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Grid Connected Wind Energy Conversion System Using Unified Power Flow Controller

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Abstract: ***This paper presents an improvement technique for the power quality of the electrical part of a wind generation system with a variable speed wind turbine generator, self-excited induction generator (SEIG) which aims to minimize the utilization of wind power injected into weak grids. In order to realize this goal, a dynamic Volt Ampere Reactive (VAR) compensator Unified Power Flow Controller (UPFC) has been proposed. UPFC is a combination of series Voltage Source Inverter (VSI) Static Synchronous Series Compensator (SSSC) and shunt VSI STAtic Synchronous COMpensator (STATCOM). Here Space Vector Pulse Width Modulation (SVPWM), voltage oriented controller and current oriented controller hysteresis current controller PWM techniques are proposed to control the inverter outputs of SSSC and STATCOM respectively. And in an attempt to minimize the percentage of Total Harmonic Distortion (THD) in the inverter current and voltage and to avoid poor power quality a LC filter is inserted between UPFC and grid. Here to show the effectiveness of the proposed model a grid connected WECS using UPDC is compared with grid connected WECS without UPFC. The improvement can be seen through the comparison of percentage of THD in both the case. This work is simulated through MATLAB.***

Keywords: Unified Power Flow Controller, Hysteresis Current Controller, Space Vector Pulse Width Modulation Controller, Total Harmonic Distortion, STATCOM, SSSC MATLAB, simulink.

1. Introduction

Due to increase in environmental pollution there is an increase in the green house gas (GHG) level. Which in turn causes, changes in climate such as temperature rise, increase in sea level, high oil price, decrease in the fossil fuel reserves, growing in power demand etc... hence it is necessary for the world to search for new sources of energy, through which the emission on GHG can be reduced to a greater extent. These problems lead scientists towards new clean power conversion systems. The renewable energy resources are suitable to meet the clean power requirements. Among renewable energy sources wind became an environmental-friendly, pure and economically viable energy source [1].

The integration of wind energy into existing power system presents a technical challenges and that requires consideration of voltage regulation, stability, power quality problems like voltage sag, voltage swell, noise, harmonics etc… the generated power, power quality is greatly affected by operation of a transmission and distribution network. The problems of power quality is great important to the wind turbine. In order to minimize these power quality problems in wind turbine system, many kinds of power conversion systems to be connected between the generator and grid line. These power electronic converters are nonlinear devices hence they are injecting harmonic currents in the AC system and intern increases the overall reactive power demanded by the equivalent load and the number of sensitive loads, that require ideal sinusoidal supply voltages for their proper operation. But in order to obtain more economical system, we do believe that, still there is a room to improve the power of grid connected wind energy conversion systems. In order to keep power quality under limits it is necessary to include compensation. There are several technical problems arising from compensation techniques and the complexity of control operation [2]-[5] .

In this paper Unified Power Flow Controller is proposed as a controller. It is a combination of series connected Static Synchronous Series Compensator (SSSC) and shunt connected STAtic synchronous COMpensator (STATCOM). Which in turn includes voltage oriented control Space Vector Pulse Width Modulation (SVPWM) and current oriented control Hysteresis Current Controller Pulse Width Modulation (HCCPWM) TO CONTROL inverter output of SSSC and STATCOM respectively.

The scope of this paper is that, the comparative analysis of grid connected Wind Energy Conversion System using UPFC under line to ground fault with the Wind Energy Conversion System without UPFC under no fault condition in terms of voltage and current control, active and reactive power improvement and reduction of percentage of Total Harmonics.

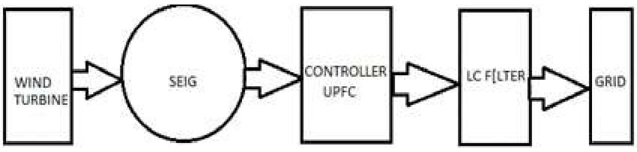

Figure 1: proposed SEIG based WECS using UPFC

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2. Wind Energy Conversion Systems

Wind power is the conversion of wind energy into a useful form of energy, such as using wind turbines to make electrical power, windmills for mechanical power, wind pumps for water pumping or drainage, or sails to propel ships. A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy.

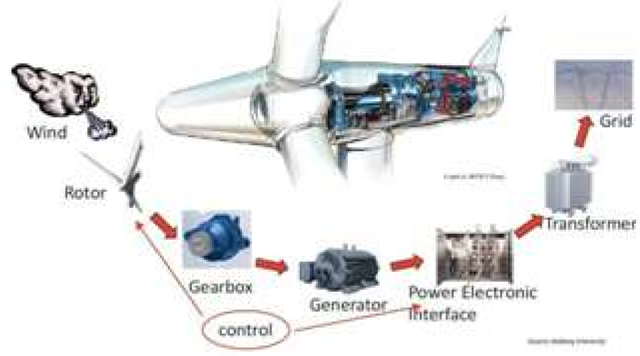

Figure 2: Wind Energy Conversion System

According to Betz theory [6], the mechanical power generated by a wind turbine is given by,

$$P_{wt} = 0.5\,\pi\,\rho\,V^3\,R^2\,C_p\,(\lambda\,,\beta) \qquad (1)$$

Where, ρ is the air density, R is the rotor radius of wind turbine and V is the wind speed. The power coefficient C_p depends on the blade pith angle β and the tip speed ratio λ which is defined as the ratio between the linear blade tip speed and the wind speed as, , $\lambda = \omega_r \cdot R/v$. where ω_r is the rotor speed of wind turbine. The output torque of wind turbine is,

$$T_{wt} = P_{wt}/w_r = 0.5\,\pi\,\rho\,V^2\,R^3\,C_T\,(\lambda\,,\beta) \qquad (2)$$

where the torque coefficient $C_T\,(\lambda\,,\beta) = C_P\,(\lambda,\beta)$. Considering the wind speed, the WECS can be divided into no load, partial load, and full load state. When the wind speed is below the cut-in wind speed or above the cut-out wind speed, wind turbine operates in the no load region. When the WECS is in the full load region, the output power must be regulated at rated power P_n , which can be achieved by changing the pitch angle. In order to maximize the captured power, the tip speed ratio needs to be controlled.

3. Self Excited Induction Generator

SEIG is a Variable Speed Wind Turbine (VSWT) generator. Self excitation in generators are known to be suitable for small scale wind power plants, because of their advantages such as flexible control within a full small power, such as variable speed operation that is ease of maintainability, availability and capability to produce electrical power even at variable speed, better performance of reactive power compensation, smooth grid connection, low cost, robustness, ease of maintenance, self protection. They can be operated in both on and off grid connected mode. If grid mode is off that is Autonomous Wind Power Conversion System (AWPCS), SEIG is used for supplying remote areas such as islands, military equipment, ships and small villages far from conventional resources. Major disadvantages of SEIG are their poor voltage, frequency regulation which depends on generator speed, amount of reactive power and load nature [7], [8].

A. Modeling of SEIG

The modeling of SEIG is useful because it allows us to analyze all of its characteristics. The d-q model of an induction machine in the synchronously rotating reference frame is shown in fig below. This model is used because it provides complete solution (transient and steady state) of the self-excitation process[8]. The voltage of an induction machine in the synchronous reference frame can be obtained as follows:

$$V_{dc} + R_s\, i_{ds} - \omega_e\, \lambda_{qs} + L_{ls}\, p i_{ds} + L_m\, p\, i_{ds} + L_m p\, i_{dr} = 0 \quad (3)$$

$$K_d - (\omega_e - \omega_r)\lambda_{qr} + R_r\, i_{dr} + L_{ls} p i_{dr} + L_m p i_{ds} + L_m p\, i_{dr} = 0 \quad (4)$$

$$V_{qs} + R_s i_{qs} + \omega_e \lambda_{ds} + L_{ls} p\, i_{qs} + L_m p\, i_{qs} + L_m\, p\, i_{qr} = 0 \quad (5)$$

$$K_q + (\omega_e - \omega)\lambda_{dr} + R_r\, i_{qr} + L_{lr}\, p\, i_{qr} + L_m\, p\, L_{qs} + L_m\, p\, i_{qr} = 0 \quad (6)$$

Where,
$\lambda_{ds} = L_s\, i_{ds} + L_m\, i_{dr}$
$\lambda_{dr} = L_m\, i_{ds} + L_r\, i_{dr}$
$\lambda_{qs} = L_s\, i_{qs} + L_m\, i_{qr}$
$\lambda_{qr} = L_m\, i_{qs} + L_r\, i_{qr}$

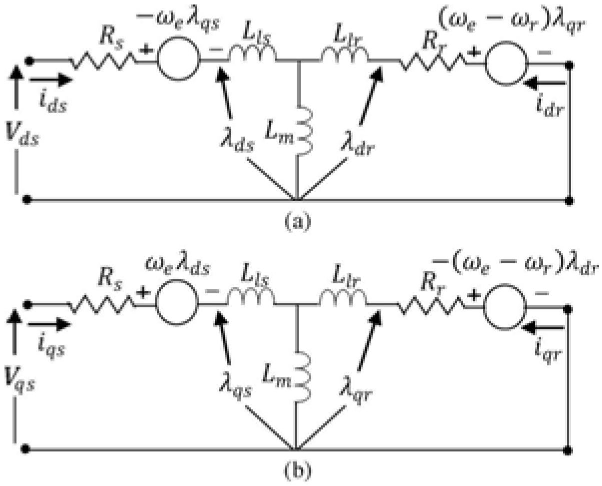

Figure 3: The *d-q* model of an induction machine in the synchronously rotating reference frame. (a) *d* –axis; (b) *q* –axis.

The electromagnetic torque is given by:

$$T_e = -\frac{3}{2}\,\frac{P}{2}\,\frac{L_m}{L_r}\left(\lambda_{dr}\, i_{qs} - \lambda_{qr}\, i_{ds}\right) \qquad (7)$$

$$T_m = J\frac{d}{dt}\omega_m + \beta\omega_m + T_e$$

Where, $V_{ds,}$ V_{qs}, i_{ds} and i_{qs} are stator voltages and currents, respectively, V_{dr}, V_{qr}, i_{dr}, and i_{qr} are the rotor voltages and currents, respectively, P is the derivative operator, i.e., P=d/dt, K_d and K_q are the residual voltage inside the induction generator, $\mathbf{V_{cd}}$ and $\mathbf{V_{cq}}$ are the initial voltages of the self-excitation capacitor bank (10 V initial charged from external power supply), ω_e and ω_r are synchronous and rotor

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angular speed, respectively, P Is the number of poles, λ_{dr}, λ_{qr}, λ_{ds}, and λ_{qs} are the stator and rotor fluxes, respectively, C Is the external self-excitation capacitance, R_s, L_{ls}, R_r and L_{lr} are the resistance and the self inductance of the stator and the rotor, respectively, L_s, and L_r are the stator and rotor inductances, respectively, L_m the mutual inductance.

The mathematical equation that relates the wind turbine output torque with the electromagnetic torque of the induction generator is given by:

$$T_m = J \frac{d}{dt} \omega_m + \beta \omega_m + T_e \tag{8}$$

Where ω_m, J and β are the mechanical angular speed of wind turbine, the effective inertia of the wind turbine and the induction generator, and friction coefficient, respectively.

Where $L = L_s L_r - L_m^2$.

4. Unified Power Flow Controller

UPFC is a fast and flexible, new Flexible Alternating Current Transmission (FACTS) power flow controller. Which can be used to control the power flow in transmission line by controlling the impedance, voltage magnitude and phase angle. This new FACTS device is a combination of two old FACTS devices: the STATCOM and the SSSC. Both STATCOM and SSSC are coupled through DC link to allow the continuous flow of real power between the series output terminal of SSSC and shunt output terminal of STATCOM. SSSC injects voltage in series with the line. STATCOM injects current at a point it is connected to the line.

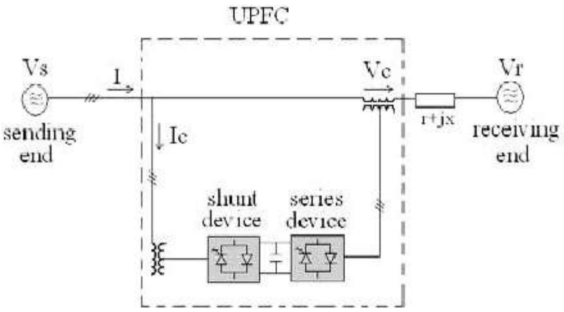

Figure 4: Unified Power Flow Controller Link in Transmission Line

The basic components of UPFC are two Voltage Source Inverter (VSI) sharing a common DC storage capacitor and are connected to the transmission line through two coupling transformers. One VSI connected to transmission line in shunt through a shunt transformer, while the other one is connected to transmission line in series through series transformer. Basic operational scheme of UPFC shown in figure above [9].

The series inverter is controlled to inject a symmetrical three phase voltage system (Vc), of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor Vdc constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point [9].

A. Space Vector Pulse Width Modulation for SSSC as a Voltage Controller

Space vector modulation (SVM) is an algorithm for the control of PWM. It is used for the creation of alternating current (AC) waveforms; most commonly to drive three phase AC powered motors at varying speeds from DC using multiple class-D amplifiers. There are various variations of SVM that result in different quality and computational requirements. One active area of development is in the reduction of total harmonic distortion (THD) created by the rapid switching inherent to these algorithms. The main aim of any PWM technique is to obtain variable output having maximum fundamental components with minimum harmonics. For three phase VSI, SVPWM was originally developed as a vector approach to PWM. And it is a more suitable approach for generating sine wave that provide a higher voltage to the motor with lower percentage of total harmonic distortion[10].

SVPWM is different from usual PWM approach, based on space vector representation of voltage in $\alpha - \beta$ plane. These $\alpha - \beta$ components are obtained from clark's transformation that is three phase quantities either in stationary or in rotating reference frame are transformed into two phase quantities. In SVPWM voltage reference is provided by revolving reference vector. In this case magnitude and frequency of the fundamental component on the line side are controlled by the magnitude and frequency respectively of the reference voltage vector. SVM provides special switching sequence on the upper three power transistors of three phase voltage source inverter and generates less harmonic distortion by effectively utilizing the DC bus voltage. Because of its superior performance, now a days it has been finding wide spread applications [11].

Considering the stationary reference frame, let the three-phase sinusoidal voltage components be;

$$V_a = V_m \sin \omega t \tag{9}$$

$$V_b = V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \tag{10}$$

$$V_c = V_m \sin\left(\omega t - \frac{4\pi}{3}\right) \tag{11}$$

These three phase sinusoidal voltage is applied to the AC machine. Which intern produces a rotating flux in the air gap of AC machine. This rotating flux is represented by single rotating voltage vector. The magnitude and angle of the rotating vector can be found by means of clark's transformation. To implement SVPWM, the voltage equation in the rotating reference frame that is a,b,c reference frame can be transformed into the stationary dq reference frame.it consists of horizontal d and vertical q axes.The relation between stationary and rotating reference frame is given by,

$$f_{dq0}= K_s f_{abc} \tag{12}$$

Where, $K_s = \frac{2}{3}\begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & -\sqrt{3}/2 & -\sqrt{3}/2 \\ 1/2 & 1/2 & 1/2 \end{bmatrix}$,

$f_{dq0}= [f_d \quad f_q \quad f_0]^T$, $f_{abc} = [f_a \quad f_b \quad f_c]^T$

f denotes either a voltage or current variable.

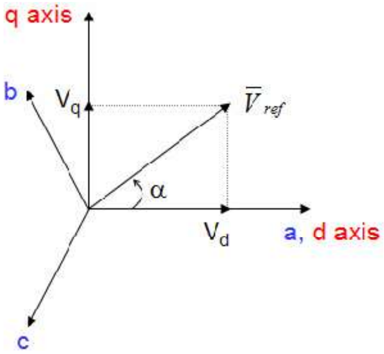

Figure 5: The relationship of abc reference frame and stationary dq reference frame

As shown in figure above, clark's transformation is equivalent to an orthogonal projection of three dimensional rotational a,b,c components onto the equivalent two dimensional stationary dq component, in a three dimensional co-ordinate system. As a result eight switching vectors are possible among them, six non-zero vectors ($V_1$to V_6) and two zero vectors(V_0 *and* V_7). Non-zero vectors shapes the axes of hexagonal as shown in fig below and they supply power to the load and the angle between any two adjacent non-zero vectors is always 60 degrees. At the same time angle between two zero vectors is always zero and they supply zero voltage to the load. These eight vectors are called basic space vectors and are denoted by $V_0, V_1, V_2, V_3, V_4, V_5, V_6, V_7$. The same transformation can be applied to the desired output voltage to get the required reference voltage vector, V_{ref} to a desired level. Hence objective of SVPWM is achieved.

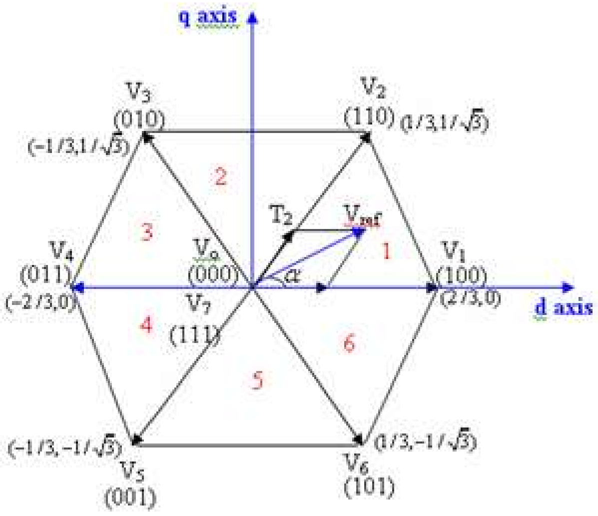

Figure 6: Basic switching, vectors and sectors.

Table 1: Switching patterns and output vectors.

Voltage vectors	*Switching vectors*			*Line to neutral voltage*			*Line to line voltage*		
	A	B	C	V_{an}	V_{bn}	V_{cn}	V_{ab}	V_{bc}	V_{ca}
V_0	0	0	0	0	0	0	0	0	0
V_1	1	0	0	2/3	-1/3	-1/3	1	0	-1
V_2	1	1	0	1/3	1/3	-2/3	0	1	-1
V_3	0	1	0	-1/3	2/3	-1/3	-1	1	0
V_4	0	1	1	-2/3	1/3	1/3	-1	0	1
V_5	0	0	1	-1/3	1/3	2/3	0	-1	1
V_6	1	0	1	1/3	-2/3	1/3	1	-1	0
V_7	1	1	1	0	0	0	0	0	0

B. Hysteresis Current Controller Pwm for Statcom as a Current Controller

It is a closed loop system. In this method of control reference current is compared with the actual current difference between them produces error. The error current generates switching signals. The main task of this type of controller is to force the input current to fallow the reference current in each phase. Each phase consists of comparator and hysteresis band [12]. The error current represents the current distortion can be calculated as follows:

$$\text{Distortion} = \frac{100}{I_{rms}} \sqrt{\frac{1}{T}\left(i_{act} - i_{ref}\right)^2 dt}\ \%$$

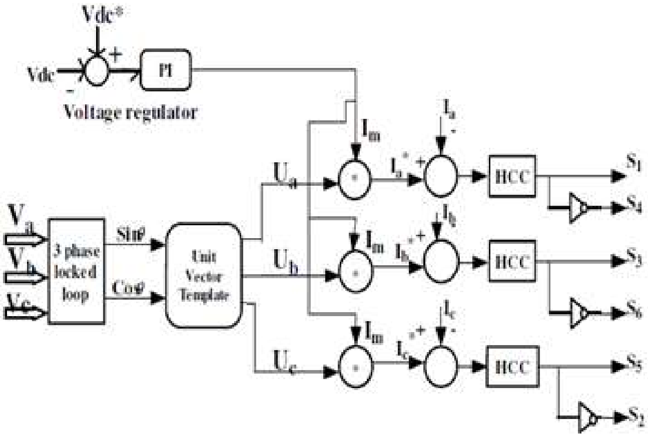

Figure 7: Block Diagram of Hysteresis Current Control for Three Phase VSI control.

In this system the hysteresis band is fixed over fundamental period, it is modeled mathematically as fallows

$$i_{ref} = i_{max}.\sin\omega t \tag{13}$$

$$i_{upper} = i_{ref} + H \tag{14}$$

$$i_{lower} = i_{ref} - H \tag{15}$$

Where,
i_{ref} = reference current
i_{upper} = upper band
i_{lower} = lower band
H = hysteresis band limit

If $i_m > i_{upper}$, then $V_m = \frac{-V_{dc}}{2}$
If $i_m < i_{upper}$, then $V_m = \frac{V_{dc}}{2}$
Where, m=a,b,c phases.
i = load side current
V_{dc} = DC link voltage of inverter.

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The switching is done in such a way that generated signals remain within limits. In this method of control, the error current is limited between the upper and lower limits of hysteresis band. If the actual current increases above the hysteresis band, the upper switch of inverter arm is switched off and the lower switch is turned on and the current starts to decrease. In contrast if the actual current reaches lower limit or below the hysteresis band limit, the lower switch of inverter arm is switched off and the upper switch is turned on hence actual current is forced to track the reference signal within hysteresis band [13].

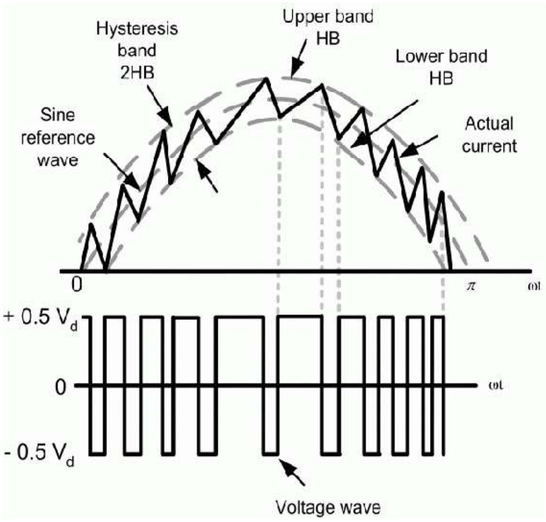

Figure 8: Basic Principal of hysteresis current controller

$$I_{a-error} = I_a^* - I_a \tag{16}$$
$$I_{b-error} = I_b^* - I_b \tag{17}$$
$$I_{c-error} = I_c^* - I_c \tag{18}$$

The switching pattern of IGBT switches can be modulated as per difference between reference current and actual current.

If $I_{inverter} > I_{inverter}^* - \text{HB}$

The upper switch of inverter S_1 is ON and lower switch S_4 is OFF.

If $I_{inverter} < I_{inverter}^* - \text{HB}$

The lower switch of inverter S_4 is ON and upper switch of inverter S_1 is OFF.

Where,
$I_{inverter}$ = actual current of inverter
$I_{inverter}^*$ = reference current of inverter
HB = hysteresis band.

Table 2: Specifications and parameters for UPFC

Symbol	*Quantity*	*Value*
f_g	Grid frequency	50 Hz
V_g	Grid voltage	120/208 V_{rms}
V_{dc}	Dc link voltage	410 V
C_{dc}	DC-link capacitance	100 μf
L_f	Filter inductance	24 mH
C_f	Filter capacitance	40 μf
f_{sw}	Switching frequency	5 kHz

Table 3: Specifications and parameters for SEIG

Symbol	*Quantity*	*Value*
P_0	Output power	1/3 hp
C_g	SEIG capacitance	70 μf
V_n	Nominal voltage	120/208 V_{rms}
n	Nominal speed	1800 rpm
I_n	Nominal current	1.7 A
V_f	Field voltage	125 V

5. Simulation Results

The main aim of any modulation technique is to obtain variable output having maximum fundamental component with minimum harmonics. The objective of Pulse Width Modulation techniques is enhancement of fundamental output voltage and reduction of harmonic content in Three Phase Voltage Source Inverters. In this paper different PWM techniques such as space vector pulse width modulation and hysteresis current controllers are used in order to control voltage and current waveforms respectively. Here wind energy conversion systems with UPFC under line to ground fault condition compared with wind energy conversion without UPFC. They are compared in terms of percentage of Total Harmonic Distortion (THD), input and output voltage and current waveform. Simulink Models has been developed for WECS with UPFC and that with respect to without UPFC. Simulation work is carried in MATLAB 10.0/Simulink.

A. Simulation of grid connected WECS using UPFC under line to ground fault condition

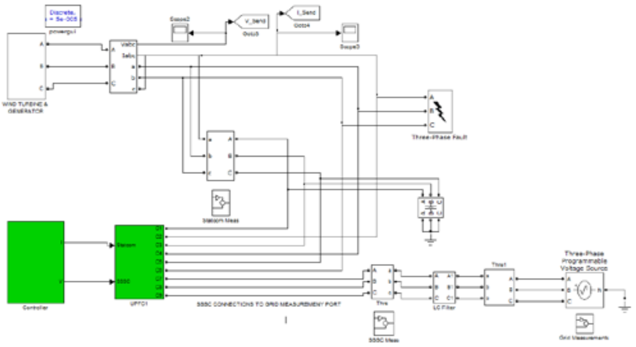

Figure 9: Block diagram of grid connected WECS using UPFC

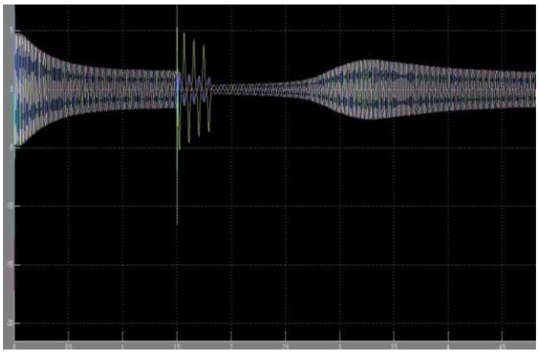

Figure 10a: Response of sending end current

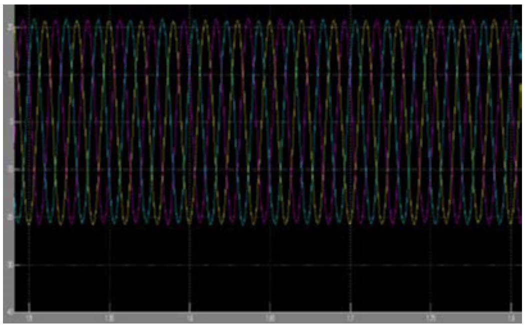

Figure 10b: Response of receiving end current in case of with UPFC

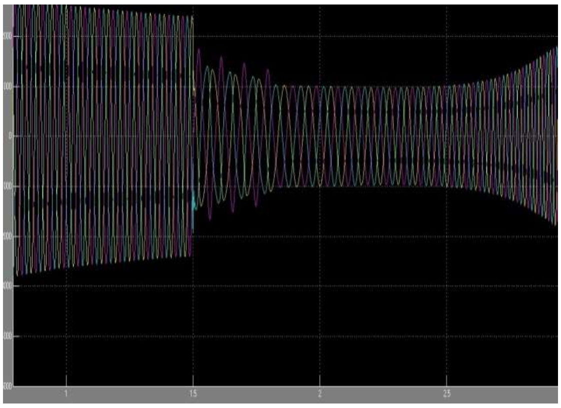

Figure10 c: Response of sending end voltage

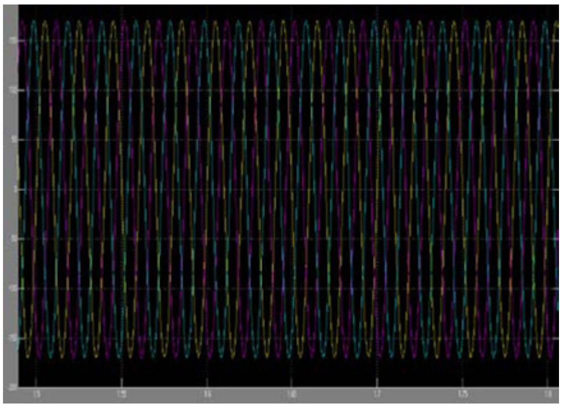

Figure 10d: Response of receiving end voltage

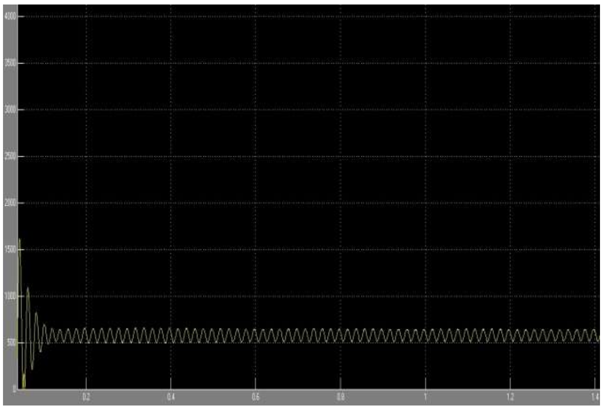

Figure 10e: Response of receiving end real power

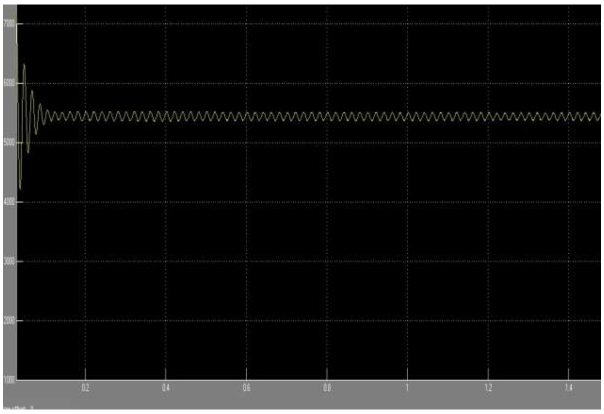

Figure 10f: Response of receiving end reactive power

A. Simulation of grid connected WECS without UPFC under no fault condition

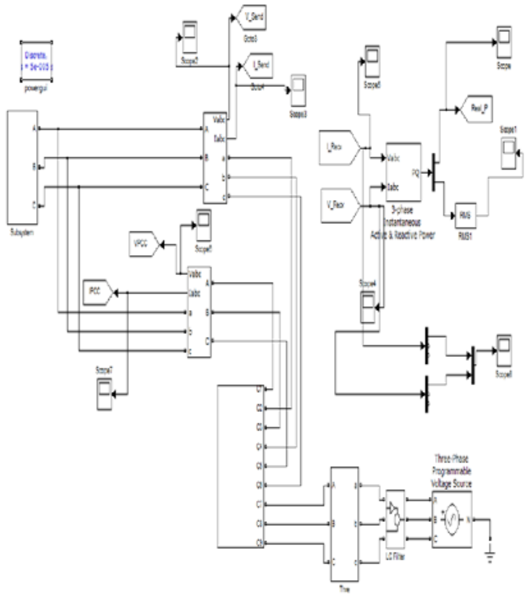

Figure 11: Block diagram of WECS without UPFC

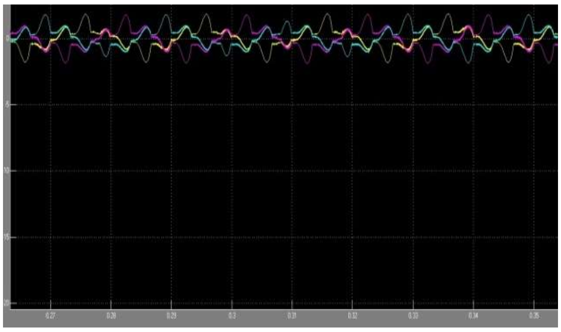

Figure11a: Response of sending end current

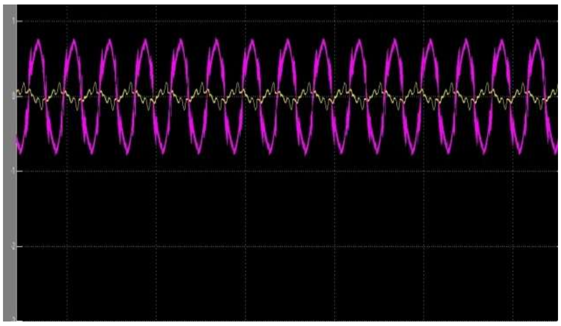

Figure11b: Response of receiving end current

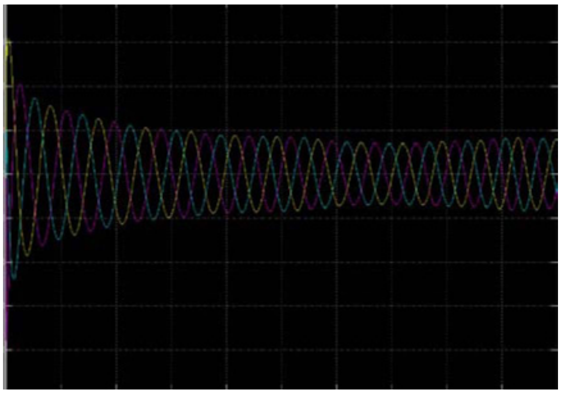

Figure 11c: Response of sending end voltage

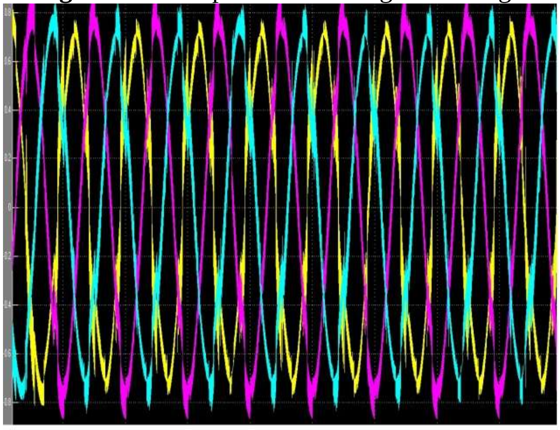

Figure 11d: Response of receiving end voltage

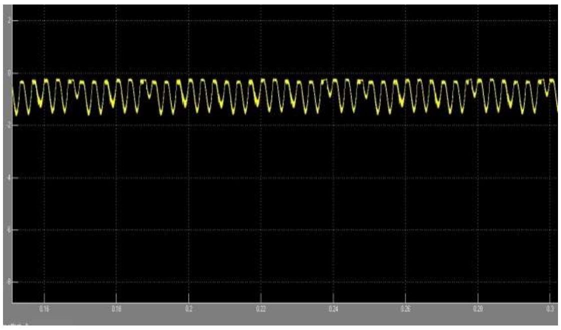

Figure 11e: Response of receiving end real power

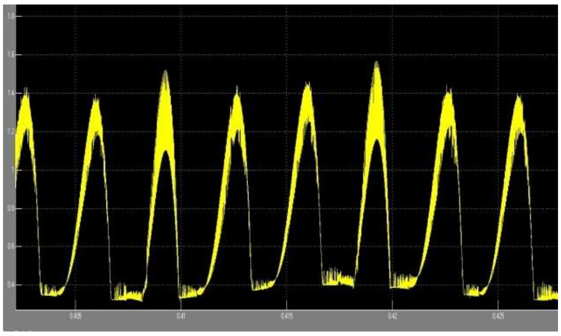

Figure 11f: Response of receiving end reactive power

6. Total Harmonics Distortion Analysis for with and without UPFC

A. THD analysis for current

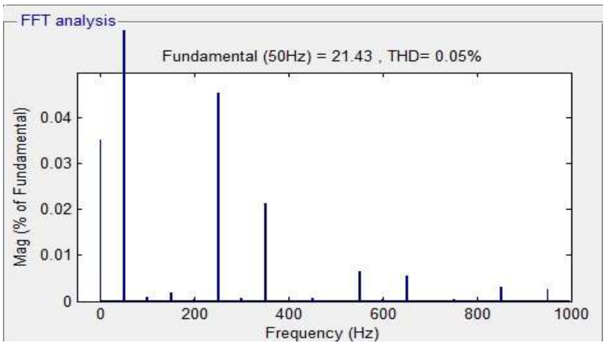

Figure 12a: Response for with UPFC

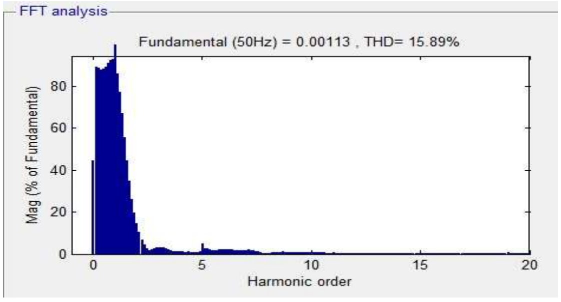

Figure 12b: Response for without UPFC

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B. THD analysis for voltage

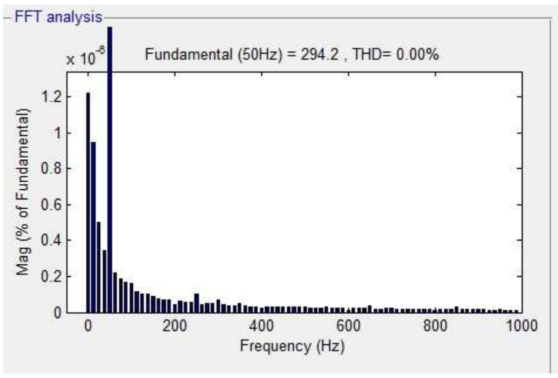

Figure 13a: Response for with UPFC

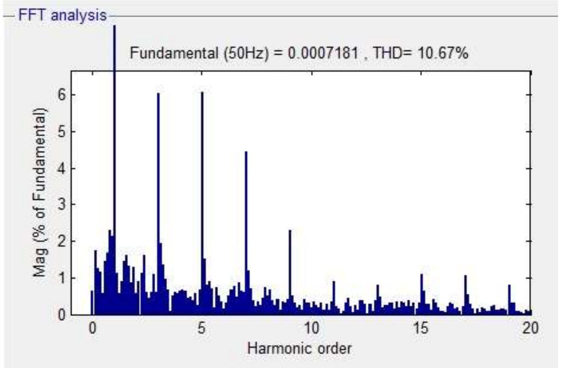

Figure 13 b: Response for without UPFC

7. Conclusion

In this paper comparative analysis of WECS using UFFC with WECS without UPFC is carried out. Space vector pulse width modulation and hysteresis current controlled pulse width modulation techniques are proposed for voltage and current harmonics reduction respectively. The simulation result reveals that WECS using UPFC gives enhanced fundamental output with better quality i.e lesser percentage of THD compared to WECS without UPFC.

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