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Design of Variable Speed Wind Turbine with Permanent Magnet BLDC Machine

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ABSTRACT:

This report studies the controlled voltage system that operates through an autonomous power system containing adjustable-speed wind turbines and permanent magnet BLDC (PMBLDC) machines uniting with PV modules and battery storage and FC units and aqua-electrolysis generators. Through its reference of DC-link voltage together with PWM inverter modulation index control the inverter can sustain its output voltage at rated specifications. The control system uses basic devices for measuring both voltage and current at the direct current level and it overlooks power measurement among all elements including PV, wind, battery, FC, electrolyser and load. The applied controllers maintain an excellent voltage quality at the load terminals while solar radiation conditions and wind speed fluctuations and changing load requirements occur. The battery state of charge Indicator enables smooth communication exchanges between wind generator and solar panel as well as battery and electrolyser and fuel cell devices.

Keywords: Variable Speed Wind Turbine; Permanent Magnet BLDC Machine; Real Time Digital Simulator.

I. Introduction

Presently numerous nations experience robust problems with inadequate electricity generation capability. Many countries face lack of electricity as their primary obstacle toward developing their rural areas. One third of all Indian rural residents live without access to electricity [1]. Fossil-fuel depletion along with traditional power plant environmental damage concerns both the global community. The escalating need for renewable energy has emerged because the energy shortage continues while air pollution remains a concern and the greenhouse effects need to be controlled. The market demand for renewable energy sources including wind power and solar energy continues to grow because of their expanding popularity.

Several countries contain distant settlements where accessing the main power system proves economically challenging or technically hard so these areas depend on diesel generators as their main electricity source. The Indian railway operates a large number of its distant railway stations using diesel generators [2]. Local installation and operation of small-scale renewable energy systems built for off-grid use provides a workable solution for such circumstances. Such power systems function as remote area power supply (RAPS) systems. Several instances of autonomous hybrid power systems include the 'PV-Wind-DG' facility at Tirumala Tirupati India [3] as well as the 'PV-Diesel' configuration in Arbaminch town of Ethiopian south [4] and other similar implementations. The standard operation of off-grid and stand-alone power networks consists of various energy sources together with storage elements and control systems. The renewable energy generators for stand-alone systems operate within proximity of their linked distribution networks.

Research conducted by the International Energy Agency in 2011 showed solar power generators will become the primary source of global electricity production within the next 50 years thus reducing environmental damage through greenhouse gas emission decreases [5]. Global installations of solar-based power generation reach 40,000 MW and solar power operates in over 100 different countries [5, 6]. The extensive sunlight availability throughout India makes PV systems highly viable for implementation in the country. Several solar-based operations have been implemented across India's regions without electricity as well as locations with irregular power availability. Solar power facilities currently have an operational capacity that reaches 110 MW. The Government of India through its Jawaharlal Nehru National Solar Mission intends to reach 1,000 MW off-grid solar applications during 2017. The 'PV-DG' hybrid system presents high market demand to deliver power to telecommunication towers and emergency systems including hospital and industrial facilities [8, 9]. The development of wind energy as a renewable power source has shown substantial growth throughout the previous few years. The gross wind potential of India stands at 45 GW whereas the state of wind power installations in January 2013 reached 19.8 GW [10]. The previous section presented evidence supporting the fact that DG systems operate as the single power supply at numerous locations. PV systems blend effectively with DG to power remote locations during such situations [13, 14]. The connection of PV systems with DG creates a power system that operates with increased reliability as well as sustainability. The operating expense decreases through reduced fuel usage because of this setup.

Weather conditions determine the natural changes in wind speed along with solar radiation patterns. Solar power and wind power maintain a constantly fluctuating production level. The establishment of energy storage facilities holds essential importance for maintaining a stable electricity equilibrium between power generation and consumption particularly in isolated power systems [15]. The energy storage technology group which includes supercapacitors and superconducting magnetic energy storage (SMES) and flywheels and batteries gives supercapacitors and SMES the fastest dynamic res[illegible]y. Supercapacitors and SMES technologies rem[illegible]ensive while their commercial implementation is limited to small power sys[illegible]

II. [illegible] Stand-Alone Wind Energy based Hyb[illegible]

Let us consider the PMSG based stand-alone wind energy system [illegible] g. 1.

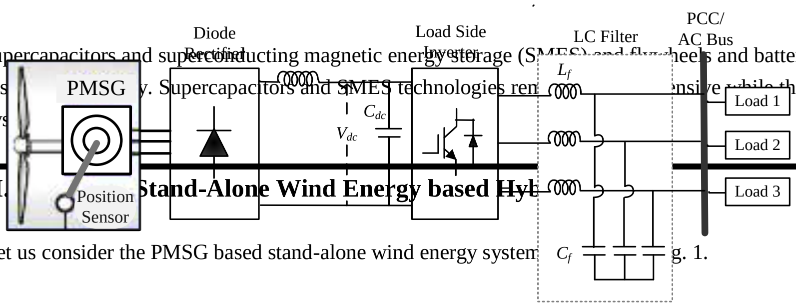


Fig. 1: Stand-alone wind energy system

The standalone operation controls the output alternating current voltage through frequency and amplitude control. The PMSG-based wind turbine provides its power to AC-DC-AC converters to sustain a specific output AC voltage amplitude and frequency level. The dynamics in wind speed together with load variations lead to changes in the DC-link voltage that spans between the rectifier and inverter. A diagram in Fig. 2 shows the variation of in response to wind speed fluctuations and load changes before connecting the battery. At time t=3s there is an rise in DC-Link voltage because the system load drops from 5 kW to 2.5 kW when wind speed stays at 12 m/s. The reduction in wind speed from 12 m/s to 7 m/s generates its impact during t=4s. The control system remains directly influenced by every change in wind speed together with changes in the system load. By controlling the modulation index of the load-side inverter a stable output level of rated voltage can be maintained as long as the reference value of this parameter remains constant. This is explained below:

The relation between dc voltage and output ac voltage of three phase PWM inverter is given by

$$V_{LL_1} = \frac{\sqrt{3}}{2\sqrt{2}} k V_{dc} \tag{1}$$

where,

V_{LL_1} = Fundamental phase-phase rms voltage on ac side

k = Modulation index of PWM inverter

V_{dc} = dc-link voltage

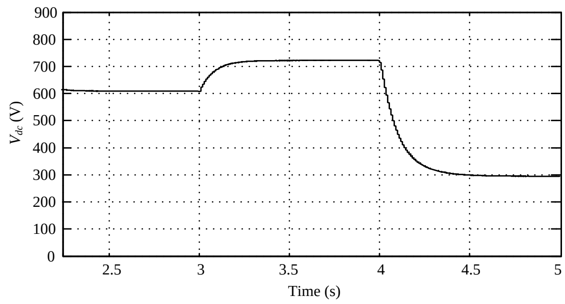


Fig. 2: DC-link voltage without battery

The rated value of AC voltage maintains itself when keeping the reference value and k=1 according to (1). The output frequency of AC voltage remains stable when choosing a specific frequency for the sinusoidal reference signal in the PWM pulse production process. A stand-alone wind energy-based hybrid system begins with PMSG-based wind conversion system coupled to battery power as well as fuel cells connected to a dump load. The aqua-electrolyse function as the systems dump load.

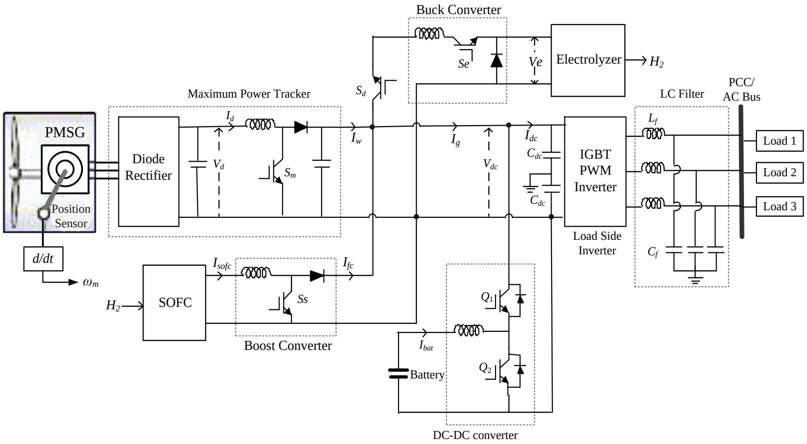


Fig. 3: PMBLDC machine based stand-alone wind turbine with energy storage and dump load

III. Control of DC-link Voltage:

The Fig. 3 represents the self-operating power system consisting of an Axial Flux PMBLDC machine wind turbine generator. The capacitors tied to the inverter receive supply through a neutral wire which appears in Fig. 3. The constructed system supports both three phase distribution along with single phase distribution by using a neutral wire. A proper real power management system must be developed to regulate the dc bus voltage at constant levels so modulation index remains in practical range while maintaining constant ac output voltage (PCC voltage) of the inverter.

The system design in Fig. 3 uses a battery alongside three additional power components and dump capacity which functions as electrolyze. The battery equipment functions both as a system source and sink among its three different operational modes. The system must control its power flow through discharge (charge) while wind energy reaches below (above) expected levels due to unstable wind conditions. The fuel cell operates as a power source only when hydrogen remains available to us. An aqua electrolyze functions solely as a sink for the overall system operation.

The dc-dc bidirectional buck-boost converter enables connection between the battery and the dc-link. The battery voltage controls at a lower level than reference dc-link voltage ( ) through bidirectional buck-boost converter operations thus reducing the required number of batteries for series connection. The proposed system operates at a battery voltage of approximately 300 V while the dc-link voltage stands at = 640V.

Unbalanced load Current compensation

Most distribution system loads primarily operate using single phase equipment which results in unequal current magnitudes and phase relationships exceeding 1200 between different phases. Unbalanced current produces negative effects against the operation of generating systems.

- Electrical torque pulsation
- Unbalanced voltages at PCC

An analysis follows concerning how to control these two issues.

(A) Effect on the generator torque and its compensation

Most existing literature indicates that the time variation of dc-link current ( ) and contains a dc component together with a second-harmonic component when an inverter drives an unbalanced load. The electrical torque of the generator will oscillate because of the second-harmonic component present in the dc current leading to reduced turbine shaft fatigue life. A dc-side active filter has been developed in this chapter as a solution to minimize electrical torque oscillations in the generator. A dc-dc converter links the dc bus to the battery thereby constituting an active filter on the dc side. The battery-related dc-dc converter undergoes a modification to serve this application as shown in Fig. 4(a).

The is filtered by a low pass filter to obtain the dc component (V'_{dc}) and subtracting V'_{dc} from V_{dc} the oscillating component (V_{dco}) is estimated. Now the responsibility of the control scheme is to produce a reference current which needs to be followed by the battery current. Since the function of the battery current is both to maintain the dc bus voltage and to reduce the second harmonic component, two control loops using PI controllers are formulated as shown in Fig. 4(a). First PI controller considering $(V^*_{dc} - V'_{dc})$ as error produces a reference current to maintain the dc bus voltage whereas and the second one uses $(0 - V_{dco})$ as its error.

The second controller sets its reference point at zero because the control system must eliminate the oscillating component from the dc voltage output. A summation of both PI controller outputs results in the final reference battery current . The controlled dc-dc converter IGBT devices (Q1&Q2) receive control signals (gating pulses) from the hysteresis band after the error between actual battery current is processed with the reference battery current. The control methods for the dc-dc converter of FC and electrolyzer also receive modifications when operating under unbalanced conditions according to Fig. 4 (b) and (c).

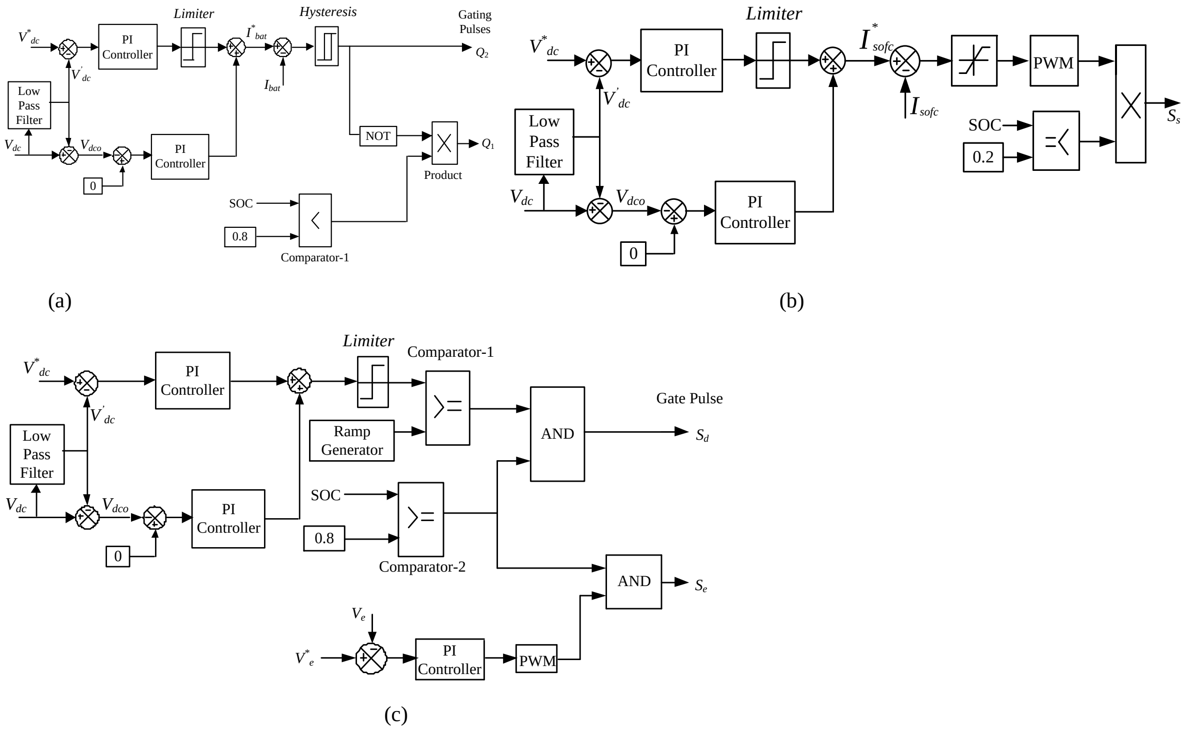


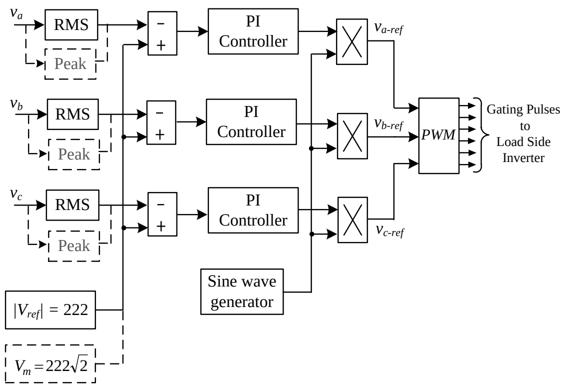
Fig. 4: Dc-dc converter for unbalanced load, (a) for battery, (b) for FC and (c) for electrolyze

(B) Effect on voltage at PCC and its compensation

An unbalanced load connected to the inverter results in unequal currents that produce unequal voltage drops in each of the LC filters used in each phase. The unproportioned voltages drops lead to unbalanced line voltages at PCC which might exceed the permissible threshold (below 1%) for the voltage unbalance factor when using the ratio of negative sequence to positive sequence of fundamental components. Voltage unbalance compensation at the PCC must be implemented because of its necessity. A PI controller receives the difference between the PCC phase voltage rms (or peak) values and the reference phase voltage to accomplish this goal. The PI controller combines its output signal with unit sine wave generation to produce the phase voltage references (va_ref, vb_ref, vc_ref). A generation of PWM pulses occurs through the utilization of va_ref, vb_ref, and vc_ref to activate and deactivate the load side inverter. The control method structure for unbalanced voltage correction appears in Fig. 5.

The controller shown in Fig. 5 seeks to establish different modulation indexes between phases for maintaining balanced conditions of unbalanced PCC voltages. External information about actual voltage feed is required by the controller for operation. Various algorithms enable the detection of voltage values in practice. The peak detection method together with the dq0transformation based approach outperforms rms measurement approach in terms of detection speed. The method detects peaks effectively under conditions with small frequency fluctuations and harmonics present. Low-pass filters LPF-1 and LPF-2 need to be used to calculate va_ref, vb_ref andvc_ref when peak detection is employed in Fig. 6. The inverter-witnessed voltages include harmonics so LPF-1 will use a cutoff frequency of 300 Hz. Polyphase voltages are measured after peak detection through the execution of a second low pass filter called LPF-2 applied at its output as illustrated in Fig. 7.

The increase in oscillations occurs when the LPF-2 cutoff frequency matches LPF-1 at 300 Hz when compared to a 50 Hz cutoff frequency. The actual peak voltage detection requires a 50 Hz low-pass filter to be placed following the peak detector output. This study assesses the transient detection speed between the peak detection algorithm and rms algorithm by implementing filters and exposing them to pure sine signals (Fig. 8 (a)). The depicted time for peak detection emerges from Fig. 8 (b) when operators use filters LPF-1 and LFP-2 simultaneously with the peak method and rms method. The transitory duration of rms detection equals both peak detector methods that use LPF-1 and LFP-2 filtering, as shown in Fig. 8 (b). ITSE method determines the parameters for PI controllers for both approaches under balanced load conditions. The transient behavior shown by the controllers during this analysis matches nearly identically in Fig.9. When using controllers that were previously tuned to operate under unbalanced conditions, the response of peak detection takes longer than the response from rms detection as shown in Fig. 10.



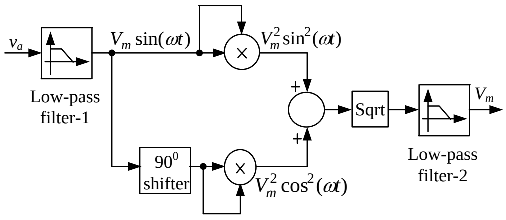
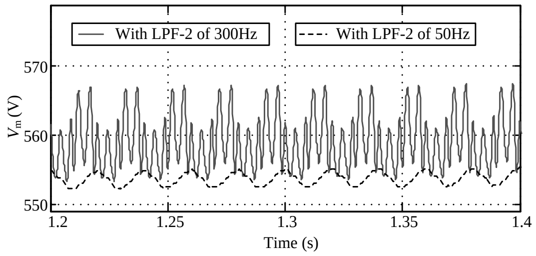


Fig. 5: PWM inverter controller for unbalanced load compensation; Fig. 6: Peak detection method



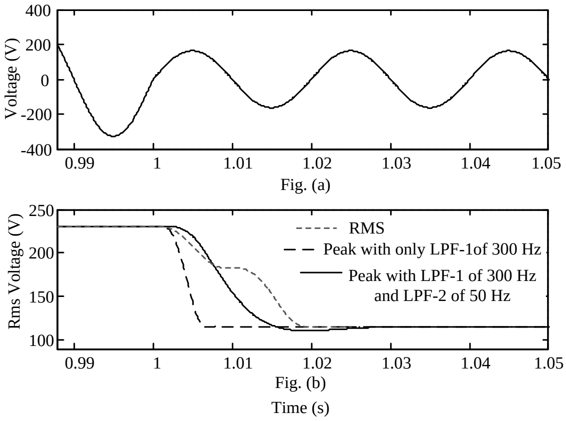
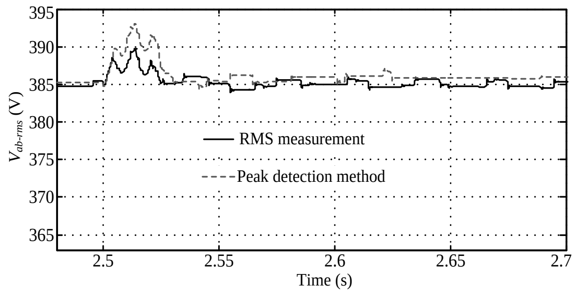


Fig. 7: Peak detected voltage after the filters; Fig. 8: (a) Measured voltage; (b) comparison of peak method along with filters and RMS measurement



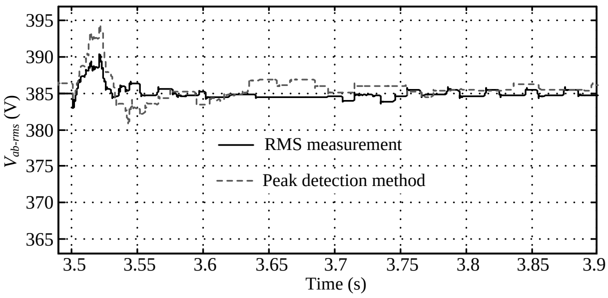
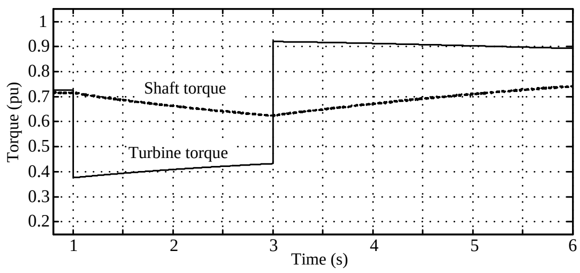


Fig. 9: Comparison of RMS and peak detection method under balanced load condition; Fig. 10: Comparison of RMS and peak detection method under unbalanced load condition

IV. Simulation Results:

The PMSG based variable speed wind turbine system obtains its simulation model through MATLAB/SIMULINK software. The model for PMBLDC operates using any chosen d-q reference frame. The paper shows a modeling system which includes PMBLDC, wind turbine, battery, and FC and electolyzer components. Additional data shows two wind turbine drives from different masses. All PI controllers receive their gain settings from integral time square error (ITSE) method tuning.

Two mass model of drive train is incorporated to get clear picture of wind turbine dynamics. The dynamics of turbine and shaft torque can be observed in Fig. 11 or the change of wind speed from 12 m/s to 10 m/s at t=1s and from 10 m/s to 13 m/s at t=3s. Carefully looking to Fig. 11, the dynamics of shaft torque is quite slow compared to that of the turbine torque. This is attributed to the two mass model representations of the wind energy conversion system (WECS). To observe whether WECS is following the MPPT or not, the mechanical torque is plotted in Fig. 12 for the change in wind speed from 12 m/s to 10 m/s at t=1s. From Fig. 12 it can be found that the ratio of initial torque (at t <=1s) to that of final torque (at t >=15s) is around 1.445. The ratio so obtained is almost equal to the ratio of square of initial wind velocity (12 m/s) to that of the final wind velocity (10 m/s). Through this sample calculation it is concluded that the designed system is following the MPPT. The relation between mechanical torque and wind velocity when MPPT is satisfied is derived.



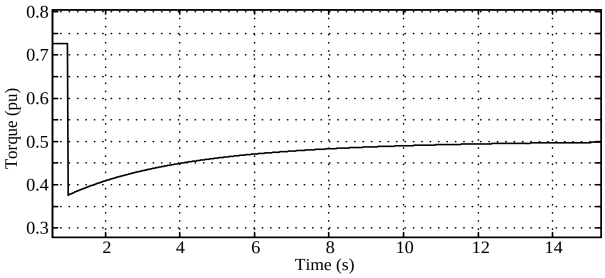
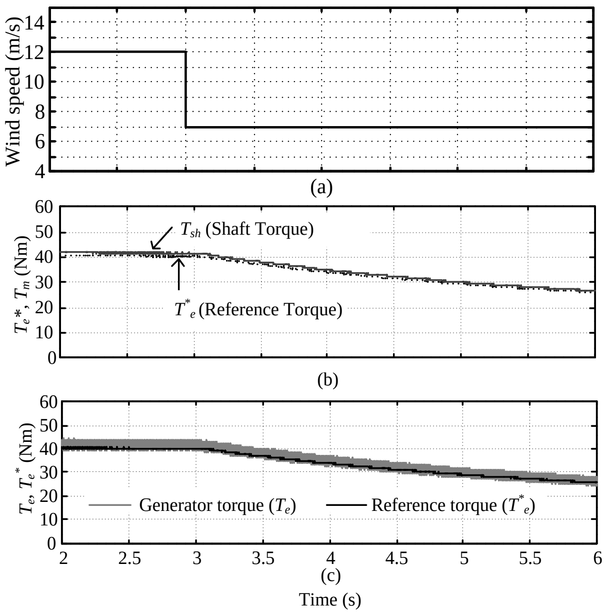


Fig. 11: Response of mechanical and shaft torque for change in wind velocity; Fig. 12: Response of mechanical torque for change in wind velocity

Case-A: Maximum power point tracking of wind and PV

The wind velocity changes from 12 m/s to 7 m/s at t=3 sec as illustrated in Fig. 13(a). A figure presents the changes in shaft torque (Tsh) output as wind speed varies in Fig. 13(b). The two mass model of the wind turbine causes the shaft torque to decrease slowly as investigated in Fig. 13(b). The reference torque estimated from MPPT controller successfully controls the generator torque together with shaft torque during the mentioned wind speed changes as shown in Fig. 13(c). Analyzing the irradiance change from 850 W/m2 to 1000 W/m2 takes place at t=5s as depicted in Fig. 14(a). The performance of the dc voltage controller demonstrated satisfactory results during steady state and transient operation according to the dynamic response of Vmpp and exhibited in Fig. 14(b). The dc-link voltage follows Vmpp that originates from P&O algorithm and because P&O algorithm transmits Vmpp as a reference signal to dc-dc converter control this enables the dc-dc converter to regulate the dc-link voltage to match Vmpp of appropriate irradiance. The PV system functions at peak power levels while the actual power reaches maximum because of dc-link voltage regulation at Vmpp. The power performance data of PV appears in Fig. 14(c).



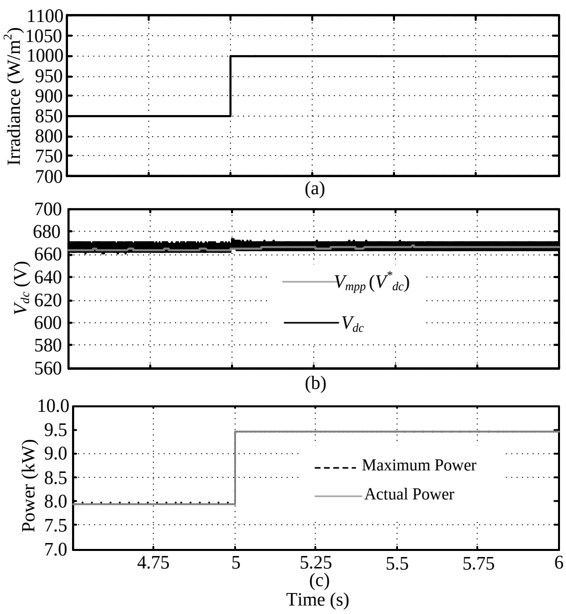


Fig. 13 (a) Wind speed; (b) Mechanical torque, reference torque; (c) Generator torque, reference torque {*Case-A*}; Fig. 14: (a) Change in irradiance, (b) reference and actual dc-link voltage, (c) maximum and actual power of PV system {*Case-A*}

Conclusions

The discussion shows how coordinated control regulates voltage within a stand-alone system which contains a variable speed wind turbine connected to PMSG alongside PV modules and batteries and FC units and an aqua electrolyzer used as a dump load. The system regulates dc-link voltage ( ) to its reference value and controls PWM inverter modulation indices which results in maintaining the inverter output voltage at its rated level. The system control uses basic measures from dc voltage and current readings and avoids power measurement of PV, wind or battery or FC or electrolyzer or load. Simulation data shows that the implemented controllers effectively sustain the load voltage even though solar irradiation strength and wind speed and load values experience fluctuations. A successful control coordination system functions through battery state-of-charge measurements to regulate the wind generator and solar power along with battery charging and discharging and FC operations and electrolysis activities.

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