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DESING OF A HYBRID RENEWABLE ENERGY SYSTEM

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Abstract- Fossil based energy resources can cause global climate changes and environmental damages that threaten living life. With the increasing global awareness of environmental protection and the goal of reducing the reliance on fossil fuels, the importance of generating electrical energy from renewable energy sources is raising impetuously. Within the scope of this study, a grid connected hybrid system formed of 10 kWp photovoltaic and 20 kW wind energy conversion system is designed to provide energy transfer to the three-phase low voltage network in accordance with the harmonic limits defined in the IEEE 519-1992 standard.

Keywords: Wind Energy Conversion System, Photovoltaic Energy Conversion System, Maximum Power Point Tracking, Total Harmonic Distortion

1. INTRODUCTION

Electrical energy consumption is increasing rapidly as a result of the overpopulation, developing technology and industrial developments in the world. A large part of the electricity produced is met from fossil originated energy sources such as natural gas, coal as well as oil. Due to the limited reserves of these sources, it is predicted that they will not be able to meet the required energy demand in the near future. Not only having limited reserves, but also fossil based resources constitute 60% of the CO_2 emissions released into the atmosphere. CO_2 gases emitted into the atmosphere create greenhouse effect and this effect exposes the world to the danger of global warming, which causes serious irreversible damages.

As a result, the importance of generating electrical energy from renewable energy sources as wind, photovoltaic, biomass, geothermic and tidal energy is grown in importance. Ongoing studies shown that electricity generation from wind energy and photovoltaic energies is more feasible and more reliable than other renewable energy sources, in addition, the pollution that they cause to the environment is less compared to alternative renewable energy sources [1].

Single source renewable energy systems such as wind or photovoltaic systems cannot generate continuous electrical energy due to their dependence on environmental conditions. For instance, in the evenings or cloudy days, photovoltaic energy system cannot produce electrical energy. Additively on a windless day, electrical energy cannot be generated from wind energy. Hybrid renewable energy systems are distributed electrical energy generation systems that consist two or more renewable energy sources to support each other and provide more stable and higher capacity for electrical energy generation [2]. Hybrid renewable energy systems are classified as grid connected and standalone systems.

Standalone systems are used as an important alternative to meet electrical energy needs for regions where it may be costly for the grid connection such as small-scale rural areas and islands.

In grid connected systems, it is aimed for transferring the electrical energy to the grid or feeding the loads cooperatively with the grid. The bus connections of the renewable energy systems that forming the hybrid structure are made with common AC or DC bus topologies [3].

In this study, a hybrid renewable energy system consisting of 10 kW peak power photovoltaic energy system and 20 kW wind energy conversion system with common DC bus structure is mathematically modelled and designed in MATLAB/Simulink environment for transferring the electrical energy to the three-phase low voltage grid with the aim of keeping the electrical energy quality at the optimum level within the harmonic limitations in IEEE 519-1992 standard.

2. PURPOSED SYSTEM

Hybrid renewable energy conversion system compromise of photovoltaic and wind energy conversion system, grid connected inverter with LC filter and low voltage grid (230V, 50 Hz) as shown in Figure 1.

Photovoltaic system forms of PV panel and MPPT controlled DC/DC boost converter. PV panel is mathematically modelled and perturb & observe controlled boost converter is designed for increasing the output panel voltage for common DC bus connection and obtaining the maximum power output from the PV panel in varying atmospheric conditions.

Wind energy conversion system is modelled as variable speed wind turbine which has horizontal axis, three blades and fixed pitch angle structure. Permanent magnet synchronous generator is used as turbine generator due to its advantages such as the brushless design, high power densities and high efficiency and as well as better thermal characteristics.

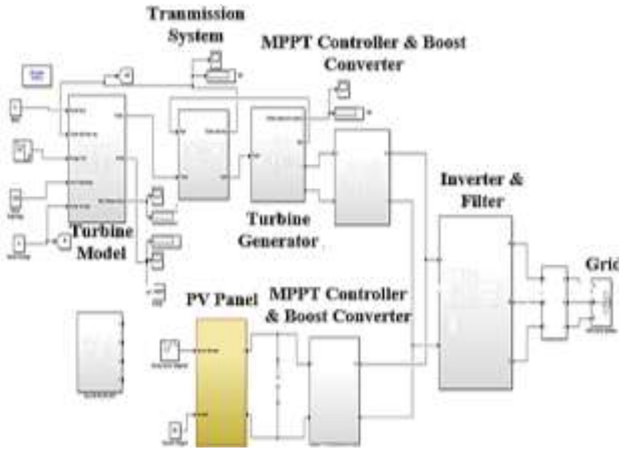

Figure 1. Hybrid renewable energy conversion system Simulink model.

Generator output signals and frequency is dependent with the turbine rotor speed which changing by wind speed. In order to rectifying the alternating generator output signals, three phase full bridge rectifier is used. Common bus connection and maximum power point tracking is carried by optimum tip speed ratio-controlled DC/DC boost converter.

Grid connection is obtained by three phase two level SPWM inverter with synchronous reference frame control system. DC voltages and currents at the common bus are converted to AC signals that frequencies, amplitudes and phases of electrical signals which is transferred to grid are produced and controlled at the desired values. With the inverter control system, common bus kept at a stable voltage and the active and reactive powers that transferred to the grid are controlled [4]. Phase locked circuit is used for grid synchronization and LC filter is designed to keep current THD values within the harmonic limitations determined by the standards.

3. SYSTEM MODELLING

3.1 PV Energy Conversion System Modelling

PV cells transform the generated energy from sunto electrical energy through the photovoltaic effect. A single PV cell has 0.5 V DC output voltage and 1-2 Watts of electrical power. In order to increase output values, photovoltaic panels are obtained by creating series and parallel connections of PV cells [5]. PV panel equivalent circuit is shown in Figure 2.

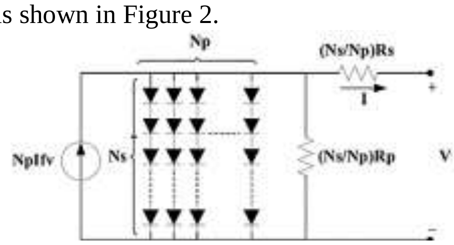

Figure 2. Hybrid renewable energy system Simulink model

PV panel output current can be derived by applying Kirchhoff Current Law to the equivalent circuit as:

$$I = N_p I_{fv} - N_p I_D\{\exp[(V + (N_s / N_p)R_s I) / (N_s V_t a)] \\ -1\} - [(V + (N_s / N_p)R_s I) / (N_s / N_p)R_p] \quad (1)$$

According to the equivalent circuit V refers to panel output voltage and I specifies the panel output current. R_s is series resistance, R_p is parallel resistance of panel, N_s and N_p parameters are number of series and parallel connections of solar cells respectively [6].

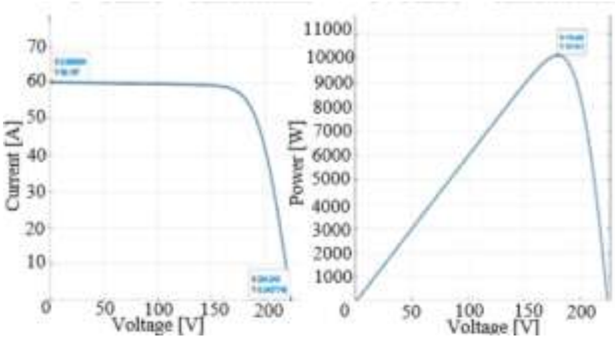

Figure 3. I-V and P-V characteristics of photovoltaic panel model

It can be observed from PV panel equations that the panel output voltage and currents are varying with solar irradiation and temperature values. So that, panel output power changes under different atmospheric conditions. In order to obtain optimum power conversion from PV panels, MPPT methods are used. In this study, perturb & observe P&O method is used for obtaining electrical energy conversion with maximum efficiency from solar panels under different solar irradiations and temperatures.

Perturb and observe method is a MPPT method based on changing the PV panel voltage or current values by continuously increasing or decreasing the duty ratio of the power converter at specified intervals with the developed mathematical algorithm. In the P&O method, the electrical values (voltage, current) of the photovoltaic panel are measured. Subsequently, power of the panel is calculated at certain intervals. By iteratively comparing the instantaneous output power values with the previous measured ones, the operating point at which panel can produce maximum power is calculated by perturbing the panel voltage or current. Duty ratio of the converter is controlled to ensure maximum power generation from the panel [7].

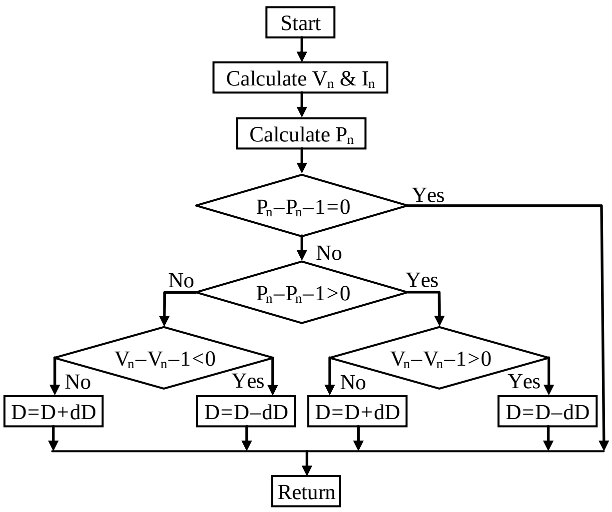

Figure 4. P&O method flowchart [8]

DC/ DC boost converter is designed and simulated for increasing the panel output voltage to common DC bus voltage level and obtaining MPPT control. Boost converter capacitor is not used in this design; instead of that common DC bus capacitor is used for filtering the output voltages.

3.2 Wind Energy Conversion Modelling

Wind energy conversion can be done by wind flow captured by the turbine blades that creates rotational movement in the turbine blades and turbine shaft. Turbine shaft provides the conversion of kinetic energy into mechanical energy which given in Equation (2):

$$P_{wind} = \frac{1}{2} C_p \, \rho_{air} \, \pi \, R^2 \, v_{wind}^3 \tag{2}$$

The R value in mechanical power equation is the turbine blade radius, v_{wind} defines the speed of wind and ρ_{air} refers air density and equals to 1.225 kg/m^3 at international standard atmospheric conditions. Wind power cannot be converted into mechanical energy completely by the turbine blades. The conversion ratio of converted wind power to mechanical power is called turbine power coefficient (C_p) and this value expresses turbine efficiency. Theoretically, 59.3% of the wind power can be converted into mechanical power and this limit is accepted as the Betz Limit. In practice, this value is around 46% to 48% for modern three-bladed horizontal axis wind turbines. Turbine power coefficient (C_p) is denoted as a function of tip speed ratio (TSR, λ) and pitch angle (β). The mathematical expressions of power coefficient and tip speed ratio are given as:

$$\lambda = \frac{\omega_{turbine} \, R}{v_{wind}} \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{4}$$

$$C_p(\lambda, \beta) = c_1 (c_2 \frac{1}{\lambda_i} - c_3 \beta - c_4) e^{-(c_5/\lambda_i)} + c_6 \lambda \tag{5}$$

Where $\omega_{turbine}$ is turbine shaft's angular velocity in rad/s, v_{wind} defines the wind speed in m/s, and the R is the radius of the turbine blades in meters. The expression λ_i in equation (4) is used to calculate the turbine power coefficient and the β indicates the pitch angle. The mathematical expression of the turbine power coefficient can be seen in equation (5). The c_1, ..., c_6 values in this equation varies according to the turbine blade and shaft design [9]. By using equation (5) and assuming the pitch angle of blades are 0^0, wind turbine's power coefficient - tip speed ratio is shown in Figure 5. This figure indicates an important characteristic curve that depends on the turbine aerodynamic design and varies accordingly to different turbine designs. When the curve is examined, it is seen that there is a constant tip speed ratio value for the optimum level of turbine power coefficient (C_{pmax}) so that the power converted from wind energy to mechanical energy is maximized. This value is defined as the optimum tip speed ratio. It is seen in the Equation (3), tip speed ratio consists of the turbine radius, wind speed and turbine shaft speed parameters.

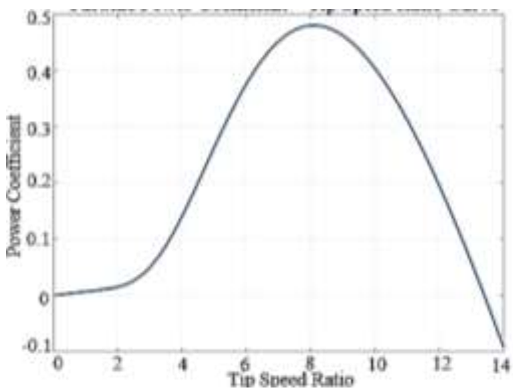

Figure 5. Turbine power coefficient - tip speed ratio curve

Considering that it is not possible to control the wind speed and radius of the turbine blades, that is a constant value, power coefficient reaches its highest value by controlling the turbine shaft speed that will give the optimum value of the tip speed ratio for different wind speed levels. Thus, maximum conversion of mechanical power at different wind levels can be done by regulating turbine shaft speed. With the power converters that controlled by maximum power point tracking methods, turbine generator load can be adjusted.

As a result, the output voltage and turbine shaft speed are controlled to obtain turbine speed shaft speed at optimum values [10].

In this study, optimum tip speed ratio control is used for maximizing the power generation from turbine. With this method, it is aimed to produce maximum power by determining the reference turbine shaft speed which will keep the blade tip speed ratio at the optimum value for variable wind speed levels. By measuring the wind speed, reference turbine shaft speed is determined using equation (6);

$$\omega_{ref} = \frac{\lambda_{opt} \, v_{wind}}{R} \tag{6}$$

Turbine shaft speed is measured and compared with the calculated reference speed value. The resulting error signal is compensated by the proportional integral (PI) controller and duty ratio of the power converter controls generator at the reference shaft speed on varying wind speeds [11].

3.3 Grid Connected Inverter Design

Electrical energy generated from PV and wind conversion systems are transferred to the grid over the three-phase grid connected inverter circuit. Two level voltage source inverter circuit converts common DC bus signals to AC signals that is suitable for grid voltage and frequency.

Inverter circuit formed by 6 IGBT's consisting three branches that in parallel with each other. Inverter rated power is 30 kVA in accordance with the energy capacity produced by the wind and photovoltaic energy conversion systems. Only active power is transferred to the grid. As a result, the power factor of the inverter is expected to be equal to 1 and the switching frequency is 15 kHz.

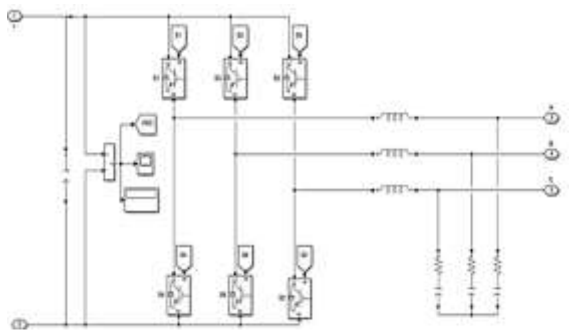

Figure 6.Grid connected inverter with LC filter model

For controlling the switching states, sinusoidal pulse width modulation (SPWM) technique is used. By comparing the reference signals that in sinusoidal waveform with 120^0 differences for each phase with output frequency and the carrier signals in triangular waveform with switching frequency, switching signals are generated. Amplitude modulation is obtained by dividing amplitudes of the reference and carrier signal. With controlling the amplitude modulation, inverter output voltage amplitude at the fundamental frequency can be controlled. LC filter is used for eliminating the high frequency harmonics to ensure sinusoidal output signals. Modulation ratio must be equal or less that 1 to ensure linear control of the output signals [12]. For considering this limitation common DC bus voltage can be selected using;

$$V_{ab1,rms} \cong 0.612\, m_g\, V_{dc} \quad (7)$$

Where $V_{ab1,rms}$ is RMS values of phase to phase output voltage, m_g is the amplitude modulation and V_{dc} refers common DC bus voltage. For this system, amplitude modulation is selected as 0.8. Considering the output phase to phase RMS output voltage is 400 V, common DC bus voltage equals to 817 V.

Synchronous reference frame control is used for inverter control system. Grid voltage and injected currents are transferred to the d-q frame that synchronously rotating with the grid voltage as DC signals. As a result, control variables can be controlled easily with PI controllers thus reduces the control complexity [13]. D-axis and q-axis currents that injected to grid from hybrid system controls the active and reactive power flow respectively. DC bus voltage and current control loops are used for controlling the power flow to the grid.

DC bus voltage control loop is used to keep the DC bus voltage at desired level. When the input power from renewable energy systems changes depending to the atmospheric conditions; the voltage of the DC bus will also change. The function of the control loop is to determine the reference value of the direct axis current, which controls the active power transferred to the grid by keeping the common DC bus voltage at constant voltage. Actual bus voltage value subtracted from reference value and the subtracted signal is compensated by PI controller that output forms the reference direct axis current signal. Reference value of the quadrature axis current is set to zero for allowing only active power flow.

Current control loop determines the reference voltage vectors for modulation signals by controlling the injected currents that tracks the reference values. Reference values of direct and quadrature axis currents subtracted from actual values that generates the error signal. Error signal goes into PI controller that output of the controller forms the reference voltage signals in d-q frame for SPWM modulation [18].

The mathematical expressions of the reference voltage vectors determined by the current control loop are given in below equations [14].

$$V_d^* = K_p(I_d^* - I_d) + K_I \int (I_d^* - I_d)dt - \omega L_f I_q + V_d \quad (8)$$

$$V_q^* = K_p(I_q^* - I_q) + K_I \int (I_q^* - I_q)dt - \omega L_f I_d + V_q \quad (9)$$

Where, K_p and K_I are proportional and integral control parameters of the controller. V_d and V_q values expresses the direct and quadrature axis vectors of the grid voltage, $\omega L_f I_d$ and $\omega L_f I_q$ indicates voltage drops in the d-q axis of the filter circuit. I_d^* and I_q^* are reference currents that injected to grid and ω is angular velocity of the grid.

D-q axis reference voltage vectors transferred three phase reference voltage signals by using reverse Clark and reverse Park transformations. Grid angle is obtained by phase locked loop (PLL) circuit in order to matching the phases of grid to inverter output voltage signals and also for vector transformations.

5. SIMULATION RESULTS

Simulations of the hybrid system were carried out for 3 seconds by selecting the sampling time of 10^{-5} seconds in fixed-step size and ode14x solver in Matlab/Simulink. During the simulation, solar radiation levels are chosen to vary at 1000 W/m^2, 500 W/m^2 and 750 W/m^2. Temperature is constant at 25^0C. Wind speeds are selected as 6 m/s, 11 m/s and 8 m/s that changes each second of simulation. Measurement outputs of simulations are shown in the graphs below.

Figure 7 show the active power generated from PV panel and Figure 8 shows the mechanical power converted from wind by wind turbine. It can be observed from Figure 9, common bus voltage maintained its reference value at all conditions.

Voltage fluctuations in the common DC busbar vary with respect of the generated active power values. When the simulation results are examined, it can be seen that the synchronous reference frame successfully performs the control of the common DC bus voltage, controlling active power flow and preventing the reactive power flow to grid with respect to varying atmospheric conditions.

At the 0-1 seconds of simulation, active power generated from renewable sources are 13180 W and transferred power is 12660 W, at the 1-2 seconds generated power is 24680 W and transferred power is 23750 W where the last step of the simulation at 2-3 seconds, generated active power equals to 15130 W and transferred power is equals 14150 W.

Power losses occurred due to the power electronic circuit components in the system are not chosen ideally. So that, generator losses are also taken into account, it has been observed that approximately 4% losses occur in the power flow to the grid where system overall efficiency is 96%.

The IEEE 519-1992 standard defines the upper limit of the total harmonic distortion levels of the currents that transferred to the grid as 5%. The harmonic distortion levels of current signals are kept below the 5% limit, except when the sudden atmospheric conditions changes. The highest distortion value was measured at 4.32% that can be acceptable by the defined limitations.

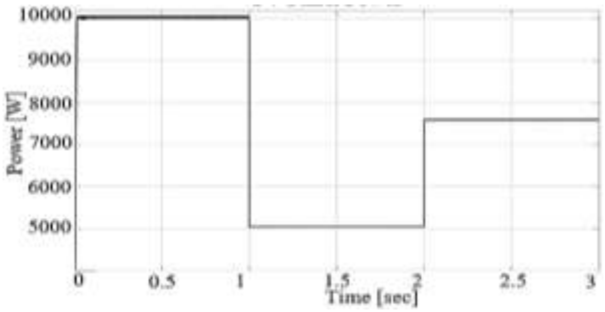

Figure 7. Active power values produced by the PV panel

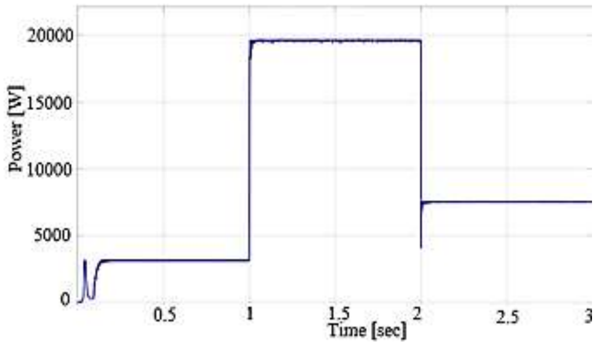

Figure 8. Mechanical power values converted by turbine

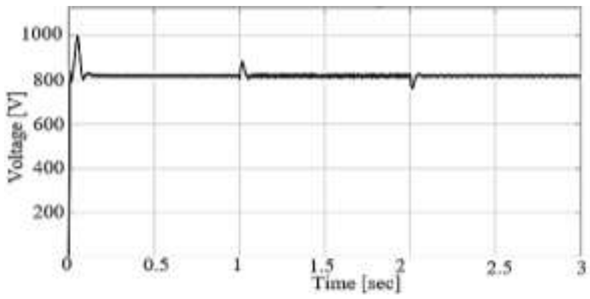

Figure 9. Common DC bus voltage

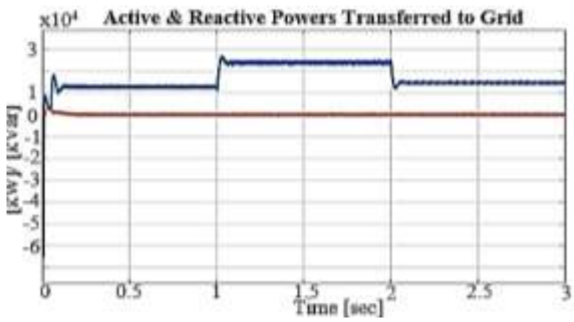

Figure 10. Active and reactive power values transferred to the grid

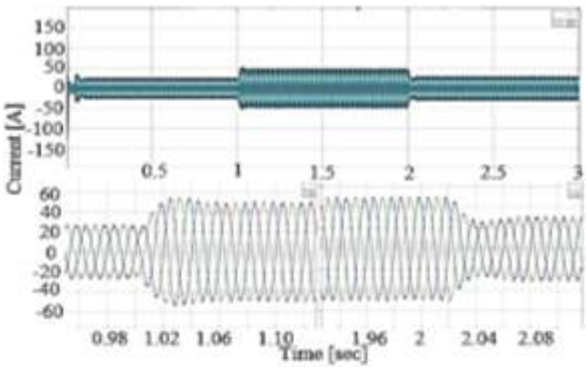

Figure 11.Waveforms of three phase currents transferred to the grid

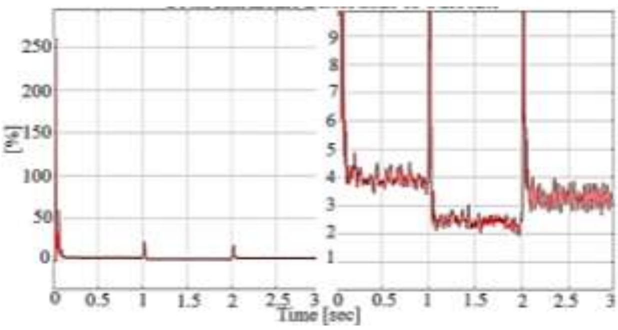

Figure 12.Total harmonic distortion (THDI) measurements of currents

6. CONCLUSIONS

In this study, 30 kW grid connected PV/Wind hybrid energy conversion system is theoretically designed and modeled in MATLAB/ Simulink environment. Electrical and control systems are designed for maximum power generation and transferring the optimum generated electrical energy to the low voltage grid. For PV energy conversion system, perturb and observe method is used for maximum power tracking where optimum tip speed ratio control is used in wind energy conversion system. For each conversion system DC/DC boost converter is designed for obtaining MPPT control and amplifying the system output voltages for bus connection. Common DC bus signals are converted AC signals as suitable for the grid connection with designed three phase two level inverter circuit. Inverter control is obtained by synchronous reference control system for power flow control. By performing simulations for variable atmospheric conditions, the quality of the electrical energy transferred to the grid for different scenarios, together with the power values transferred to the grid are examined and the results were interpreted.

APPENDICES

Table 1. PV Panel Parameters

Parameter	Rating
Power, P_N (W_p)	10080
Open Circuit Voltage V_{OC} (V)	180
Short Circuit Current I_{SC} (A)	56.7
Parallel Resistance,R_p (Ω)	0.34886
Series Resistance, R_s (Ω)	277.7787
Number of Series Connected Cells, N_s	60
Diode ideality factor, a	1.1018

Table 2. PV Boost Converter Parameters

Parameter	Rating
Input Voltage, V_{IN} (V)	180-185
Output Voltage, V_{OUT} (V)	817
Output Power, P_{PV} (kW)	10
Switching Frequency, f_{SW} (kHz)	10
Inductance, L (mH)	0.836
DC Bus Capacitance, C_{DC} (mF)	1

Table 3. Wind Turbine Parameters [16]

Parameter	Rating
Rated Power, P_N (kW)	20
Blade Radius, R (m)	4
Air Density,ρ_{air} (kg/m^3)	1.225
Pitch Angle, β	0^0
Rated Wind Speed (m/s)	11
Optimum Tip Speed Ratio, λ_{opt}	0.48

Table 4. Turbine Generator Parameters [16]

Parameter	Rating
Rated Power, P_N (kW)	20
Stator Resistance, R_S (Ω)	0.1764
Stator d-q Inductances, L_d –L_q(mH)	4.48
Rated Speed, n_N(rpm)	211
Stator Rated Phase Currents, $I_{s,N}$ (A)	35.1
Permanet Magnet Flux Linkage, Ψ_{PM} (Wb)	0.92
Pole pairs, p	18
Moment of Inertia, J_{TOT} (kgm^2)	1.8
Friction Constant, B (Nm/s)	0

Table 5. Wind System Boost Converter Parameters

Parameter	Rating
Input Voltage, V_{IN} (V)	375 – 545
Output Voltage, V_{OUT} (V)	817
Output Power, P_{OUT} (kW)	10
Switching Frequency, f_{SW} (kHz)	10
Inductance, L (mH)	1.266
DC Bus Capacitance, C_{DC} (mF)	1

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BIOGRAPHIES

Alpcan Antekin was born in Balikesir, Turkey in 1996. He received the B.Sc. degree in Electrical Engineering from Istanbul Technical University, Istanbul, Turkey in 2021. He is currently working at Arcelik R&D, Test and Verification Department as project assistant. His interests include energy conversion systems, electrical machines and power electronics.

Ozcan Kalenderli was born in Istanbul, Turkey in 1956. He received the B.Sc., M.Sc. and Ph.D. degrees all in electrical engineering from Istanbul Technical University, Istanbul, Turkey in 1978, 1980 and 1991, respectively. Presently, he is a full professor at the same university. He mainly interests with the areas of discharge phenomena, generation and measurement of high voltages, numerical analysis of electrostatic fields, protection against over-voltages and grounding.

Conference Topic:
6. Renewable Energy Sources (06RES)