Modelling Utility Connected Dispersed Generation on an Electromagnetic Transients Program

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Abstract

Presently, there is an abundant supply of computer software available for utility engineers to adequately plan and operate their networks. However, many utilities are currently investigating methods of incorporating renewable energy resources into their network and now require new models to represent the operation of these sources in their simulation software. This paper presents flexible models for both solar and wind resources which enable the effects of random variations, as well as sudden changes due to adverse weather patterns, on the output of these renewables to be investigated. The randomness of wind is modelled by generating an ensemble of functions which represent the power spectral density obtained from sets of wind data while the randomness of solar radiation is represented by a phenomenological representation of the characteristics of solar radiation dependent upon the type of day. The models have been incorporated into a time domain simulation program and results from photovoltaic and wind output is used to illustrate the usefulness of these models.

1 INTRODUCTION

Many power system utilities are currently investigating the potential of renewable energy sources, such as photovoltaic (PV) devices or wind energy conversion systems (WECS), to meet future customer load growth or to replace aging conventional generation. The outputs from these renewable sources are generally highly variable, being limited by the amount of energy available rather than the installed capacity usually associated with conventional generation. For example, large variations in the output of PV may result from rapid cloud movement while similar variations may occur in the output from WECS due to wind speed fluctuations. Since the output from these renewables will be uncertain under both normal operating conditions and during faults, it is of primary importance that computer models representing these resources in dynamic simulation software also reflect this uncertainty.

Computer simulation is a powerful tool with which to investigate the unique characteristics of renewable energy sources and their interaction with the grid. Such tools provide utility engineers who may be unfamiliar with these technologies with an opportunity to examine, in detail, system operation under normal and faulted conditions. Although there have been an increasing number of utilities using small test systems to investigate the potential problems that may occur with grid connected renewables, computer simulation techniques are now readily available to provide answers to these questions. These tools can then be used to ensure that adequate controls are in place to avoid adverse affects that could arise from connecting renewables to the power system without risking personnel or equipment damage.

There have been relatively few published studies which use time-domain analysis for investigating interconnection issues related to grid connected renewables, especially within the sub-minute time frame. However, several excellent papers exist which provide accurate models for complete simulation studies of large wind turbines [1], [2], [3]. These models include highly detailed representations for the wind characteristics, turbine aerodynamics, drive train, generator and control system. The randomness of wind is modelled by generating an ensemble of functions which represent the power spectral density obtained from sets of wind data, however, transient studies using a sub-second time-step may produce an unrealistic representation of wind fluctuations.

Unlike WECS, grid-connected PV systems are still relatively new technology and have a significantly smaller installed base. Although this may be the case, PV technology represents a completely new generation of generation devices capable of static power injection, instantaneous control of reactive power without the large inertia and long time constants associated with conventional generation technology. Since there are many uncertainties related to grid-connected PV, it is important to provide accurate models to represent these sources to enable their interaction with the grid to be scrutinised. Several [illegible] have already highlighted that there are serious problems that can occur in systems with high penetration levels of PV [4], [5]. The majority of PV studies are based upon analytical rather than time-series simulation methods and focus on the issue of islanding [6], [7]. Such methods cannot accurately represent the dynamic nature of these sources, especially their control system dynamics during disturbances.

This paper presents computational models for PV and WECS for implementation in a time-domain dynamic simulation. This research attempts to provide flexible tools for modelling weather effects on the output of renewables to assist in providing insight into the problems that may arise from the interaction of utility connected renewable sources under normal operation and under faulted conditions. The results presented illustrate some of possibilities using these models in an electromagnetic transient program (EMTP).

2 SOLAR CELLS

Photovoltaics have the potential to provide substantial amounts of customer load. Grid-connected PV represents a generator with several unique characteristics.

- The output is dc and must be converted to ac,
- the output is current limited,
- the output is also stochastic and may vary wildly, and
- instantaneous power control is possible.

A computer simulation approach can be used in order to ensure that these characteristics are compatible with existing utility infrastructure. This section describes computational models for both PV and its fuel, solar radiation.

2.1 *Modelling Solar Arrays*

Solar cells form the building block from which solar arrays are assembled. The present generation of solar cells can only provide output power in the order of 2-3 watts at maximum output. Individual cells with similar characteristics can be connected in series and encapsulated as modules to increase output power. Solar arrays are made up of series and parallel connected modules to provide an even greater output power, more useful for the supply of electricity to satisfy a wide range of different applications. Solar cells are usually represented by

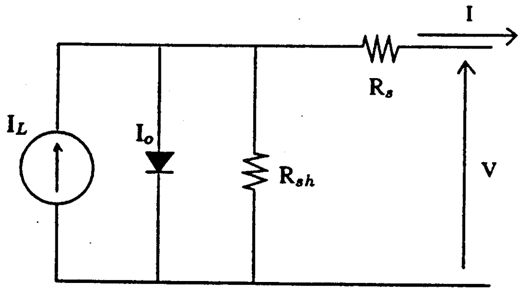

Fig. 1. Single Diode Model of a Solar Cell

the dc equivalent circuit shown in Fig. 1 and described by the the classical solar Eqn. [8],

$$I = I_L - I_o\left\{\exp\left[\frac{V+IR_s}{nKT/q}\right]-1\right\} - \frac{V+IR_s}{R_{sh}} \quad (1)$$

where I_L is the light generated current, I_o is the dark saturation current, R_s is the series resistance, R_{sh} is the shunt resistance, K is Boltzmann's constant, q is the electron charge, T is the absolute cell temperature and n is the ideality factor. The single diode model of Fig. 1 has been shown to achieve less than 3% RMS error in calculated current values [7].

For an array of N_s cells in series by N_p cells in parallel, Eqn. (1) becomes,

$$I = N_pI_L - N_pI_o\left\{\exp\left[\frac{V+IR'_s}{nKT/q}\right]-1\right\} - \frac{V+IR'_s}{R'_{sh}} \quad (2)$$

where $R'_s = \dfrac{R_sN_s}{N_p}$ and $R'_{sh} = \dfrac{R_{sh}N_s}{N_p}$.

This nonlinear implicit function can be solved by iterative numerical analysis. One technique which results in fast solution convergence is Newton's method of successive approximation, defined here as,

$$I_{n+1} = I_n - \frac{f(I_n)}{f'(I_n)} \quad (3)$$

where $f(I_n)$ is a function of I and $f'(I_n)$ is its derivative.

Two limiting parameters used to characterise the output of solar cells are solar irradiance and cell temperature. The transient performance of solar cells is solely dependent on the variation of solar irradiance from one time interval to the next. Variations in cell temperature do not play an important part for the typical time intervals involved in dynamic simulation studies.

3 Modelling Solar Radiation

Solar radiation reaching the earth's surface is attenuated by permanent gases, water vapour and aerosols, and also clouds. Existing techniques for estimating solar irradiance are based upon complex forecasting models requiring detailed long-term site dependent data and extensive knowledge about the make-up of the atmosphere [9], [10], [11]. This type of detailed data and atmospheric observations may not be readily available for many sites which are under investigation as suitable for renewables. For example, although solar radiation S falling on a tilted array will consist of three components, direct, diffuse and reflected solar radiation, such detailed data will usually not be available for many locations. Furthermore, most solar radiation data is obtained from horizontal surfaces while solar arrays are usually tilted towards the sun. Moreover, these models usually provide forecasts over a one hourly time interval and are, therefore, not suitable for time-series analysis over shorter time periods [12].

A flexible model for estimating the solar insolation level over a wide variety of time scales, from sub-second up to an hour, has been developed which does not require complex forecasting. It is based upon a phenomenological representation of the characteristics of solar radiation dependent upon the type of day τ_D. It is comprised of a basic sinusoidal component S_b associated with insolation from sunrise until sunset, a ramping component S_r for rapid cloud movement and a random component S_n for small random fluctuations,

$$S = S_b + S_r + S_n \quad (4)$$

3.1 *Basic Insolation Component*

This basic insolation characteristic is represented by a sinusoidal function whose magnitude is a function of the type of day. The maximum amount of insolation received must be less than the solar constant. The solar constant S_0 is the amount of solar radiation striking a unit area normal to the sun's rays at the average sun-earth distance in the absence of the earth's atmosphere, and places an upper limit on the solar radiation striking terrestrial solar panels.

$$S_0 = 1,377 \ \text{Wm}^{-2} \quad (5)$$

Furthermore, the maximum value is also a function of the earth's orbit about the sun as the sun-earth distance varies according to [13],

$$S_{\max} = 0.0167\, S_0 \cos\left\{(D-1)\frac{360}{365}\right\} \quad (6)$$

where D is the number of days elapsed since December 20.

The base insolation component is therefore represented by,

$$S_b = \begin{cases} 0 & , t < T_r \\ \frac{S_{\max}}{K_b}\left\{1-\cos\left(2\pi\left[\frac{t}{L}-\frac{T_r}{L}\right]\right)\right\} & , T_r < t < T_r + L \\ 0 & , t > T_r + L \end{cases} \quad (7)$$

and $K_b = \begin{cases} 1, & \text{for sunny weather} \\ 2, & \text{for cloudy weather} \\ 3, & \text{for overcast weather.} \end{cases}$

where K_b is a constant representing the type of day, T_r is the time at sunrise and L is the length of time from sunrise to sunset at a latitude l, given by [13],

$$L = \frac{2}{15} \cos^{-1}(-\tan l \, \tan \delta) \tag{8}$$

and δ is the declination angle given by,

$$\sin \delta = -\cos \left\{ (D-1) \frac{360}{365} \right\} \sin 23.45 \tag{9}$$

3.2 Ramping Component

Modelling cloud movement is an important aspect of PV dynamic simulation studies. Rapid cloud movement is described by a ramping function,

$$S_r = \begin{cases} 0 & , t < T_{r_0} \\ K_r \left[\frac{1-(t-T_r)}{(T_{r_0}-T_r)} \right] & , T_{r_0} < t < T_r \\ 0 & , t > T_r \end{cases} \tag{10}$$

where K_r is the insolation change, T_{r_0} is the start time, T_r is the end time of the change and $T_r > T_{r_0}$.

3.3 Random Component

The random noise component is described by a function whose magnitude is dependent upon the type of day τ_D, the magnitude of the base function and the simulation time-step Δt,

$$S_n = \left(\frac{\tau_D}{a} \right)^b \alpha \, S_b \, \Delta t \tag{11}$$

where a and b are constants which vary the level of randomness, and α is the random number drawn from a normal distribution with a mean of zero and unity variance.

The randomness of the solar radiation model is scaled by the base insolation component S_b since the effects of array shading are considered proportional to the level of insolation, that is, array shading has a greater effect at higher levels of insolation, for example, at midday. The random component S_n is also scaled by the time-step of the simulation to ensure that the magnitude of the noise at small time-steps does not exceed that at larger time-steps.

The power spectral density function for the typical insolation characteristic over a twenty four hour period has also been used to describe this single dimensional random process.

3.4 Model Characteristics

A unique problem with a random model for solar insolation is that there is one additional constraint; the output must return to zero at sunset. Furthermore, a simple memoryless model which perturbs the basic sinusoidal characteristic of S_b at each time interval cannot represent large variations in the incoming radiation which occur over time since the simulation time-step may be less than one millisecond. A random walk based model is required to represent such effects. Additional restrictions must be included in such models to ensure that the output returns to zero at sunset.

Fig. 2 provides a comparison between actual data recorded from observations of solar radiation from Albany, Australia,

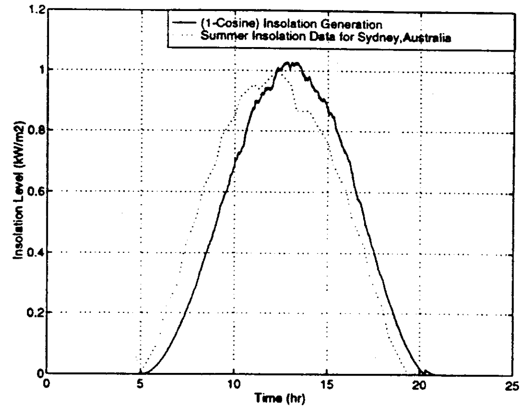

Fig. 2. Comparison of Simulated Solar Radiation Levels and Actual Data for Sunny Weather

in January 1972, in the middle of summer, (from [14], [15]) and those generated using the model described in this section. This illustrates that the above model is capable of describing the stochastic nature of solar radiation.

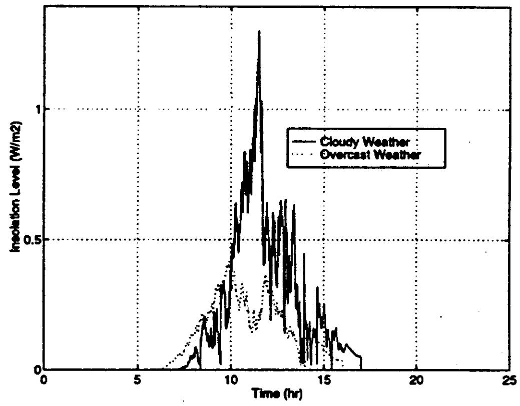

Fig. 3. Simulated Solar Radiation Levels for Cloudy and Overcast Weather

Fig. 3 shows the typical output from the model due to cloudy and overcast weather patterns where the magnitude of randomness has been adjusted according to the type of day.

4 Wind Energy Conversion Systems

A conventional WECS consists of a wind turbine with a low speed shaft, gearbox, high speed shaft and an induction generator. The power output from a wind turbine is proportional to the cube of the wind speed. Therefore, the power generated by the turbine can vary rapidly due to changes in wind speed. Many turbines have pitch angle controls to enable greater control especially during start-up and shut-down of the machines and to provide adequate aerodynamic braking for overspeed protection. This section extends a simulation approach for modelling the stochastic nature of wind fluctuations for sub-second time-intervals based on [2].

4.1 *Wind Turbine Dynamics*

The torque developed by a wind turbine at any instant depends on the wind speed V and angular velocity of rotation ω. The wind torque on each blade can be expressed as a non-linear function [16],

$$T_b = \frac{1}{2} C_p \, \rho \, \gamma A \, V^2 \qquad (12)$$

where where C_p is the power coefficient, ρ is the density of air, γ is the tip speed ratio, A is the area swept by the rotor and V is the wind speed. The output characteristic for a typical

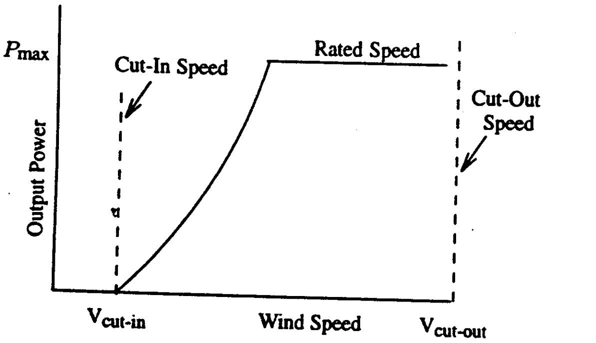

Fig. 4. A Typical Wind Speed Power Transfer Function for Wind Turbines

wind turbine is shown in Fig. 4. Power is produced in the speed interval,

$$V_{\text{cut-in}} \leq V \leq V_{\text{cut-out}} \qquad (13)$$

For wind speeds above the rated level, the generator will tend to be overloaded and the output is controlled to keep the stator current close to its rated value to prevent machine overloading. When the wind speed is lower than the rated value, the generator is driven below its rated speed and there is no danger to the generator from excessive currents. The generator speed will be controlled such that its output is maximised.

For wind speeds between cut-in and rated, the blade angle will remain constant and the output will depend entirely upon the wind speed. At higher wind speeds, the blade angle is adjusted to maintain constant speed and output until the point where the turbine is furled.

The lowest wind speed for which a wind turbine will deliver its rated maximum power output is the rated wind speed V_r, usually about 1.5 times the annual average wind speed. Complete models for the blade and shaft dynamics, and those for pitch control can be found in [2].

5 Modelling Wind Behaviour

A flexible model has also been used to accurately represent the spatial effects of wind behaviour. It includes allowances for rapid wind changes, gusting and the general random nature of wind [2],

$$V = V_b + V_r + V_g + V_n \qquad (14)$$

where V_b represents the base wind velocity component, V_r represents the ramping component, V_g represents the gusting component and V_n represents the background noise component.

5.1 *Base Wind Component*

The base wind velocity component is described by a non-negative constant K_b,

$$V_b = K_b\,, \quad K_b \geq 0 \qquad (15)$$

5.2 *Ramping Wind Component*

Rapid wind changes are described by a ramping function,

$$V_r = \begin{cases} 0 & , t < T_{r_0} \\ K_r \left[\frac{1-(t-T_r)}{(T_{r_0}-T_r)} \right] & , T_{r_0} < t < T_r \\ 0 & , t > T_r \end{cases} \qquad (16)$$

where K_r is the velocity change, T_{r_0} is the start time of the change, T_r is the end time and $T_r > T_{r_0}$.

5.3 *Wind Gusting Component*

Wind gusts are described by a $(1 - \cos)$ function,

$$V_g = \begin{cases} 0 & , t < T_{\gamma_0} \\ \frac{K_g}{2}\left(1 - \cos\left(2\pi \left[\frac{t}{T_\gamma} - \frac{T_{\gamma_0}}{T_\gamma}\right]\right)\right) & , T_{\gamma_0} < t < T_{\gamma_0} + T_\gamma \\ 0 & , t > T_r + T_\gamma \end{cases} \qquad (17)$$

where K_g is the velocity change, T_{γ_0} is the start time and T_γ is the gust period.

5.4 *Random Wind Component*

The random component is described by a single dimensional random process [17],

$$V_n = 2 \sum_{i=1}^{N} \left[S_v(\omega_i) \Delta\omega \right]^{\frac{1}{2}} \cos(\omega_i t + \phi_i)\,, \;\; t < 0 \qquad (18)$$

where the spectral density function $S_v(\omega_i)$, derived from the theory of turbulent flow, is the defined by [18],

$$S_v(\omega_i) = \frac{2 K_N F^2 |\omega_i|}{\pi^2 \left[1 + \left(\frac{F \omega_i}{\mu \pi} \right)^2 \right]^{\frac{4}{3}}} \qquad (19)$$

where $\omega_i = (i - \frac{1}{2})\Delta\omega$, ϕ_i is a random variable with uniform probability density, K_N is the surface drag coefficient, F is the turbulence scale and μ is the mean wind speed.

5.5 *Model Characteristics*

Once again a random model incorporating memory must be used otherwise wind fluctuations become limited due to the sub-second time-intervals involved during transient simulation studies. However, the large inertia associated with WECS rotating machinery will limit the usefulness of such detailed models. Wind gust modelling forms an important part of any dynamic study of wind turbine models. Fig. 5 shows the output from the wind generation model for a five second gust together with background noise superimposed on the signal.

Fig. 6 compares the random fluctuation componment from a memoryless random generator of wind with that of a memory base model during a five minute period. Note that the memoryless model can only represent a limited value at each time interval.

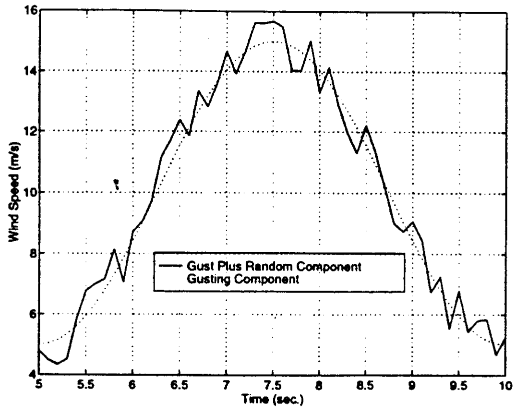

Fig. 5. Generated Wind Gust with a Random Component

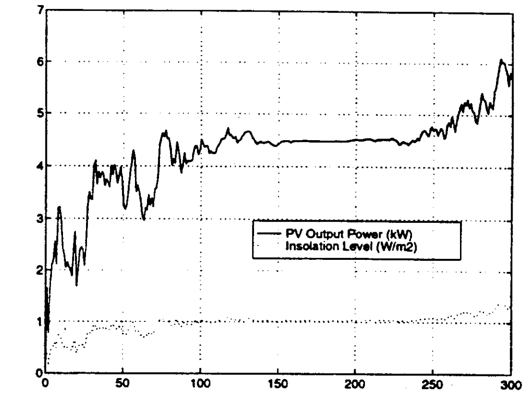

Fig. 7. PV Output from Computer Generated Solar Radiation Data

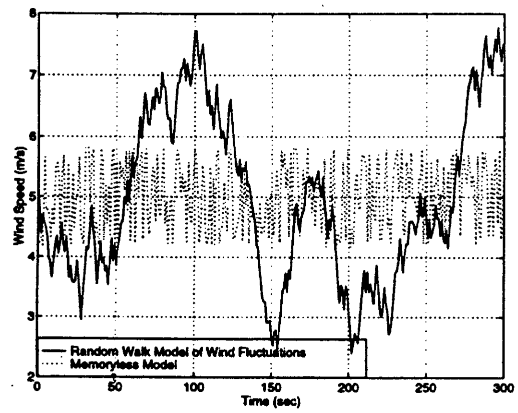

Fig. 6. Generated Random Wind Component

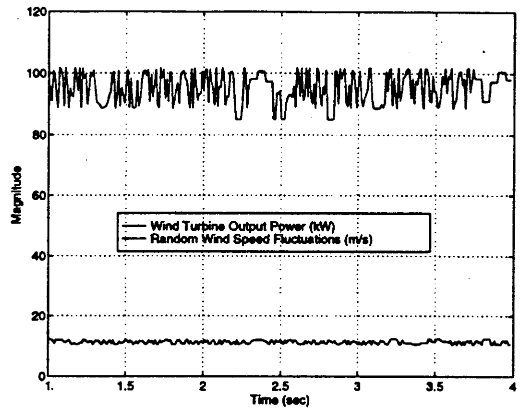

Fig. 8. Wind Output from Computer Generated Solar Radiation Data

6 Modelling on an EMTP

PV and WECS weather models have been integrated into a EMTP to allow investigational studies regarding the effects of stochastic sources, operating in both concentrated and dispersed modes.

Fig. 7 shows the typical output obtained from the PV model of a 6 kW array during midday on a sunny day when implemented into an EMTP. The fluctuations of wind

Fig. 8 shows the typical output obtained from the PV model of a 100 kW wind turbine connected to a induction generator from random wind fluctuation data generated from the above models.

7 Conclusion

This paper presents flexible models for both solar and wind resources which enable the effects of random variations, as well as sudden changes due to adverse weather patterns, on the output of these renewables to be investigated. The randomness of wind is modelled by generating an ensemble of functions which represent the power spectral density obtained from sets of wind data while the randomness of solar radiation is represented by a phenomenological representation of the characteristics of solar radiation dependent upon the type of day. The models have been incorporated into a time domain simulation program and results from photovoltaic and wind output is used to illustrate the usefulness of these models.

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