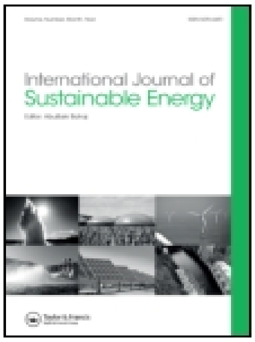

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Asynchronous interconnection of large-scale photovoltaic plants: site selection considerations

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Large-scale penetration of photovoltaic (PV) energy in a distribution network requires careful planning of its location on the distribution network since it evidently demands large space, flexible maintenance access and exposure to driving energy sources such as sunlight for PV plants. Besides that, the technical aspects of the design should consider possible constraints that may introduce inefficiency in the generation or simply unexpected loss in the distribution. This paper addresses the decentralisation requirement for large-scale deployment of PV power sources as it resists the intermittency of the PV output naturally. In this study, a Monte Carlo method was used to justify the validity of this implication. A modified Gaussian distribution function was used to model the random fluctuations of the PV source and was used in the Monte Carlo simulation. The result shows considerable boost in the average power level and suppression of the fluctuation rate while the interconnected sources are uncorrelated.

Keywords: modified Gaussian; virtually centralised generating system (VCGS); distributed generation; photovoltaic plants; energy storage system (ESS)

1. Introduction

The need to identify the potential challenges to the penetration of photovoltaic (PV) energy in electricity arises from the inherent stochastic output of PV power sources subjected to the variation of solar light irradiation. Even though the motion and size of the clouds obstructing the sunlight are not beyond estimation through the use of weather radars administered by the Geographic Information System (GIS) or remote sensing (Marcello, Eugenio, and Marqués 2009) stations, these might help an operator to choose an action or trigger an automated sequence of jobs programmed ahead. This can be considered as a dynamic control of the PV sources to adapt to the changes in the weather conditions and operate the PV plant in the most efficient way. However, the use of energy storage systems (ESSs) for larger renewable sources (typically few megawatts) is commercially rare due to the associated cost and efficiency considerations. The basic constraints of deploying large-scale ESSs also include a higher overhead cost due to low cell voltage that needs to be in series. It reduces its reliability because of excessive modules that are being operated in series. A two-component two-state Markov model can be used to demonstrate that the ratio of the failure rate of a series-connected pair component to that of the parallel-connected one is commonly much greater than unity (Bollen) as shown below:

$$\frac{\lambda_s}{\lambda_p} = \frac{\lambda_1^{-1} + \lambda_2^{-1}}{\mu_1^{-1} + \mu_2^{-1}}, \quad \text{where } \lambda \ll \mu \text{ in practice.} \tag{1}$$

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Here, λ_s is the rate of failure of a system with two units in series, λ_p the rate of failure of a system with two units in parallel, λ_1 the rate of failure of unit no. 1, λ_2 the rate of failure of unit no. 2, μ_1 the rate of recovery of unit no.1 after a failure and μ_2 the rate of recovery of unit no. 2 after a failure, where all the rates are specified on a common time duration base and under a similar usage environment (i.e. no unusual hazardous environment or dissimilar operating environment).

In Section 2, an analysis is presented from the viewpoint of statics. The ESS is not included in the consideration of this typical case. In general, the application of an ESS covers a wider area and can add high costs for large-scale sources. Moreover, the analysis also shows how the interconnected system can resolve the intermittency problem. Additionally, the use of an ESS in a number of power conditioning applications including as a voltage or a power regulator is proven. Regardless of the availability of any compatible ESS, PV energy can be penetrated in large scales within an existing grid as we can hypothetically deduce it from the experience of commercial wind power sources that are being interconnected through the High Voltage Direct Current (HVDC) links around the globe for years. The US Department of Energy conducted a study on renewable source interconnection in spring 2007 and allotted funds and a number of grants to research groups and agencies nationwide in preparation for large-scale integration of PV energy in the grid. The main focus of this research initiative was to identify potential challenges on existing grids and plan to overcome them. The accuracy of the models and resource estimation can thus establish a concrete foundation for large-scale penetration of renewable sources in the US power grid (Achilles *et al.* 2008). One of the subtopics is related to the power system planning practices that should maximise its benefits and reduce the risks. A common fear is the intermittency or fluctuation of power level leading to voltage and frequency deviation in the system. In this paper, it is shown that appropriate interconnection of PV sources located in diverse geographical locations can mitigate the power fluctuation problem considerably. In Section 2, the superiority of asynchronous connection is explained mathematically using a modified Gaussian distributed randomly varied solar output over time indexed mean. In Section 3, an example is presented using field data from three PV sources in two distinct locations. In Section 4, an expanded interleaved DC interconnection of PV plants is described as a proposed option for asynchronous interconnection realising virtually centralised generating system (VCGS).

2. Model of PV sources as stochastic sources

2.1. *The model for simulation*

PV sources can be modelled in different ways. In the case discussed here, the variation in the output power of the complete system is considered rather than analysing the individual components of the model. Few parameters are very common in most PV models:

- There is a finite limit on the PV output from zero to its maximum capacity.
- The PV output has a time-dependent deterministic shape that varies stochastically with respect to the day and time of a year.
- The Maximum Power Point Tracking (MPPT) is assumed to be an integral part of the PV systems (Altas and Sharaf 2007).
- The influence of the PV cell temperature, wind speed and irradiation is considered as a stochastic function of the day and time of the year combined to a single Gaussian distributed variation. This is indeed a valid assumption as can be inferred from the central limit theorem.

MatLab/Simulink® provides a built-in PV model block that can take solar irradiation and ambient temperature as variable inputs. In reality, both the parameters vary stochastically. The time-dependent Markov Transition Matrix model (Kamal and Jafri 1999, Muselli *et al.* 2001, Li and

Niu 2009) has been found to be better predictive than the autoregressive moving average (ARMA) model (Wang *et al.* 2009) of solar irradiation in a particular area for two apparent reasons:

(1) All commercial PV sources employ a maximum power point (MPP) boost converter that has a definite output within a small solar irradiation power band. Readers can recall the PV model MatLab/Simulink© model properties.
(2) If we exclude all the extreme weather conditions, then we are left with a finite-space weather model that is recurring. The only aspect that can suppress this proposition is the global climate change, which is a collective of slow thermodynamic processes, and thus omitted here due to the complexity of modelling these processes.

In this paper, we use a truncated Gaussian distributed random variation of a solar panel output with a positive mean. In the case addressed here, the word 'truncated' is described as bounded by two limiting parameters – the maximum capacity of the PV source or PV cell saturation and the minimum threshold solar irradiation (watt per metre squared) required to initiate the power flow. The accurate modelling is not the focus of this paper. Instead, it is shown that the interconnection of statistically uncorrelated sources can yield a considerably less fluctuated output with a positively raised mean. This is well proven in some recent experiments done with interleaved DC–DC converters or cell interconnection methods (Betten and Kollman 2005, Liccardo *et al.* 2007, Durañ *et al.* 2009) without a firm justification from a statistical viewpoint, which is elucidated in this section. However, the common benefits observed from all the tests referred in Li and Niu (2009), Kamal and Jafri (1999) and Wang *et al.* (2009) are as follows:

- higher power output,
- higher output ripple frequency that eases filtering,
- higher terminal voltage and
- improved reliability of service; that is, the failure of a single string will not cease the whole system in the case of a multi-string interleaved connection.

In the system addressed here, the power output profile of three PV source units that were not centrally interconnected was used for statistical analysis and curve-fitting purposes. The data were collected from three PV sites in the Tampa Bay and the St. Petersburg area. The PV output power has a positive mean and a finite sample length. The mean μ_i and the variance λ_i are functions of a reasonably small time segment t_i (not the time instance) where the mean and its variance can be considered to be stationary. Thus, for the worst case, we can consider the PV output to be as simple as a *random walk*, a special case of the ARMA model as shown below:

$$Y_i = \mu_i + X_i(0, \sigma_i), \text{ where } \sigma_i = \sqrt{\lambda_i}, \tag{2}$$

where Y_i is the PV output at the ith interval, X_i the zero mean random noise and μ_i the mean of the stochastic model. We truncated the output of the Gaussian random source into a finite space bounded by zero to maximum capacity. However, by doing so, we indeed denounced our naming since if we observe the histogram plot shown in Figure 1, it will be clear that the modified Gaussian source merely preserved its property of symmetry and that is all.

An analysis of the histogram plot suggests that it resembles the discrete probability distribution functions more rather than any continuous one. Interested readers can verify that all the generating functions given below with a common trend and, say, a maximum or a minimum on the same

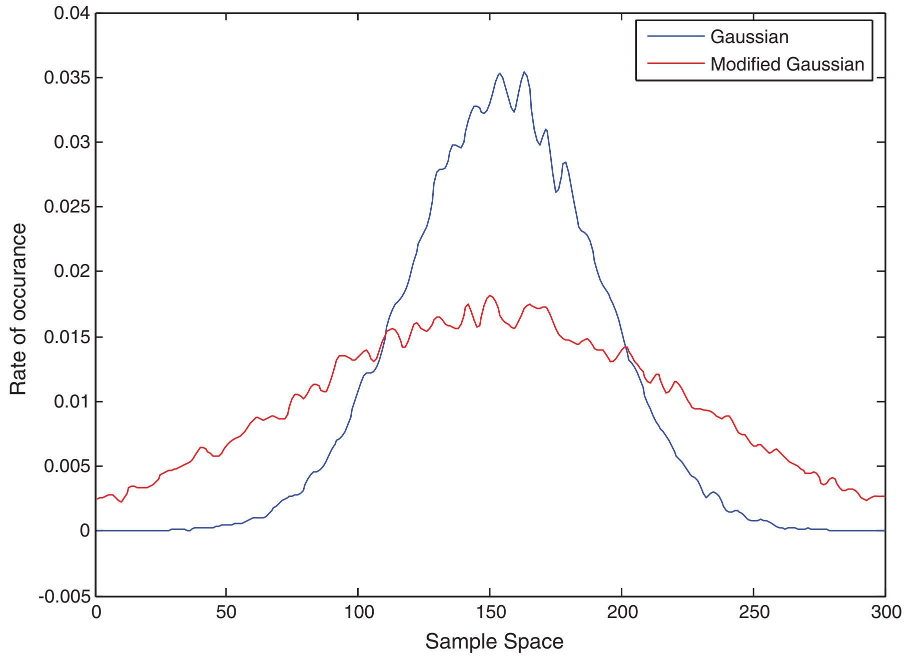

Figure 1. The histogram plot of Gaussian and modified Gaussian sources.

axis, produce histogram plots of the same shape:

$$f(x) = x \cdot e^{(x^2-0.5)}, \tag{2a}$$

$$f(x) = (\tfrac{2}{3}) \cdot |(1-2x)|, \tag{2b}$$

$$f(x) = 1 - \sqrt{(0.75^2 - (x-0.5)^2)}, \tag{2c}$$

where x is a uniformly distributed random variable. Note that all the functions produce histogram plots of exactly the same shape if one generates a sufficiently large number of samples. However, none of them matches the shape that we obtained from truncating the Gaussian output sample space. We can show that if we use a generating function with a common trend but with multiple and periodic maxima or minima, then possibly we can get closer to what we had obtained from the modified Gaussian source. The following generating function can be used to verify this claim:

$$f(x) = 0.6x + 0.8\cos^2(8\pi x) + 0.25\cos^2(6\pi x). \tag{2d}$$

The conclusion of the discussion is that the grid-tied PV power output can be reliably modelled using a homogeneous finite-space Markov process.

2.2. *The algorithm of the simulation model*

The proposed modified Gaussian solar irradiation model was used to simulate the contribution resulting from the interconnection of multiple PV units (five in our case) located in diverse geographical areas. For simplicity, it is assumed that all the PV sources are dispersed on the land under a utility service territory. In MatLab©, the 'RndStream' command was used to remove the correlations of randomly generated data streams by each generator before using the data sampler. The algorithm is given below:

(1) Generate five independent Gaussian distributed data streams of a large size (1000 and 40,000 were used in the study case).
(2) Filter each stream using the *Dead Zone* block (can be found in MatLab Simulink). The output of the filter is a modified Gaussian distributed random data stream.
(3) Downsize each of the data streams by averaging a small data block in the same sequence.
(4) Add up the data samples from all the streams in the same order.
(5) Compare the adder's output with that of the five time-amplified versions of any of the downsized data streams.

Figure 3 shows the results of the above analysis along with a brief description of the graph legends.

2.3. *Interconnected or parallel units*

By Bienaymé formula (Loeve 1977), it can be shown that the variance of the mean of the sum of n number of variables with the same variance σ^2 is σ^2/n. Conversely, if the variables are correlated on the average by the factor ρ, then the variance of the mean of the sum will spread by $(n-1)\rho$. Even though it is inappropriate for the so-called modified Gaussian source, the principle still holds true and can be estimated statistically. The two subsets of the Gaussian generated sample space are (1) the sum of the five independent PV sources of the same rated capacity and (2) a single PV source of capacity five times that of any of them (Figure 2).

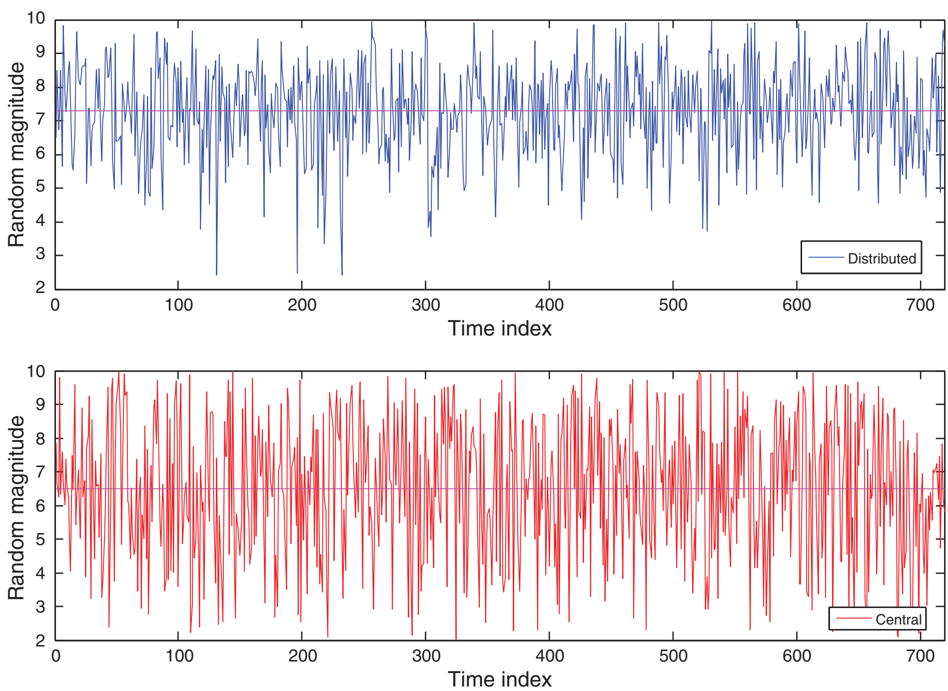

Figure 2. The stream of a truncated Gaussian subset.

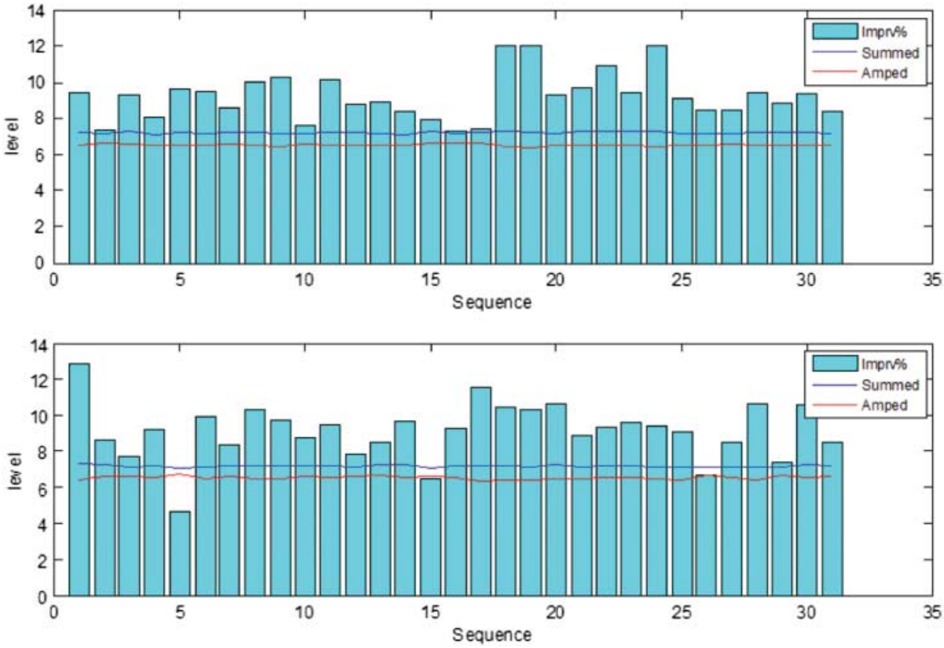

Figure 3. The mean output of the PV source in noon on a given scale (0–10) – 1000 samples/run (top) and 40,000 samples/run (bottom).

The mean of the output stream of the interconnected PV sources is higher than the amplified version of any of them. It was also found to be definite as evident from the Monte Carlo simulation. The Monte Carlo simulation result appeared to be stable (Figure 3). The fluctuation in the interconnected and uncorrelated sources was suppressed and can be perceived just from the visual inspection of Figure 2. Roughly 30% damping on the fluctuation was estimated from the simulation with an average rise of the power by 12%.

The vertical light blue bars in Figure 3 indicate the percentage difference between the estimated mean (the blue line) of the interconnected system and that of the single PV source of equal size (red line). An interesting fact is that these lines do not intersect within the span of the observation. The sample size is indicative of the rate of change. Note that if the rate of change is too high, the average difference decreases (the heights of the vertical bars). However, rapid changes in the PV outputs within the area of interest are unlikely to occur, implying a higher output from the interconnected system. The connotation is that the mean of the interconnected system will most likely be higher than its single equivalent. If Figure 3 is zoomed in, it can be inferred that the mean of the output from the interconnected system is also flatter than its equivalent single unit. Recall that the so-called virtually central generation is credited for this purpose. This can also be verified from the practical data collected from the two sites described in the following section.

3. Field data analysis

3.1. *Presorting of the collected data*

To explain the intuition from practical systems, three of the standalone PV sources were chosen. Of these, two were in proximity (within a quarter mile) and the other was apart by 45 miles approximately. Table 1 can give an idea of their physical locations.

Table 1. Geographic location of the PV sources.

Physical location	Latitude	Longitude
Tampa Lowry Park Zoo, Tampa, Florida	28.011°	82.472°
USF, St Petersburg, Florida	27.763°	82.635°

From the Table, it can be seen that the geographical distance between the two sites is 0.248° South and 0.163° West from the Tampa location. A distance in the East-West direction would result in longer exposures to sunlight. Conversely, the distance in the North-South direction would render higher peaking on the interconnected system. The reason is straightforward – the solar motion and eccentricity are the major players. The steps that were followed in this analysis are as follows:

(1) The output power was normalised on the nominal rating of the PV panels.
(2) The profiles were time aligned. The small longitudinal difference was ignored.
(3) The data were manipulated to be comparable (real power in this case).
(4) The data were segmented in such a way that each data segment had a stable statistical mean with a sufficiently small variance within the segment. This would ensure identical weather conditions (Figure 4).

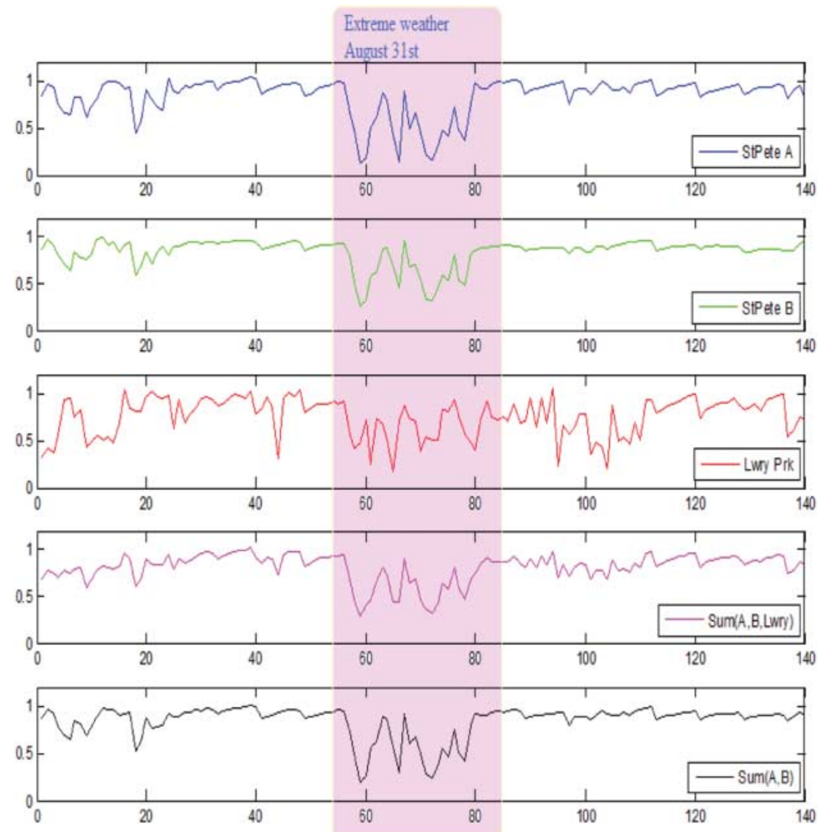

Figure 4. The PV output variation due to weather conditions.

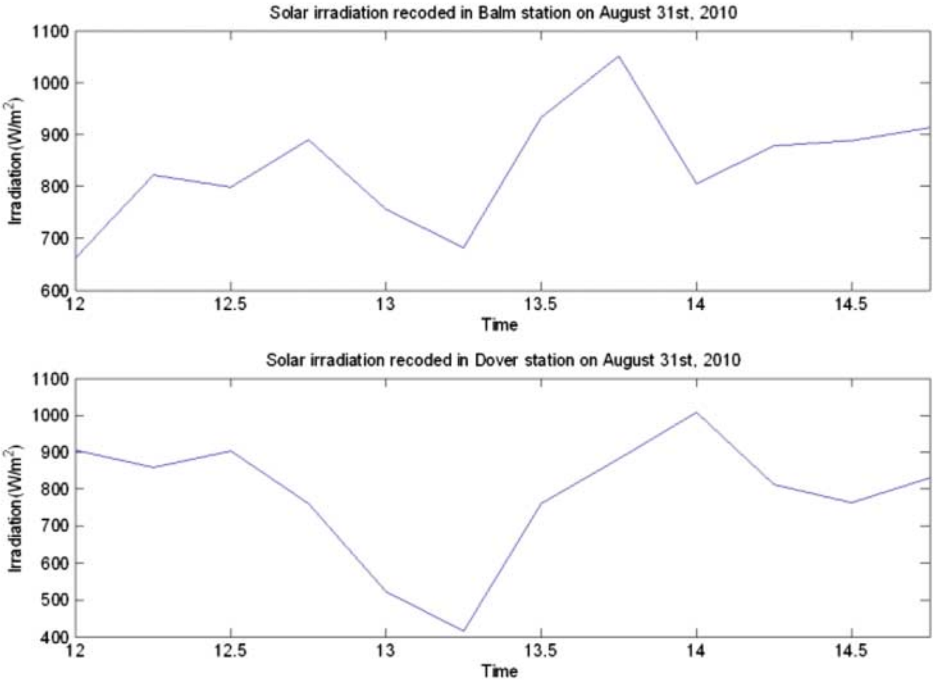

Figure 5. The weather radar-recorded solar irradiation.

The sources connected through asynchronous links and coupled to the power distribution networks through a common interface (e.g. set of synchronous converters) can be considered to be virtually central since their individual identities are no longer distinguishable behind the interface. Instead, the aggregated output of these sources can be modelled as a stochastic source of a finite sample space. This explains the naming of the so-called VCGS. Let us consider a more specific example – a number of PV panels followed by individual MPP boost converters' output transmitted to a central converter station are also equivalent to central generation even though they could be distributed over a vast geographical region. This scenario is addressed with a brief technical overview in Section 4.

3.2. *Data analysis*

The few noticeable facts about the PV outputs are as follows:

(1) The output variation is apparently a function of a panel's orientation to solar incidence. The outputs of the two closely located PV sources are very much identical with the same mean or strongly correlated statistically, but one can see that the variation in *St Pete. A* is higher than that in its peer *St Pete. B*.
(2) The correlation diminishes as the distance increases. By comparing the output of *St Pete. A* (or *B*) with that of *Lwry Prk*, this can be perceived easily.
(3) Extreme weather conditions, those spread over the vast land where the PV sources are located, can establish the correlation regardless of their mutual distance. It can be stated in terms of the speed of wind that drives the large clouds. This is clear from the shape of the PV output variation shaded in magenta colour – the distinguishable three peaked outputs of the PV source.

(4) The shape of the sum of the strongly correlated PV sources (*St Pete. A* and *St Pete. B*) is identical to that of any of them.
(5) The sum of the less correlated sources has higher ripple frequency and least fluctuation.

As a support to the claim made in (3), the plot of solar irradiation recorded at the Florida Automated Weather Network station located in Balm and Dover city (distant by 18 mile North-South) is shown in Figure 5. The time span chosen is aligned with indexes 55–65 in Figure 3.

In Figure 5, two plots clearly possess a common shape and the shift in the maxima or the minima roughly indicates the speed of the cloud cover. From National Climatic Data Center (NCDC), the following information was extracted from the 31 August record:

RESULTANT WIND SPEED: 7 mph
RESULTANT WIND DIRECTION: NE (60)
HIGHEST WIND SPEED: 14 mph
HIGHEST WIND DIRECTION: NE (50)
HIGHEST GUST SPEED: 23 mph
AVERAGE SKY COVER: 0.5

4. Interleaved asynchronous connection

4.1. *Connection methodologies*

A group of multi-string PV arrays tied to a common DC bus (Liccardo *et al.* 2007, Vasquez *et al.* 2008) is the basic structure of the proposed method of asynchronous interconnection of cells operating independently (Figure 6). The difference is that here the DC bus is considered far from the cells requiring a power transmission line. The design challenges of this scheme may be presumed to be as follows:

(1) transmission loss,
(2) communication among the cells and
(3) interleaving method.

The discussion on the challenges mentioned above will be confined to the following limited system:

- PV sources within 5–20 MW maximum capacity. This limitation ideologically opposes the building of any PV plant with a higher capacity as deduced from the study presented in Sections 2 and 3. Besides this, plotting such a scheme in the city area or even close to the city is fairly unreal. For example, to generate 20 MW electricity from a 12% efficient system, 200,000 sq. ft (4.5 acres) (Luque and Hegedus 2005) of area for the PV panel is needed to be exposed to sunlight. It is indeed a tough requirement (regarding the cost and availability of space) to realise similar projects within the city limit, where the load centre is located. The remote the area from the city, the more the space likely to be open; similarly, the more remote the load centre, the more favourable the HV transmission.
- Transmission line length 25–50 km. This is a rough figure implied from the idea of non-correlated sources. It should not be confused with the capability of the Medium Voltage Direct Current (MVDC) or the HVDC transmission as in the case addressed here the transmission is simply an extended version of the feeder that feeds the common DC bus. Here, the DC bus is not meant to be a heavy metallic bar, instead it is meant as an asynchronous power interface.

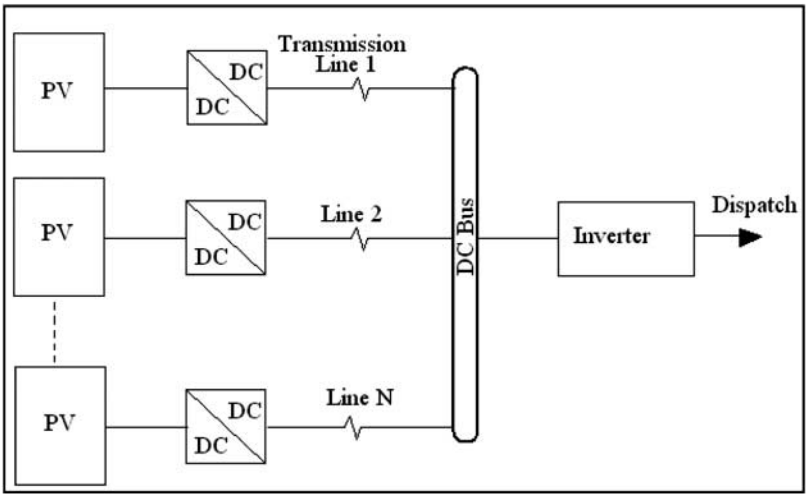

Figure 6. Virtually central generation.

4.2. *Network topology*

If the above two conditions are met, a simple calculation would show that a transmission voltage greater than 95 KV DC (see Appendix) suffices. If the PV output voltage from the series–parallel combination is taken to be about 500 V, then it implies a voltage boost ratio of 1:190. This is indeed a tough specification to consider in the design of the boost converters.

The converter design problem for this application is beyond the scope of this paper. The next issue would be the design of a structural framework. Some of the key features that are considered as the basic advantages of a DC transmission system and are the motivations behind the proposed system are described below:

- Construction of a new pole is not required if the site is chosen close to the medium-high voltage transmission line. A clear insight is presented in Kim *et al.* (2009)
- No extra *right-of-way* or *easement* is required if the voltage level is properly chosen. *Right-of-way* is the property that is purchased from land owners for the maintenance access to a transmission line, whereas easement is sharing without purchasing of any property for additional ease of access and compensated to the owner.

Similar to the aggregated load profile of a load centre with diverse load profiles of the constituent consumers, interconnected systems show a much smoother output fluctuation than the individual generating members (Freris and Infield 2008).

5. Conclusion

The site selection considerations for large-scale PV plants presented in this paper point out few of the obvious reasons behind the idea of asynchronous interconnection among remotely distributed PV cells. The main goal was to clarify some of the serious issues before proceeding to the next step. The design challenges for the converters, costs and tradeoffs are not discussed and they are the second set of determining factors that need to be considered. Recently, some research groups in the USA (National Renewable Energy Laboratory, Sandia Lab, etc.) have supported the idea that PV power-driven inverters should include larger reactive components as a mean of grid voltage support through reactive power compensation. Schugart (2011) pointed out that in order to support the interconnection standard, a utility-scale solar model has to follow the wind industry model. In that case, similar to the HVDC interconnection of off-shore wind power plants with on-shore plants, PV plants are needed to be interconnected in a similar fashion.

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Appendix

Let us consider the cable **1C150 0A+500LZN, single circuit**, **110 KV concrete tower**. This cable can be found in the design library in EDSA/Paladin Design Base©, DC system. Let us assume that we have to transmit 25 MW power to an inverter located 50 km away. This is equivalent to a series resistance of 19.9 Ω (0.398 ∗ 50 = 19.9 Ω). If a maximum of 3% voltage drop is allowed under a full load. Also assume that a maximum of 2% loss in the transmission is permitted. From the transmission loss relation, we can write

$$I(=\text{full load current})^2 \times 19.9$$
$$= 2\% \text{ of } 20\,\text{MW} = 400\,\text{KW},$$

hence maximum current $I = \sqrt{\frac{0.4}{19.9} \times 10^6} = 141.77\,\text{A}$ that would result in voltage drop $= 141.77 \times 19.9 \approx 2822\,\text{V}$, 2822 V is 3% of 95 KV approximately.