Differential power algorithm based maximum power point tracking for a standalone solar PV system

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Abstract
We report on an improved maximum power point tracking (MPPT) system based on a differential power algorithm. In the proposed algorithm, which is a modified form of a perturb and observe (P&O) algorithm, differential powers, as well as voltages at different time, are compared. The proposed algorithm has been implemented with a highly efficient boost converter, in which duty cycle of a switch is varied in such a way, that the power reaches a maximum at any instant of the day, irrespective of the environmental conditions. The improved MPPT is able to reduce the number of oscillations and tracking time significantly before reaching the maximum power point (MPP). The simulated I-V and P-V characteristic curves (individual and combined) of a solar PV module were generated in MATLAB.

Keywords: solar PV system, MPPT, efficiency, control algorithm, boost converter

1. Introduction
Generation of power from renewable energy sources is an important way to reduce carbon footprints in our environment. Low efficiency and high cost are the main factors which impedes the global utilization of renewable energy resources for generation of electrical power. Power generation, using solar PV (Koutroulis *et al.,* 2001), is not popular (especially in developing countries) due to the higher cost and lower efficiency (D'Souza *et al.,* 2005) of solar PV modules. The efficiency of a solar PV system can be maximized using a maximum power point tracker (MPPT). The MPPT is a power electronic circuit of an efficient DC-DC converter, which is controlled by an algorithm. The function of the control algorithm is to minimize the deviations (Hua and, Lin, 2003) from a maximum power point so that the maximum possible power can be extracted from the PV module(s) under varying atmospheric conditions (Subudhi, and Pradhan, 2013)] with minimum possible wastage of power. Various MPPT techniques and control algorithms (Esram and Chapman, 2007; Hohm and Ropp, 2003; de Brito *et al.,* 2013; Moacyr *et al.,* 2007; Thounthong, *et al.,* 2013) have been studied.

2. Standalone solar PV system modelling
Modelling of a standalone PV system is the basic requirement for obtaining the characteristic curve on which MPP is to be tracked. A standalone solar PV system (Amin et al., 2009; Xiao and Dunford, 2004) consists of a PV module, load, power electronic converters (DC-DC conversion or DC-AC conversion), charge controller (Xiao and Dunford, 2004) (to avoid undercharge and overcharge conditions of the battery) with battery (for storage) and Maximum Power Point Tracker (MPPT). The function of control algorithm is to decrease or increase the duty cycle of the switch (Subudhi and Pradhan, 2013; Koutroulis and Blaabjerg, 2012) power switch of DC-DC converter (Salam *et al.,* 2010) by means of Pulse Width Modulation (PWM) in order to track the maximum power points on the characteristic curves of the PV module. Figure 1 represents a typical standalone solar PV system.

For implementing the proposed algorithm, it is required to model a solar PV system with maximum power points on the I-V and P-V characteristic curve of the PV module. The following section describes the electrical equivalent circuit and associated equation for the modelling of a solar PV module and to finally obtain the characteristic curves.

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a) Electrical equivalent circuit of a solar PV module
An electrical equivalent circuit of a solar PV cell is shown in Figure 2. The circuit consists of a current

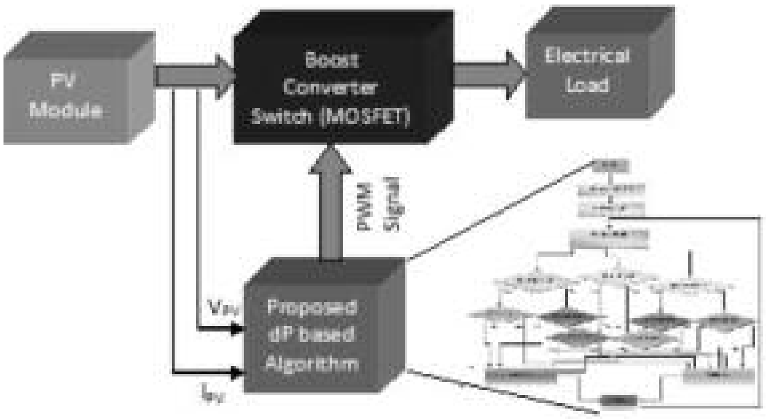

Figure 1: Standalone Solar PV system with dP based algorithm

source connected with a diode in parallel and two resistors R_{SH} in parallel and R_S in series. The current produced by solar cell is given by equation (1).

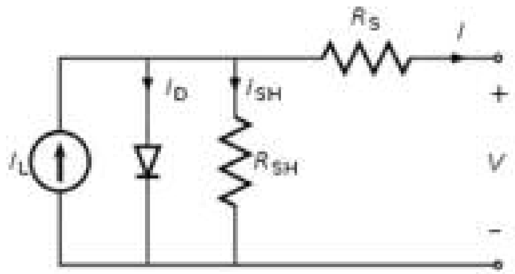

Figure 2: Electrical equivalent of solar PV module

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor (using Kirchhoff's current law) (Weidong *et al.*, 2013:

$$I = I_L - I_o\left[\exp\left(\frac{qV + IR_S}{nkT}\right) - 1\right] - \frac{V + IR_S}{R_{SH}} \quad (1)$$

where,
I_L = light generated current
I_0 = reverse saturation current q = charge of electron
V = voltage across output terminals R_S = series resistance
R_{SH} = shunt resistance
n = ideality factor of diode k = Boltzmann's constant
T = room temperature

b) Simulated results of I-V and P-V characteristics of PV module

We obtained the simulated results for the I-V and P-V Characteristic curves of a PV module using MATLAB. The thick portion on these curves is due to continuous overlapping of different curves. The following I-V characteristic curves have been obtained by adjusting the series resistance ($R_{S=}$0.340000) and parallel resistance ($R_{P=}$164.585828) of a two diode model (Femia *et al.,* 2005) of a solar PV cell.

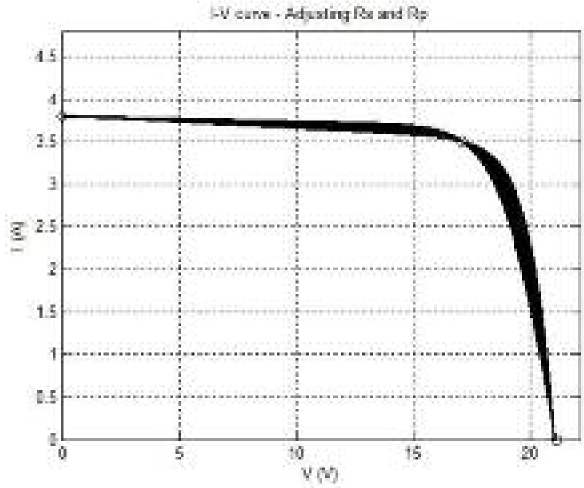

Figure 3: I-V characteristic curve of PV module

The following P-V characteristic curve was obtained in MATLAB by adjusting the peak power (Pmax= 59.85 W). This curve is the superposition of several curves, closely spaced in order to obtain its present form. This curve shows the shifting of maximum power point (MPP) for various solar irradiation levels. By adjusting the peak power, global MPP is obtained by different local MPPs on the P-V characteristic curves.

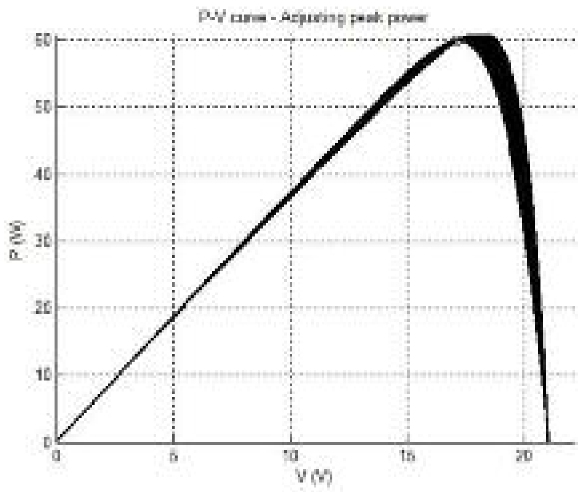

Figure 4: P-V characteristic curve of PV module

The following characteristic curve (I-V and P-V in one plot) has been obtained by superimposing the I-V and P-V at various values of voltage, current and power (in varying insolation) as shown in Figure 5.

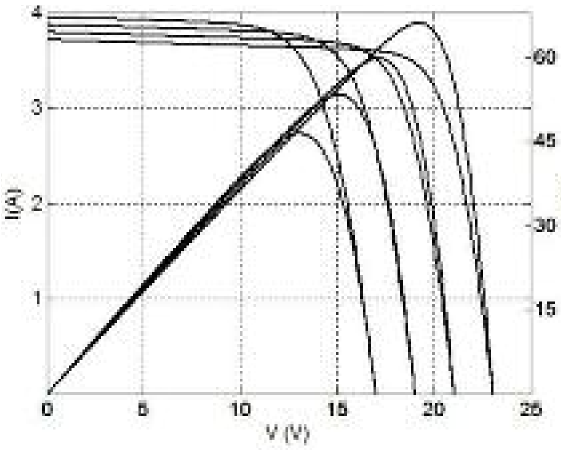

Figure 5: I-V and P-V characteristic curve of PV module in one plot

4. Boost converter

A boost converter is required to vary the output voltage (as shown in characteristic curves) of the solar PV systems in order to obtain the MPP. The boost converter is a highly efficient power electronic converter which only raises voltage. The control algorithm is used to control the duty cycle of the switch of the boost converter. The duty cycle of the boost converter is formulated by:

$$D = \frac{T_{ON}}{(T_{ON} + T_{OFF})}$$

where,
T_{ON} = On period of switch of boost converter T_{OFF} = Off period of switch of boost converter

The output voltage is related with the duty cycle of the boost converter as following:

$$V_{out} = \frac{V_{in}}{(1 - D)}$$

where,
V_{in} = input voltage to the boost converter, V_{out} = output voltage from the boost converter
D = duty cycle of the switch of boost converter.

The control algorithm is used to calculate the duty cycle (on and off time) of the switch of the boost converter. The proposed algorithm (based upon the difference of consecutive power and voltage levels) has been implemented to control the duty cycle of the switch of the boost converter.

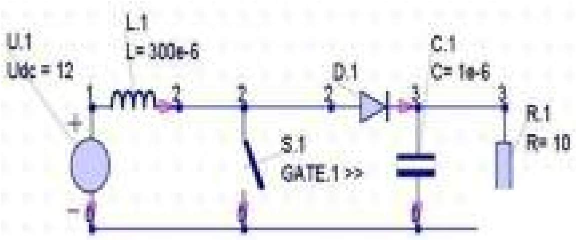

Figure 6: Boost converter circuit

The boost converter circuit is described as follows:

1. DC voltage source (V_{dc} = 12 V), which is used for energizing the circuit
2. Inductor (L = 300e^{-6} H), which is used for storing and releasing the electrical energy
3. Power electronic switch, which is used for keeping ON and OFF of the switch
4. PN junction diode, which is used for blocking the reverse flow of current from load to source.
5. Capacitor (C = 1e-6 F) is used as voltage filter.

The results have been taken from Gecko Circuits simulation software (GeckoCIRCUITS). The results for various parameters [i.e. input voltage (u1), output voltage (u2), switch voltage (uS), inductor current (I_L), capacitor current (I_C)] are obtained in Gecko Circuits and shown in Figure 7.The variation in output voltage (u2) along with the constant input voltage (u1) has been shown in Figure 7(a). This figure shows that the output voltage increases from 0 V to 16 V (peak value) after 170 e^{-6} sec. from the beginning. It further reduces from peak value to 8.5 V in the next 340 e^{-6} sec. Consequently, this waveform stabilizes at 408 e^{-6} sec. This waveform has been constant and almost overlapping with the input voltage.

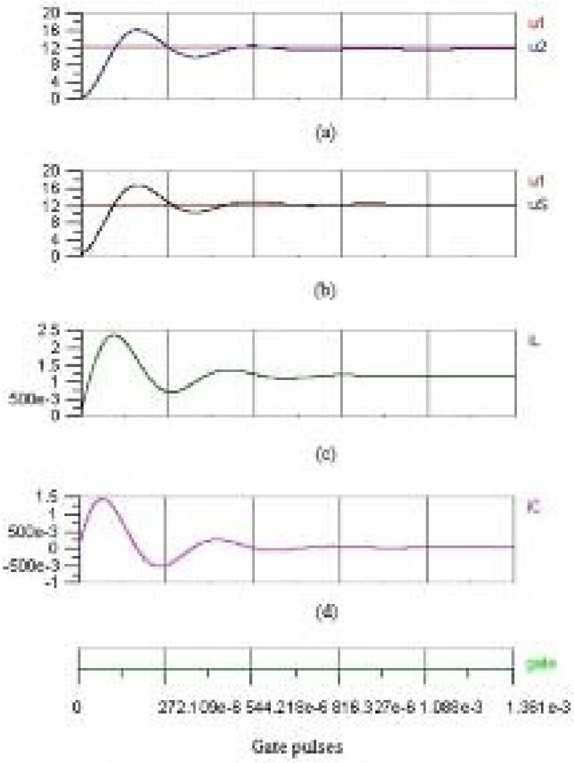

Figure 7: Simulation results of boost converter

In Figure 7(b), the waveform of switch voltage (uS) is almost the same as that of output voltage (u2) with some oscillation before stabilization. Figure 7(c) represents the variation in inductor current (I_L). In this figure, I_L reaches to the peak value of 2.75 A in 136 e^{-6} sec. Further, I_L goes down to the bottom value of 0.75 A at 280 e^{-6} sec. Subsequently, it goes up to the value of 1.25 A at 415 e^{-6} sec. Then after some minor oscillations, it stabilizes with the value of 1.15 A at 860 e^{-6}.

The variation of capacitor current (I_C) is depicted in Figure 7(d). The I_C increases from 0 A to the peak value of 1.5 A in 68 e^{-6} sec. Then it reduces slowly and reaches to the bottom value of -500 e^{-3} sec at 250 e^{-6} sec. Subsequently I_C further goes up from this value to 0.25 A at 410 e^{-6} sec. After some minor oscillations, I_C stabilizes at 0.9 e^{-3} sec. Sequence of gate pulses is represented in Figure 7.

5. Differential power (dP) algorithm

The control algorithm proposed in this paper is based upon the simple and widely used Perturb and Observe (P&O) algorithm (Amrouche *et al.,* 2007; Villalva *et al*., 2009; Mohammed *et al.,* 2012). In the proposed algorithm, the perturbation and observation steps are increased in order to closely track the maximum power point with minimum possible oscillations around the operating point on the characteristic curve of the solar PV module. In this algorithm, the different values of power are compared with each other at different instance of time. The presented algorithm is based upon the difference of old and new power values. Therefore, this algorithm may be called as differential power (dP) based algorithm.

In this algorithm, the difference of three consecutive power levels, as given in equations (1), (2) are calculated. Then the voltage differences of the corresponding power levels are calculated. Consequently, the voltage of the converter is increased and decreased accordingly. Due to this, the duty cycle (thereby pulse width) of the power switch is also modulated in order to efficiently track the MPPs.

$$dP = P(n) - P(n-1) \quad (1)$$

$$dP' = P(n-1) - P(n-2) \quad (2)$$

$$dP'' = P(n-2) - P(n-3) \quad (2)$$

After comparing the differential power, from equations (1), (2) and (3), the corresponding voltages are also compared. Consequently, the duty cycle of the switch of the boost converter is modulated as shown in the dP algorithm (Figure 9). The main advantage of this method is that it works on the basis of calculation of power difference in consecutive instants throughout the day. Due to this, it provides the direct determination of maximum power from a solar PV system. The implementation circuit and simulation results are presented in the next section.

6. Results and discussion

The proposed algorithm has been implemented in Gecko Circuits as shown in the following circuit diagram in Figure 8. The simulation results of the MPPT with proposed algorithm are in Figure 8(a) and shows that the output voltage stabilizes rapidly, within a fraction of a second in comparison to the input PV voltage and inductor current (I_L) which both stabilize at 4.975 seconds. In Figure 8(b), the voltage across the switch (sg.1) is also stabilized after 4.975 seconds. At the same time, the PV voltage (filter i.e. across C2) and PV current (filter i.e. through C2) decreases and increases respectively that follow the law of conservation of energy.

The results shown in Figures 8(a) and 8(b) indicate that the proposed algorithm is not only able to effectively reduce the stabilizing time (tracking time) of output (load) voltage but it also able to reduce the ripples and oscillations in the output. The result shows that the proposed method is able to track the MPP with a reduced number of oscillations and thereby higher stability of the solar PV system. At the same time, the efficiency of the solar PV system is increased due to lower amount of oscillations and the performance of the overall solar power system has been upgraded. The main disadvantage of this algorithm is that it has increased complexity.

7. Conclusion

In this paper, a differential power algorithm is presented and consequently implemented to control the operation of the boost converter. By the efficient control of the boost converter, the output power from the solar PV power generating system has been significantly increased for an optimal efficiency. The simulation results for characterization of the PV module (i.e. I-V and P-V characteristics) are presented. The simulation results of the realized circuit with the proposed algorithm are also presented, which shows the stable operating point for maximized constant output power from a solar PV system.

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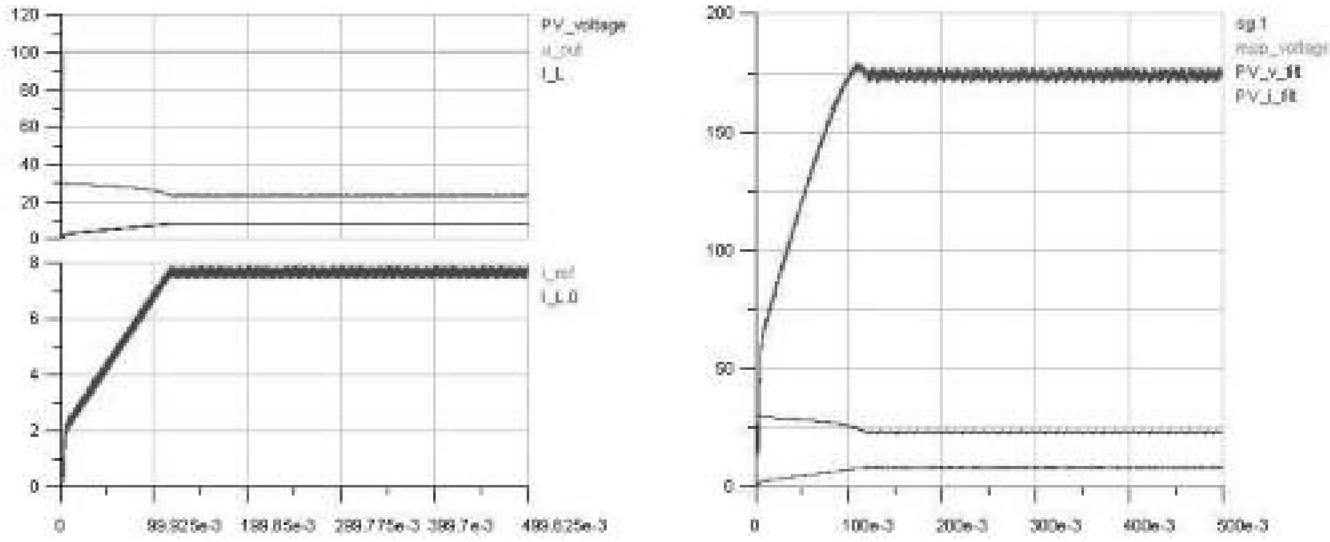

(a) **(b)**

Figure 8: Simulation results for variation of voltage and currents of solar PV system with proposed algorithm

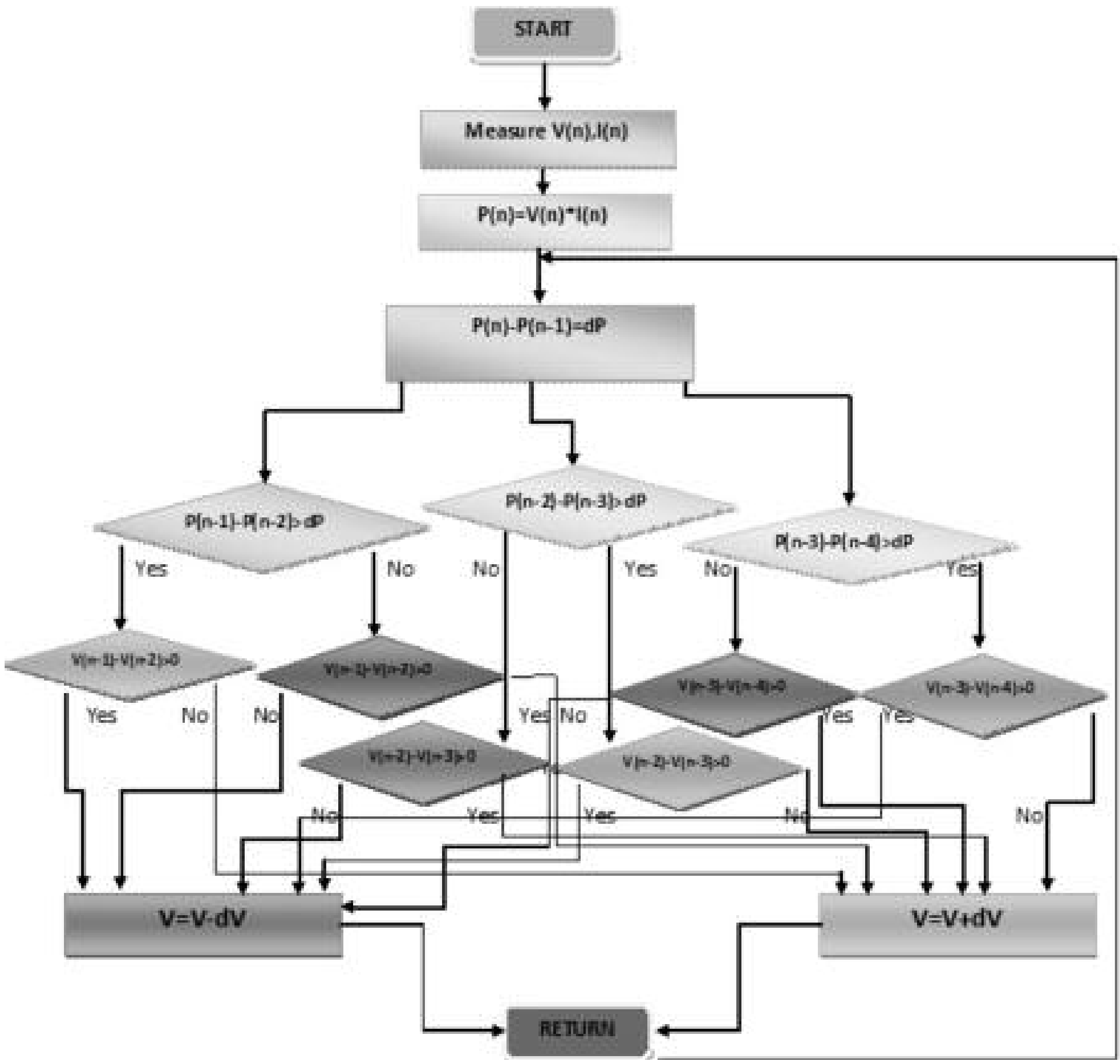

Figure 9: Differential power (dP) algorithm

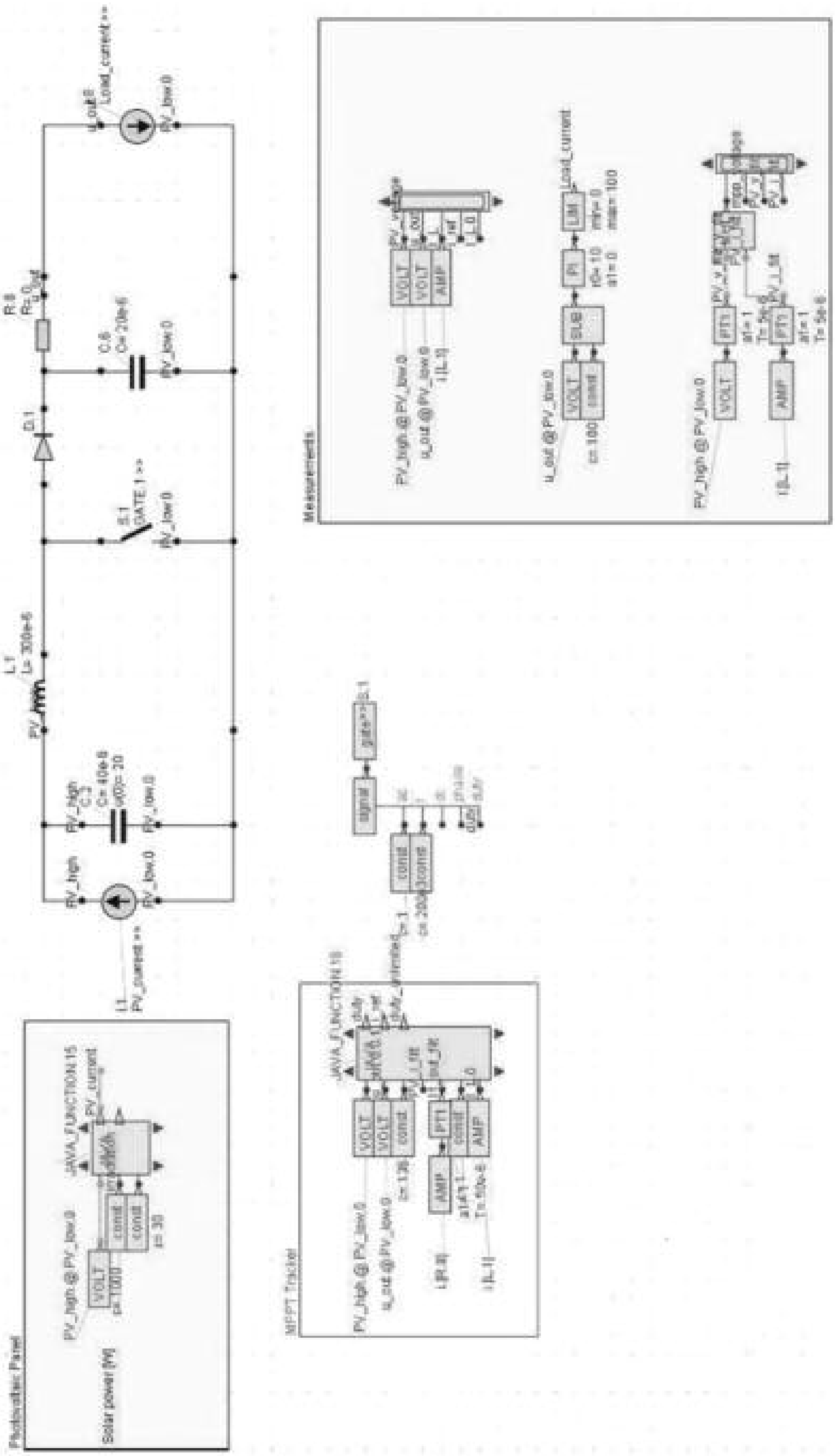

Figure 10: Circuit implementation of dP algorithm based MPPT

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