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MODIFICATION OF THE INCREMENTAL CONDUCTANCE ALGORITHM IN GRID CONNECTED PHOTOVOLTAIC SYSTEMS

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Operation of solar energy conversion systems influences the total efficiency during variable temperature and variable solar irradiations. In addition to these atmospherical conditions, shading also affects the solar array efficiency. Due to nonlinear current and voltage characteristics and variable efficiency of solar cells, operation point of solar cells should be fixed at maximum power and efficiency. In order to generate maximum energy, solar photovoltaic (PV) systems should be run with maximum power point trackers (MPPTs). Therefore it is reached to maximum power point changing with above external factors. MPPT units are implemented to control converters which are connected to terminals of PV arrays. MPPTs operate according to some algorithms to reach maximum power level in various conditions. This study presents a new modification on incremental conductance (IncCond) algorithm, one of the well-known algorithms, to improve total efficiency of solar energy conversion systems. Proposed modified algorithm is able to catch the new maximum power point quickly compared to conventional type and oscillations are also decreased reaching to new operating point.

1. INTRODUCTION

Recent studies on solar energy conversion systems have focused on efficiency and cost of the systems. Solar PV arrays generate the electric energy with maximum efficiency and minimum losses at maximum power point (MPP). MPP is not a fixed point. It changes depending on solar cell characteristics. Solar cells have two important characteristics such as *I–V* and *P–V* characteristics. These characteristics are also affected by some external factors such as ambiance and surface temperature and solar irradiations. These factors might be changeable and unpredictable. Therefore, solar PV arrays should be promoted by an MPPT to capture maximum power and efficiency continuously [1]. PV systems are always required to run at different weather conditions to convert energy at maximum efficiency [2, 3].

In Fig.1, *I–V* (current-voltage) characteristics of the solar panels simulated in this paper are illustrated with variable solar irradiations.

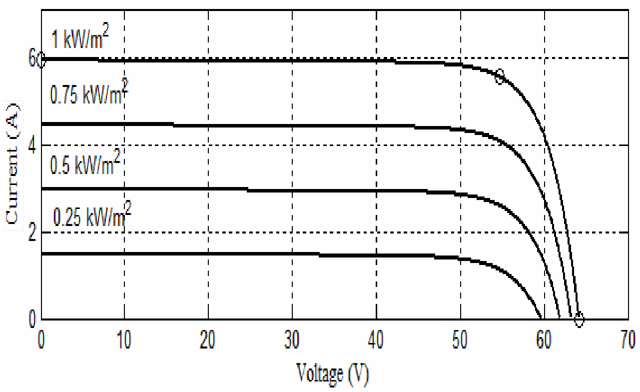

Fig. 1 – *I–V* characteristic of considered solar cell module.

Solar insolation increases the current and power from the solar panel under different test conditions. The most important drawback of PV systems is the low-efficient power generation. Connection losses, clouding and shades on solar panels also decrease the total efficiency. Therefore PV systems should be operated at their maximum power point to increase total efficiency [4]. MPPTs are applied to reach highest power level in various conditions. Hence, it is possible to produce maximum power from the PV systems. Integration to the power system can be done in one stage with the application of a voltage source inverter or in two stages with the application of both dc-dc converter and inverter [5]. MPPT algorithms are applied to control dc-dc converters so as to track variable voltage and current among panel and load. MPPT design includes both converter type and algorithm. This study focuses on an optimization of IncCond algorithm. The conventional IncCond algorithm is used with constant iteration step size. Therefore, its decision-making speed increases in proportion to step size of error. But, higher step size reduces the efficiency of MPPT. This difficulty causes more power losses and complicates the control actions. Therefore, some calculation procedures of conventional IncCond algorithm is needed to modify. So, proposed mo-dification has variable step size. Proposed modification is simulated in grid connected energy conversion systems including solar panel, dc-dc converter and inverter given in Fig. 2.

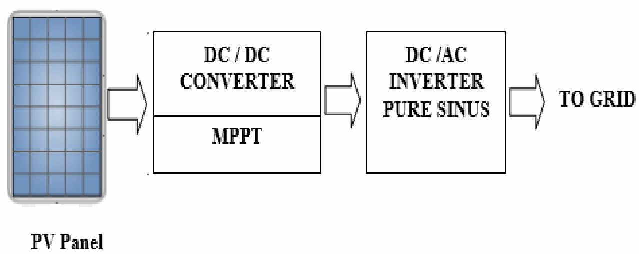

Fig. 2 – Conventional on-grid PV energy conversion system with MPPT.

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2. MAXIMUM POWER POINT TRACKING IN PHOTOVOLTAIC SYSTEMS

Solar cells have non-linear power and voltage characteristics as described in previous chapter. Fig. 3 presents a well-known electrical equivalent diagram. In this model, solar cells behave as a diode which has a PN junction. As sun light hits on the cell surface, a potential difference between positive and negative end of cells appears. If there is a load resistance, a load current drawn by the load occurs formulized as Eq (1).

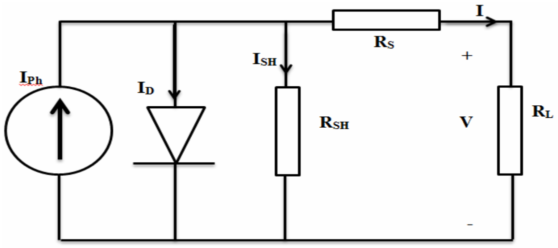

Fig. 3 – Equivalent circuit diagram for solar cells.

$$I = I_{PH} - I_S \cdot \left\{ \exp\left[\frac{q}{A \cdot k \cdot T} \left(V + I \cdot R_L \right) \right] - 1 \right\} - \\ - \frac{\left(V + I \cdot R_S \right)}{R_{SH}}, \quad (1)$$

where I_{PH}, I_S, R_L, R_S, R_{SH}, V and I are photo-current, saturation current, load resistance, series equivalent circuit resistance, parallel equivalent circuit resistance, output voltage and load current respectively.

The IncCond algorithm is derived from the output power of PV array with respect to voltage and setting the equal to zero as given as follows:

$$\frac{\mathrm{d}P}{\mathrm{d}V} = \frac{\mathrm{d}(VI)}{\mathrm{d}V} = I + V \cdot \frac{\mathrm{d}I}{\mathrm{d}V} = 0 . \quad (2)$$

So that the validity of condition (eq. 2) is equivalent to the following:

$$\frac{I}{V} = -\frac{\mathrm{d}I}{\mathrm{d}V}, \quad (3)$$

which means that left-hand side of eq. (3) represents the opposite of the PV array's instantaneous conductance, as the right-hand side represents its incremental conductance. As a consequence, the method requires the application of a repeated perturbation of the voltage value, until the next condition [6, 7] occurs as follows.

$$\frac{I_k}{V_k} = -\frac{I_k - I_{k-1}}{V_k - V_{k-1}}, \quad (4)$$

where the subscripts k and k–1 refer to two sequential samples of the voltage and current of PV. An illustration about the conventional IncCond algorithm [8, 9] is given Fig. 4.

Conventional IncCond algoritm given in Fig. 4 uses the following equations to reach maximum power point.

$$\frac{\mathrm{d}I}{\mathrm{d}V} = -\frac{I}{V} \; ; \left(\frac{\mathrm{d}P}{\mathrm{d}V} = 0 \right) \; ; \text{ at MPP} \quad (5)$$

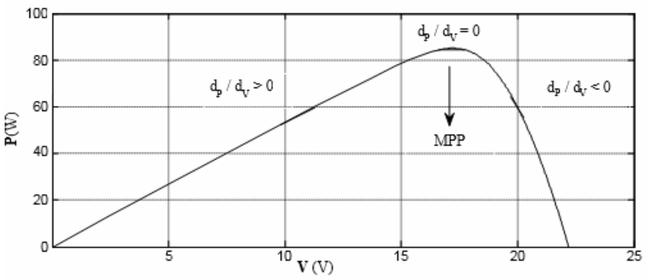

Fig. 4 – Operating power (P) and voltage (V) curve of the conventional IncCond algorithm.

$$\frac{\mathrm{d}I}{\mathrm{d}V} > -\frac{I}{V} \; ; \left(\frac{\mathrm{d}P}{\mathrm{d}V} > 0 \right) \; ; \text{ left of MPP} \quad (6)$$

$$\frac{\mathrm{d}I}{\mathrm{d}V} < -\frac{I}{V} \; ; \left(\frac{\mathrm{d}P}{\mathrm{d}V} < 0 \right) \; ; \text{ right of MPP} \quad (7)$$

3. PROPOSED MODIFICATION ON INCREMENTAL CONDUCTANCE ALGORITHM

The "fill factor", more commonly known by its abbreviation "FF", is a parameter which, in conjunction with V_{oc} and I_{sc}, determines the maximum power from a solar cell. The FF is defined as the ratio of the maximum power from the solar cell to the product of V_{oc} and I_{sc}. In PV system design, FF value of used solar cell must be 0.7 or greater [3, 10, 11]. Mathematically, fill factor (FF) can be expressed by the Eq (8).

$$\mathrm{FF} = \frac{P_{max}}{V_{oc} . I_{oc}} = \frac{V_{max} \cdot I_{max}}{V_{oc} \cdot I_{oc}} . \quad (8)$$

In the proposed algorithm, instead of a constant step coefficient ΔP, equation (8) was adopted as equation (2) in order to attain maximum power point as seen in equation (9).

$$\Delta P = \mathrm{FF} \cdot \left(V_k \cdot I_k - V_{k-1} \cdot I_{k-1} \right) . \quad (9)$$

In other words, power change generates ΔP and it provides a faster way for identifying maximum power point. The meaning of $\Delta P = 0$; no iteration was performed with regards to duty cycle changing and ripple was minimized. So, a parallel coefficient was provided for power change to faster identify maximum power point. In addition, at MPP, $\frac{\mathrm{d}I}{\mathrm{d}V} + \frac{I}{V} = 0$ and no iteration is performed. Epsilon ε is a number close to zero.

This ε value can generate ripple under the variable solar irradiation [7]. The ripple causes power loss. So, if absolute value of $\frac{\mathrm{d}I}{\mathrm{d}V} + \frac{I}{V}$ is smaller or equal to ε, the step of duty cycle will be reset (ΔP=0) which means that $D_k = D_{k-1}$ and so ripple will be eliminated.

The flowchart in Fig. 5, was designed in order to prevent ripple emerging during attempts to identify maximum power point of the IncCond algorithm and to faster identify this point following significant power changes. In this approach, ΔP denotes power change. When duty cycle D_k is increased or decreased in accordance with this power change, it is found out in the simulation results that ripple is reduced and D_k at maximum power point is identified sooner. In case of no power change, $\Delta P = 0$ or $\text{abs}(\frac{dI}{dV}+\frac{I}{V}) \le \varepsilon$ no iteration is performed in small changes of solar irradiation to avoid unnecessary power loss.

Also, in practice, it is difficult to obtain zero error due to part of dc converter switching elements [12]. In this case, ripple around maximum power point under variable solar irradiation is eliminated thus improving the algorithm.

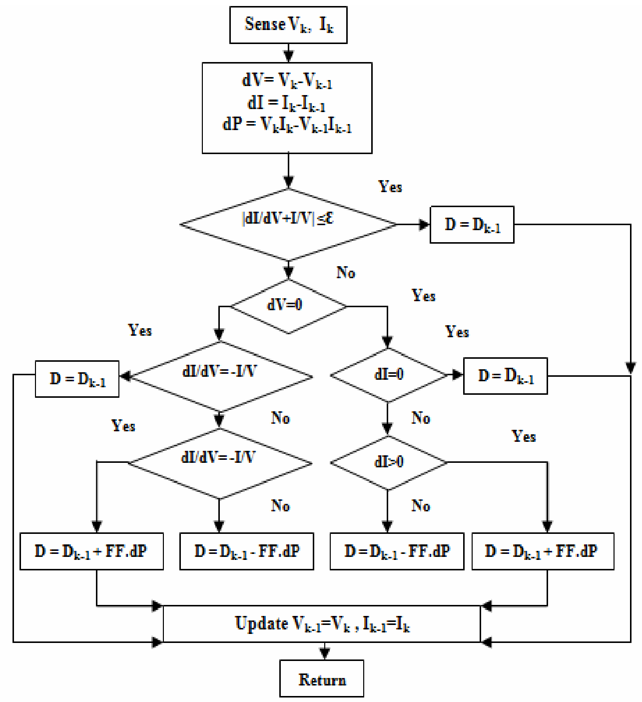

Fig. 5 – Flowchart for proposed IncCond algorithm.

When power change increases, iteration coefficient increases. Otherwise, iteration coefficient decreases. At the left side of MPP, if D_k increases, power increase and if D_k decreases, power decreases too. Oppositely, at the right side of MPP, when D_k increases, power will decrease and when D_k decreases, power will increase too.

Therefore, when duty cycle is changed, if there is an increase in power, changing on same way should be kept on (step which equal absolute value ΔP should be added). If there is a decrease in power, changing should be continued in an inverse way (ΔP should be subtracted). If $D_k > D_{\max}$ or if $D_k < D_{\max}$, then D is to be equaled to D_{k-1} ($D_{\max}$ and $D_{\min}$ are the limits of duty cycle of the dc-dc converter).

Thus, a more determined algorithm is developed. MPPT is a power tracking system that enables to obtain maximum power from PV panels. In MPPT block, dc-dc converter is controlled by IncCond algorithm through producing duty cycle. As a result of this, the maximum power level from PV panel is reached. In this configuration, in parallel with the atmospheric changes, the changing duty cycle controls dc-dc converter and inverter to reach maximum power point. The control code was written by using MATLAB code and also tested and run using MATLAB function block.

4. RESULT AND SIMULATION

In simulations, two cases are considered to compare with both algorithms. In the first case, the same parameters are also considered when insolation increases and decreases. In the other case, outputs of inverter (ac side) are considered when insolation increases or decreases.

4.1. RESULTS FOR CASE I

In this case, insolation is changed as seen from Fig. 6a. At starting point ($t = 1.6$ s), a linear decreasing is started from 1150 W/m^2 to 950 W/m^2 until $t = 2$ s. At $t = 2.35$ s, insolation is 1050 W/m^2 and $t = 2.65$ s, insolation is reached to 1225 W/m^2. After 50 millisecond, it is decreased to 950 W/m^2 again and increasing is continued until $t = 3$ s. Power responses are also seen in Fig. 6b. Proposed method is illustrated by the black line and conventional method is represented by the blue line. In proposed method more active power from the solar panels is provided and no oscillations occurred as seen from Fig. 6b. Power can be changed smoothly according to insolation. Smoothing in changing of insolation also provides fewer losses.

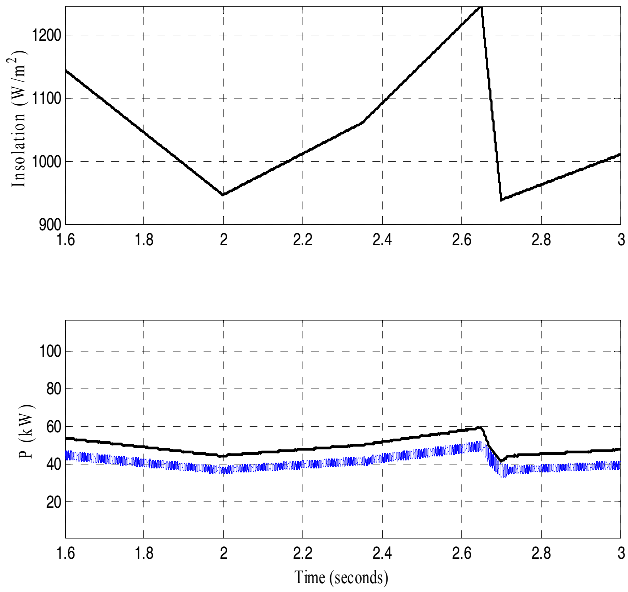

Fig. 6 – a) Solar insolation; b) output power of dc side for both algorithms case I.

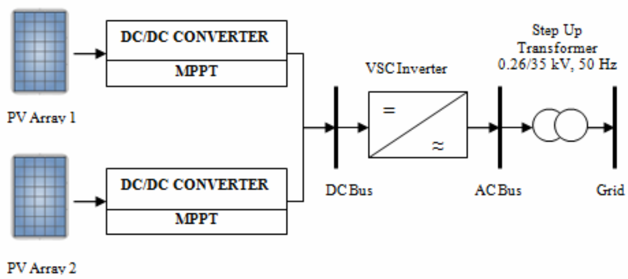

Fig. 7 – Schematic block diagram of simulated systems.

4.2. RESULTS FOR CASE II

In this case, only ac side waveforms are considered and given in the next figures. Block scheme for both this case and previous case is given in Fig. 7.

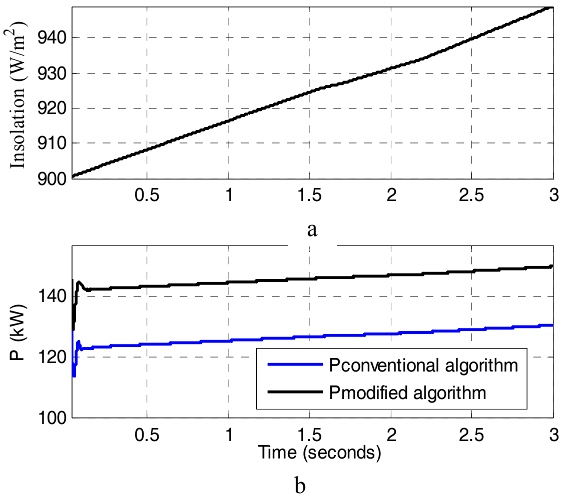

Fig. 8 – a) Changing of solar insolation (W/m²) and grid power (kW) for b) conventional algorithm (lower trace) and c) modified incremental conductance algorithms in case II.

In this case, a linear changing in insolation is considered as seen in Fig. 8a. This figure illustrates the ac side active power. Insolation is increased from 900 W/m^2 to 950 W/m^2 almost linearly. It can be seen from Fig. 8b, the active power is increased about 17 % compared to conventional algorithm. The current increase can be seen clearly in Fig. 9

Figure 9 shows the instantaneous current waveform. In this case, power flows from PV sources to grid because there is no local load. It can be seen from Fig. 9, proposed tracker causes 17 % more magnitude compared to conventional one. Proposed modified algorithm also reaches maximum power point in less time than conventional one. Fig 10 shows the voltage waveform for both methods. As seen in this figure, the voltage waveforms are almost similar, because grid power level is so big compared to PV source, so, the grid voltage cannot be affected.

Additionally, modified algorithm produces fewer ripples than conventional algorithm under various solar insolation conditions and modified algorithm is more efficient than conventional one. However, in conventional one, both ripples occur and maximum power point is attained slightly later.

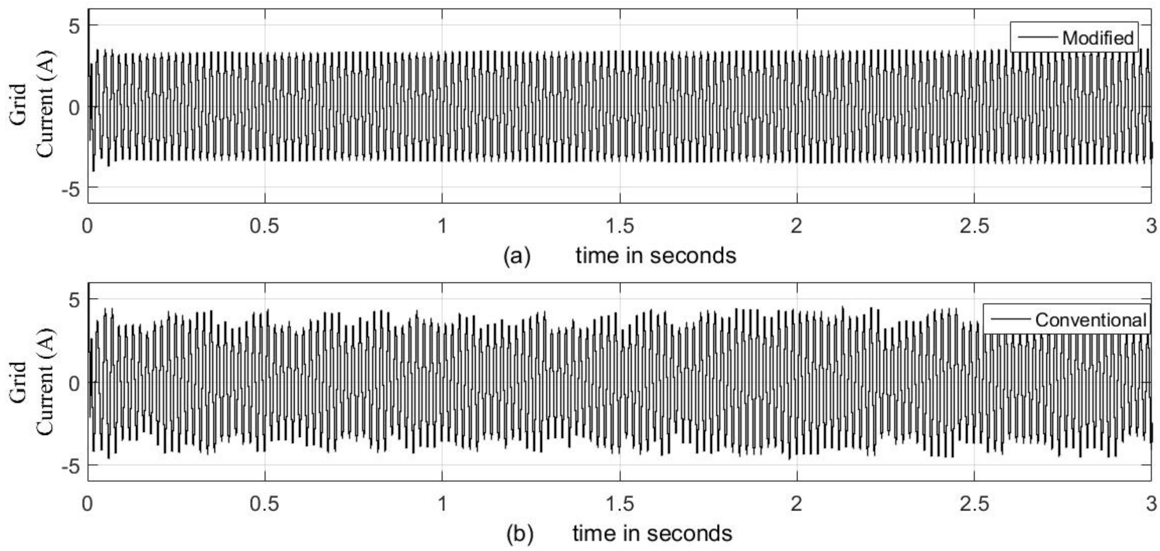

Fig. 9 – Grid current (b) conventional and (a) modified incremental conductance methods for case II.

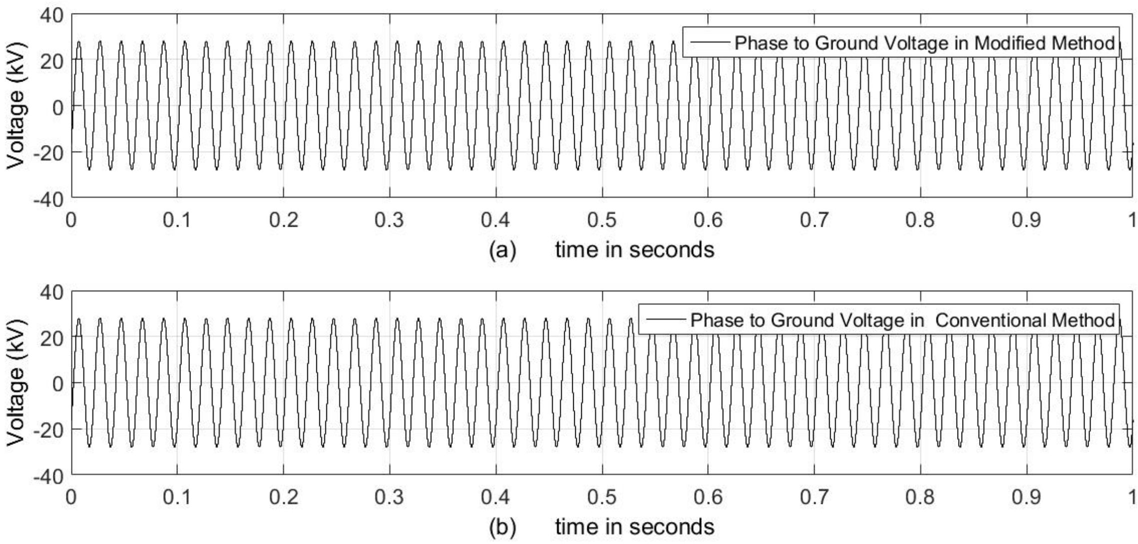

Fig. 10 – Ac side voltages (b) conventional and (a) modified algorithm for case II.

Particularly ripples in power and current continue for a specific period of time as shown in following figures. These ripples can also influence total efficiency of the system negatively. As a result of the ripples, losses may be encountered due to varying parameters. As these results also suggest, less ripple, less power loss and slow response persist in conventional methods. These problems bring out disadvantages because they affect total efficiency of the panel and extend MPPT identification time.

5. CONCLUSIONS AND DISCUSSION

Overall efficiency covers many equipment and parameters in the system. Efficiency of a single solar cell may differ from that of the panels comprised of these cells. Installation errors negatively affect panel efficiency. There are also other factors such as panel angle, obstruction from high buildings or cloudy weather conditions which cause total or partial shadowing and thus total efficiency can be affected negatively. Software and hardware problems in MPPT also decrease efficiency. Meanwhile switching losses also may have negative influence on total efficiency too. Slow response rate of the algorithm and occurrence of ripples are also important problems under variable solar insolation conditions. These factors force us to improve the algorithm.

This study focuses on improving algorithm and eliminating ripple problems in IncCond algorithm under variable conditions. In order to increase the efficiency of system, it is suggested that the algorithm should be improved accordingly. It is also possible to suggest that changes in the algorithm will bring out no difficulties in terms of hardware, which makes it suitable for experimental purposes. Modification algorithm is proposed to modulate the duty cycle of the boost converter, inverter, and thus the tracking speed increased. It is concluded that the proposed algorithm shows better performance than conventional algorithm under changing conditions and it reduces the power losses.

APPENDIX

Electrical parameters of PV system power circuit:

Open-circuit voltage (V_{oc}): 64.2 V
Short-circuit current (I_{sc}): 5.96 A
Voltage at P_{max} (V_{mp}): 54.7 V
Current at P_{max} (I_{mp}): 5.58 A
Number of series-connected modules per string: 5
Number of parallel string: 66
Nominal power: 200 kW.
Nominal grid frequency: 50 Hz
Nominal grid voltage: 35 kV,
Nominal LV side voltage of transformer: 260 V
Nominal dc bus voltage: 500 V
Line lenght of grid: 5 km
Positive sequence resistance: 0.01153 Ω/km
Zero sequence resistance: 0.413 Ω/km
Positive sequence inductor: $1.05 \cdot 10^{-3}$ H/km
Zero sequence inductor: $3.32 \cdot 10^{-3}$ H/km
Positive sequence capacitor: $11.33 \cdot 10^{-9}$ F/km
Zero sequence capacitor: $5.01 \cdot 10^{-9}$ F/km

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