

Power Quality Analysis of a Grid-Connected Solar/Wind/Hydrogen Energy Hybrid Generation System

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ABSTRACT

A grid connected hybrid generation system (HGS) consisting of wind energy conversion System (WECS)/Photo voltaic (PV) System/solid oxide fuel cell (SOFC) is designed and simulated by using Matlab/Simulink. SOFC is the replacement of battery, attached to produce the clean energy when these renewable energy sources are unable to produce required amount of electric power. A controller is used to regulate the flow of H₂ through the valve to the SOFC and the rest amount of H₂ is stored in storage tank. Also, an operational control strategy (OCS) is developed to utilize maximum amount of power of PV to the required load and rest amount of power is coming from wind to fulfill the load demand. Hence, the electrolyzer is supplied by the wind power to convert the water in to H₂ and oxygen. Also the power quality factor (PQF) analysis is exercised to measure the quality of power transmission.

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1. INTRODUCTION

In recent years, renewable energy sources (RESs) are more effective and pollution free. Also, these sources are continuous and cost free. Now-a-days, the RESs such as wind and PV are the main sources of energy, which are used to fulfill the power requirement [1, 2]. The numerous type of renewable energy sources such as PV, wind energy, wave energy, tidal energy are combined with each other and to form a HGS. For the instance hybrid PV thermal systems are well documented in the literature [3, 4]. Various simulation models are used for the PV and wind energy sources and their combination is known as hybrid generation system [5, 6]. In the hybrid models, FC and battery bank (BB) are used as the storage devices and these storage devices store the excess energy of RESs and used to provide backup power supply when the power deficit occurs or at the time when no generation occurs by the RESs due to the bad atmospheric conditions (when PV or wind power is not available). So, it is necessary to keep an energy storage system (ESS) as described in [7-9]. Further, a secondary energy source is necessary for the improvement of the HGSs. Therefore, a FC is essential to connect with the electrolyzer. Then, this combination gives continuous energy supply to the consumer. A better power management strategy is the combination of wind and PV with the FC which associates with electrolyzer and battery storage. This technique provides better reliability for the energy requirement [10-12]. In [13], a novel HGS combination of PV/wind/FC is modeled and designed. Also a novel MPPT technique is used to produce maximum energy and satisfy the power demand of the remote areas. A FC provides clean energy and low pollution; also it gives the required energy sources by

taking hydrogen as a fuel. So FC is available commercially for the backup generation in the HGS. The standalone HGS i.e WECS/PV/FC converts solar as well as wind power in to electricity which can be used in domestic purposes. The Maximum energy of the PV [14-16] and wind [17] can be tracked by using the highly accurate MPPT.

As far as the components of the hybrid energy systems are concerned, Sarrias-Mena, et al [18] have presented the electrolyzer models for hydrogen production from wind energy Systems. Modeling and analysis of MW-level grid-connected PV plant has been presented by Lei, et al [19]. A MATLAB-simulink-based PV module model and its application under conditions of non-uniform irradiance have been by discussed by Ding, et al [20]. Altas, et al [21] have described a photovoltaic array simulation model for MATLAB Simulink GUI environment. Further, Uzunogle, et al [22] have presented a static VAR compensator based reactive power management scheme for SOFC power plants. Grid connected fuel cell and PV hybrid power generating system design with Matlab Simulink has been presented by Bayrak, et al [23]. Recently, Molina, et al [24] have developed modeling and simulation of grid-connected photovoltaic energy conversion systems and demonstrated its effectiveness. Also a control strategy is developed for the wind and fuel cell connected to grid as well as a power management strategy is developed for the hybrid system described in [25] and [26]. The quality of power transfer can be determined by a single indicator ranging from zero to one known as power quality factor (PQF) for the 3-Ø supply and this supply is connected to the load as described in [27]. So it can be mentioned that the power transfer quality is low due to the harmonic content in supply voltage, nonlinear load and unbalanced voltage supply or caused due to both of them. According to the ref. [27], in a distribution network, a suggested PQF determines the quality of power at any point by the help of single indicator without taking many factors and their values.

An attempt has been made in this paper to design and analyze a HGS assembling PV, wind, SOFC, electrolyzer and storage tank connected to grid. It describes detailed modeling of each component including storage tank whose detailed modeling is not available in the literature and also the control strategy is well explained. Further, the power quality analysis is done briefly in this paper. Finally the effectiveness of the proposed system is verified under several conditions and simulation results are presented.

2. EXPLANATION OF GRID CONNECTED HYBRID GENERATION SYSTEM

The detailed model of HGS is represented in Figure 1. A hybrid model having PV/wind energy generation system is designed and simulated and connected with the SOFC for the backup power supply when there is no power supply from wind and PV. In the HGS, SOFC takes the H₂ as fuel for the backup power generation and this H₂ is produced by the electrolyzer when the water is divided into two halves (H₂ and Oxygen) through the electrolysis process in the electrolyzer. The electrolyzer operates by taking the excess amount of electrical power from the PV/wind generation. The amount of H₂ flow to the SOFC is controlled by the fuel cell controller and the rest amount of H₂ is stored in the storage tank.

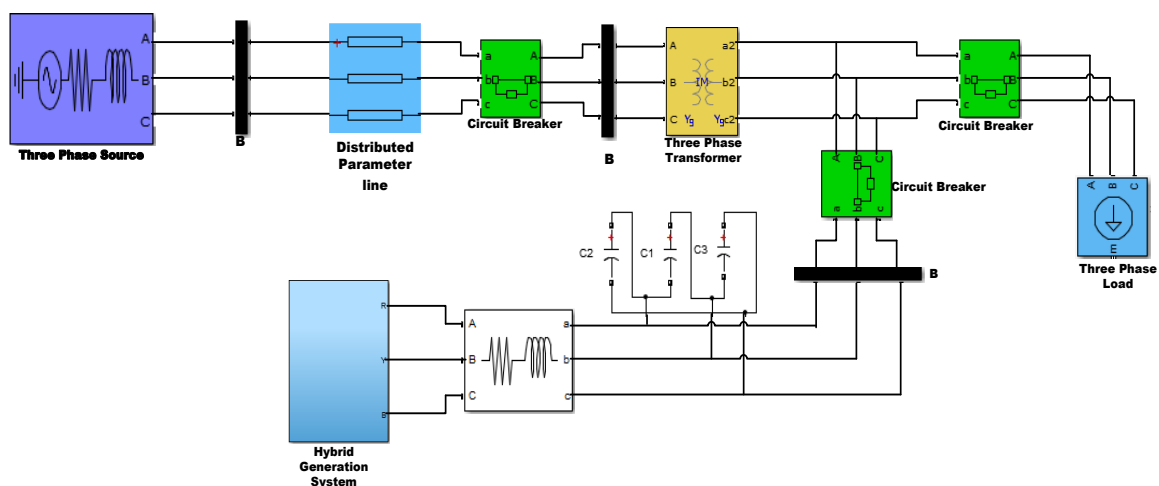


Figure 1. Grid connected Hybrid Generation System (Detailed Model).

In the model of HGS maximum energy can be tracked by the help of MPPT from the PV and WECS. Then these energies are supplied to the boost converter to enhance the DC voltage level. Hence, this boosted DC voltage is applied to the inverter (DC/AC Converter) to convert DC voltage to AC voltage.

The strategy of the power management of the HGS is considered to maximize the power delivery to the load at the time of bad weather and geographical conditions. Hence, the proposed HGS offers clean output power that compensates load demand.

3. DETAILED EXPLANATION OF PV MODEL

For designing the PV model basically Single-diode or two-diode models are broadly used. Mostly single-diode model is more appropriate to use as described in [19-21]. The designing of PV model is done by applying the Equation (1). Table 1 shows the parameters of the PV module.

$$V_{pv} = \frac{N_s a k T}{q} \ln \left[\frac{I_{sc} - I_{pv} + N_p}{N_p I_0} \right] - \frac{N_s}{N_p} R_s I_{pv} \quad (1)$$

Parameters are taken for modeling of the PV system such as, I_0 is the reverse saturation current of PV model in [A], I_{sc} is the short-circuit PV cell current in [A], I_{pv}/I_{ph} is the output current of PV model in [A], k is the boltzmann's constant in [J/oK], a is the completion or ideality factor, q is the electron charge in [C], R_p in the parallel resistance of the PV model in [Ω], R_s in the series resistance of PV model in [Ω], N_s is the no. of cells are connected in series in a string of the PV model, N_p is the no. of parallel strings, T is the temperature in [K], V_{pv} is the terminal voltage of the PV model in volt in [V], V_{mp} is the maximum power of the PV cell in volt in [V], V_{oc} is the open-circuit voltage of the PV cell in volt in [V]

In the PV system maximum power output depends upon the load current as well as solar radiation. So a control techniques is employed to track the maximum amount of power from the PV system is known as MPPT according to [14-16]. In this literature P&O technique is used for the MPPT.

Table 1 Parameters of Photovoltaic (PV) System

Specification	Value
No. of series connected PV cell	96
No. of Modules in parallel	66
No. of Modules in series	05
Open circuit voltage(V_{oc})	64.2 V
Short circuit current(I_{sc})	5.96 A
Maximum Power of PV cell	305W
Temperature(T)	25
Irradiance	1000

4. DETAILED REALIZATION OF WECS

Kinetic Energy (KE) of the wind is converted into mechanical energy by means of blades of the wind turbine, then a generator is connected to the wind turbine to converts mechanical energy to electrical energy. So, a relationship is established in between the wind speed and mechanical power which is described below:

$$P_M = \frac{1}{2} \rho A V_w^3 C_p \quad (2)$$

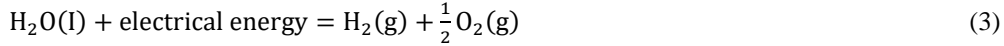
Parameters are taken for modeling of the WECS such as, P_M is the mechanical power in [W], ρ is the air density in [kg/m^3], A is the Swept area in [m^2], V_w is the wind speed in [m/s], C_p is the power coefficient of wind turbine, λ_T is the speed ratio, β is the pitch angle of the blade, w_m is the speed of the turbine, R_T is the blade radius, C_p is the function of λ_T and β and can be realized as $C_p(\lambda_T, \beta)$. Where $\lambda_T = \frac{w_m R_T}{V_w}$. The coefficient of power C_p depends on the λ_T . To capture maximum power, wind turbine is run for a certain value of wind speed. The maximum value of the C_p is 0.59 according to the Betz limit [11].

To extract the maximum power from the WECS a control technique is employed. Basically, P&O technique is used in the MPPT for the WECS according to [17].

5. DETAILED MODEL OF ELECTROLYZER

An electrolyzer consists of the no. of series-connected cells. Two electrodes are presented in the electrolyzer and separated by an electrolyte. Water (H₂O) is decomposed into H₂ and oxygen in the electrolyzer when the current is passed through it according to [2, 18].

The electrochemical reaction of H₂O is given below:



Parameters are taken for modeling of the electrolyzer such as, i_e is the current of an electrolyzer in [A], n_c is the no. of electrolyzer cells connected in series, n_{H_2} is the hydrogen generation in moles per second in the [mol s⁻¹], F is the faraday constant in the [C kmol⁻¹], η_F is the Faraday efficiency.

H₂ is produced by the electrolyzer and rate of its production depends upon the current flow through it given in Faraday's law [12].

$$n_{\text{H}_2} = \frac{\eta_F n_c i_e}{2F} \quad (4)$$

Faraday efficiency is noted as the ratio of actual production of H₂ to its theoretical value.

$$\eta_F = 96.5e^{\left(\frac{0.09}{i_e} - \frac{75.5}{i_e^2}\right)} \quad (5)$$

With the help of Equation (4) and (5) an electrolyzer is designed by using Matlab-Simulink software.

6. DETAILED MODELLING OF STORAGE TANK

The generation of H₂ from the electrolyzer can be kept in a storage tank for the future use. Basically three methods are applicable to store the H₂, these are (a) high-pressure gas in compressed form, (b) liquid storage and (c) hydrogen absorbing materials. The H₂ is stored in compressed high pressure gaseous form for the domestic application. Equation (6) is considered for the designing of hydrogen storage tank according to [11].

$$P_b - P_{bi} = z \frac{N_{\text{H}_2} R T_b}{M_{\text{H}_2} V_b} \quad (6)$$

Parameters are taken for modeling of the SOFC such as, Z is the pressure compressibility factor, N_{H_2} is the amount of hydrogen stored in the storage tank in moles per second in the [kmol s⁻¹], M_{H_2} is the Hydrogen molar mass in [kg kmol⁻¹], T_b is operating temperature in [oK], P_{bi} is the storage tank pressure at initial stage in [Pa], P_b is the storage tank pressure in [Pa], R is the Rydberg/Universal gas constant in [J (kmol oK)⁻¹], V_b is the storage tank volume in [m³].

7. DETAILED MODELLING OF SOFC

SOFC is used to convert chemical energy of a fuel (methanol, hydrogen, gasoline, natural gas and many more) into an electrical power. Also, the fuel cells provide clean energy and no emissions.

Parameters of the SOFC which are used to develop the mathematical model according to [22] such as, B and C is the activation voltage constants in SOFC system in [V], CV is the conversion factor in $\left[\frac{\text{Hydrogen (kmoh)}}{\text{Methen (kmoh)}}\right]$, E_0 is the normal no load voltage in [V], E is the nernst immediate voltage in [V], F is the Faraday's constant in [C (kmol⁻¹)], IFC is the feedback current of SOFC in [A], k_1 is the gain of PI (proportional-integral), K_{an} is the anode valve constant in $[\sqrt{\text{kmol kg}(\text{atm s})^{-1}}]$, K_r is the modeling constant in [kmol SA⁻¹], $K_{\text{H}_2\text{O}}$ is the molar constant of water valve in [kmol (atm s⁻¹)], K_{H_2} is the molar constant of hydrogen valve in [kmol (atm s⁻¹)], K_{O_2} is the molar constant of oxygen valve in [kmol (atm s⁻¹)], M_{H_2} is the hydrogen molar mass in [kg kmol⁻¹], $P_{\text{H}_2\text{O}}$ is the water fractional pressure in [atm], P_{H_2} is the hydrogen fractional pressure in [atm], P_{O_2} is the oxygen fractional pressure in [atm], N_0 is the no. of fuel cells are in series in a stack, q_{H_2} is the molar flow of hydrogen in [kmols⁻¹], q_{methane} is the methane flow rate in [kmols⁻¹], q_{O_2} is the input molar flow of oxygen, [kmols⁻¹], $q_{\text{H}_2}^{\text{in}}$ is the input flow of hydrogen in [kmols⁻¹], $q_{\text{H}_2}^{\text{out}}$ is the hydrogen output flow in [kmols⁻¹], $q_{\text{H}_2}^{\text{r}}$ is the hydrogen flow amount that reacts in [Kmol⁻¹], $q_{\text{H}_2}^{\text{req}}$ is the hydrogen flow amount that meets load change in [kmols⁻¹], R is the

rydberg (Universal) gas constant in $[(1\text{atm}) (\text{kmol K})^{-1}]$, R_{int} is the internal resistance of SOFC in $[\Omega]$, T is the absolute temperature in $[\text{K}]$, U is the utilization rate, V_{an} is the volume of the anode in $[\text{m}^3]$, V_{cell} is the SOFC dc output voltage in $[\text{V}]$, τ_1, τ_2 is the reformer time constants in $[\text{s}]$, τ_3 is the PI controller time constant in $[\text{s}]$, τ_{H_2} in the hydrogen time constant, $[\text{s}]$, $\tau_{\text{H}_2\text{O}}$ is the water time constant in $[\text{s}]$, τ_{O_2} is the oxygen time constant in $[\text{s}]$, Z_{act} is the activation over voltage in $[\text{V}]$, Z_{ohmic} is the ohmic over voltage in $[\text{V}]$.

The ratio of molar flow hydrogen throughout the valve to the hydrogen partial pressure in the chamber may be written as [22]:

$$\frac{q_{\text{H}_2}}{p_{\text{H}_2}} = \frac{K_{\text{an}}}{\sqrt{M_{\text{H}_2}}} = K_{\text{H}_2} \quad (7)$$

Three major aspects taken into consideration for the molar flow of hydrogen are (a) input flow of hydrogen, (b) output flow of hydrogen and (c) hydrogen flow during the reaction.

Hence, the Equation can be written as:

$$\frac{d}{dt} p_{\text{H}_2} = \frac{RT}{V_{\text{an}}} (q_{\text{H}_2}^{\text{in}} - q_{\text{H}_2}^{\text{out}} - q_{\text{H}_2}^{\text{r}}) \quad (8)$$

The reacted hydrogen flow depends upon the fuel cell current and the rate of flow of hydrogen. The Equation of reacted hydrogen flow rate is shown below.

$$q_{\text{H}_2}^{\text{r}} = \frac{N_{\text{O}} I_{\text{FC}}}{2F} = 2K_{\text{r}} I_{\text{FC}} \quad (9)$$

By considering the Equations (7) and (9) and taking Laplace Transform of these Equations, then partial pressure of hydrogen is determined as:

$$p_{\text{H}_2} = \frac{1/K_{\text{H}_2}}{1 + \tau_{\text{H}_2} s} (q_{\text{H}_2}^{\text{in}} - 2K_{\text{r}} I_{\text{FC}}) \quad (10)$$

$$\text{Where, } \tau_{\text{H}_2} = \frac{V_{\text{an}}}{K_{\text{H}_2} RT} \quad (11)$$

In this manner partial pressures of water and oxygen are determined. Hence, polarization curve of the SOFC is found out from the summation of the ohmic over voltage, activation over voltage and the Nernst's voltage. A constant assumption is taken for the oxygen concentration and temperature and hence, the SOFC output voltage can be determined as:

$$V_{\text{cell}} = E + \eta_{\text{act}} + \quad (12)$$

$$\text{Where, } \eta_{\text{act}} = -B \ln(CI_{\text{FC}}) \quad (13)$$

$$\text{And } \eta_{\text{ohmic}} = -R^{\text{int}} I_{\text{FC}} \quad (14)$$

Hence, the Nernst's voltage can be stated as:

$$E = N_{\text{O}} \left[E_{\text{O}} + \frac{RT}{2F} \log \left[\frac{p_{\text{H}_2} \sqrt{p_{\text{O}_2}}}{p_{\text{H}_2\text{O}}} \right] \right] \quad (15)$$

To control the required amount of H₂ flow to the SOFC according to output power of SOFC, a PID controller is taken into consideration. A feedback control strategy is achieved by taking SOFC output current feedback to the current input terminal of SOFC. So, availability of hydrogen in a hydrogen tank is expressed as [22]:

$$q_{\text{H}_2}^{\text{req}} = \frac{N_{\text{O}} I_{\text{FC}}}{2F U} \quad (16)$$

A 5 KW SOFC is developed by taking the parameters as represented in Table 2 and a detailed model of SOFC is developed with the help of Matlab/Simulink according to [23]. In this paper four no. of 5 KW SOFC are taken.

Table 2 Particulars of SOFC to develop the mathematical modeling

Specifications	Value
Activation voltage constant (B)	0.04777 [A ⁻¹]
Activation voltage constant (C)	0.0136 [V]
Conversion factor (CV)	2
Faraday's constant (F)	96 484 600 [Ckmol ⁻¹]
FC system internal resistance (R _{int})	0.26664 [Ω]
FC absolute temperature (T)	343 [K]
Hydrogen time constant (τ _{H2})	3.37 [s]
Hydrogen valve constant (K _{H2})	4.22 x10 ⁻⁵ [kmol (s atm) ⁻¹]
Hydrogen-oxygen flow ratio(r _{H2O})	1.168
Kr constant =N ₀ /4F	2.2802 x 10 ⁻⁷ [kmol (s A) ⁻¹]
Line reactance (X)	0.0809 [Ω]
Methane reference signal (Q _{methref})	0.000015 [kmol s ⁻¹]
No load voltage (E _o)	1.18 [V]
Number of cells (N _o)	88
Number of stacks (N _s)	1
Oxygen time constant (τ _{O2})	6.74 [s]
Oxygen valve constant, (k _{O2})	2.11 x10 ⁻⁵ [kmol (s atm) ⁻¹]
PI gain constant (k _i)	0.25
Reformer time constant (τ ₁ , τ ₂ , τ ₃)	15 [s]
Universal gas constant (R)	8314.47 [J kmolK ⁻¹]
Utilization factor (U)	0.8
Water time constant (τ _{H2O})	18.418 [s]
Water valve constant (K _{H2O})	7.71610 ⁻⁶ [kmol (s atm) ⁻¹]

8. INTERNAL ARRANGEMENT OF HYBRID GENERATION SYSTEM

The detailed model of proposed HGS is shown in Figure 1 whereas; the internal model diagram is represented in Figure 2. In Figure 2a two RESs are shown, one of them is PV system and another one is WECS. A PV system tracks the maximum power from the sun by means of MPPT where as, WECS utilizes the kinetic energy of the wind and converts this into electrical power by the help of MPPT. The electrical power coming from the PV system is given to DC-DC boost converter to enhance the voltage. The same principle is happening in the WECS. In WECS, as shown in Figure 2a, V_{wind_ac} is applied to the AC-DC converter where, AC voltage is converted to the DC voltage and this DC voltage is applied to DC-DC boost converter to enhance the voltage level. The DC-DC boost converters employed in WECS and PV system are triggered by the pulses generated from the MPPT. These MPPTs are used in WECS and PV systems. As given in Figure 2a, the enhanced voltages of the both DC-DC converters of the WECS and PV system are applied to DC-AC converter to convert DC voltage to AC voltage. This DC-AC converter is triggered by gate pulse generated by the control technique of the voltage source converter (VSC). This control technique of VSC is employed to synchronize the voltages of the grid and HGS. The extra amount of power from the WECS and PV is utilized for the H₂ production by the electrolyzer and the H₂ further acts as the input of SOFC as a fuel. Again a DC-DC converter is connected to the SOFC to enhance the voltage level of SOFC as shown in Figure 2b. A VSC is used to synchronize the voltages between grid and system. The control technique applied to VSC is divided into two parts as described below.

DC-Link voltage controller

The DC-link voltage regulates the desired value of the active power. Then i_d^* is the output of the DC-link PI controller taken as the reference of the active current controller (current PI controller) and represented in Figure 2c.

Internal current loop

The Synchronous Reference Frame (d-q control) transforms the grid voltages (V_a, V_b, V_c) to V_d and V_q as well as grid currents (i_a, i_b, i_c) to i_d and i_q reference frame that rotates synchronously along with grid voltage. V_d, V_q, i_d and i_q are the DC values obtained by the help of d-q controller, also these DC values are easier for designing and controlling. Grid voltage (V_a, V_b, V_c) regulates PLL (Phase Lock Loop), hence the phase angle is obtained and used in d-q controller for abc → dq transformation. As shown in Figure 2c, the reference reactive current i_q^{*} is set to zero and applied to current PI controller. Hence, pf (power factor) is preserved to be one (Unity). The voltage output that is V_d^{*} is obtained by comparing i_d^{*} and i_d, also V_q^{*} is obtained by comparing i_q^{*} and i_q. Then, the V_d^{*} and V_q^{*} are applied to PWM generator to generate the pulses which are employed to trigger the DC-AC converter as shown in Figure 2a.

As shown in the Figure 2b, a buck converter is connected across the electrolyzer which takes the extra amount of power from the WECS and provides that extra power to the electrolyzer to convert the water into H₂ and oxygen. This H₂ is used as the input fuel of SOFC and the rest amount of fuel is stored in the storage tank. The requirement of H₂ flow to the SOFC as a fuel depends upon the load demand. Figure 2d shows the graphical structure of the fuel cell flow controller where V_{sofc_boost} is the output voltage of the boost converter connected across the SOFC. PID controller takes the input voltage of the boost converter (V_{sofc_boost}) connected across the SOFC and gives the controlling signal to the valve. Hence, the valve regulates the amount of H₂ flow which is given to the SOFC according to load requirement. The values of PID controller shown are chosen by the help of self-tuned mode of the Matlab/Simulink (P = 0.00013317, I = 3.3925227e-05, D = -6.254254172870e-05).

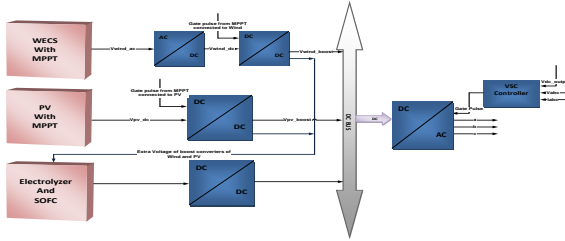


Figure 2a. Block diagram Representation of Hybrid Generation System (HGS)

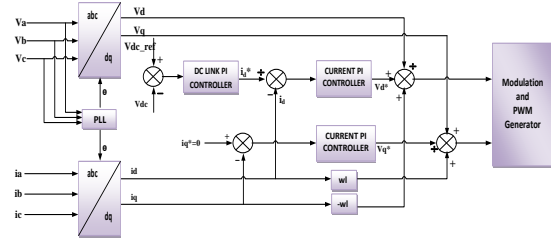


Figure 2c. Graphical diagram representing the control techniques applied to VSC

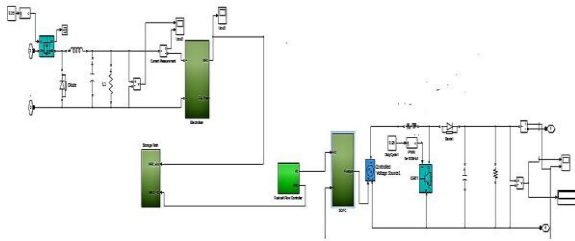


Figure 2b. Simulation diagram of H₂ flow from electrolyzer to Storage Tank and SOFC

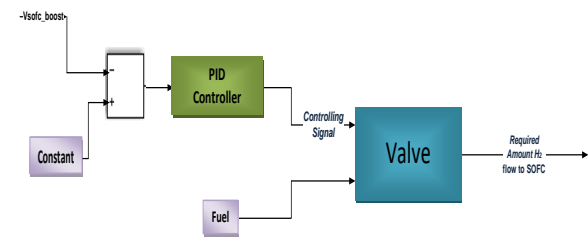


Figure 2d. Graphical structure representation of Fuel Cell Flow Controller

9. OPERATIONAL CONTROL STRATEGY OF THE HYBRID GENERATION SYSTEM

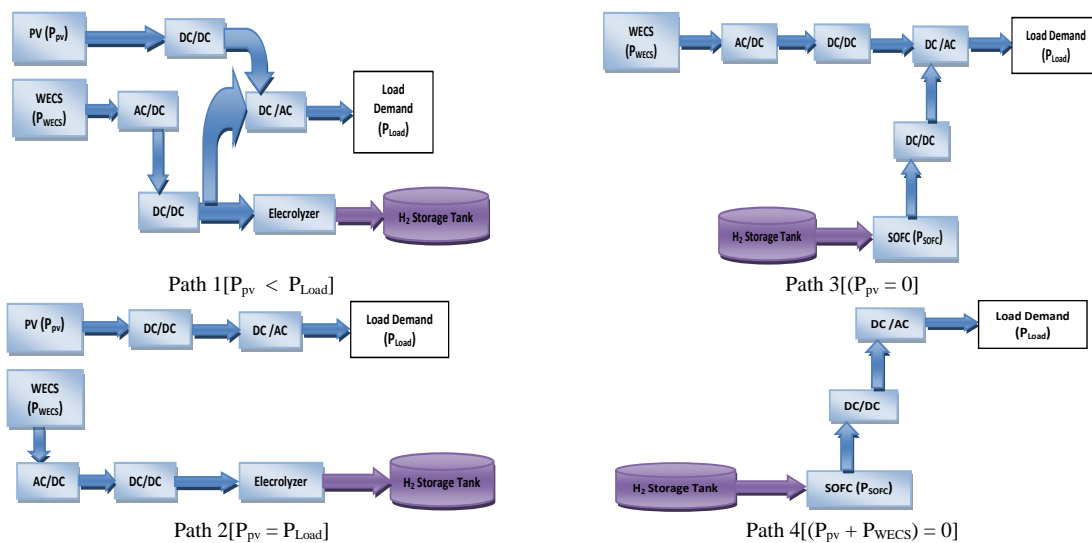


Figure 3. various path describing the control strategy of HGS

Figure 3 shows the operational control strategy (OCS) of the HGS. The usefulness of this control strategy is to make relationship between the power demand and generation of HGS. So, the whole operation is conducted in a smooth manner. Basically in this topic the required load demand considered is greater than PV power. But, there are four possible ways for the OCS to regulate the model smoothly as described below.

- While PV power (P_{pv}) is less than the demand power (P_{demand}) i.e., $P_{pv} < P_{demand}$, then path 1 should be followed. Total amount of PV power and required amount of WECS power (P_{WECS}) are supplied to fulfill the load demand. Then the rest amount WECS power is given to the electrolyzer, where it dissolved the water into H₂ and oxygen and this H₂ is kept in a storage tank. Further, this H₂ is taken as the input fuel of SOFC.
- While PV power (P_{pv}) is equal to demand power (P_{demand}) i.e., $P_{pv} = P_{demand}$, then path 2 should be followed. At that time the total PV power is used to fulfill the demand of the load and WECS power (P_{WECS}) is used to supply the electrolyzer.
- While PV power (P_{pv}) is equal to zero i.e., $P_{pv} = 0$, then path 3 should be followed. To fulfill the power demand the required amount of power is supplied from SOFC along with the WECS power (P_{WECS}) to the load. Here, SOFC gets the H₂ as fuel from the storage tank to generate the SOFC power (P_{SOFC}).
- While PV power (P_{pv}) as well as WECS power (P_{WECS}) is equal to zero i.e., $(P_{pv} + P_{WECS}) = 0$, then path 4 should be followed. Here, no WECS and PV power are supplied to fulfill the power demand, only SOFC power (P_{SOFC}) is supplied to fulfill the demand requirement.

10. STUDY OF THE POWER QUALITY FACTOR

The three essential features on which PQF depends are described below.

10.1 Voltage and Current Harmonics Distortion levels

Total harmonics distortion level of the voltage (VTHD) and total harmonics distortion level of the current (ITHD) are the distortions levels of the harmonics respectively, for the 3Ø as well as 1Ø circuits.

$$[V_{THD}]^2 = \frac{\sum_{h \neq 1} V_h^2}{V_1^2} \quad (17)$$

$$[I_{THD}]^2 = \frac{\sum_{h \neq 1} I_h^2}{I_1^2} \quad (18)$$

Where, V and I are rms values, h = harmonic order, 1 = fundamental

Losses are less in lower order harmonics but more in higher order harmonics having the same amplitude. Hence, total regulated harmonics distortion of the current and voltage are represented below.

$$[V_{THD}]_{H-A}^2 = \frac{\sum_{k \neq 1} (C_h V_h)^2}{V_1^2} \quad (19)$$

$$[I_{THD}]_{H-A}^2 = \frac{\sum_{k \neq 1} (D_h I_h)^2}{I_1^2} \quad (20)$$

Where, $C_h, D_h = (>1)$ known as weighting factors.

Further, Equations (17) and (18) may be considered in a 3Ø network according to [27] as:

$$V_{eH}^2 = \sum_{h \neq 1} \frac{V_{ah}^2 + V_{bh}^2 + V_{ch}^2}{3} \quad (21)$$

$$I_{eH}^2 = \sum_{h \neq 1} \frac{I_{ah}^2 + I_{bh}^2 + I_{ch}^2}{3} \quad (22)$$

Where, V_{eH} is the equivalent harmonics of the rms voltage in the 3Ø network and I_{eH} is the equivalent harmonics of the rms voltage in the 3Ø network

By putting the Equations (21) and (22) in the Equations (19) and (20), the equivalent current and voltage adjusted harmonics values are obtained as shown below.

$$V_{eH-A}^2 = \sum_{h \neq 1} C_h^2 \frac{V_{ah}^2 + V_{bh}^2 + V_{ch}^2}{3} \quad (23)$$

$$I_{eH-A}^2 = \sum_{h \neq 1} D_h^2 \frac{I_{ah}^2 + I_{bh}^2 + I_{ch}^2}{3} \quad (24)$$

So, QA_1 is the quality aspect of VTHD and QA_2 is the quality aspect of ITHD.

$$QA_1 = VTHD = \frac{V_{eH-A}}{V_{e1}} \quad (25)$$

$$QA_2 = ITHD = \frac{I_{eH-A}}{I_{e1}} \quad (26)$$

Where, V_{e1} is the 3ϕ network equivalent fundamental phase voltage and I_{e1} is the 3ϕ network equivalent fundamental phase current.

$$V_{e1}^2 = \frac{V_{a1}^2 + V_{b1}^2 + V_{c1}^2}{3} \quad (27)$$

$$I_{e1}^2 = \frac{I_{a1}^2 + I_{b1}^2 + I_{c1}^2}{3} \quad (28)$$

Equations (21) to (24), (27) and (28) represent 3ϕ network losses where it is equal to those of actual systems taken into consideration. So, a few assumptions are represented below:

- The losses of the line equipment are related to the square of current or voltage
- Parameters of the equipment and line are considered as symmetrical

10.2 Degree of Unbalance

The transfer quality of the power is influenced by the unbalance voltage and current in a poly-phase circuit. Many reasons are taken into consideration for the above problem such as overloading in neutral conductor in four wire system of distribution network, increased losses occurred in the line at the same power transfer level. The 3ϕ sinusoidal voltage consists of three components: Positive-sequence V^+ , Negative-sequence V^- and Zero sequence V^0 as shown below.

$$\begin{cases} \underline{V}^+ = \frac{1}{\sqrt{3}} (\underline{V}_a + a\underline{V}_b + a^2\underline{V}_c) \\ \underline{V}^- = \frac{1}{\sqrt{3}} (\underline{V}_a + a^2\underline{V}_b + a\underline{V}_c) \\ \underline{V}^0 = \frac{1}{\sqrt{3}} (\underline{V}_a + \underline{V}_b + \underline{V}_c) \end{cases} \quad (29)$$

Where, \underline{V} = phasor of V and $a = \exp(j2\pi/3)$

So, by using the Equations (27) to (29) the equivalent voltage is developed as:

$$V_{e1}^2 = \underline{V}^{+2} + \underline{V}^{-2} + \underline{V}^{02} \quad (30)$$

In this manner the current Equation can be written as:

$$I_{e1}^2 = \underline{I}^{+2} + \underline{I}^{-2} + \underline{I}^{02} \quad (31)$$

So, quality analysis can be found out as given below.

$$QA_3 = \frac{[V_{e1}^2 - (\underline{V}^+)^2]^{\frac{1}{2}}}{V_{e1}} \quad (32)$$

$$QA_4 = \frac{[I_{e1}^2 - (\underline{I}^+)^2]^{\frac{1}{2}}}{I_{e1}} \quad (33)$$

10.3 Phase displacement between the voltage and current at their fundamental frequency

Phase displacement between voltage and current at given fundamental frequency shows less or full utilization of equipment at distribution or generation side. Traditionally power factor (pf) can be defined as the ratio between the active power (P) and apparent power(S) which is possible for sinusoidal situation. But, for the non-sinusoidal situation pf definition described above is misleading. So, instantaneous voltage and current give the results of the instantaneous power as given in [27]. Conventional active power is the time average values of the instantaneous power with respect to time. Also, the instantaneous power (S) has no physical meaning. So, at each instant voltage and current values are not taken into consideration.

All the above said inadequacies may be circumvented, when the utilization of the power is poor due to the physical entity. This entity is known as phase difference between the voltage and current at fundamental frequency either on load side or source side. Hence, to reveal this aspect on the power quality a new factor is considered named as orthogonal current factor (OCF) as given in [27].

$$OCF = \frac{I_{1a}\sin\theta_{1a} + I_{1b}\sin\theta_{1b} + I_{1c}\sin\theta_{1c}}{I_{1a} + I_{1b} + I_{1c}} \quad (34)$$

$$QA_5 = |OCF| \quad (35)$$

$$QA_5 = |OCF| \quad (36)$$

PQF determines the power quality. In the above Equation w_i is known as weighting factor ($\cong 1$) whereas, QA_i is the different quality aspects.

11. EXPERIMENTAL VERIFICATION RESULTS WITH THE HELP OF SIMULATION

The proposed HGS is designed by using Matlab Simulink and verified under different conditions.

Figure 4a represents the H₂ flow from electrolyzer, when it takes the extra amount of WECS power which is described in path 1 and path 2 of Figure 3. SOFC takes the amount of H₂ flow according to the power demand and controlled by the PID controller as shown in Figure 4b and Figure 4c. Figure 4d represents the voltage output of boost converter of the SOFC, which is connected across the SOFC.

The voltage and current waveforms of HGS are shown in Figure 5a. Figure 5b shows the voltage, current and power waveforms of the 3 ϕ load as shown in Figure 1 having the active power (P) = 14 KW, inductive power (QL) = 2 KVAR and capacitive power (QC) = 100 VAR.

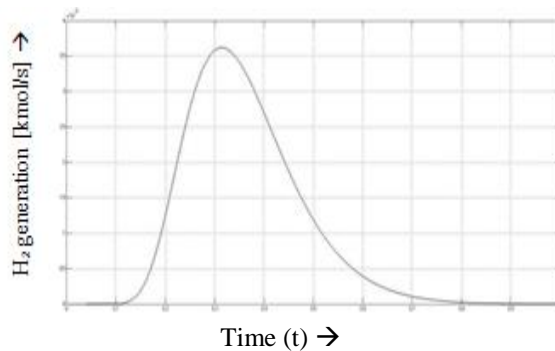


Figure 4a. H₂ generation from the Electrolyzer

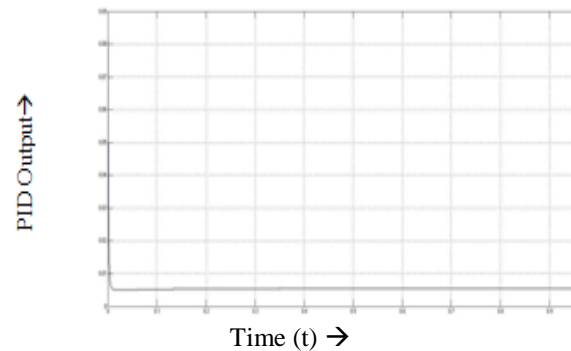


Figure 4c. Output of the PID Controller

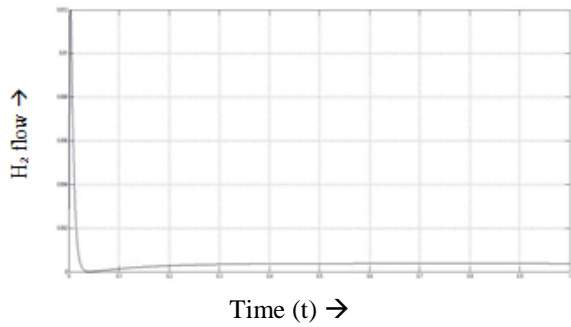
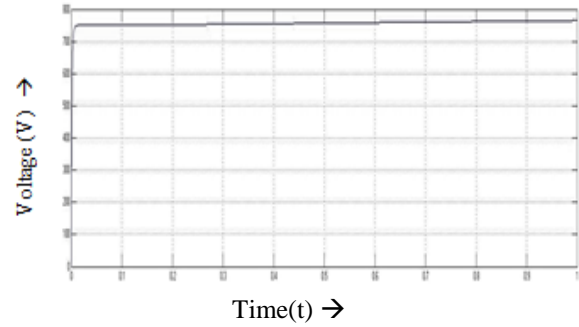
Figure 4b. Flow of H₂ to the SOFC

Figure 4d. Boost converter voltage Output connected across SOFC

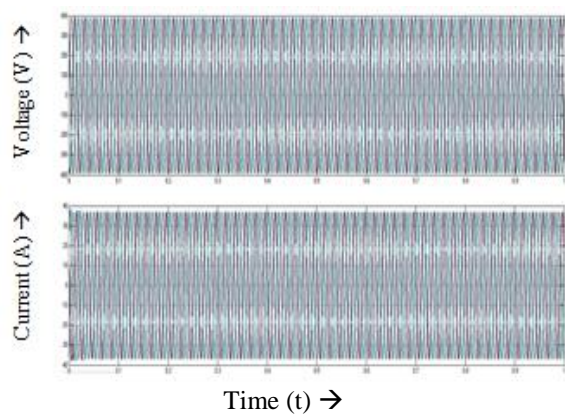
Figure 4. A detailed diagram of H₂ flow to SOFC and its control.

Figure 5a. voltage and current output of HGS

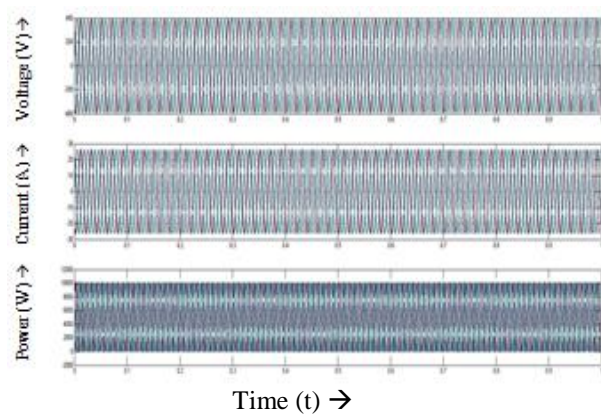
Figure 5b. voltage, current and power output of 3 ϕ LoadFigure 5 Waveforms of HGS and 3 ϕ Load

Figure 6a shows voltage harmonic distortions of the HGS, where QA_1 is 0.096770128418209. In this manner QA_2 is 0.15316754105403, QA_3 is 0.70746094530003, QA_4 is 0.70746096868184 and QA_5 is 2.741285073468, which is shown in figure 6b. Lastly, PQF is measured having the value 95.593855343078 for the HGS.

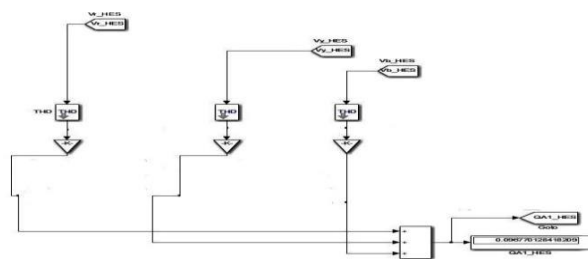
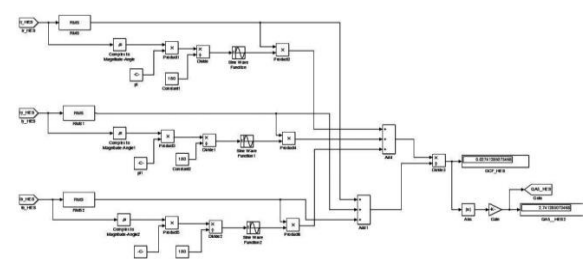
Figure 6a QA_1 of the HGSFigure 6b QA_5 of the HGS

Figure 6 Power Quality analysis of HGS

The values of power quality analysis parameters of the 3 \emptyset load are found to be $QA_1=0.09676948529051$, $QA_2=0.10841717126841$, $QA_3=0.70745768279552$, $QA_4=0.72509355201857$, $QA_5=2.7412850738216$ and $PQF=95.620977034805$.

12. CONCLUSION

In this paper a novel grid connected hybrid WECS/PV/SOFC generation system is designed in the Matlab/Simulink environment. A new operational control strategy is developed to control the HGS according to the power generation and demand. The total generated PV power and the rest amount of power coming from WECS is used to fulfill the load demand because the load demand is normally greater than the generated PV power. In particular the total generated PV power along with power generated from WECS is utilized to fulfill the demand. After utilization of WECS power for the load demand, the rest amount of WECS power is used to produce H_2 through the electrolyzer. When the wind as well as PV power is not sufficient to generate power to fulfill the power demand then, SOFC is used to fulfill the requirement of the demand by taking H_2 as an input fuel. Also, the amount of H_2 flow to SOFC through the designed valve is described in details and controlled by the controller to satisfy the power demand. PQF analysis is done to verify the quality of power of the HGS as well as 3- \emptyset load. Further, the proposed system may be practically implemented for various power scenarios in future.

REFERENCES

- H. Fathabadi, "Novel standalone hybrid solar/wind/fuel cell power generation system for remote areas," *Solar Energy*, vol.146, pp. 30-43, 2017.
- [2] S. Tamalouzt, *et al.*, "Performances analysis of WT-DFIG with PV and fuel cell hybrid power sources system associated with hydrogen storage hybrid energy system," *International Journal of Hydrogen Energy*, vol. 41, pp. 21006-21021, 2016.
- [3] S. Singh, *et al.*, "Design, modeling and performance analysis of dual channel semitransparent photovoltaic thermal hybrid module in the cold environment," *Energy Conversion Management*, vol. 114, pp. 241-250, 2016.
- [4] S. Singh, *et al.*, "Application of genetic algorithm with multi-objective function to improve the efficiency of glazed photovoltaic thermal system for New Delhi (India) climatic condition," *Solution Energy*, vol. 117, pp. 153-166, 2015.
- [5] E. Kabalci, "Design and analysis of a hybrid renewable energy plant with solar and wind power," *Energy Conversion Management*, vol. 72, pp. 51-59, 2013.
- [6] S.V. Karemore and S.Y. Kamdi, "Multi-objective design procedure for hybrid (wind-photovoltaic) system by GA," *International Journal Innovative Research Electrical, Electronics, Instrumentation & Control Engineering*, vol. 4, pp. 144-147, 2013.
- [7] A. Eid, "Utility integration of PV-wind-fuel cell hybrid distributed generation systems under variable load demands," *Electrical Power and Energy Systems*, vol. 62, pp. 689-699, 2014.
- [8] N.A. Ahmed, *et al.*, "Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems," *Energy Conversion Management*, vol. 10, pp. 2711-2719, 2008.
- [9] S. Obara, *et al.*, "Economic efficiency of a Renewable energy independent microgrid with energy storage by a sodium-sulfur battery or organic chemical hydride," *Internal Journal of Hydrogen Energy*, vol. 38: pp. 8888-8902, 2013.
- [10] A.M. Dizqah, *et al.*, A. Kamjoo, "A multivariable optimal energy management strategy for standalone DC microgrids," *IEEE Transactions on Power Systems*, vol. 30, pp. 2278-2287, 2015.
- [11] H. Sun, *et al.*, "Feasibility study of a hybrid wind turbine system – Integration with compressed air energy storage," *Applied Energy*, vol. 137, pp. 617-628, 2015.
- [12] O.C. Onar, *et al.*, "Dynamic modeling design and simulation of a wind/fuel cell/ultra-capacitor-based hybrid power generation system," *Journal of Power Sources*, vol. 161, pp. 707-722, 2006.
- [13] H. Fathabadi, "Fuel cell/back-up battery hybrid energy conversion systems dynamic modeling and harmonic considerations," *Energy Conversion Management*, vol. 103, pp. 573-584, 2015.
- [14] H. Fathabadi, "Lambert W function-based technique for tracking the maximum power point of PV modules connected in various configurations," *Renewable Energy*, vol. 74, pp. 214-226, 2015.
- [15] J. H. R. Enslin, *et al.*, "Integrated photovoltaic maximum power point tracking converter," *IEEE Transactions on Industrial Electronics*, vol. 44, pp. 769-773, 1997.
- [16] A. K. Abdelsalam, *et al.*, "High-performance adaptive perturb and observe MPPT technique for photovoltaic-based microgrids," *IEEE Transaction Power Electronics*, vol. 26, pp. 1010-1021, 2011.
- [17] M. A. Abdullah, *et al.*, "A review of maximum power point tracking algorithms for wind energy systems," *Renewable Sustainable Energy Revolution*, vol. 16, pp. 3220-3227, 2012.
- [18] R. Sarrias-Mena, *et al.*, "Electrolyzer models for hydrogen production from wind energy systems," *International Journal of Hydrogen Energy*, vol. 40: pp. 2927-2938, 2015.
- [19] Y. Lei, *et al.*, "Modeling and analysis of MW-level grid-connected PV plant," International Proceeding of 37th IECON'11, Melbourne, Australia, pp. 890-895, November 2011.

- [20] K. Ding, *et al.*, "A MATLAB-simulink-based PV module model and its application under conditions of non-uniform irradiance," *IEEE Transactions on Energy Conversion*, vol. 27, pp. 864-872, 2012.
- [21] I. H. Altas and A. M. Sharaf, "A photovoltaic array simulation model for MATLAB Simulink GUI environment," ICCEP'07, Capri, Italy, pp. 341-345, May 2007.
- [22] M. Uzunoglu and O.C. Onar, "Static VAR compensator based Reactive power Management for SOFC power plants," *International Journal of Hydrogen Energy*, vol. 33, pp. 2367-2378, 2008.
- [23] G. Bayrak and M. Cebeci, "Grid connected fuel cell and PV hybrid Power generating system design with Matlab Simulink," *International Journal of Hydrogen Energy*, vol. 39, pp. 8803-8812, 2014.
- [24] M. G. Molina and E. J. Espejo, "Modeling and simulation of grid-Connected photovoltaic energy conversion systems," *International Journal of Hydrogen Energy*, vol. 39, pp. 8702-8707, 2014.
- [25] A. Naderipour, *et al.*, "A New Compensation Control Strategy for Grid-Connected Wind Turbine and Fuel Cell Inverters in a Microgrid," *International Journal of Power Electronics and Drive System*, pp. 272-278, 2017.
- [26] B. S. Sami, "An Intelligent Power Management Investigation for Stand-Alone Hybrid System Using Short-Time Energy Storage," *International Journal of Power Electronics and Drive System*, pp. 367-375, 2017.
- [27] D. Sharon, *et al.*, "Power Quality Factor for networks supplying unbalanced nonlinear loads," *IEEE Transactions on Instrumentation and Measurement*, vol. 57, pp. 1268-1274, 2008,

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