Enhancement of Power Quality using UPQC for A Environmentally Clean and Efficient Hybrid PEMFC and PMSG Based Wind Energy System Connected to Weak Grid

G. Mallesham, CH. Siva Kumar

Department of Electrical Engineering, University College of Engineering, Osmania University

Hyderabad, India

ABSTRACT - Now-a-days globe is facing few of the important problems, the first and foremost one is global warming, depletion of conventional energies and more demand for quality electrical energy. One of the most polluting electrical energy sources is thermal power plants, uses coal as input source which last not more than one to two hundred year on the globe. One of the solutions to the above problems is dependence on the environmentally clean and efficient combined operation of renewable energy sources. These combined operation of renewable energy sources leads to power quality issues as theses sources have their own characteristics. In this work build up a environmentally clean and efficient hybrid system consisting of proton exchange membrane fuel cell and permanent magnet based wind energy system connected to weak grid. To mitigate the power quality issues aroused due to wind turbine tower shadowing effect on the weak grid is mitigated by one of the custom power device unified power quality conditioner. Further, the conditioner is used mitigated the power quality issues like sags produced due to load variations, swells raised due to unsymmetrical operating conditions on the power system effectively with in the international standards.

Keywords - *hybrid renewable energy sources, power quality, custom power device, unified power quality conditioner, sag, swell, fuel cell, weak grid.*

INTRODUCTION

Electricity is one of the most important commodities in day to day life and playing a major important role in developing the economy of countries. We cannot imagine a day without electrical energy. The revolutionary developments in transport systems: electric trains, electric vehicles; amusements, modern electrical equipments: smart phones, laptops, computers, different industries: food and manufacturing industry etc. demands more electrical energy. This demand for electrical energy increased during the last year around is about 10% across the globe [1]. While utilizing the power by these different kinds of loads injects the harmonics into the power system and deviates the original characteristics of the electrical quantities leads to power quality issues. Apart from this issue to meet the demand during peak and off peak load periods the power suppliers depends on renewable energy sources like solar, wind energy, fuel cells, geothermal, ocean thermal energies as additional sources to the existing conventional energy sources. As these sources have their own operating characteristics and behave differently in different operating conditions of power system. But, the impacts of these effects are more in weak grids and it creates another power quality issues.

Apart from these issues discussed the power system is also subjected to different unbalanced and nonlinear heavy electrical loads likely to cause disturbances to the customers are: resistance welding machines, arc welding machines, rolling mills, mine welders, wood chipping machines, rock/ mineral crushing equipment, large motors with varying loads, arc furnaces, induction welding machines, induction furnaces etc. The most affected ones due to power quality issues are customers like: designers of plants - defects in designs, electrical distributers – more loses, system manufactures – unexpected outcomes, public authorities and general public and end users. The quality of power is characterised with the electrical quantities in terms uninterruptable power supply with expected voltage magnitude, phase angle, balance, harmonic distortion, frequency, surges, blackouts, transients, noise, spikes etc. The critical power quality issues are like changes in voltage, frequency and waveform distortions. The members of the IEEE society discuss, develop and recommend the electrical standards and the details of classified of power system disturbances, definitions, standards and guidelines are presented in [2],[3]. With the recent advancements in power electronic applications to power systems strength ended the use of renewable energy sources to generate electrical energy. Out of all existing renewable energies the growth rate of wind is high during the last decade [4 - 6]. Apart from the wind energy sources another promising future energy source is fuel cell because of its promising features like: with zero decibels noise level, no mechanical movements, co-generation capabilities, modular designs, and pollution free etc. Even though the wind energy system is an alternative energy to thermal energy system to produce the clean and neat energy with no greenhouse gas emission, less cost and zero water consumption have its own characteristics when put into operation [7],[8].

As this wind energy system capacity increases with the increase in height of the tower and rotor diameter creates active and reactive power fluctuations in the grid especially in weak grids cause the power quality problem [9],[10]. The solutions to this power quality issue are solved using custom power device UPQC. On the other hand a very high power density fuel cell called polymer electrolyte membrane fuel used as a second source of energy connected to weak grid to form a hybrid power system. The detailed review of high temperature polymer electrolyte membrane fuel cell presented in [11], [12] respectively.

In this work to maintain the power quality of a weak grid system developed a hybrid system consisting of permanent magnet based wind energy system and proton exchange membrane fuel cell to meet the electrical power demand. To mitigate the power quality issues a p-q theory based custom power device named unified power quality condition developed and the effectiveness of the conditioner is verified with simulation studies [13], [14]. The work is presented in this paper as follows: under the heading of simulation models discussed: modelling of wind turbine, PMSG, weak grid, proton exchange membrane fuel cell, and unified power quality compensator. Under the heading of simulation studies: simulation work is carried for different operating conditions to improve power quality. In final session concluded the progressed work.

COMPUTER SIMULATION MODELS

The new inventions and developments in computer software and hardware has become the backbone for the new inventions in all the fields of engineering and non engineering. The software packages provide a handy tool to engineers in research and developments to study and analyse a complex systems dynamically. For these studies need to develop mathematical models of the system to be studied and analysed. For the work proposed in this paper developed the following models:

A. MATHEMATICAL MODELLING OF WIND TURBINE

The cost less, freely available wind energy has become a major source of renewable energy. Wind turbine used to convert this dynamically moving air energy into rotational mechanical energy. The overall extraction of energy from wind depends on the factors like: design aspects of aerodynamics of blades, drive mechanism and electrical generator etc. From dawn to dusk the wind flows with different structures and velocities under these operating conditions a double fed induction generator or a permanent magnet synchronous generator is more suitable because of its better performance than that of doubly fed induction generator [15]-[17]. In this work a combination of horizontal axis based wind turbine and permanent magnet synchronous generator considered.

The estimated maximum energy that can be extracted from wind energy is expressed as:

$$P_m = \frac{1}{2}\rho A v_w^3 C_p \tag{1}$$

where, C_P – represents the power coefficient called Betz limit, ρ air density (1.225 kg/m3).

$$C_p = f(\lambda,\beta) \cong \frac{16}{27} = 0.593 \tag{2}$$

where, - λ represents the tip speed ratio, - β represents the turbine blade pitch angle.

The following mathematical expression is to find the output power of variable speed wind turbine:

$$P_m = \frac{1}{2}\rho A v_w^3 C_p(\lambda,\beta) \tag{3}$$

where, - A is the area swept by wind turbine rotor blades in m^2, - υ_w is the wind velocity in m/s, - C_p is the power coefficient - 0.59.

The wind turbine mechanical output in terms of torque is expressed as:

$$T_m = \frac{P_m}{\omega} \quad \text{in N-m} \tag{4}$$

where, - the estimated output power of wind turbine P_m in watts, - is the rotor angular velocity ω in rad/s.

In terms of Cp and V_d the mechanical torque of the wind turbine is expressed as:

$$T_t = \frac{1}{2} \quad \rho\pi r^3 C_p V_d^2 \tag{5}$$

In [19]-[21] researchers presented the tower parameters and wind shear variation. The following mathematical expression represents tower shadowing disturbance caused by the wind turbine:

$$V_d = V_h(1 + v_m + v_{tower}) \tag{6}$$

where, - mechanical torque of the wind turbine is represented as T_t, the incoming wind speed represented as V_h, air density as - ρ, disturbed wind speed as - V_d, - wind shear variation as - v_m, - tower shadow disturbance as v_{tower}. Wind turbine systems with the following technical specifications are used for the simulation: Nominal wind turbine mechanical output power 21.6e6, Base wind speed - 14 m/s, Maximum pitch angle – 45.

B. Modelling of Proton Exchange Membrane Fuel Cell

In this proposed work modelled proton exchange membrane fuel [22], of two series connected 50 kW, 625 V of DC. The V-I characteristics of PEMFC is shown in Fig.1.

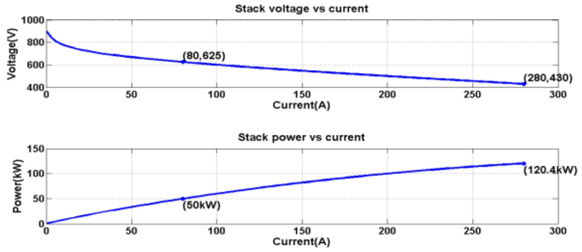

Fig. 1. V - I Characteristics of PEMFC fuel cell.

The following are the chemical reaction equations at anode and cathode of a PEMFC:

anode equations : $H2 \rightarrow H+ + 2e-$ (7)

cathode equation : $½ O2 + 2H + 2e- \rightarrow H2O$ (8)

The modified open circuit voltage and the Tafel slopes in the flow rate of PEMFC follows:

$$E_{oc} = N(E_n - AIn(i_0)) \text{ and } A = \frac{RT}{z\alpha F} \quad (9)$$

where, - R is 8.3145 J/(mol K), - F is 96485 A s/mol, - z is number of moving electrons, - E_n is Nernst voltage, - i_0 is exchange current, - is charge transfer coefficient, - T is operating temperature of the cell. The rate of conversions of hydrogen

The expressions for the Nernst voltage and the exchange current density of PEMFC represented as:

$$E_n = \begin{cases} 1.22+(T-298)\frac{-44.43}{zF}+\frac{RT}{zF}In(P_{H_2}P^{1/2}o_2) & \text{T} \leq \text{ } 100^{\circ}C \\ 1.22+(T-298)\frac{-44.43}{zF}+\frac{RT}{zF}In(\frac{P_{H_2}P^{1/2}o_2}{P_{H_2}o}) & \text{T} \leq \text{ } 100^{\circ}C \end{cases}$$

(10)

$$i_o = \frac{zFk(P_{H_2}+Po_2)}{Rh}e^{\frac{\Delta G}{RT}} \quad (11)$$

where, P_{H_2}, P_{o_2} P_{H_2o}

are partial pressure of hydrogen, oxygen and water vapor inside the stack are and respectively, Boltzmann's constant - k, Planck's constant - h and - ΔG size of the activation barrier which depends on the type of electrode and catalyst used. In the simulation work a PEMGC with nominal stack power - 50kW/fuel cell, fuel cell resistance - 0.65604 ohms, nominal utilization of hydrogen- 99.25%, and nominal utilization of oxygen - 58.67% are used.

C. Weak Grid

The weak grid is expressed as:

$$\tau = \frac{S_{SC}}{P_{WF}} \approx 5.5 \quad (12)$$

Where S_{sc} is the ratio between short circuit power and rated wind form power values of $r \leq 20$ are considered as a weak grid.

. defines as a weak grid. The value of short circuit power in BB6 is $SSC \approx 120$MVA this ratio has been calculated as[23]:

D. Modelling of Unified Power Quality Compensator

Fig. 2 represents a generalised block diagram representation of UPQC. As it consists of two power filters connected by a common DC link capacitor as a common source[14]. Where V_s and I_s represents the source voltage and currents respectively used to control the UPQC along with the DC link voltage V_{DC}.

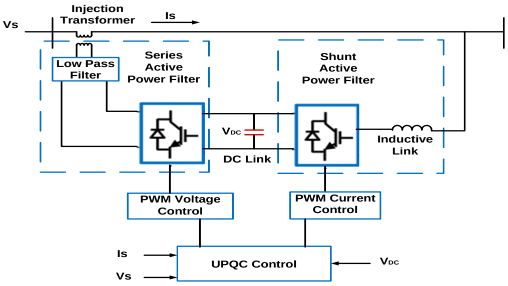

Fig 2: Generalized block diagram representation of UPQC

The expressions to determine the reference voltage are represented as:

$$V_{Sh}^{Re} = K_p \Delta I_{Sh}^{Re} + K_I \int \Delta I_{Sh} dt \quad (13)$$

$$\Delta I_{Sh} = I_{Sh}^{Re} - I_{Sh} \quad (14)$$

where, shunt active power filter reference current - I_{Sh}^{Re}, proportional gain proportional gain - K_P, integral gain of the PI controller - K_I. ΔI_{Sh} estimated using the PI controller. At PCC, the shunt compensator of UPQC injects the currents in to the power system to compensate the change in active power ΔP and reactive power ΔQ fluctuations. The series controller of UPQC compensates the fluctuations of voltages of the system by injecting the voltage by subtracting the PCC voltage from the reference voltage [24].

SIMULATION STUDIES

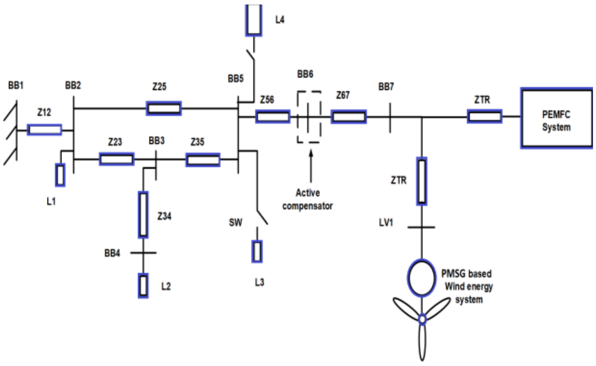

Fig. 3 shows the network used for implementing the proposed work to enhance the quality of power for a hybrid distribution generating system consisting of PEMFC and PMSG wind energy system connected to a weak grid

In Fig. 3, the bus bar number represented as – BB, the impedance between the bus bars i and j Zij. Grid - BB1; impedance of the transmission line - ZTR. At point of common connection BB6 UPQC is connected. LV1 represents the low voltage busbar. A combined total of wind energy system of 21.6MW is connected to the weak grid through a transformer rating of 690 V/ 33 kV, 630 kVA with a fixed capacitor bank of 200 kVAr. The following two case studies have been carried out.

Case 1: Balanced sags.(with and without UPQC)

Case 2: Unbalanced swells.(with and without UPQC)

Case 1: Balanced Sags

In this case, the following steps carried out during the simulation. (i) Simulation started at time t = 0.0 seconds along with the operation of UPQC series controller. At time t = 2.6 seconds the shunt controller is put into operation. (ii) At time t = 3.4 seconds an inductive load of 15 MW + j 6.6.6 MVAr is connected at the common point of Z23 and Z25. (iii) At time t = 3.9 seconds an inductive load of 10 MW - j 12.5 MVAr is connected in between Z23 and Z35. (d) At time t = 4.4 seconds a capacitive load of 9.0 MW + j 2 MVAr is connected at the common point of Z25 and Z25. (e) At time t = 5.0 seconds an inductive load of 22 MW + j 16 MVAr is connected at the common point of Z25 and Z25. The variation of the wind speed is shown in Fig. 4. During the entire simulation period the wind speed varied randomly in between form 12m/s to 14m/s.

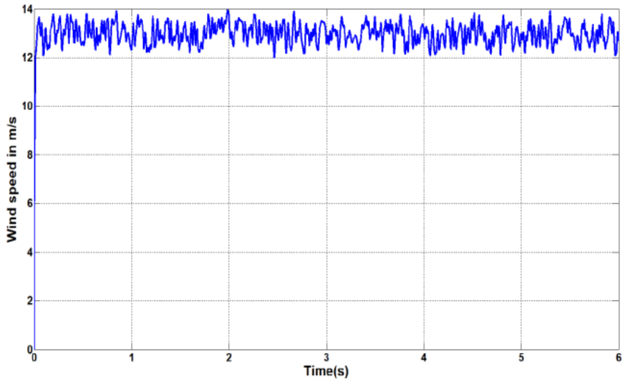

Fig 4: Random variation of wind speed in between 12 to 14 m/s.

Fig. 5 clearly demonstrates power fluctuations due to tower shadowing effect of wind turbine has been generated for variations in wind speeds as per in eq. 6 and torque equation eq. 5. The fluctuations in active power and reactive at grid are -2.6 MW to -1.6 MW and 2.2 MVAr to 8.2 MVAr respectively. Similar fluctuations observed at PMSG based wind system and PEMFC based energy system. If these oscillations continually exits which affects the entire power system. The UPQC shunt controller is put into operation at t = 2.6 seconds. From the Fig. 5 it is clear that the compensator mitigated the fluctuations in a weak grid at the PMSG based wind system and PEMFC based energy system. Fig. 6(a) shows the phase 'a' voltage at the point of common coupling. It clearly demonstrates that fluctuations introduced due to the tower shadowing effect of the wind turbine up to 2.6 seconds. Variations in terminal voltages at point of common coupling between 2.64 × 10^4 Volts (peak-peak) and 2.68× 10^4Volts (peak-peak) which is crossing the limits of IEC standard IEC61000-4-15[25]. Hence, under these circumstances a controller can effectively bring back to constant.

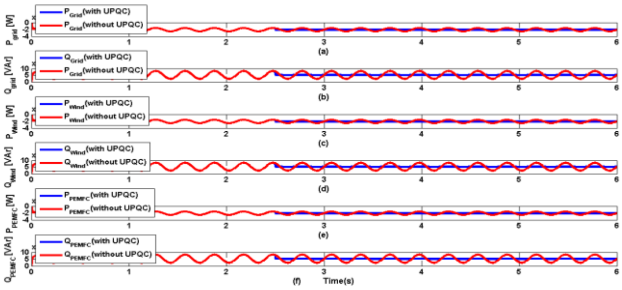

Fig. 5. Active and reactive powers(with and without UPQC) (a) P at grid (b) Q at grid (c) P at PMSG based wind system (d) Q at PMSG based wind system (e) P at PEMFC system and (f) Q at PEMFC system.

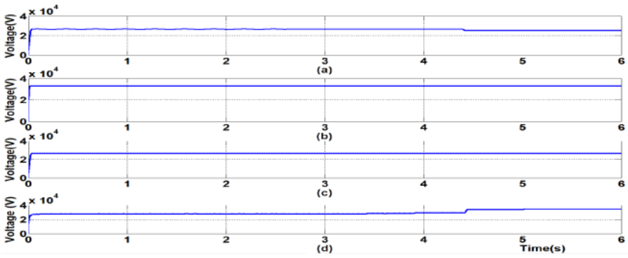

Fig. 6. Voltages across (a) Phase ’a’ Voltage at common coupling (b)Phase ’a’ voltage at grid (c) Phase ’a’ voltage at PSSG based wind energy system (d)Phase ’a’ voltage at PEMFC.

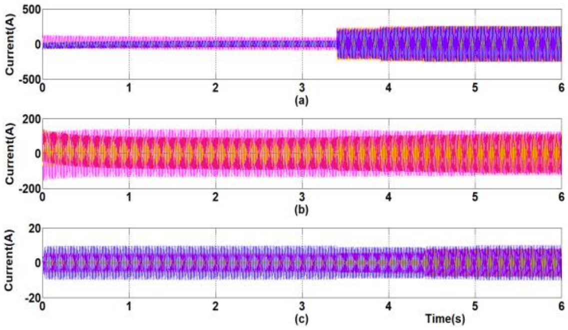

Fig. 7. Three phase currents with UPQC at (a) grid (b) PMSG based wind energy system (c) PEMFC system.

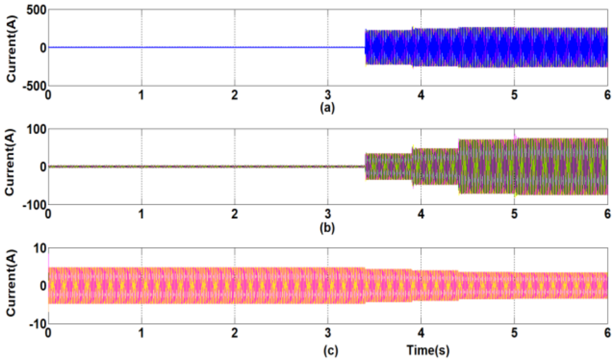

Fig. 8. Three phase currents without UPQC at (a) grid (b) PMFG based wind energy system (c) PEMFC system.

Fig. 6(b), Fig. 6(c) and Fig. 6(d) represents the phase ’a’ voltages at grid, PMSG based wind energy system and PEMFC system in respectively. Further investigated from the simulation results that the voltages at the grid and the PMSG based wind systems has been maintained constant by the controller effectively. Fig. 7 and Fig. 8 shows the simulation output results of three phase currents drawn from grid, PMSG based wind energy system and PEMFC energy with and without UPQC respectively. Fig. 7 and Fig. 8 demonstrates clearly that the variations in currents at different operating conditions of the weak grid. Moreover, it clearly shows that the current drawing is more as it consumes the reactive power by drawing the currents from the available sources more from weak sources.

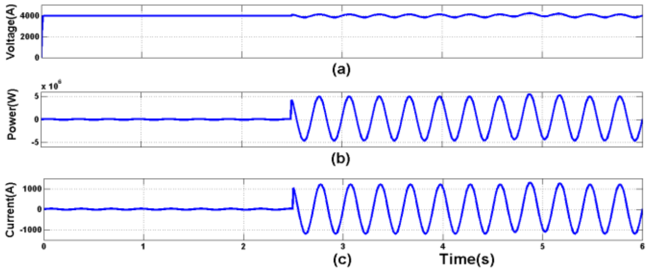

Fig. 9. (a) Voltage across the DC link (b) DC link power (c) DC link current.

In Fig. 9(a), Fig. 9(b) and Fig. 9(c) shows the simulation results of the variations in DC voltage, DC powers and DC currents. As the shunt active filter of the UPQC put into operation at t = 2.6 seconds. To maintain the DC link voltage the shunt active filter draws the currents form the point of common connection.

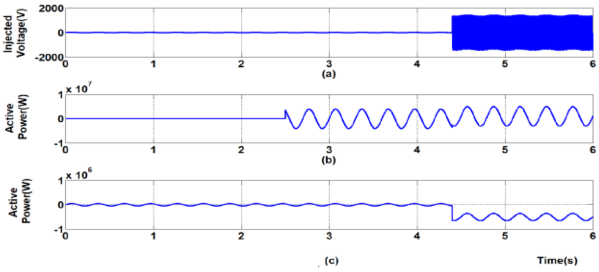

Fig. 10. (a) Series controller injected voltage (b) shunt controller active power (c) series controller active power.

The simulation results shown in Fig. 10(a), Fig. 10(b) and Fig. 10(c) represents the UPQC series controller phase ’a’ voltage, UPQC shunt controller active power variations and UPQC series controller power variations respectively. The moment the complete UPQC is put into operation, the variations of the reactive power on the system is provided by the shunt controller alone i.e., no reactive power burden is on the sources of the power system considered during the sag conditions is shown in Fig. 10(b). To compensate the voltage at point of common connection UPQC series controller injects voltages. Fig. 10(a) that has been shows the series controller injected phase a voltage to maintain the terminal voltages within the IEEE 1159-1995 standards [26]. The above all the simulation outputs its clearly indicates that the compensator effectively mitigated the power fluctuations due to tower shadowing effect of wind turbine.

Case 2: Unbalanced Swells

The simulation carried out in the following sequence of operations: a) Simulation work started at time t = 0.0 seconds along with the shadowing effect and series controller of the UPQC. b) At time t = 2.6 seconds the shunt part of UPQC controllers is put into operation. c) At time t = 3.4 seconds a load of 15 MW + j 6.6 MVAr is connected. d) At time t = 3.9

seconds a load of 10 MW - j 12.5 MVAr is connected. e) from time t =4.4 - 4.6 seconds a three phase fault with fault resistance of 0.001 ohms and a ground resistance of 0.001 ohms has been created on low voltage side of the 630 kVA, 33 kV/690 V which is connected in between the Z25 and Z35 distributed line parameters. f) from time t = 5.2 - 5.4 seconds a line to line fault with the resistance of 9 ohms (high resistance fault) with ground resistance of 0.001 ohms has been created on low voltage side of the 630 kVA, 33 kV/690 V which is connected in between the Z25 and Z35 distributed line parameters. f) from time t = 5.6 - 5.8 seconds a line to ground fault with ground resistance of 0.001 ohms has been created on low voltage side of the 630 kVA, 33 kV/690 V which is connected in between the Z25 and Z35 distributed line parameters.

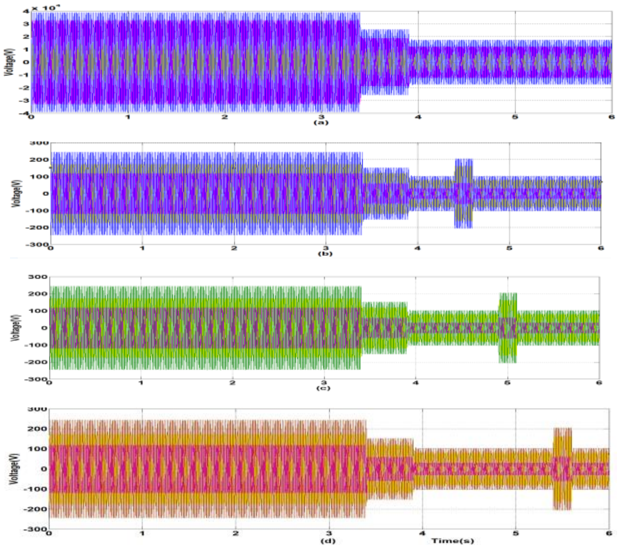

Fig. 11. Three phase voltages (a) At 33kV side of the transformer for three phase fault. (b) Voltages at low voltage side of the transformer for three phase fault with ground resistance of 0.001 ohms. (c) Voltages at low voltage side of the transformer for line-to-line fault with fault resistance of 9 ohms and with ground resistance of 0.001 ohms. (d) Voltages at low voltage side of transformer for line to ground fault with ground resistance of 0.001 ohms.

The tower shadowing effect of wind turbine and respective power fluctuations are mitigated effectively by UPQC, which is similar case to the previous case study. Fig. 11(a) clearly demonstrates that during the entire simulation period the transformer 33 kV side voltages is maintained constant by the UPQC compensator within the IEEE 1159-1995[23]. At time t = 4.6 - 4.8 seconds i.e., during the three phase fault with ground resistance of 0.001 ohms period the voltage has raised from 110 V(peak−peak) to 225 V(peak−peak) is shown in Fig. 11(b). At time t = 4.5 - 4.7 seconds a three phase fault with ground resistance of 0.001 ohms. During this period the voltage has raised from 115 V (peak−peak) to 225 V (peak−peak) is created at low voltage side of the transformer is shown in Fig. 11(b). Similarly, a line to line fault with fault resistance with fault resistance of 9 ohms with ground resistance of 0.001 ohms created during t = 5.2 – 5.4 seconds and a line to ground fault with a ground resistance of 0.001 ohms created. The simulated results shown in Fig. 11(c) and Fig. 11(d) are respectively to created the voltage swells.

CONCLUSION

In this present work, modelled a p-q theory based UPQC to improve the power quality of a hybrid renewable system with proton exchange membrane fuel cell system and permanent magnet synchronoues generation based wind energy systems connected to a weak grid. The developed PMSG based wind system injecting the power quality issue into the weak grid in terms of power fluctuations. The developed UPQC conditioner effectively mitigated these power fluctuations effectively within the international standards of IEC 61000-4-15. And further the compensator mitigated the symmetrical voltage sags due to load variations and unsymmetrical swells due to unsymmetrical conditions within the IEEE 1159-1995.

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