Implementation of ANN-Based UPQC to Improve Power Quality of Hybrid Green Energy System

C. H. Siva Kumar and G. Mallesham

Abstract The rapid increase in the contribution of naturally replenished green energy sources to increase the generating capabilities of a modern power system poses a challenging task for engineers to maintain its power quality. The zest of the paper is to address the power quality issues that arose due to the presence of a wind energy system in a hybrid PEMFC and PMSG based wind energy system connected to a weak grid system. In this work, built a mathematical model of a hybrid renewable system consisting of a wind energy system with a permanent magnet synchronous generator, proton exchange membrane fuel cell system and estimated the carbon emission reductions. The work is further focuses on power quality issues aroused in a geographically weather-dependent wind variation impact. As these impacts limit the freedom of utilizing different power sources, it causes a variable voltage and output powers, especially in a weak grid system. To improve the power quality of hybrid weak grid systems modelled and simulated an ANN-based UPQC using MATLAB/Simulink. Simulation results are shown to verify the performance of the compensator to mitigate active power, reactive power fluctuations and voltage fluctuations due to the wind energy system and to mitigate symmetrical sags due to symmetrical loading conditions and swells due to unsymmetrical conditions.

Keywords Hybrid green energy system · Wind energy system · Proton exchange membrane fuel cell

1 Introduction

The annual rise in carbon dioxide around the world is about 1.3% [1]. This growth further increases across the globe as there is a rapid growth in all industrial sectors,

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power sectors, transport systems, etc., which further worsen weather conditions on the globe [2, 3]. Globally, many governments set new policies and their targets at sub-national level for decarbonization, with increasing private sector players in the generation of electrical energy results in growing the market for green renewable energy sources. As per the Renewables 2019 Global Status Report, during the last year, a total significant capacity of 2378 gigawatts (GW) of renewable power was added globally out of which around 28% is wind energy [4]. As the penetration levels of these green renewable energy systems increases to reduce the decolonization in one aspect, in another aspect, it increases the power quality issues in the modern power system. There is another emerging research field in electrical engineering is fuel cell systems. The benefits of using fuel cell-based charging stations are improving profit, fast installation of station, fast and smart charging, easy conversion of hydrogen, reliable, low-maintenance, quiet in operation, [5, 6], etc. The above two situations demand a combined operation of differently characterized green renewable energy resources like wind-fuel cell systems, wind-solar, wind-hydro systems, wind-geothermal, etc. A hybrid renewable energy system is a stand-alone electrical power source consisting of two or more electrical energy sources working together to meet the demand. Working together in a common grid as a hybrid grid, working under these situations is a challenging task for the working engineers to generate, coordinate and controlling of diversified characterized renewable energy systems in a grid, especially weak electrical grid system [7]. The above-mentioned problems come under the category of power quality problems of utility systems. These power quality problems cannot be handled by the utility system on its own. With the recent progress in power electronics devices and applications to electrical power systems for the benefit of end-users called custom power devices. Out of all custom power devices, UPQC has the best features of controlling power quality issues [8].

Many research works proposed different control approaches to extract distorted components like Akagi et al. [9] proposed instantaneous active and reactive power concept, Enhanced PLL based SRF control method [10], hybrid fuzzy back-propagation control scheme [11], a new SRF-based power angle control method [12], etc., for controlling of UPQC for a single power source and grid systems. The complete work of the paper is organized into different sections. The main part of the work is mathematical modelling of hybrid renewable systems: wind energy system with wind turbine and permanent magnet synchronous generator and fuel cell system, modelled a multilayer feedforward-type ANN-based UPQC in Sect. 2. In Sect. 3 discussed in detail about performance analysis of ANN-based UPQC in a weak grid network. Finally concluded the work in Sect. 4.

2 Carbon Emission Reduction Using HRES

The human activities that emit the greenhouse gases are transportation, generation of electricity, industrial, commercial residential and agricultural sectors. It is worth using a hybrid renewable energy system to reduce the percentage of carbon emissions from the power sector as per Kyoto protocol to limit greenhouse gas emissions [13]. This work is one of the best solutions to reduce greenhouse gas emissions as it is using a hybrid renewable energy system for the production of electrical energy. A total of 21.61 MW of electrical power is produced using HRES which reduces the carbon emission by 21.19941 t [14].

3 Mathematical Modelling of Components Using MATLAB/Simulink

The most promising tool used by the engineers to solve effectively and safely is simulation. To understand the complete behavior of any systems using computer simulation studies needs a mathematical representation of the system. It needs the complete mathematical model-based description with the complete physical properties of a system to study and analyze. It reduces real-time cost, time of operation, flexibility to redesign the system, suggests required modifications and complete insights of any system to study and analyze. To carry this work, MATLAB/Simulink model-based design software is used. The following sub-sections describe the respective mathematical modelling of the components. In this section presented the mathematical modelling of wind turbine, permanent magnet synchronous generator is presented.

3.1 Modelling of Wind Turbine

A mathematical model gives the relationships between various variables. The mathematical expression for power output of a wind turbine (variable speed) and output torque is represented as

$$P_{\mathrm{m}} = \frac{1}{2}\rho A \upsilon_{\mathrm{w}}^{3} C_{\mathrm{p}}(\lambda, \beta) \tag{1}$$

$$T_{\mathrm{t}} = \frac{1}{2}\rho \pi r^{3} C_{\mathrm{p}} V_{\mathrm{d}}^{2} \tag{2}$$

where ρ: air density (1.225 kg/m^3), A: swept area (m^2), υ_{w}: wind velocity (m/s) and C_{p}: power coefficient—0.59, V_{d}: disturbed wind speed. The overall output power of a wind turbine is (mechanically): 21.6e6 W and operated with a base wind speed by 14 m/s (fluctuating between 13 and 15 m/s).

3.2 Modelling of Permanent Magnet Synchronous Generator

The recent developments in synchronous generators: permanent magnet synchronous generators (PMSGs). PMSG is increasingly being used as variable speed turbines. As it reduces the cost of slip rings with high conversation efficiency, less maintenance, high reliability and reductions of weight of the nacelle. The dynamics of the machine referred [15–17].

The mathematical expression for torque is represented with the following notations: L_q and L_d are generator quadrature and direct axis inductances, R_s is the resistance, ω generator speed.

$$T_e = \frac{3}{2} p\left[\left(L_d - L_q\right) i_{sq} i_{sd} - \lambda_m i_{sq}\right] \tag{3}$$

3.3 Electrical Weak Grid System

One of the factors on which the manufacturers of wind tribunes depend tolerances on Short Circuit Ratio. It determines the stiffness of the gird. If the SCR below 2.5 is treated as a weak grid and on the other hand, it is considered as a strong grid its SCR value is greater than 20. A weak grid is sensitive to voltage fluctuations and to reactive power and a strong grid has the capability to maintain the reactive power variations due to voltage fluctuations. The *r*-value of the system considered is 5.5 [18].

3.4 Modelling of Proton Exchange Membrane Fuel Cell

The electrochemical technology of fuel cells has salient features like fuel flexibility, property of portability, noise-free operation, quick start-up, high power density and operates at relatively low temperatures. These features made a strong comeback of this technology for the generation of power in distributed power generation sectors. For the continuous operation of fuel cells, fuel is supplied continuously to anode and the corresponding reactant at cathode. Polymer membrane which conducts protons through it is used as an electrolyte. V-I characteristics of PEMFC are shown in Fig. 1 the following is the chemical reactions that take place in PEMFC [19, 20]:

$$\text{anode equation}: \mathrm{H_2} \rightarrow \mathrm{H^+} + 2\mathrm{e^-} \tag{4}$$

$$\text{cathode equation}: 1/2\ \mathrm{O_2} + 2\mathrm{H} + 2\mathrm{e^-} \rightarrow \mathrm{H_2O} \tag{5}$$

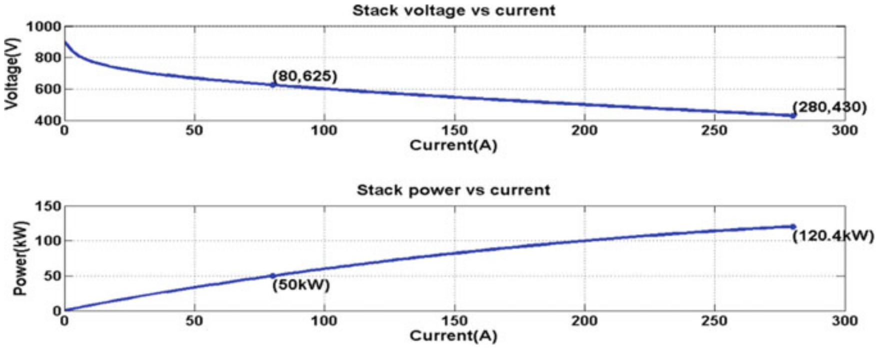

Fig. 1 V-I characteristics of PEMFC fuel cell

3.5 Modelling of ANN-Based UPQC

In the present scenario, power quality issue is one of the major issues in the electrical power distribution system to maintain the system parameters within the international standards like IEEE Standard 519-1992 (1992); IEEE Standard 1547-2003 (2003), etc. Custom power devices are the solutions to handle and control power quality issues at the distribution level. In this work a custom power device is called UPQC is modelled using the ANN control technique. A UPQC consists of three major parts: series: shunt and a common DC source: DC link [21]. Different power theories and techniques for UPQC have been used by the researchers are discussed in the introduction.

Combined intelligence of human intelligence, applications of machine processes and computer system: Artificial intelligence has become a part of design, analysis, processing, planning and controlling. With the introduction of these systems, reducing human errors fastens the best solutions to single and multiple objectives, solutions to non-linear systems, etc. have made a significant transformation in all fields of engineering and non-engineering sectors. In this work, a sub-area of Artificial intelligence: ANN technique is basically derived from the human nervous system: neurons in the brain. In this work an ANN-based UPQC (*p*-*q* theory) is built to improve the power quality of a hybrid green energy system with the following parameters: ANN: No. of layers hidden layers: 3, No. of epochs: 500, No. of inputs: 1 and outputs: 1 of the error voltage of PCC and DC link voltage. Training control scheme used is Gradient descent back-propagation with adaptive learning algorithm, which has the highest performance and quick convergence than back-propagation algorithms. The MATLAB/Simulink model of ANN shunt controller is shown in Fig. 2.

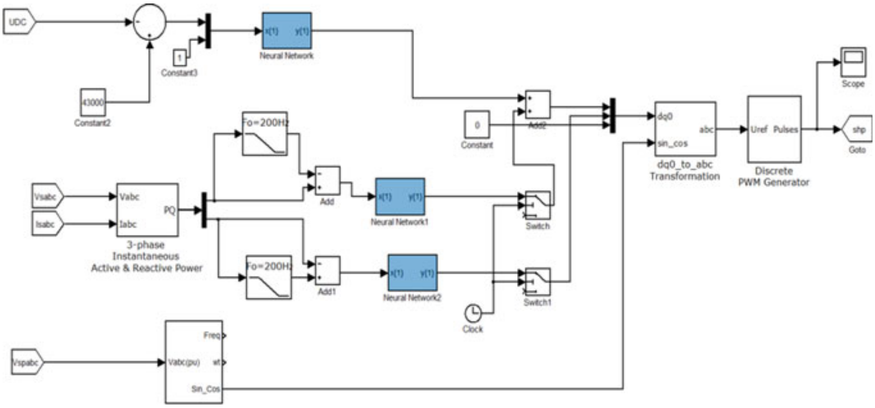

Fig. 2 ANN shunt controller block diagram

4 Performance and Analysis of ANN-Based UPQC

Built a hybrid network shown in Fig. 3 using MATLAB/Simulink to study the performance and analysis of ANN-based UPQC [22]. The network consists of a weak grid with a voltage level of 33 kV, a 21.6 MW PMSG based wind energy system, a 100-kW rated PEMFC. The notation i^{th} and j^{th} is used to represent the impedance Z between the nodes Z_{ij}. An ANN-based UPQC placed in the network at BB6. To study the performance of the built ANN-based UPQC the following case studies have been carried.

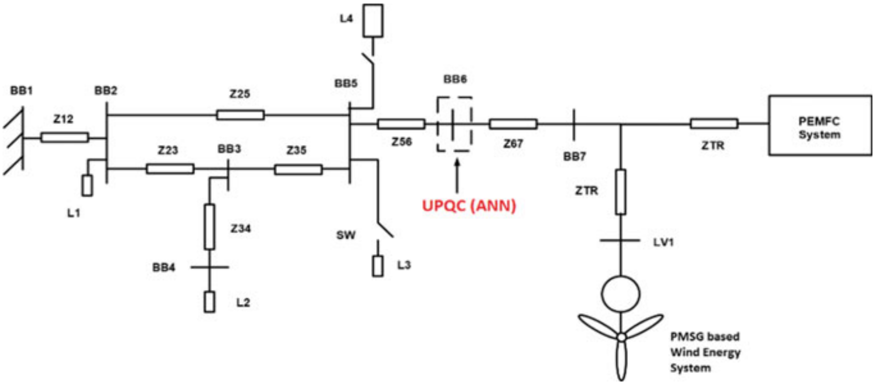

Fig. 3 Hybrid green energy system connected to weak grid

4.1 Simulation Case Study 1: Fluctuating Wind and Balanced Sags

The simulation is carried for a time period of 6 s with different balanced loading L_1: 15 MW $+ j$ 6.31 MVAr, L_2: 12 MW $- j$ 2.4 MVAr, L_3: 9.2 MW $+ j$ 1.85 MVAr and L_4: 20 MW $+ j$ 15 MVAr, respectively, at 3.6, 4.2, 4.6 and 5.2 s, respectively. Figure 4a–c clearly demonstrates the active and reactive power fluctuations due to fluctuating wind and its impacts at grid, wind energy system and fuel cell system (without using UPQC). Figure 5a–c clearly demonstrates the active and reactive power fluctuations exits till 2.5 s so, then on-wards there are no active and reactive power fluctuations. These active power and reactive power fluctuations resulted due

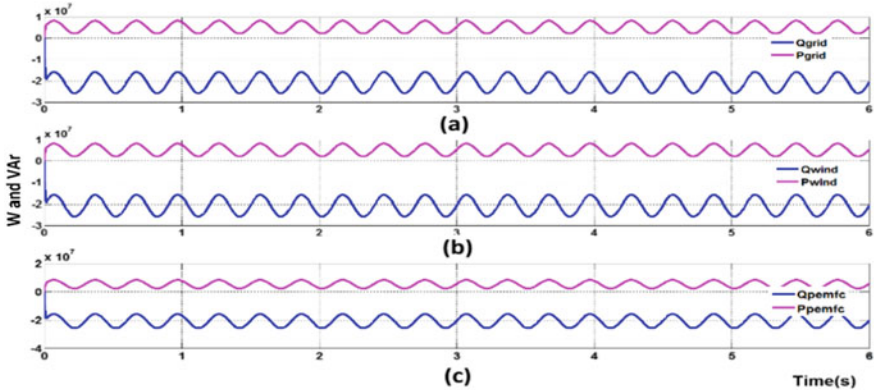

Fig. 4 Without UPQC: active and reactive powers: **a** P and Q at grid, **b** P and Q at PMSG based wind energy system, **c** P and Q at PEMFC

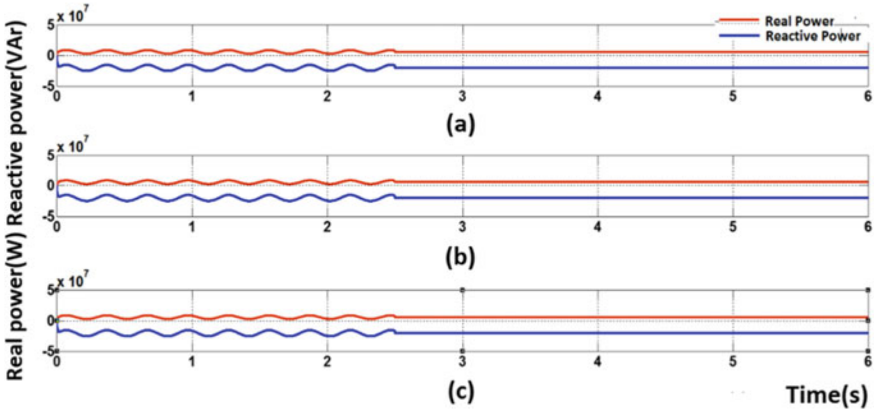

Fig. 5 With UPQC: active and reactive powers: **a** P and Q at grid, **b** P and Q at PMSG based wind energy system, **c** P and Q at PEMFC

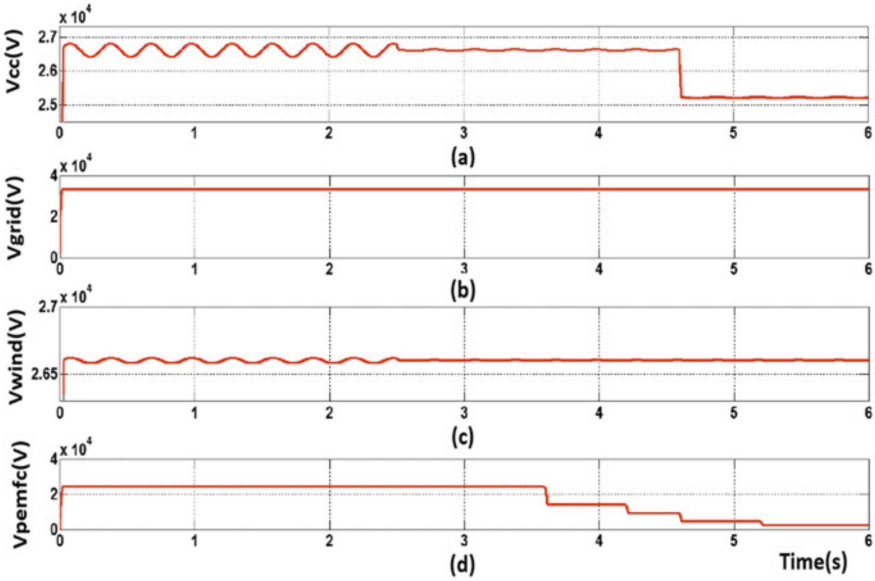

Fig. 6 Terminal voltages at: **a** point of common connection (PCC), **b** grid, **c** PMSG based wind energy system and **d** PEMFC system

to torque variations in wind turbine Eq. (2). At time 2.5 s both the series and shunt controllers of ANN-based UPQC is put into operation. The simulation results shown in Figs. 5 and 6 are the evidence of improvement of power quality using modelled an ANN-based UPQC. In Fig. 5a–c clearly demonstrated that after 2.5 s the controller put into operation results in nullyfying the power fluctuations in grid, wind and fuel cell systems. In Fig. 6a–d represented the terminal voltage at the point of common connection, grid, wind energy system and fuel cell system for the entire simulation period. As it is clearly demonstrated in Fig. 6c the voltage fluctuations are existing till 2.5 s, i.e. before the complete UPQC put into operation. And carried the analysis and it is found that these fluctuations are with IEC 61000-4-15.

4.2 Simulation Case Study 1: Unbalanced Swells Due to Unsymmetrical Conditions

Another important power quality aspect that generally the power system subjected to is: Voltage swell is quite opposite to sag: increasing the voltage more than one cycle and less than a few seconds. This power quality issue arises due to: sudden change in the reference of the ground, raise in un-faulted phases, large loads de-energization, insulation failure, damage to the very sensitive loads, etc. To analyze the compensator under these conditions built a system with different unsymmetrical conditions. This case study is also carried for the simulation time period of 6 s. Initially loaded the system with balanced loads of 15 MW $+ j$ 6.31 and 12 MW $- j$ 2.4 MVAr same that of the case 1. The following unsymmetrical conditions are created to analyze ANN-based UPQC. Faults are created on LV side of 630 kVA, 33 kV/690 V. 1. 4.6 to 4.8 s: 3-phase fault with R_f—0.001 Ω ground resistance: R_g 0.001 Ω 2. 5.2 to 5.4 s: L-L fault with 9 ohms resistance ground resistance: 0.001 Ω. 3. 5.6 to 5.8 s: L-G fault with ground resistance: 0.001 Ω.

Figure 7a–c results in different swell conditions on the secondary side of the transformer, the primary voltage is Fig. 7d maintained remains constant for all unsymmetrical conditions using ANN-based UPQC within IEEE 1159-1995 standards [23].

5 Conclusion

In this paper, the performance of an ANN-based custom power device UPQC carried for the proposed differently characterized hybrid green energy system with permanent magnet synchronous generator-based wind energy system and proton exchange membrane fuel cell system in a weak grid. The modelled compensator effectively handled both voltage and power fluctuations due to fluctuating wind effect of wind energy system without any difficulty by injecting appropriate voltage components and power quality issues due to symmetrical sag and unsymmetrical loading conditions within IEC 61000-4-15 and IEEE 1159-1995 international standards. These results will beneficial to researchers of hybrid renewable energy systems to improve the power quality issues.

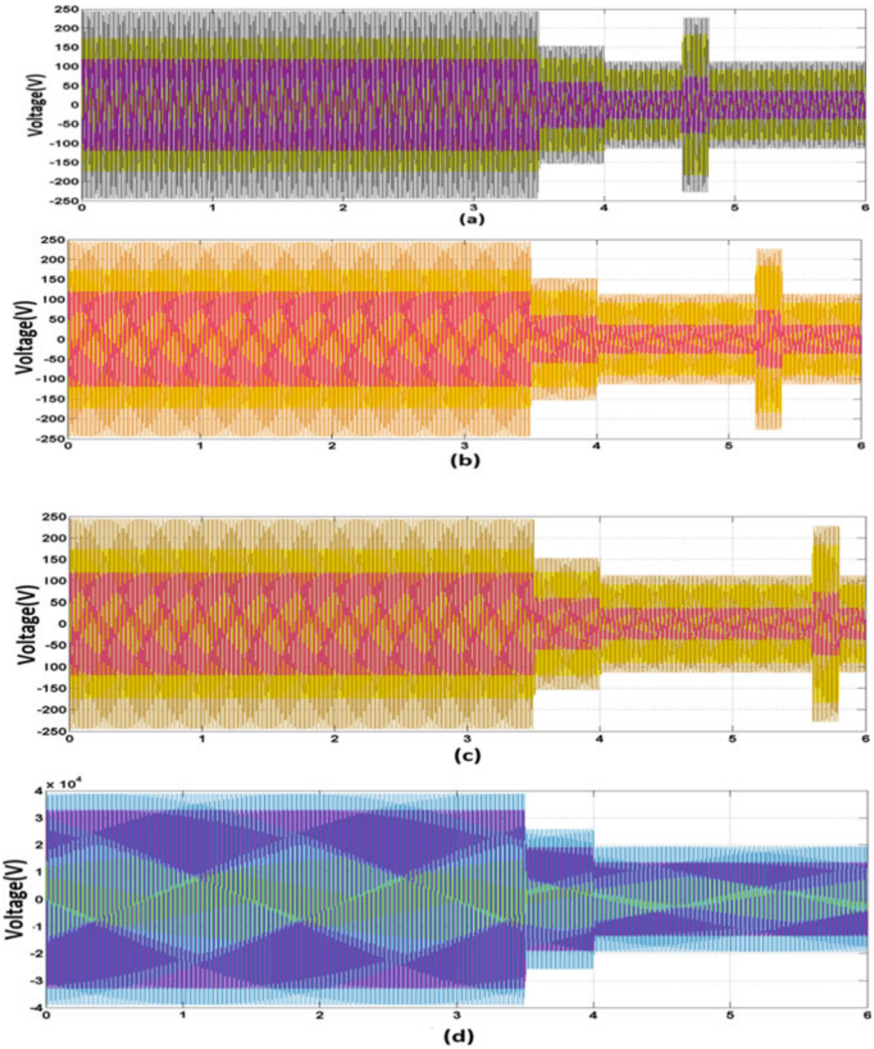

Fig. 7 Fault voltages on LV side of the transformer: **a** three-phase fault with fault resistance, **b** line to line fault with fault resistance, **c** L-G fault with fault resistance and **d** the HV side terminal voltage during the above three faults

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