MODELLING AND SIMULATION OF HYBRID RENEWABLE ENERGY SOURCES CONNECTED TO UTILITY GRID

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ABSTRACT

The proposed system presents power-control strategies of a grid-connected hybrid generation system with versatile power transfer. This hybrid energy system allows maximum utilization of freely available renewable energy sources like wind and photovoltaic energies. For this, an adaptive MPPT algorithm will be used for the system.

Also, this configuration allows the two sources to supply the load separately or simultaneously depending on the availability of the energy sources. The turbine rotor speed is the main determinant of mechanical output from wind energy and Solar cell operating voltage in the case of output power from solar energy. Permanent Magnet Synchronous Generator is coupled with wind turbine for attaining wind energy conversion system.

The inverter converts the DC output from non-conventional energy into useful AC power for the connected load. This hybrid energy system operates under normal conditions which include normal room temperature in the case of solar energy and normal wind speed at plain area in the case of wind energy. The simulation results are presented to illustrate the operating principle, feasibility and reliability of this proposed system.

Keywords: Energy management, grid control, grid operation, PV system, wind power generation.

I. INTRODUCTION

Increasing electrification of daily life causes growing electricity consumption, rising number of sensitive/critical loads demand for high-quality electricity, the energy efficiency of the grid is desired to be improved, and considerations on climate change are calling for sustainable energy applications [1][2]. All these factors are driving the conventional electricity grid to the next generation of grid, i.e.
smart grid, which is expected to appear and coexist with the existing grid, adding to its capacity, reliability, and functionalities [3]. Consequently, the applications of distributed generation (DG) systems are emerging, and most will be interfaced to the grid through power-electronics converters. However, the grid will become much more complex due to the increasing number of DG systems. For instance, the traditional one way power flow is broken by the bidirectional power flow.

Fig. 1. An example of the future application of grid-interfacing converters for connecting multiple DG systems to the utility grid

Furthermore, more voltage quality problems may be introduced if the DG systems are not well controlled and organized [4]. It has been implicated that power electronics-based converters not only can service as interfaces with the utility grid, but also have the potential for mitigating power quality problems [5]. Some auxiliary functions such as active filtering have been reported [6]. Other works such as voltage unbalance compensation, grid support, and ride-through control under voltage dips have been presented in [7][8]. Therefore, to adapt to future smart grid application, it will be a tendency of grid interfacing converters to integrate voltage quality enhancement and DG together.

The desirable approach should be able to maintain high-quality power transfer between DG systems and the utility grid, even in distributed grids, and be able to improve the voltage quality at both user and grid side. Figure 1 shows an example of the future application of grid-interfacing converters. On the left-hand side, multiple DG systems together with energy storage and local loads are interconnected to construct a hybrid energy grid. Energy storage systems (e.g., super capacitor, battery, fuel cell, etc. [9]) are used to store excess energy from the grid and send the stored energy back to the utility grid when needed, which are necessary for grid applications.

II. SYSTEM CONFIGURATION AND MODELLING

1. Grid Configuration

Fig. 1 shows a conceptual Hybrid energy system configuration where various ac and dc sources and loads are connected to the corresponding dc and ac networks. The ac and dc links are connected together through two transformers and two four-quadrant operating three phase converters. The ac bus of the energy grid is tied to the utility grid. A compact Hybrid energy grid as shown in Fig. 2 is modelled using the Simulink in the MATLAB to simulate system operations and controls. Forty kW PV arrays are connected to dc bus through
Fig. 2. A compact representation of the proposed Hybrid energy grid

A dc/dc boost converter to simulate dc sources. A capacitor $C_v$ is to suppress high frequency ripples of the PV output voltage. A 50 kW wind turbine generator (WTG) with doubly fed induction generator (DFIG) is connected to an ac bus to simulate ac sources. A 65 Ah battery as energy storage is connected to dc bus through a bidirectional dc/dc converter. Variable dc load (20 kW–40 kW) and ac load (20 kW–40 kW) are connected to dc and ac buses respectively. The rated voltages for dc and ac buses are 400 V and 400 Vrms respectively. A three phase bidirectional dc/ac main converter with R-L-C filter connects the dc bus to the ac bus through an isolation transformer.

2. Grid Operation

The grid can be operated in two modes. In grid-tied mode, the main converter is to provide stable dc bus voltage and required reactive power and to exchange power between the ac and dc buses. The boost converter and WTG are controlled to provide the maximum power. When the output power of the dc sources is greater than the dc loads, the converter acts as an inverter and injects power from dc to ac side. When the total power generation is less than the total load at the dc side, the converter injects power from the ac to dc side. When the total power generation is greater than the total load in the Hybrid grid, it will inject power to the utility grid. Otherwise, the grid will receive power from the utility grid. In the grid tied mode, the battery converter is not very important in system operation because power is balanced by the utility grid. In autonomous mode, the battery plays a very important role for both power balance and voltage stability. Control objectives for various converters are dispatched by energy management system. DC bus voltage is maintained stable by a battery converter or boost converter according to different operating conditions. The main converter is controlled to provide a stable and high quality ac bus voltage. Both PV and WTG can operate on maximum power point tracking (MPPT) or off-MPPT mode based on system operating requirements. Variable wind speed and solar irradiation are applied to the WTG and PV arrays respectively to simulate variation of power of ac and dc sources and test the MPPT control algorithm.
Two important parameters to represent state of a battery are terminal voltage \( V_b \) and state of charge (SOC) as follows [13]

\[
V_b = V_0 + R_b \cdot i_b \cdot K \frac{\theta}{Q + j \int i_b \, dt} + A \cdot \exp(B \int i_b \, dt) \quad (4)
\
\text{SOC} = 100(1 + \int \frac{\dot{\phi}}{\dot{\phi}_0} \, dt) \quad (5)
\]

where \( R_b \) is internal resistance of the battery, \( V_0 \) is the open circuit voltage of the battery, \( i_b \) is battery charging current, \( K \) is polarization voltage, \( Q \) is battery capacity, \( A \) is exponential voltage, and \( B \) is exponential capacity.

4. Modelling of Wind Turbine Generator

Power output \( P_m \) from a WTG is determined by (6)

\[
P_m = 0.5 \rho \, A \, C_p (\lambda, \beta) V_w^3 \quad (6)
\]

where \( \rho \) is air density, \( A \) is rotor swept area, \( V_w \) is wind speed, and \( C_p(\lambda, \beta) \) is the power coefficient, which is the function of tip speed ratio and pitch angle.
The mathematical models of a DFIG are essential requirements for its control system. The voltage equations of an induction motor in a rotating coordinate are as follows:

\[
\begin{bmatrix}
  v_d & v_q & v_r
\end{bmatrix}
= 
\begin{bmatrix}
  -R & 0 & 0 \\
  0 & -R & 0 \\
  -R_s & 0 & -R_r
\end{bmatrix}
\begin{bmatrix}
  i_d & i_q & i_r
\end{bmatrix}
\]

\[+
\begin{bmatrix}
  \lambda_d & \lambda_q & 0 \\
  \lambda_d & \lambda_q & 0 \\
  -L_{d} & -L_{q} & 0
\end{bmatrix}
\]

\[+
\begin{bmatrix}
  \lambda_{d} & \lambda_{q} & 0 \\
  \lambda_{d} & \lambda_{q} & 0 \\
  0 & 0 & 0
\end{bmatrix}
\]

\[
\begin{bmatrix}
  \lambda_{d} \\
  \lambda_{q} \\
  \lambda_{r}
\end{bmatrix}
= 
\begin{bmatrix}
  -L_{d} & 0 & L_{s}\omega \\
  0 & -L_{q} & 0 \\
  0 & 0 & -L_{r}
\end{bmatrix}
\begin{bmatrix}
  \lambda_{d} \\
  \lambda_{q} \\
  \lambda_{r}
\end{bmatrix}
\]

(7)

(8)

The dynamic equation of the DFIG

\[
\frac{\partial}{\partial t}\left[\begin{array}{c}
  \omega_d \\
  \omega_q
\end{array}\right] = T_m - T_{em}
\]

\[T_{em} = \frac{L_{m}}{L_{r}} (i_{d}i_{d} - i_{q}i_{q})
\]

(9)

(10)

where the subscripts \(d\), \(q\), \(s\), and \(r\) denote \(d\)-axis, \(q\)-axis, stator, and rotor respectively, \(L\) represents the inductance, \(\lambda\) is the flux linkage, \(u\) and \(i\) represent voltage and current respectively, \(\omega_1\) and \(\omega_2\) are the angular synchronous speed and slip speed respectively, \(\omega_1 \equiv \omega_m - \omega_r\), \(T_m\) is the mechanical torque, \(T_{em}\) is the electromagnetic torque.

If the synchronous rotating \(d-q\) reference is oriented by the stator voltage vector, the \(d\)-axis is aligned with the stator voltage vector while the \(q\)-axis is aligned with the stator flux reference frame. Therefore, \(\lambda_{d} \equiv 0\) and \(\lambda_{q} \equiv \lambda_s\). The following equations can be obtained in the stator voltage oriented reference frame as [14]:

\[
\begin{aligned}
  \dot{i}_{d} &= \frac{L_{s}}{L_{r}} i_{d} \\
  \dot{i}_{q} &= \frac{L_{s}}{L_{r}} i_{q} \\
  \dot{i}_{r} &= \frac{L_{s}}{L_{r}} i_{r} \\
  \sigma &= \frac{\omega_1 - \omega_r}{\omega_1 - \omega_r}
\end{aligned}
\]

\[
\begin{aligned}
  \frac{\partial}{\partial t} i_{d} &= \frac{L_{s}}{L_{r}} \left( \frac{\partial}{\partial t} i_{d} + \sigma \frac{\partial}{\partial t} i_{q} \right) \\
  \frac{\partial}{\partial t} i_{q} &= \frac{L_{s}}{L_{r}} \left( \frac{\partial}{\partial t} i_{q} + \sigma \frac{\partial}{\partial t} i_{d} \right)
\end{aligned}
\]

\[
\begin{aligned}
  \frac{\partial}{\partial t} \omega_1 &= \frac{L_{s}}{L_{r}} \left( \frac{\partial}{\partial t} \omega_1 + \sigma \frac{\partial}{\partial t} \omega_2 \right)
\end{aligned}
\]

(11)

(12)

(13)

III. CO-ORDINATION CONTROL OF THE CONVERTERS

There are five types of converters in the Hybrid energy grid. Those converters have to be coordinately controlled with the utility grid to supply an uninterrupted, high efficiency, and high quality power to variable dc and ac loads under variable solar irradiation and wind speed when the Hybrid energy grid operates in both isolated and grid tied modes. The control algorithms for those converters are presented in this section.
Grid-Connected Mode

When the Hybrid energy grid operates in this mode, the control objective of the boost converter is to track the MPPT of the PV array by regulating its terminal voltage. The back-to-back ac/dc/ac converter of the DFIG is controlled to regulate rotor side current to achieve MPPT and to synchronize with ac grid. The energy surplus of the Hybrid energy grid can be sent to the utility system. The role of the battery as the energy storage becomes less important because the power is balanced by the utility grid. In this case, the only function of the battery is to eliminate frequent power transfer between the dc and ac link. The dc/dc converter of the battery can be controlled as the energy buffer using the technique [15]. The main converter is designed to operate bidirectionally to incorporate complementary characteristic of wind and solar sources [16], [17]. The control objectives of the main converter are to maintain a stable dc-link voltage for variable dc load and to synchronize with the ac link and utility system.

The combined time average equivalent circuit model of the booster and main converter is shown in Fig. 4 based on the basic principles and descriptions in [18] and [19] for booster and inverter respectively.

Power flow equations at the dc and ac links are as follows:

\[ P_{in} + P_{ac} = P_{dcf} + P_{b} \]  \hspace{1cm} (14)

\[ P_{g} = P_{w} - P_{acL} - P_{ac} \]  \hspace{1cm} (15)

where real power \( P_{w} \) and \( P_{w} \) are produced by PV and WTG respectively, \( P_{acL} \) and \( P_{acL} \) are real power loads connected to ac and dc buses respectively, \( P_{ac} \) is the power exchange between ac and dc links, \( P_{b} \) is power injection to battery, and \( P_{g} \) is power injection from the Hybrid grid to the utility.

The current and voltage equations at dc bus are as follows:

\[ V_{g} - V_{T} = L_{1} \cdot \frac{d\theta_{1}}{dt} + R_{L} i_{1} \]  \hspace{1cm} (16)

\[ I_{g} - i_{1} = L_{1} \cdot \frac{V_{g}}{\theta_{1}} \]  \hspace{1cm} (17)

\[ V_{T} = \frac{V_{g}}{d} \cdot (1 - d_{1}) \]  \hspace{1cm} (18)

\[ \dot{\theta}_{1} \cdot (1 - d_{1}) - C_{d} \cdot \frac{dV_{g}}{dt} - \frac{1}{H_{L}} V_{g} - \dot{\theta}_{b} - \dot{\theta}_{ac} = 0 \]  \hspace{1cm} (19)

where \( d_{1} \) is the duty ratio of switch ST.
Equations (20) and (21) show the ac side voltage equations of the main converter in ABC and \(d-q\) coordinates respectively [20]

\[
\begin{bmatrix}
\frac{d}{dt} \dot{u}_A \\
\frac{d}{dt} \dot{i}_B \\
\frac{d}{dt} \dot{i}_C 
\end{bmatrix} + \begin{bmatrix}
R_2 \\
0 \\
0
\end{bmatrix} \begin{bmatrix}
\dot{i}_B \\
\dot{i}_C \\
\dot{i}_A
\end{bmatrix} = \begin{bmatrix}
\frac{v_{sA}}{L_2} \\
\frac{v_{sB}}{L_2} \\
\frac{v_{sC}}{L_2}
\end{bmatrix}
\]

(20)

\[
\begin{bmatrix}
\frac{d}{dt} \dot{v}_{eq} \\
\frac{d}{dt} \dot{v}_{eq}
\end{bmatrix} = \begin{bmatrix}
-H_2 \\
0
\end{bmatrix} \dot{v}_{dc} + \begin{bmatrix}
\omega L_2 \\
-\omega L_2
\end{bmatrix} \begin{bmatrix}
\dot{v}_{eq} \\
\dot{v}_{eq}
\end{bmatrix} + \begin{bmatrix}
\frac{v_{eq}}{L_2} \\
\frac{v_{eq}}{L_2}
\end{bmatrix}
\]

(21)

In order to maintain stable operation of the Hybrid energy under various supply and demand conditions, a coordination control algorithm for booster and main converter is proposed based on basic control algorithms of the grid interactive inverter in [19]. The control block diagram is shown in Fig. 5. The reference value of the solar panel terminal voltage \(V_{\text{PV}}\) is determined by the basic perturbation and observation (P&O) algorithm based on solar irradiation and temperature to harness the maximum power [21], [22]. Dual-loop control for the dc/dc boost converter is described in [23], where the control objective is to provide a high quality dc voltage with good dynamic response. This control scheme is applied for the PV system to track optimal solar panel terminal voltage using the MPPT algorithm with minor modifications. The outer voltage loop can guarantee voltage reference tracking with zero steady-state error and the inner current loop can improve dynamic response.

**Fig. 5.** The control block diagram

### IV. SIMULATION RESULTS

The operations of the utility grid under various source and load conditions are simulated to verify the proposed control algorithms. The parameters of components for the hybrid energy grid are explained as follows:

- The load demand to fulfill is 10 KW throughout the time scale except at 4 to 5 sec when it increases to 14 KW.
- Solar energy drops its irradiance to 15% from 2 sec.
- Wind turbine initially rotating at 5m/s excels to base speed 12m/s after 0.5 sec. Its rotating speed is decreased to 25% of its base speed.
- All these conditions are clearly observed in the below graph.
The Maximum Voltage is of PV Array is observed at around 640 V. the curve below explains that the varying irradiance is the deciding factor of the maximum voltage derived.

Fig 6: PV output power

Fig 7: Battery output power

Fig. 6 and Fig.7 shows the PV output power, and battery output power respectively. Initially the solar energy is of full radiance. Here battery and PV is responsible to supply partially to the load in 0-1 sec. From 2-3 sec the solar energy is reduced by 15% and battery stores 3.5kw. Load is increased by 40% in 4-5sec where battery is responsible to meet the demand. From the above figures we can observe the rise and fall of irradiance levels and charging and discharging of battery accordingly.

Fig 8: Wind output power
Fig. 8 shows that the wind turbine speed is minimum at 0sec and attains to maximum speed at 1sec slowly after 0.5sec. From 1-3secs the wind turbine generates maximum power tracked by MPPT and helps battery to charge along with solar power. As wind speed is not constant at all the time both the combination of wind and PV sources is used to meet the load demand through the application of the battery.

![Figure 9: Load Sharing Action Performed by the Hybrid Energy](image)

V. CONCLUSION

A simple and cost effective MPPT technique is proposed for the effective utilization of energy drawn from PV and wind turbine. The power from the PV array or the wind turbine can be delivered to the utility grid individually or simultaneously using the proposed MPPT technique. This hybrid system is controlled to give maximum output power under all operating conditions to meet the load demand either from wind or solar system with the help of battery. Simulation results presented that the wind and PV systems are controlled effectively to operate at their point of maximum power under all operating conditions.

REFERENCES


