead to non-linearity, which in turn results distortion in current and voltage at the PCC (Point of Common Coupling). In case, a milli-second fluctuation in the supply voltage leads to a major impact on the equipment, affecting the productivity and performance. So, it is essential to provide a quality power to the end user [1]-[2]. An efficient and reliable operation of the power system is accomplished only when there is no deviation of voltage and current magnitude from its nominal value; this is attained by the proper control of reactive power. For proper harmonic mitigation, PQ improvement and voltage stabilization, FACTS (Flexible AC Transmission Systems) are utilized which provides improvised stability and reliability; there are several FACTS devices which includes active and hybrid filters [3]-[4].

Different PQ issues solved using different FACTS devices are discussed as follows: TCSC (Thyristor Controlled Series Capacitor) is a series FACTS device which provides improved stability with better load sharing but there exhibits voltage instability [5]-[6]. Shunt Active Filters (SAF) are employed for improvising the PQ and there are different techniques to control the SAF like MPC (Model Predictive Control), Fuzzy, SMC (Sliding mode control) etc., [7]-[10]. Similar to SAF, D-STATCOM is also employed for harmonic mitigation by utilizing different controllers like SMC, MPC, Fractional order SMC etc [11]-[13]. DVR (Dynamic Voltage Restorer) has been employed for mitigating the harmonics for unbalanced grid settings by using CDSC (Cascaded Delay Signal Cancellation) [14]. In [15], ANC (Adaptive Noise Cancelling) technique has been utilized in DVR for compensating the harmonics and voltage. The voltage sags are compensated by employing DVR and D-STATCOM is employed for compensating both the reactive power and voltage sag, but these devices are suitable only for solving certain type of PQ issues [16]-[17]. These FACTS devices deal with the compensation of the voltage harmonics only, and so a device like UPFC

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is essential which compensates both the current and voltage harmonics; UPFC also improvises the system stability and minimizes the transmission losses and harmonics [18]-[19].

In UPFC, the shunt and the series converters are coupled by a dc-link; it is vital to control the link voltage and also to generate the reference signal, by which both the converters are being controlled. Choosing an effective reference theory is more essential and there are two aspects like time or frequency domain. The techniques like Fourier, p-q and d-q theories comes under time domain approaches. p-q theory is the simplest theory which is not suitable for1ϕ networks whereas the d-q theory is mostly used in many works for the generation of the reference current [20]-[21]. Integration of renewable energy (RE) with the UPFC assists in clean energy which is available anywhere. PV (Photovoltaic) energy is an abundantly available energy, which is facing issues related with intermittency and so wind energy is preferred in many cases; also, by using RE, the grid's PQ gets improved [22]. In WECS (Wind Energy Conversion Systems), there are different types of Generators being used, among which DFIG (Doubly Fed Induction Generators) is the commonly used generator. The DFIG results in better efficiency with generates good energy yield [23]-[24].

In this article, the PQ issues are solved by employing WECS fed UPFC, in which Crow Search (CS) algorithm is utilized for controlling the rectifier in WECS whereas the reference signal for UPFC is generated by d-q theory and the UPFC is regulated with the assistance of the Cascaded Fuzzy algorithm.

2. Proposed System

In UPFC, the series and the shunt converters are interfaced back-to-back by a common dc-link; UPFC regulates both the voltage and current; it also assists in compensating the reactive power. The layout of the proposed work is illustrated in the Figure 1.

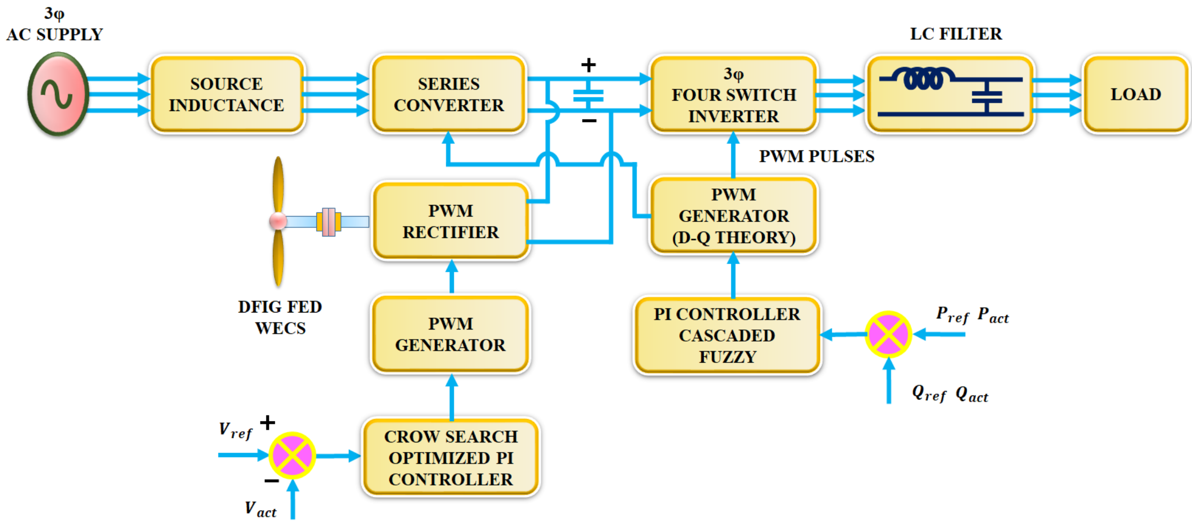

Fig. 1. Layout of the proposed work

The UPFC is fed by a DFIG based WECS, in which the DFIG assists in the conversion of rotational energy assessed from the wind. Again, another conversion is needed for feeding the WECS power to the UPFC, hence PWM rectifier is utilized. It is vital to retain the WECS output and so a PI controller is exploited whereas its parameters (K_p, K_i) are tuned with the assistance of CS algorithm. CS algorithm is chosen as it is easy to implement, resulting in accurate outputs with least parameters. The d-q theory is executed for extracting the reference signal and cascaded fuzzy is also employed, by which the two converters of the UPFC gets controlled. Hence an effective harmonic mitigation and sag/swell rectification are performed by using the proposed work. The modelling of the system components is given elaborately as follows:

2.1 DFIG based WECS fed UPFC

The UPFC has been employed for compensating the voltage disturbances and also it prevents the load current harmonics by which the PQ get enhanced. Shunt and the series are the two converters of UPFC which is illustrated in Figure 2. The series converter assists in the elimination of voltage-based distortions, whereas the shunt converter assists in the elimination of current based distortions. Both the converters are coupled back-to-back by the capacitor which is connected in between them.

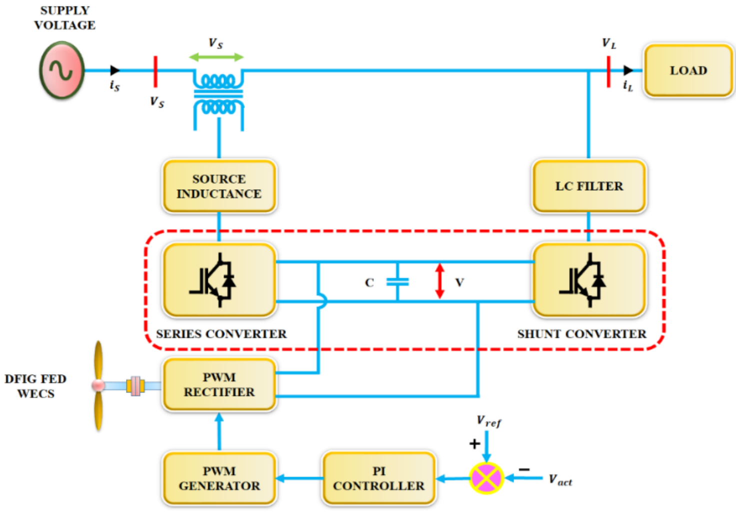

Fig. 2. UPFC-schematic illustration

The WECS comprises of a wind turbine, a generator and a PWM rectifier which assists in the AC-DC conversion. The aerodynamic torque (T_a) and the kinetic power P_a of the turbine are given as,

$$T_a = \frac{P_a}{\Omega_t} = \frac{1}{2\Omega_t}\rho S C_p(\lambda,\beta)V^3 \quad (1)$$

$$P_a = \frac{1}{2}\rho S C_p(\lambda,\beta)V^3 \quad (2)$$

Here, the Ω_t refers the turbine speed; the wind speed, air density, area covered by the blades, the efficiency are given respectively mentioned as V, ρ, S, C_p whereas $\rho = 1.225\ kg/m^3$

In DFIG, the dc-link of the UPFC is linked with the stator, whereas the rotor is linked with the generator and the DFIG's dynamic model is stated in arbitrary rotating frame. The voltage expressions for the stator and the rotor are given as,

$$\begin{cases} v_{ds} = R_s i_{ds} + \frac{d}{dt}\phi_{ds} - \omega_s \phi_{qs} \\ v_{qs} = R_s i_{qs} + \frac{d}{dt}\phi_{ds} + \omega_s \phi_{ds} \\ v_{dr} = R_r i_{dr} + \frac{d}{dt}\phi_{dr} - \omega_r \phi_{qr} \\ v_{qr} = R_r i_{qr} + \frac{d}{dt}\phi_{qr} + \omega_r \phi_{dr} \end{cases} \quad (3)$$

Here, the voltage, current, flux, resistance and electrical frequency are denoted respectively as , $i, \phi, , R\ and\ \omega$; the current and voltage are given separately for both the stator s and the rotor r whereas the reference frame components are mentioned as $d\ and\ q$.

The flux equation for $s\ and\ r$ are given as follows, in which the inductance and the mutual inductances are denoted as L and M respectively.

$$\begin{cases} \phi_{ds} = L_s i_{ds} + M i_{dr} \\ \phi_{qs} = L_s i_{qs} + M i_{qr} \\ \phi_{dr} = L_r i_{dr} + M i_{ds} \\ \phi_{ds} = L_r i_{qr} + M i_{qs} \end{cases} \quad (4)$$

For DFIG based WECS, the mechanical equation and the electromagnetic torque (T_{em}) are given as,

$$J\frac{d\Omega}{dt} = T_a - T_{em} - f\Omega \quad (5)$$

$$T_{em} = p\frac{M}{L_s}(\phi_{qs} i_{dr} - \phi_{ds} i_{qr}) \quad (6)$$

Here, the inertia, DFIG speed, pole pairs and damping coefficient are denoted respectively asJ, Ω, p and f. In the stator side, the active and reactive power are given as,

$$\begin{cases} P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \\ Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \end{cases} \quad (7)$$

The PI controller's transfer function is given as,

$$G_c(s) = \frac{U(s)}{E(s)} = \frac{K_p + K_i}{s} \quad (8)$$

The DFIG generates an AC output which is then fed to the UPFC via PWM rectifier after AC-DC conversion. The link voltage is controlled by employing a PI controller, in which CS algorithm is utilized for tuning the controller parameters(K_p, K_i).

2.2 CS Algorithm

This metaheuristic algorithm is designed based on the intelligent behaviour of crows and its memory. Among all the birds, crows are considered as clever as its brain size is bigger when analogized with its body size. Some of the common characteristics of crows are: Crows live in flocks; it has good memory; it has following nature for theft; also, it has good protecting ability. Based on these behaviours, the algorithm is framed for obtaining$K_p\ and\ K_i$. AP Is the awareness probability which is controlled to maintain a better balance among intensification and diversification. This algorithm holds well by lowering the value ofAP, to find an optimal solution by which intensification increases. The flow chart is highlighted in Figure 3 and the steps of CS algorithm are as follows:

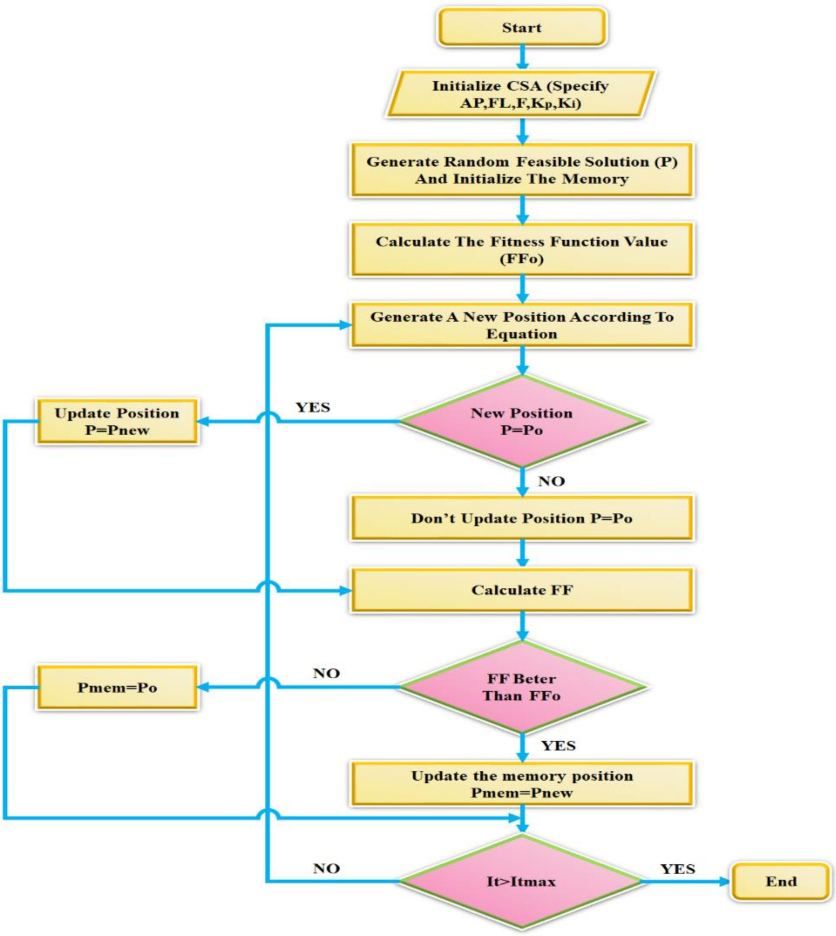

Fig. 3. Flowchart-CS algorithm

a) Generation of flock matrix

In this algorithm, every crow is considered as a possible solution and the matrix is framed based on the crow's number in a certain flock.

$$Crows = \begin{bmatrix} x_1^1 & x_2^1 & \dots & x_d^1 \\ x_1^2 & x_2^2 & \dots & x_d^2 \\ \vdots & \vdots & \ddots & \vdots \\ x_1^F & x_2^F & \dots & x_d^F \end{bmatrix} \quad (9)$$

Here the decision variables and the flock size are denoted as d *and* F respectively.

b) Parameters Adjusting

Specify the constraints, decision variables and problem; and the CS parameters like F, FL (Flight Length), AP,it_{max}(iterations number), K_p *and* K_i are initialized.

c) Initialize crow's position ($x^{i,it}$)

For i number of crows ($i = 1,2,\dots,F$) and it number of iterations,

$$x^{i,it} = [x_1^{i,it}, x_2^{i,it}, x_3^{i,it}, \dots, x_d^{i,it}] \quad (10)$$

d) Initialize crow's memory (mem)

Assume that the food is at the initial position, based on which the memory is initialized.

$$mem = \begin{bmatrix} m_1^1 & m_2^1 & \dots & m_d^1 \\ m_1^2 & m_2^2 & \dots & m_d^2 \\ \vdots & \vdots & \ddots & \vdots \\ m_1^F & m_2^F & \dots & m_d^F \end{bmatrix} \quad (11)$$

e) Compute the Fitness (f)

By computing the fitness value, the crow's position is defined for every row by including the decision variables.

f) Generate crow's new position

Based on a random crow j, the new position of the i^{th} crow is generated and then the i^{th} crow follows the j^{th} crow for the hidden food (m^j). Now the i^{th} crow's new position is given as,

$$x^{i,it} = x^{i,it} + r_j * f^{i,it} * (m^{j,it} - x^{i,it}) \quad (12)$$

Here, the random number is denoted as r_j and its range is [0,1].

g) Feasibility checking for the new position

A checking is done for updating the position, if possible, the position is updated or else the crow remains as such in its old position.

h) Compute fitness for the updated position.

i) Updating memory is based on the equation,

$$m^{i,it} = x^{i,it} * f(x^{i,it}) \quad (13)$$

The crow updates its position if the new fitness value (by equation 13) is better when analogized with the already memorized one.

j) Termination

The steps (e) to (h) are repeated until the iteration goes maximum or the optimal solution is reached. Based on this algorithm, the optimal values for the K_p *and* K_i are attained. Thus, the PWM rectifier's output is retained which is then fed to the UPFC.

2.3 Reference signal generation by d-q theory

d-q theory is also termed as SRF (Synchronous Reference Frame) theory, which is one the simple theories utilized for the generation of the reference signal. By this theory, the harmonics are extracted accurately from the distorted load currents which operates on the basis of the synchronously revolving d-q frame; the schematic of d-q theory is given in Figure 4.

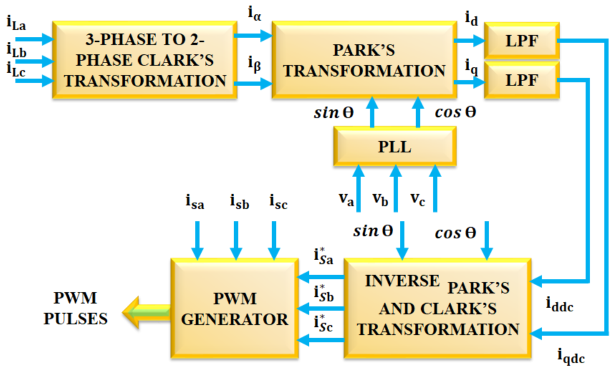

Fig. 4. d-q theory

The voltage (V_a, V_b, V_c) and currents $I_{L_a}, I_{L_b}, I_{L_c}$ are taken as the inputs; the PLL (Phase Locked Loop) process the voltage and thus generates cosine and sine signals. There occurs variation in the harmonic frequency, and so LPF is used and the PLL block is used for generating the angleθ. The step-by-step procedure for the d-q theory is given as follows:

1. The abc frame is transformed to $\alpha\beta0$ frame by Clarke's transformation,

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & -1/2 & 1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_{L_a} \\ I_{L_b} \\ I_{L_b} \end{bmatrix} \quad (14)$$

2. The $\alpha\beta0$ frame is transformed to abc frame by Park's transformation.

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} \quad (15)$$

3. This step's output has both DC and AC (harmonic) component and LPF is used to eliminate this harmonic component and so the equation without AC component is expressed as,

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \begin{bmatrix} \overline{I_d} & \widetilde{I_d} \\ \overline{I_q} & \widetilde{I_q} \end{bmatrix} \quad (16)$$

4. The algorithm is further processed for reverse transformation from $0dq$ to abc stationary frame in the following two expressions.
5. The reverse Park's transformation $(0dq\ to\ 0\alpha\beta)$ is achieved as,

$$\begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}^{-1} \begin{bmatrix} I_d \\ I_q \end{bmatrix} \quad (17)$$

6. The transformation from $(0\alpha\beta\ to\ abc)$ is done with reverse Clark's transformation as follows,

$$\begin{bmatrix} I_a^* \\ I_b^* \\ I_c^* \end{bmatrix} = \sqrt{2/3} \begin{bmatrix} 1 & 0 \\ -1/2 & \sqrt{3}/2 \\ 1/2 & \sqrt{3}/2 \end{bmatrix} \begin{bmatrix} I_\alpha^* \\ I_\beta^* \end{bmatrix} \quad (18)$$

Thus, the based on these transformations, the reference signal for eliminating the harmonics is being generated.

2.4 Control of UPFC by Cascaded Fuzzy Algorithm

FLC (Fuzzy Logic Controller) is an intelligent controller which works on the basis of rules and based on that the solution is obtained. By the cascaded FLC logic, the FLC logic gets simplified in which the output of one FLC is fed as the input for the next FLC. The illustration of cascaded FLC is given in Figure 5.

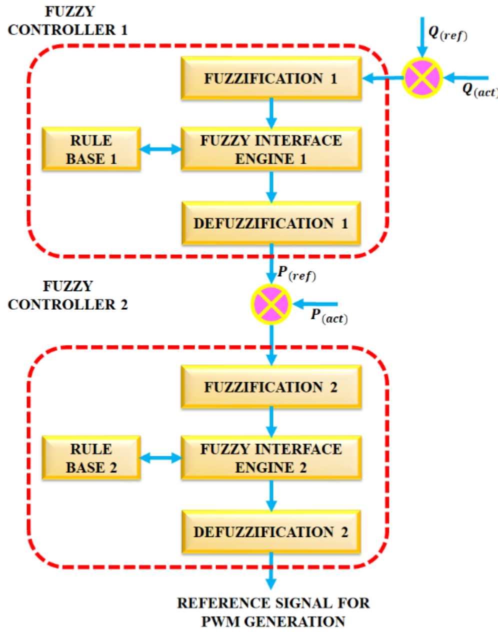

Fig. 5. Cascaded FLC

In FLC, fuzzify is the initial step, in which the given input is made as crisp values (between 0 and 1). In this step, the fuzzy subsets and the membership functions are defined. A rule base is created on the basis of the actual and reference values of the real and reactive power. Here, 7×7 rule base is framed. Based on the rules, the exact values are chosen and again defuzzified to get the real-world values.

Table 1. Fuzzy Rules

		Error (e)						
		NB	NM	NS	ZE	PS	PM	PB
Change in Error (ce)	NB	NB	NB	NB	NB	NM	NS	Z
	NM	NB	NB	NB	NM	NS	Z	PS
	NS	NB	NB	NM	NS	Z	PS	PM
	ZE	ZE	NM	NS	Z	PS	PM	PB
	PS	NM	NS	Z	PS	PM	PB	PB
	PM	NS	Z	PS	PM	PB	PB	PB
	PB	Z	PS	PM	PB	PB	PB	PB

It is assumed that at each input, the membership functions are equal. For M inputs and N membership functions, the number of rules R in the cascaded logic are framed as,

$$R = N^M \tag{19}$$

The cascading logic minimizes the overall rules framed and the number of layers (F) is given as,

$$F = \left[\frac{(M-1)}{(L-1)}\right] \tag{20}$$

Here L refers the inputs at each level and the resultant rules number CR is given as,

$$CR = F * N^M \tag{21}$$

By using cascaded FLC, both the shunt and the series controller are controlled, in which the actual and reference values of real and reactive powers are given as input. Based the on the changes in the load side, the gating sequence is generated for the control of both the converters.

3. Results and Discussions

The PQ enhancement is discussed elaborately in this article by employing various control techniques for each part. The proposed algorithms have better ability in solving the PQ issues like voltage swell and sag. WECS with DFIG has been utilized here and the PWM rectifier is controlled with the assistance of PI controller tuned with CS algorithm. The shunt and the series controller are controlled by employing cascaded FLC. The simulation is performed in MATLAB and the parameters are given in Table 2.

Table 2. Simulation parameters

Parameters	Values
Source Current	$0 - 30A$
Source Volage	$330 - 470V$
Load Resistance	100Ω
Load Inductance	$10mH$

The results are analysed for voltage sag and swell conditions and the detailed discussion is given in the following two cases:

Case (1) for step magnitude -0.3

The voltage sag is analysed in this section; at0.1s to 0.2 s, the sag is applied as displayed in Figure 6; the voltage is at 400V initially and once there is a sag, it is shown that the voltage is decreased; at this instant the current seems to be increased to 50A. The corresponding source current and voltage are also shown, in which there is a decrease in voltage and an increase in current; the corresponding power factor is also displayed in the figure.

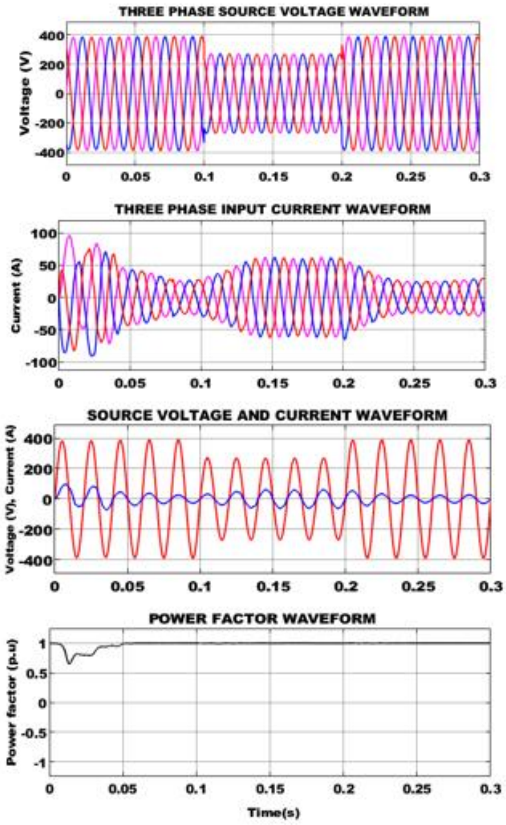

Fig. 6. Analysis of Voltage sag

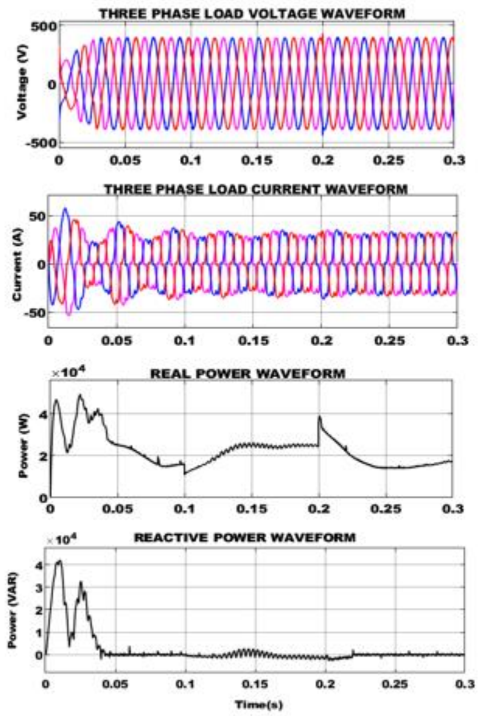

Fig. 7. Resultant waveforms after mitigating voltage sag.

The source voltage and current depiction shows PQ issues and so the system is analysed after the application of the proposed algorithms. The CS algorithm is executed for controlling the WECS output and the cascaded FLC for controlling the UPFC. Though the source parameters show voltage variations, the load current and voltage does not show any variations as in Figure 7. The voltage sag issue is not reflected in the load current and voltage depictions from$0.1s\ to\ 0.2\ s$; also, the real power falls to $2W$ whereas the reactive power nears zero, which implies that the real and reactive power compensation is also accomplished.

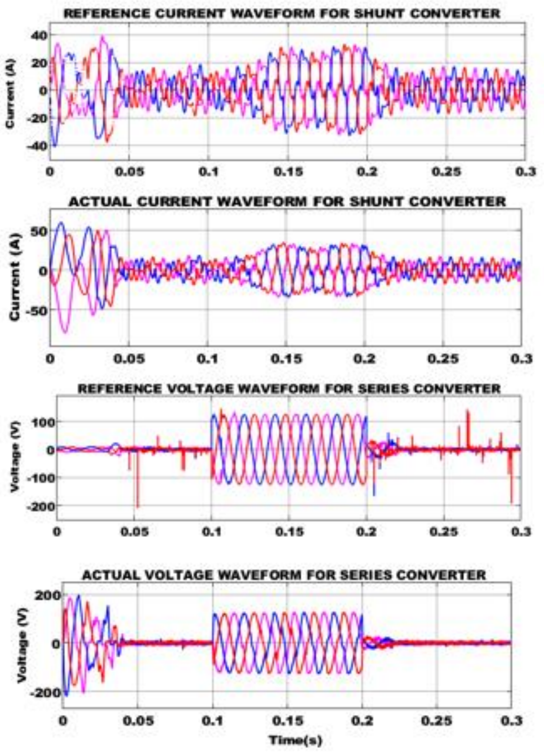

Fig. 8. UPFC parameters after mitigating voltage sag

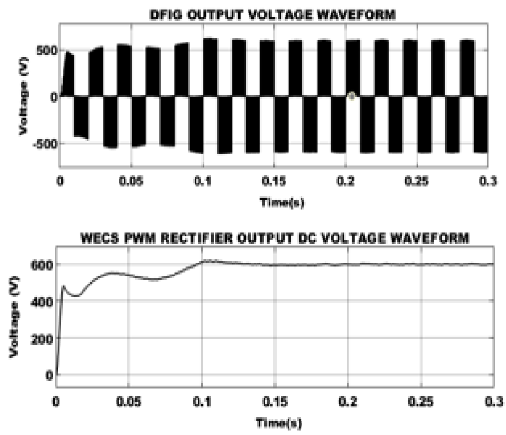

Figure 9. WECS parameters

The reference signal for UPFC is generated with the assistance of d-q theory, the actual, reference voltage and current illustrations are displayed in Figure 8. Figure 9 displays the DFIG's output and the PWM rectifier's output; the DFIG output is of square type and the voltage is from $+600V\ to - 600V$. After the AC-DC conversion by the PWM rectifier controlled by CS algorithm, the voltage is retained at 600V with a settling time of 0.25 seconds.

Case (II) for step magnitude +0.3

Similar to case (I), the voltage swell has been analysed in this section; from $0.1s\ to\ 0.2\ s$, there is a voltage swell and at this instant, the voltage reaches 500V and at the remaining instant the voltage is at 400V as given in Figure 10, which is also reflected in the current waveform. The source current and voltage for a single phase is given in the figure, which implies that both are in-phase delivering an unity power factor.

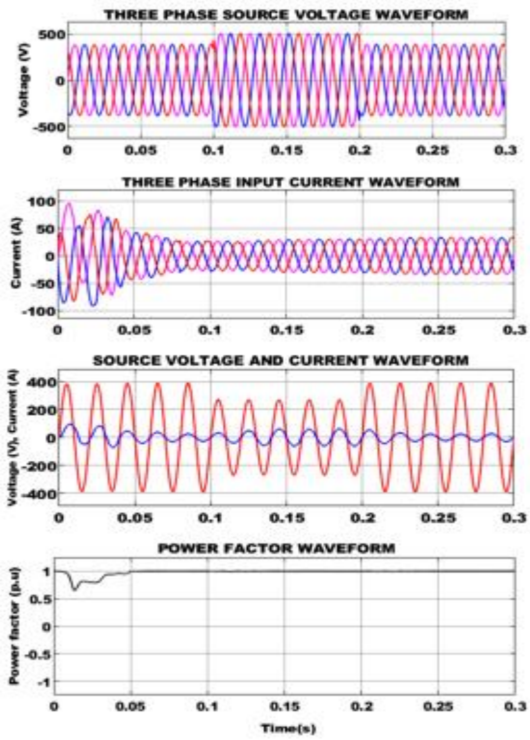

Fig. 10. Analysis of Voltage swell

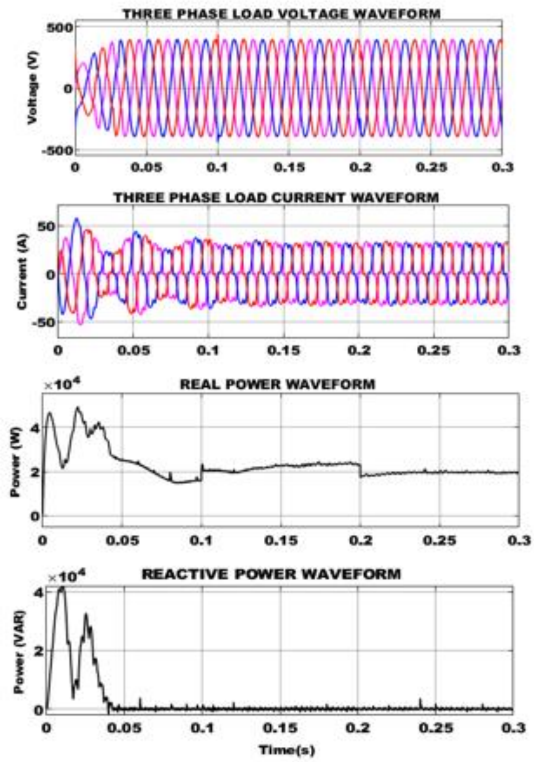

Fig. 11. Resultant waveforms after mitigating voltage swell

Though there is a voltage swell in the source side, Figure 11 suggests that the voltage swell is alleviated with the assistance of the proposed algorithms. The load voltage remains at 400V and the load current remains around 300V whereas the real power reaches 2W and the reactive power falls to zero ensuring the compensation of both the real and reactive powers.

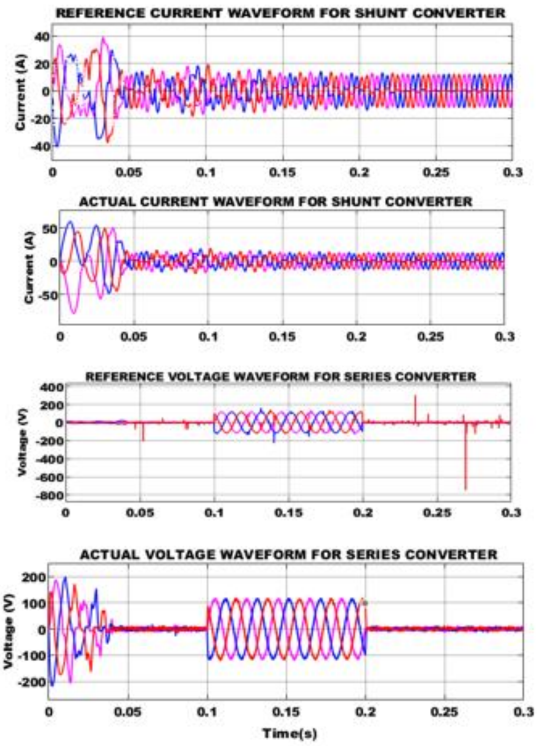

Fig. 12. UPFC parameters after mitigating voltage sag

After applying the d-q theory for reference signal generation and cascaded FLC, the generated signal and its actual signal for both the controllers are given in Figure 12. The figure reveals that the during $0.1s\ to\ 0.2\ s$, the reference and actual voltages has some variations.

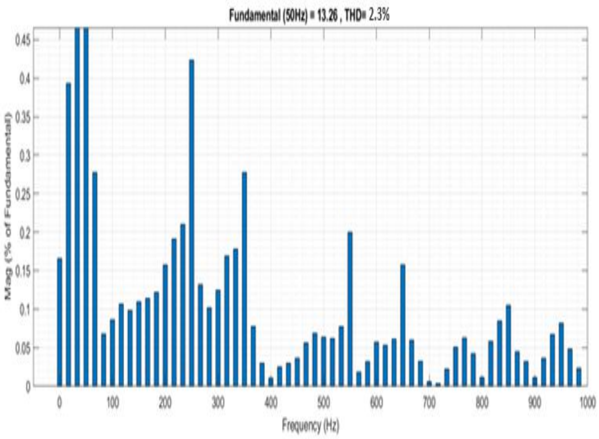

Fig. 13. THD analysis

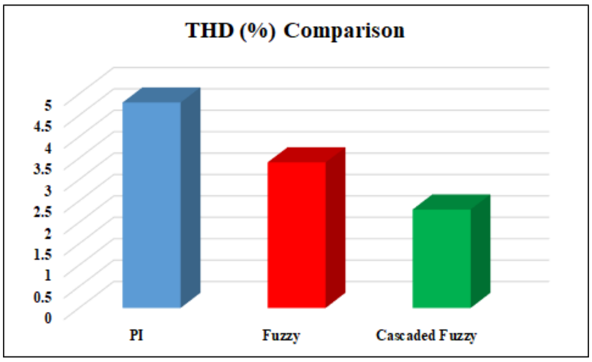

Fig. 14. THD comparison

Harmonics is a vital fact in assessing the PQ, and here FFT analysis is done for obtaining the THD as displayed in Figure 13, which shows a THD of 2.3%. The performance of the cascaded fuzzy is analogized with PI controller and Fuzzy in terms of THD as displayed in Figure 14. When analogized wit PI and fuzzy, cascaded fuzzy delivers a THD of 2.3% while PI and fuzzy delivers a THD of 4.8% and 3.4% respectively.

4. Conclusion

Numerous PQ issues arises in the power systems because of the frequent usage of power devices and these issues are to be addressed properly to get rid of the system failure and to avoid economic losses. Hence WECS based UPFC is utilized in this article for the effective mitigation of the PQ issues like sag, swell and harmonics. In WECS, the DFIG has been used and the outcome of WECS is regulated by executing a PI controller tuned with CS algorithm. The structure of UPFC has a shunt and a series converter and it is vital to control both the converters. Here, d-q theory is utilized for generating the reference signal and cascaded fuzzy logic is utilized for the control of UPFC. The system is simulated in MATLAB and the results were analysed for both the sag and swell conditions. The THD is also minimized to 2.3% which is found better when analogized with the PI controller and Fuzzy.

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