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Study and Analysis of Transmission and Integration of Photovoltaic Power Generation in Distribution System

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ABSTRACT

Major concern in photovoltaic power plants these days is how much is the maximum allowable penetration level. Photovoltaic Power Generation (PPG) has now become a significant source in power distribution systems. However, PPG may bring both positive and negative effects to the distribution system. But extracting power from solar photovoltaic arrays according to the demand of the load under changing grid conditions and environmental conditions has been a challenge. In this work, active/reactive power control and maximum power point tracking control strategies are investigated. The developed solar array is investigated under varying solar irradiation and varying temperatures. The effect of these factors on voltage, current and consequently on power is observed. The power at AC and DC sides of the inverter is verified. This two stage configuration is more complex in nature with three control loops.

Keywords- Grid-connected PV module, Penetration levels, Photovoltaic power generation, Power distribution

1. Introduction

In recent times, the researchers are exploring the integration of Photovoltaic Power Generation (PPG) in the power system and every day such studies are increasing in numbers, thereby drawing vast interest [1]. The integration of PPG units in an electrical distribution system may contribute to several benefits such as loss reduction, voltage support, power quality improvement and system reliability. However, the designing of PPG module must ensure that the penetration level does not exceed the maximum threshold limit in terms of overall losses to the systems in order to maintain its efficiency and reliability. Issue that could become significant as penetration of PV power production increases is voltage flicker [2]. This effect occurs when one generating source reactive power output increases or (more commonly) decreases faster than the remaining generators can compensate. Rapid changes in irradiance (up to 15% per second) as clouds pass over will lead to PV power transients that are expected to tax the ability of rotating machine generators to react and restore system voltage [3].

Figure 1 shows a schematic diagram of a grid-connected PV system which typically consists of a PV array, a DC link capacitor, an inverter with filter, a step-up transformer, and a power grid [4]. The DC power generated from the PV array charges the DC link capacitor. The inverter converts the DC power into AC power, which has a sinusoidal voltage and frequency similar to the utility grid. The diode blocks the reverse current flow through the PV array. The transformer steps up the inverter voltage to the nominal value of the grid voltage and provides electrical isolation between the PV system and the grid. The harmonic filter eliminates the harmonic components other than the fundamental electrical frequency. Figure 2-4 shows two basic storage architectures commonly found with grid-connected PV systems. This arrangement leaves the inverter to provide backup battery charge control from the utility power grid when insufficient PV power is available, but does not allow efficient extraction of excess PV power for supply to the grid when the batteries are fully charged.

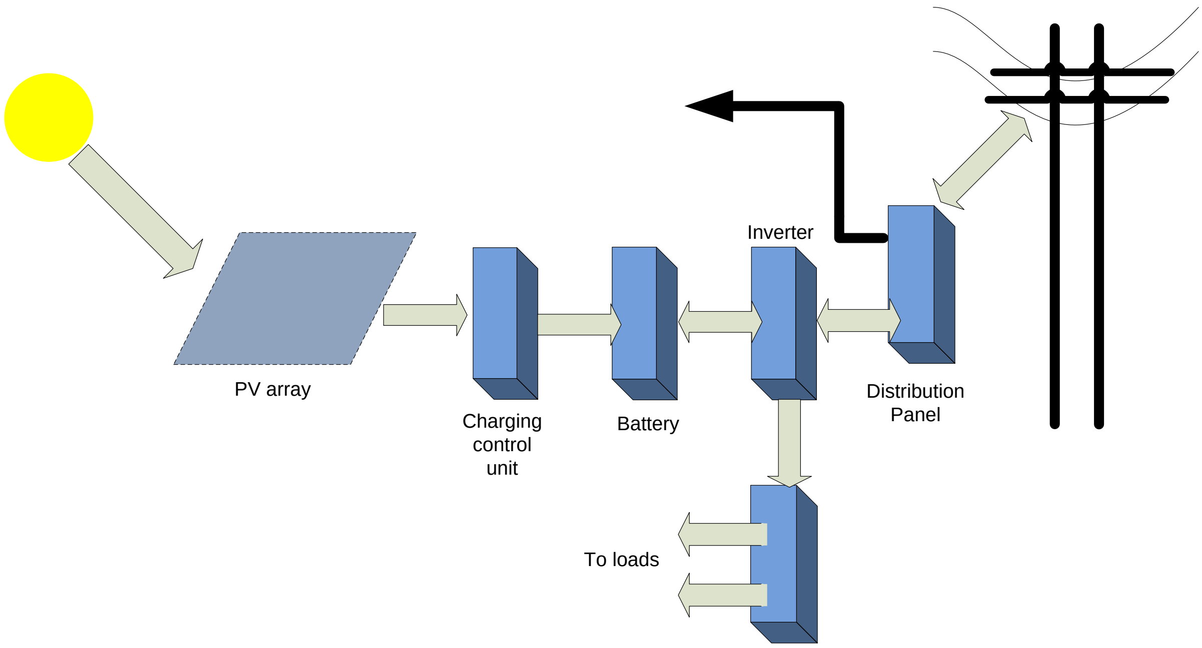

Figure 1 Grid-Connected PV Systems with Storage using separate PV charge control and inverter charge control

2. Related Work

An electrical schematic diagram of the same basic grid-connected system is shown in Figure 2. The PV system typically appears to the grid as simply a controlled current source, with no voltage regulation capability. The inductor (L1), capacitor (C1), and resistor (R1) represent a local electrical load, perhaps that of a building on which the PV is mounted. The utility source is at the right, represented by its simplest Thevenin equivalent model (voltage source with series impedance). The inverter handles all grid interface functions (synchronization, over/undervoltage and over/underfrequency disconnects, anti-islanding) and PV array control functions (maximum power point tracking).

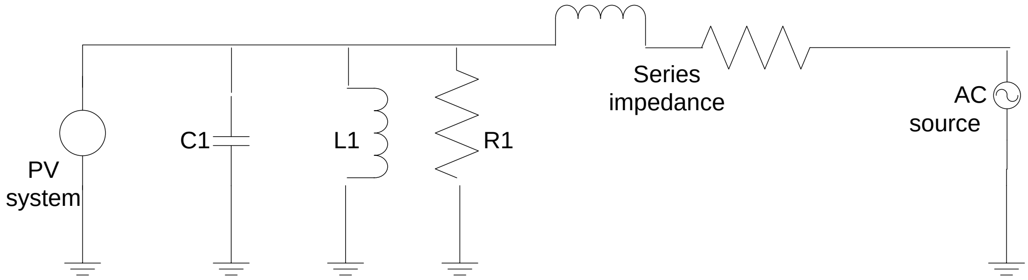

Figure 2 Schematic drawing of a modern grid-connected PV system

2.1 Current Status of Existing PV System Designs

PV power generating systems can be divided into independent PV systems and grid-connected PV systems, and further divided according to the installation environment. Stand-alone PV systems are called off-grid PV systems. Major categories of existing PV system designs include grid-connected without storage, grid-connected with storage, and off-grid systems.

3. Potential Problems Associated with High Penetration Levels of Grid-Tied PV

An extensive literature search was conducted to collect the available information on expected problems associated with high penetration levels of grid tied PV. [5] examined cloud transient effects if the PV were deployed as a central-station plant, and it was found that the maximum tolerable system level penetration level of PV was approximately 5%, the limit being imposed by the transient following capabilities (ramp rates) of the conventional generators. At penetration levels of 15%, cloud transients were found to cause significant but solvable power swing issues at the system level, and thus 15% was deemed to be the maximum system level penetration level.

The PV contribution to voltage distortion was found to be about 0.2%, which was far less than the contributions made by many customer loads [6]. It was thus concluded that harmonics were not a problem as long as the PV inverters were ‘‘well designed’’. This paper also mentions the potential value of PV systems being able to provide reactive power to keep the power factor of a feeder approximately constant.

Many researchers [7-15] studied the impact of high penetrations of PV on grid frequency regulation which responding to synthetically generated short-term irradiance transients due to clouds. The study looked at system frequency regulation, and also at the ‘‘break-even cost’’ which accounts for fuel savings when PV is substituted for peaking or base load generation and the cost of the PV. This study concluded that, the break-even cost of PV is unacceptably high unless PV penetration reaches 10% or so. The thermal generation capacity used for frequency control increases more rapidly than first thought, and that a 2.5% increase in frequency control capacity over the no-PV case is required when PV penetration reaches 10%. For PV penetration of 30%, the authors found that a 10% increase in frequency regulation capacity was required, and that the cost of doing this swamps out any benefit. Based on these two competing considerations, the authors conclude that the upper limit on PV penetration is 10%.

Authors in [16] concluded that for DG penetration levels of 40%, such that the system is heavily dependent on DGs to satisfy loads, voltage regulation can become a serious problem. The sudden loss of DGs, particularly as a result of false tripping during voltage or frequency events, can lead to unacceptably low voltages in portions of the system. During periods of low load but high generation and with certain distribution circuit configurations, the reverse power flow condition could cause malfunctions of the series voltage regulators. Again, voltage regulation becomes a problem.

4. Implementation Requirements for Integration of PPG with Distribution System

The implementation methodology for optimal placement and sizing of PPG is depicted in Figure 3. A function is formulated to minimize the total losses, voltage distortion (Vi) and voltage deviation in a distribution system. The algorithm for implementing the general optimization techniques for determining optimal placement and sizing of PPG is proposed as follows.

Algorithm	
i.	Gather network details
ii.	Randomly generate initial positions within feasible solution combination, such as the PPG location, size and controllable bus voltage
iii.	Check for the run count
iv.	Validate all parameters
v.	Run loadflow and harmonic loadflow to obtain the total power loss
vi.	Check whether voltage distortion V_{max} >=(V_i)>= V_{min}
vii.	Calculate the fitness function
viii.	Check whether population limit is exceeded. If exceeded, repeat step (v) or else terminate
ix.	Update the optimization parameters
x.	Repeat the process until the stopping criteria are achieved and the best solution is obtained

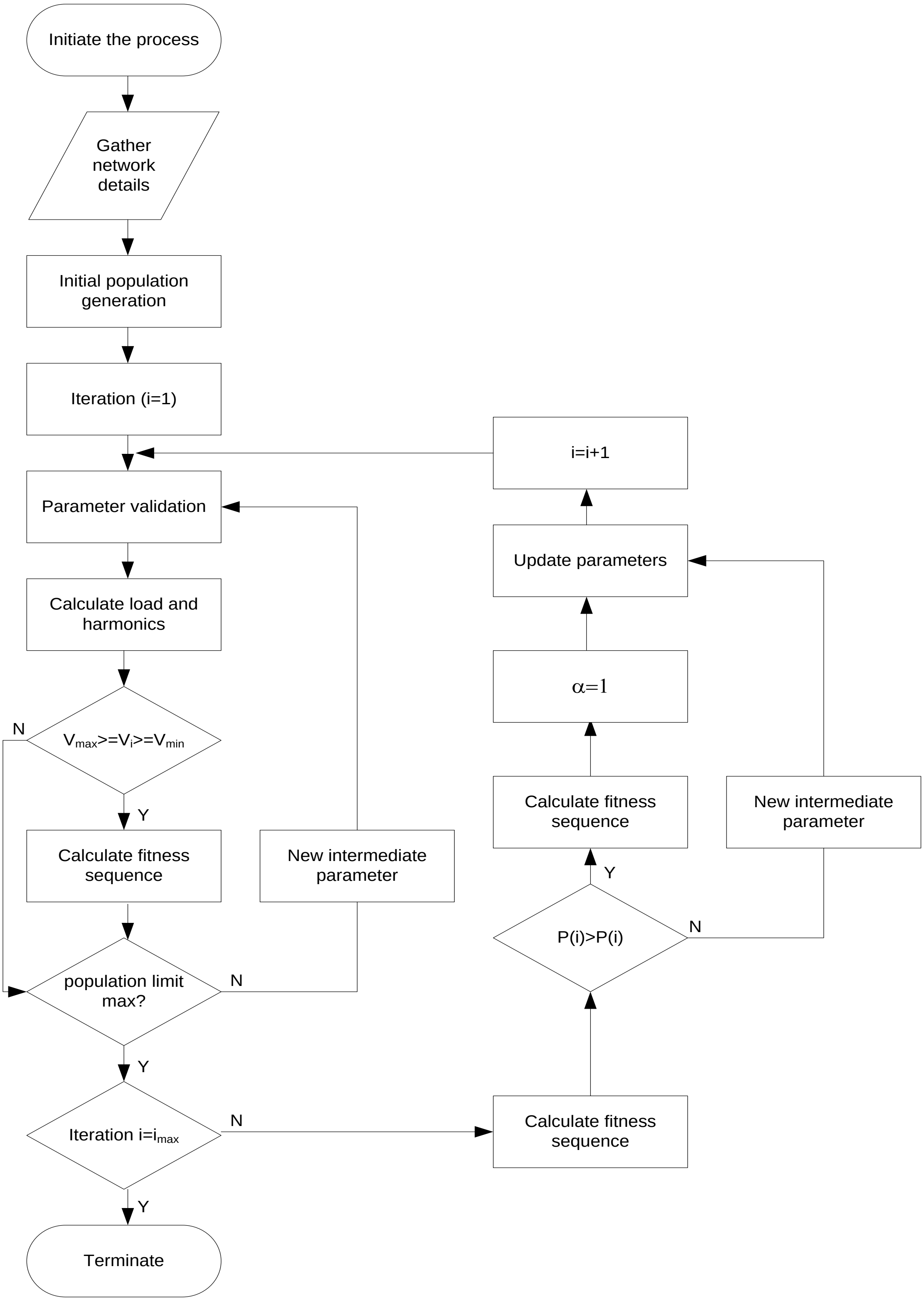

Figure 3 Flowchart of the optimization technique for determining optimal placement and sizing of PPG in a power distribution system

The total loss for the system is 0.89 MW. A PPG unit is placed at smallest load which is connected with 0.37 MW load. The minimum loss identified is 0.8709 MW. Thus, the suitable range of PPG integration in order to maintain minimum losses is between 1 MW and 11 MW. This indicates that the PPG integration must not exceed 41% of total connected load. The relationship between PPG integration and system losses is illustrated in Figure 4.

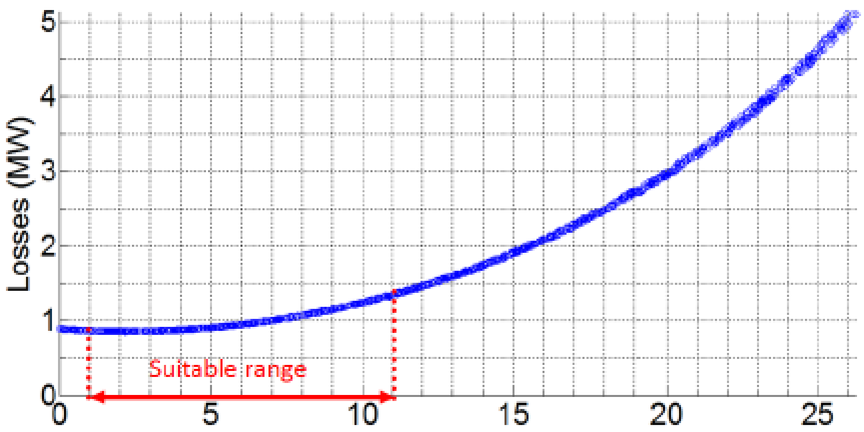

Figure 4 PPG integration and system losses

The DC-AC converter or inverter is the most important component within a PV conversion system. Nowadays, so many inverter topologies have been developed and are commercially available [17-18]. Obviously, inverters are available with different power ratings depending on the consumers' needs. However, matching the inverter input to the output voltage/current/power of the PV array is not always an easy task. Mainly, when designing a PV system, the designer, upon the consumer need, is supposed to award a special care to the following points:

- Number of strings.
- Number of PV modules and their semiconductor type.
- The area to install the PV modules.
- The maximum operating power at 1000W/m2 and 50 °C (kW).
- The most suitable inverter/inverters matching the consumer need.

5. Load Frequency Controller Design Procedure

For the design of robust controller, four blocks are considered which are integral control block, governor, turbine and generator block and their transfer functions are:

$$\frac{d}{dt}(x_1) = \frac{1}{T_P}x_1 + \frac{K_P}{T_P}x_2 + \frac{K_P}{T_P}\Delta P_d \quad (1)$$

$$\frac{d}{dt}(x_2) = \frac{1}{T_P}x_2 + \frac{K_T}{T_T}x_3 \quad (2)$$

A=

$-{}^{1}/_{T_p}$	${}^{K_p}/_{T_p}$	0	0
0	$-{}^{1}/_{T_T}$	${}^{1}/_{T_T}$	0
$-{}^{1}/_{RT_g}$	0	$-{}^{1}/_{T_g}$	$-{}^{1}/_{T_g}$
K	0	0	0

B =

0	0	${}^{1}/_{T_g}$	0

C =

$-{}^{K_p}/_{T_p}$	0	0	0

The nominal parameters are taken from original model shown in Figure [2] and the matrix is obtained as

A =

-2.551	6	0	0
0	-3.33	3.33	0
-5.208	0	-12.5	-12.5
0.6584	0	0	0

B =

0	0	12.5	0

C =

-6	0	0	0

For the implementation of the LQR, the built-in lqr function of MATLAB is used.

[K, S, e] = lqr(A,B,Q,R) calculates the state feedback law that minimizes the cost function.

J = Integral {x'Qx + u'Ru} dt

Subject to the continuous constraint equation:

$$\frac{d}{dt}(x) = Ax + Bu;$$

'K' is the optimal feedback gain matrix, 'S' is the Riccati solution and 'e' is the closed loop eigen values; e = EIG(Ad-Bd*K). The matrices A and B specify the continuous plant dynamics.

The values thus obtained are:

K =

K1	0.1386
K2	0.7936
K3	2.3798
K4	0.4142

S =

0.0038	0.0044	0.0001	0.0082
0.0044	0.0085	0.0006	0.0114
0.0001	0.0006	0.0019	0.0003
0.0082	0.0114	0.0003	0.0373

e =

-41.4706
-3.0660 + 1.1278j
-3.0660 – 1.1278j
-0.5254

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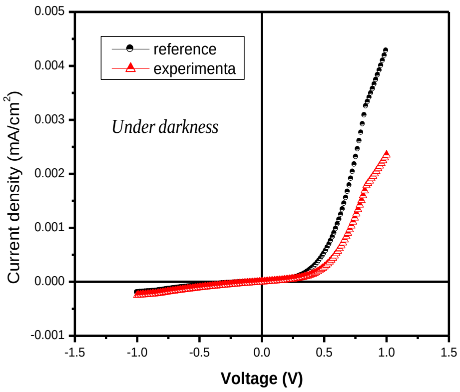
6.Performance Evaluation

Table 1 Simulation and Experimental Parameters

Parameter	Range
Maximum power	220W
Open-circuit voltage	88V
DC link voltage	240V
Grid voltage	120V
Short-circuit current	5.08A
DC/DC boost converter inductor L_e	3.5mH
Output inductor L	2.8mH
Energy storage capacitor C	410μF
Apparent power	115VA
Power factor	62%
Gain	0.08
Grid Frequency	60Hz
DC/DC boost converter switching frequency F_s	43kHz
Inverter switching frequency F_d	80kHz

The study and analysis is started with reference device and control device. Figure 5 shows J–V characteristics of reference device and control device under darkness and under illumination.



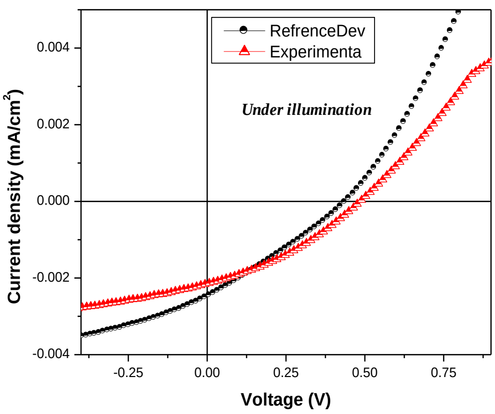


Figure 5 J–V characteristics and control device in darkness and in light

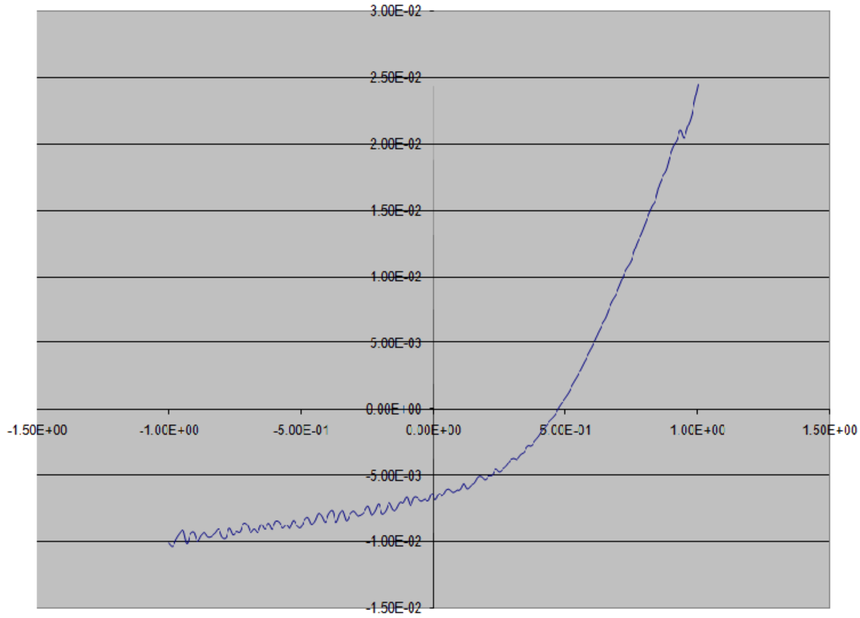


Figure 6 Cell characteristics in light

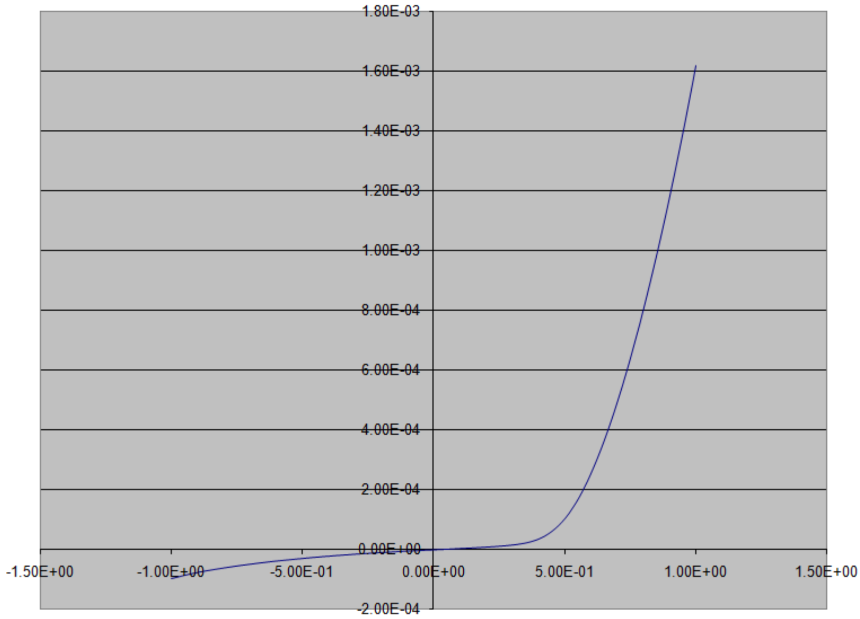


Figure 7 Cell characteristics in dark

6. Conclusion

This paper describes an overview of the relevant aspects related to PPG and the impacts it might have on the distribution system. This paper evolves the background of PPG and its impacts on power quality and the maximum allowable penetration level of PVDG connected to a distribution system. The implementation of the general optimization technique for solving the optimal placement and sizing of PPG problem with multiobjective functions has been performed. The penetration level of PV systems does not significantly influence how often and for how long balanced conditions between the load and the PV systems occurs. Although the best photovoltaic solar cells that have been produced so far are less efficient that their silicon counterparts, they produce much higher open circuit voltages. The carrier mobility of semiconducting organics remains around 10^{-3} cm^2/V-s while the mobility of single crystalline silicon is of the order of about 10^3 cm^2/V-s. This indicates that the photogenerated charge carriers in semiconducting organics require more time to be collected from electrodes.

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