Dynamic Simulation Model of a Hybrid Power System: Performance Analysis

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Abstract- This paper reports an investigation to develop a dynamic hybrid power system simulation model to maximize the renewable energy extraction and to analyze disturbances. The investigated model is based on two types of renewable power generation: wind turbine generator and photovoltaic generator, connected to a three-phase isolated grid constituted by a diesel generator. The interconnection between the renewable sources and the AC diesel generator is made by a DC-link with buffer batteries and an inverter. First, the system is sized according to the electric demand and the availability of renewable energy resources. Then, each component of the hybrid power system is dynamically modelled in order to maximize the renewable energy to total energy ratio and to analyze the disturbances that affect the correct operation.

1. INTRODUCTION

Diesel generator is generally used to provide an uninterrupted energy on islands and remote areas. For these regions, the association of diesel generator (DG) and renewable energy sources, wind turbine (WT) generators and photovoltaic (PV) panels, may be especially useful [1].

The increase of renewable energy penetration levels in isolated power system, as well as at the distribution grid level of interconnected systems, has accentuated the difficulties related with the integration of this kind of energy in isolated electric power system. Among the issues that frequently arise, are indicatively the following:

- Voltage unbalance
- Voltage dips (due to the short-circuit or starting up of a large load)
- Voltage swells
- Voltage flicker
- Voltage and current harmonic distortion

For a proper analysis and evaluation of such issues a complete model of the investigated system is required. Therefore, a dynamic hybrid power system simulation model has been developed in order to investigate some problems encountered with this kind of systems.

The modelling capabilities include the dynamic representation of induction and synchronous generator, WT drive train, PV panels, batteries, diesel engine, converters and controllers.

The purpose of the present work is to investigate a dynamic simulation model of the Hybrid Power System (HPS) (Figure 1), after determining the most appropriate combination of components according to the variations in loads and resources oscillation. The simulated system approach is outlined for the main system components and selected architecture. The attention focuses on:

- Maximizing the electric power produced by the WT generator and PV generator by detecting and tracking the point of maximum power.
- Analysis of voltage disturbances - symmetrical or unsymmetrical.

In this paper, the simulated system approach is outlined for the main system components (WT, PV generator, diesel generator and controllers).

2. SYSTEM CONFIGURATION

The system (Fig. 1) consists of a WT, a PV array, buffer batteries and a diesel generator. The load is directly supplied by the common AC point formed by the voltage source inverter and the DG. The connection of the WT and the PV array is through a DC-link voltage. The system control associated with each converter maximizes and regulates the flow of power from the sources.
After several simulations with HOMER (the optimization model for distributed power), the size of each source was defined according with resources availability and load profile. The system must serve an electric demand of 500 KWh/d scaled annual average. The resources availability are: 8 m/s wind speed and 5 KWh/m²/d solar radiations (annual average). The rated power of each source of the system and the annual electrical energy production are shown in Table I.

<table>
<thead>
<tr>
<th>System architecture</th>
<th>Annual electrical energy production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 * 22 KW WT</td>
<td>36%</td>
</tr>
<tr>
<td>18 KW PV</td>
<td>14%</td>
</tr>
<tr>
<td>1*33 KW DG</td>
<td>50%</td>
</tr>
</tbody>
</table>

Table 1. System sources rated power and annual electrical energy production

Short time excess energy is stored in a buffer battery with 4020 KWh throughput to control the DC-link voltage according to disturbances. Fig. 2 shows the monthly average electric production of the system with 0.5 renewable fraction.

This configuration of the HPS was modelled and dynamically simulated in order to analyze the complex interaction of power sources with very different operating characteristics and outputs.

3. MODELLING APPROACH

MATLAB/Simulink is the software used for simulating the whole system. The main concern is the power sources with their control and subsequent disturbances which may affect the correct operation of the system.

3.1. Wind Turbine

Because of robustness, low maintenance and relative cheapness, induction machine has been considered a good choice as electrical generator of the WT. The model of the Squirrel Cage Induction Generator (SCIG) has been expressed in a synchronous frame aligned to the rotating field (rotor flux $\Psi_r$). The relationship between real and imaginary components of the current space vector in the original stationary two-axis reference frame and the new rotating reference frame is shown in Figure 3.
Thus the voltage current equations can be written under the form:

\[
\begin{align*}
    u_{ad} &= R_s i_{ad} + \frac{d}{dt} \phi_{ad} - \omega_s \phi_{ad} \\
    u_{aq} &= R_s i_{aq} + \frac{d}{dt} \phi_{aq} + \omega_s \phi_{aq} \\
    0 &= R_s i_{sd} + \frac{d}{dt} \phi_{sd} - \omega_s \phi_{sd} \\
    0 &= R_s i_{sq} + \frac{d}{dt} \phi_{sq} + \omega_s \phi_{sq}
\end{align*}
\]

(1a)

(1b)

(1c)

(1d)

In the mechanical system, the rotor frequency and the electromagnetic torque can be expressed:

\[
\omega_r = \omega_s - p\Omega_m
\]

(2)

\[
T_{em} = \frac{3}{2} p (i_q \phi_{rd} - i_d \phi_{dq})
\]

(3)

where \(\omega_s\) is the stator supply frequency, \(p\) represents the pole pair number, \(\phi_{rd}\) rotor d and q axis fluxes.

The induction generator is driven by the aero dynamical part of the WT through a gear box. To achieve maximum wind energy, the conversion system is variable speed and driven at the optimal shaft speed [2]. The control structure for the turbine feeding SCIG is shown in Figure 4.
The principle of the control scheme is similar to the one used in motor drive [3]. In fact, for a motor operating, we control the flux and the rotor speed. In our case, the flux is kept to a constant value and the electromagnetic torque is controlled according with maximum efficiency characteristics [4]:

\[ T_{em} = K_{opt} \Omega_m^2 - D \Omega_m \]  

(4)

where \( \Omega_m \) is measured or estimated generator speed, \( D \), an equivalent friction coefficient and \( K_{opt} \), a constant defining the relationship between the maximum power and shaft speed for a given blade characteristic [4].

By choosing a synchronous frame in order to have \( \phi_{rq} = 0 \), the flux \( \phi_{rd} \) and the electromagnetic torque \( T_{em} \) are given by:

\[ \phi_{rd} = L_m i_r = \frac{L_m}{1 + T_s} \]  

(5)

\[ T_{em} = \frac{3}{2} p L_m i_r \phi_{rd} \]  

(6)

where \( L_m, L_r \) are magnetizing and rotor inductance. \( T_s \) is the rotor time constant.

### 3.2. Solar Cell Modelling

A solar cell is usually represented by an electrical equivalent one-diode model as shown in Fig. 5.

![Solar Cell Diagram](image)

The output current source is the difference between the photocurrent \( I_{ph} \) and the normal diode current \( I_0 \) [5] [6] and is directly proportional to the light falling on the cell. The diode determines the current-voltage (I-V) characteristics of the cell.

\[ I = I_{ph} - I_0 = I_{ph} - I_0 \left( \exp \left( \frac{e(V + I \cdot R_s)}{mKT_c} \right) - 1 \right) \]  

(7)

For this work, a model of moderate complexity was used. The model included temperature dependence of the photocurrent \( I_{ph} \) and the saturation current of the diode \( I_0 \). A series resistance \( R_s \) was included and it takes into account the contact resistance between the metallic contacts and the semiconductor, as well as, the resistance of the semiconductor material of the solar cell [5]. In the above equation, \( m, K \) and \( T_c \) represent respectively the diode quality constant, Boltzmann’s constant and temperature.

In PV system, cells are normally grouped into “modules”. The manufacturers supply PV cells in modules, consisting of \( N_p \) parallel branches, with \( N_s \) solar cells in series each.

The PV module’s current \( I^m \) under arbitrary operating conditions can be described as:

\[ I^m = I^m_{sc} \left( 1 - \exp \left( \frac{V^m - V_{oc}^m - R_s^m I^m}{N_s V_{oc}^m} \right) \right) \]  

(8)

The expression of the PV module’s current \( I^m \) is an implicit function, depending on short circuit current of the module \( I^{m}_{sc} \), the open circuit voltage of the module \( V_{oc}^m \), the equivalent serial resistance of the module \( R_s^m \), and the thermal voltage in the semiconductor of a single solar cell \( V_{oc}^m \).

The modules in PV system are typically connected in arrays with \( M_p \) parallel branches with \( M_s \) modules in series each. If it is assumed that the modules are identical and the ambient irradiation is the same on all the modules, the current of the array is:
$I^* = M_pI^m$  \hspace{1cm} (9)

### 3.3. Maximum Power Point Tracker (MPPT) Algorithm

The characteristics at Standard Test Conditions (STC) provided by the manufactures, show that the power supplied by PV module depends on the irradiation, cell temperature and module voltage. Therefore MPPT device is required to extract maximum power from the PV module.

Several MPPT methods have been reported [7][8]. For this research work, the sources incremental conductance method is the used MPP search algorithm.

As shown in [7], the incremental conductance algorithm tracks fast the MPP under rapid changing atmospheric conditions. The output voltage and current from the source are monitored, the MPPT controller relying on them to calculate the conductance and incremental conductance and to make its decision (to increase or decrease duty ratio output).

This algorithm is described by the flowchart in Fig. 6 at every MPP sampling, where $\Delta t$ is the time step, $d(t)$ is the duty ratio at the present time step, $d(t-\Delta t)$ is the duty ratio at the previous time step and $\Delta d$ is the incremental duty ratio.

The output power from the PV source can be expressed as:

$$P_{pv} = i_{pv} v_{pv}$$  \hspace{1cm} (10)

To demonstrate the algorithm, the equation 10 is differentiated:

$$\frac{1}{v} \frac{dP}{dv} = \frac{i}{v} + \frac{di}{dv}$$  \hspace{1cm} (11)

The source conductance and incremental conductance are defined by $G$ and $\Delta G$ respectively:

$$G = \frac{i_{pv}}{v_{pv}}$$  \hspace{1cm} (12)

$$\Delta G = \frac{di_{pv}}{dv_{pv}}$$  \hspace{1cm} (13)

This algorithm searches the voltage operating point at which the conductance is equal to the incremental conductance. These ideas are graphically shown in Fig. 7:

The control of the voltage $V_{pv}$ of the PV panels (Fig. 8), with the help of the boost converter, allows tracking the maximum power extraction.
In the present work, the averaged model of boost converter [9][10] was used and its equations can be deduced from Fig. 8:

\[
\frac{di}{dt} = \frac{1}{L} [- (1 - d)v_{DC} + v_{pv}]
\]

(14)

\[
\frac{dv_{pv}}{dt} = \frac{1}{C_{pv}} (i_{pv} - i_c)
\]

(15)

The current generated by the PV generator on the DC-link can easily be calculated if the converter losses are neglected:

\[i_c = (1 - d)i_i\]

(16)

### 3.4. DC-link voltage

The DC-link voltage is kept at the reference voltage by controlling the energy flow from the batteries to the DC-link. When energy from the WT and PV array is insufficient to supply sudden increments in load demand, the DC-link voltage drops below the reference value. Energy is pumped to the DC-link from the batteries in order to maintain the voltage at the set reference value. When there is excess energy, the batteries are recharged.

![Diagram of DC link with batteries charging](image)

**Fig. 9. DC link with batteries charging block diagram**

Fig. 9 shows the architecture of the DC-link. The used DC/DC converter [9] has quite similar topology with the DC/DC converter used in previous section but is current reversible and the control strategy is different. The voltage PI controller enables the voltage error to be minimised in the steady-state operation.

### 3.5. AC side converter

The connection between the common DC bus and the AC bus is made by a bi-directional converter [3]. Its configuration is shown in Fig. 10:

![Diagram of AC side converter](image)

**Fig. 10. AC side converter block diagram**

As for control of WT, a synchronous frame PI current regulator was chosen to control the converter. Synchronous frame controllers operate by transforming the three-phase AC currents \(i_a, i_b, \text{ and } i_c\) in the synchronous rotating frame. This allows the steady-state error, that is normally associated with the application of PI control, to be eliminated and also provides independent control of real and reactive power flow.

Once in the synchronous frame, the quantities \(i_d, i_q\) and \(i_0\) are regulated using conventional PI feedback control loops—one for each current. The control of the zero sequence current, and thus, the zero sequence voltage, is employed to attenuate the 0-channel disturbance [11].
In most cases, it is reasonable to assume that the converter switching frequency is significantly higher than the power system frequency and will have negligible impact on the model of the inverter control loop dynamics. Therefore, the inverter switches can be replaced by a function representing their averaged value [10].

### 3.6. Diesel Generator

Remote area or island grids are typically fed by conventional diesel power stations. Suitable dynamic models are included in HPS for all important elements of conventional diesel power stations, namely the diesel engine, speed governor and synchronous generator.

For the diesel engine, simple or more sophisticated models available in the literature are employed, depending on the data available [12]. However, experience has shown it is often sufficient to use the simple model of Fig. 11, where the speed governor is represented by its droop and integral gain (PI controller), along with a first order lag for the valve actuator mechanism.

The electrical side of the diesel generator is carried out by a simplified model of three-phase synchronous machine. The simplified synchronous machine block models both the electrical and mechanical characteristics of a simple synchronous machine. The electrical system for each phase consists of a voltage source in series with RL impedance, which implements the internal impedance of the machine.

### 4. SIMULATION RESULTS

#### 4.1. SCIG vector-control performance

Fig. 12a shows the speed tracking response to a wind-step of 5m/s to 9m/s, corresponding to an optimal shaft speed of 65 and 117 rad/s respectively. The evolution of \(i_d\) and \(i_q\) currents is also shown in the Fig. 12. The time response of the tracking strategy is dependent on the step size. The speed tracking performance was tested also with a typical wind profile, Fig. 12b, obtained from [4]. The optimal speed corresponds to the instantaneous wind speed and the real shaft speed is seen to follow well.
4.2. PV panel and Power Point Tracker performance

Equation (8) was used in Matlab to model Shell SQ75 photovoltaic solar module. The I-V characteristics from simulation Fig. 13, obtained with this model, correlate well with the I-V curves provided by the manufacturer, which means that the model can be used with the above presented MPPT algorithm.

Fig. 13a shows the simulation result for PV generator with MPPT when the irradiation is variable and the temperature is constant. The irradiation input data was measured every 15 s during 5 mn and the temperature was kept at 25 °C. The relationship between PV power and the temperature is displayed in figure 14b where the irradiation was kept constant at 1000 W/m².

Fig. 14a shows the simulation result for PV generator with MPPT when the irradiation is variable and the temperature is constant. The irradiation input data was measured every 15 s during 5 mn and the temperature was kept at 25 °C. The relationship between PV power and the temperature is displayed in figure 14b where the irradiation was kept constant at 1000 W/m².
4.3. DC-link controller during voltage disturbances

The effect of the voltage disturbances has been analyzed by comparing the DC-link voltage, which should ideally be constant, and using the DC-link controller shown in Fig. 9. Two kind of voltage disturbances have been investigated by operating the system in three-phase balanced and unbalanced load. In Fig. 15a, the DC-link voltage for the proposed control is shown in case of balanced three-phase load increase by about 90%. In this case the DC-link voltage is constant, only during the short transient at the beginning and the end of the disturbance a peak value can be noticed.

Unbalance condition was created by loading one phase with about 6.5 KW less than the two others. Voltage unbalance in three-phase system causes voltage ripples in the DC-link with twice the fundamental frequency Fig. 15b.

5. CONCLUSIONS

A complete dynamic HPS has been modelled according to the complexity of the investigated subject. Generation-side control and modelling of the voltage disturbances effects are emphasized. It is shown that the investigated model is particularly interesting for designing control strategy and for analyzing the behaviour of the system affected by different kinds of disturbances. In the near future, the developed model together with a test bench that emulates the HPS will be used to test control strategy in order to mitigate voltage disturbances.

REFERENCES

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