A model of mismatched photovoltaic fields for simulating hybrid solar vehicles

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Abstract – **A numerical model of photovoltaic fields that allows simulating both uniform and mismatched operating conditions is introduced in this paper. It allows the simulation of a photovoltaic generator whose subsections, e.g. cells, groups of cells, panels or group of panels, work under different solar irradiation values and/or different temperature. Furthermore, different nominal characteristics, rated power, production technology, shape and area can be accounted for any subsections of the photovoltaic generator. The proposed model is reliable and results into a non linear system of equations that requires a moderate computational burdensome, both in terms of memory use and processor speed. Numeric simulations confirm the usefulness of the proposed approach in automotive applications, especially in solar hybrid vehicles, in order to design a proper electronic controller ensuring the extraction of the maximum power from the photovoltaic generator.**

I. INTRODUCTION

Renewable energy sources are gaining more and more interest in recent years due to the exploitation of oilfields and to political crises in some strategic areas of the world. Among them, photovoltaic (PV) sources have found new applications, e.g. solar hybrid vehicles. They work with greatly varying solar irradiation levels due to the movement and, especially if the solar cells are not placed only on the roof, different subsections of the PV generator may receive different sun irradiance levels.

In any case, it is mandatory to match the PV source with the load/battery in order to draw the maximum power at the current solar irradiance level. To this regard, a switching dc-dc converter controlled by means of a Maximum Power Point Tracking (MPPT) strategy is suitable to ensure the source-load matching by properly changing the operating voltage at the PV array terminals in function of the actual weather conditions. Any efficient MPPT technique must be able to detect the voltage value corresponding to the maximum power that can be delivered by the PV source.

In literature, many MPPT strategies have been proposed, the greatest part of them being derived by the basic Perturb and Observe (P&O) and Incremental Conductance (IC) approaches. Both P&O and IC strategies, if properly designed, correctly work in presence of a uniform irradiance of the PV array, since they are able, although by means of different processes, to detect the unique peak of the power vs. voltage characteristic of the PV array. Unfortunately, in automotive applications, the PV field does not receive a uniform irradiation and/or not all its parts (panels as well as single cells) work at the same temperature, so that mismatches among different parts of the array may arise. Such a situation has been evidenced in literature and the detrimental effect due to a panel of a PV array working under an irradiation level or at a temperature, which is sensibly different than that characterising the other panels has been experimentally investigated.

Mismatching conditions are more likely to occur in automotive applications than in stationary ones. For example, parts of the array may be shaded by other parts of the vehicle when the sun is at low angle and, moreover, unpredictable shading takes place when the vehicle passes under the shadows of buildings, trees, advertising panels. Even in automotive applications characterized by a relatively small duty cycle in the use of the vehicle, mismatching may play a strong role on battery charging during the long parking time. In such cases the shadows produced by objects surroundings the car can give rise to a marked waste of available solar energy.

To relieve the power drop caused by a mismatch, a bypass diode is used in anti-parallel with each PV basic unit, e.g. a panel. A blocking diode is placed in series with each totem of PV basic units connected in series. This precaution increases the plant cost, but avoids that a basic PV unit or a series of them absorbs the current produced by others.

Whenever a mismatch occurs, both P&O and IC based MPPT techniques have a high probability to fail the MPPT goal. Indeed, the power vs. voltage characteristic of a PV field under a uniform solar irradiation exhibits a unique maximum point that is easily tracked by standard MPPT techniques. Unfortunately, mismatches deeply affect the shape of the PV characteristic, which may exhibit more than one peak, with one absolute maximum point and one or more relative points of maximum power. In this case, standard MPPT techniques are likely deceived and consequently track a point where dP/dv=0, but that is not the maximum power point.

In order to design a MPPT strategy able to perform a "global" tracking of the true PV array voltage associated to the maximum power, without being trapped in local maxima, it is of fundamental importance the realization of an accurate numerical model of the PV field. It must be able to simulate the PV basic units mismatching in a reliable and fast manner, also accounting for the behaviour of real bypass and blocking diodes.

In this paper a model with these characteristics is introduced: features and drawbacks are illustrated by means of simulations carried out in Matlab and PSIM environments.

The paper is organized as follows: Section II shows the details of the proposed model and puts in evidence its features. Section III shows the results of some application examples and Section IV is devoted to conclusions and hints for a future work.

II. THE MODEL

In fig.1 the usual circuit model of a photovoltaic (PV) panel is shown.

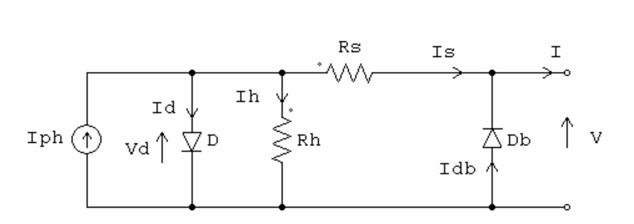

Fig.1 Circuit model of a PV panel including the bypass diode Db.

Such a model recurs in literature very often (e.g. in []). It includes the light induced current generator Iph and series and shunt resistances R_s and R_h respectively; Db is the bypass diode. We suppose, without loss of generality, that one bypass diode is placed in antiparallel with the whole panel.

The relation between the PV generator current I and voltage V is evaluated by solving the following system of non linear equations:

$$I_d = I_{sat,d}\left(e^{\frac{V_d}{V_{t,d}}} - 1\right) \tag{1}$$

$$I_{db} = I_{sat,db}\left(e^{-\frac{V}{V_{t,db}}} - 1\right) \tag{2}$$

$$I = I_{db} + I_{ph} - I_d - I_h \tag{3}$$

$$V_d = V + R_s \cdot I_s = V + R_s \cdot (I - I_{db}) \tag{4}$$

$$I_h = \frac{V_d}{R_h} = \frac{V + R_s \cdot (I - I_{db})}{R_h} \tag{5}$$

It has been obtained by using Kirchhoff voltage and current laws (3) and (4), linear characteristic equations for shunt and series resistors (4) and (5), and non linear equations for the diode D included in the model of the panel (1), and for the bypass diode Db (2). In (1) $V_{t,d}=\eta_d \cdot V_{T,d}$ and in (2) $V_{t,db}=\eta_{db} \cdot V_{T,db}$, $V_{t,d}$ and $V_{t,db}$ are expressed as the product of the diode ideality factor and the thermal voltage. The latter, as well as the two saturation currents $I_{sat,d}$ and $I_{sat,db}$, depend on temperature T only, whilst the light induced current I_{ph} depends on the irradiance level S and on the array temperature T [1].

The system of equations (1)-(5) clearly shows that the PV array current I is a nonlinear and implicit function of the PV array voltage V, of the irradiance level S and of the temperature T. Nevertheless, such a non linear system can be symbolically solved in one of the symbolic calculation environments, such as Matlab and Mathematica, actually available. In this way, a non linear relationship between the current I and the voltage V at the basic PV unit terminals can be obtained. For space reasons such relationship is reported in (6), at the end of the paper. It makes use of the LambertW function of the term θ whose value depends on the terminal voltage V and is reported in (7).

It is well known [3] that the LambertW function of the variable θ, herein indicated as LambertW(θ), is a non linear function of θ and it is the inverse function of:

$$f(\theta) = \theta \cdot e^{\theta} \tag{8}$$

Note that the use of the LambertW function allows the apparently explicit calculation of the array current as a non linear function of the terminal voltage. The value of the Lambert function, for an assigned value of the independent variable θ, is efficiently provided in simulation environments such as Matlab and Mathematica.

Expression (6), together with well known LambertW function properties, allow to calculate the first derivative of the panel's current with respect to the terminal voltage, again in apparently explicit form. In (9) it has been reported the property expressing the derivative of the LambertW(θ) function with respect to θ, and in (10) the expression of the derivative of I with respect to V at the panel's terminals is given (see the end of the paper). In this way, the differential conductance of the panel is explicitly expressed as function of the panel's voltage V only, by means of a non linear function.

Thus, in this way, both the PV current and its derivative with respect to the PV voltage have been expressed in closed form as functions of the sole voltage.

This greatly helps in formalizing the non linear algebraic system that describes a PV field composed by an arbitrary number of panels ,which can be connected both in series and in parallel.

In order to explain this concept, let us refer to a string of PV panels connected in series. Fig.2 shows the string of N series-connected panels and the blocking diode that avoids current backflows.

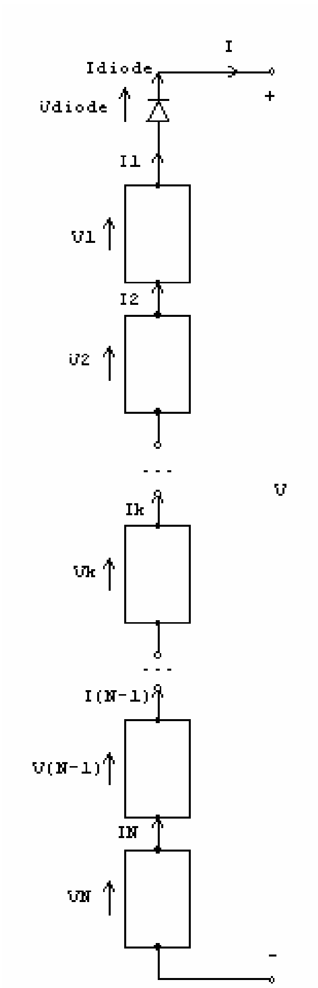

Fig.2 String of N PV panels connected in series and including the blocking diode.

In order to model this series, it is possible to build up a system of (N+1) equations in the same number of unknowns $\{V_1,V_2,...,V_k,...,V_{N-1},V_N,V_{diode}\}$. It is enough to write one Kirchhoff voltage law and N Kirchhoff current laws. The topological constraints are formalized in (11) at the end of the paper; they can be matched with the N equations of the panels, expressed as in (6) in terms of $I_k=I_k(V_k)$, k=1,2,...,N, and with the characteristic equation of the blocking diode expressed in the form (1), and taking into account the dependency of such a characteristic equation from the physical parameters of the real diode used. The non linear system (11) includes N non linear equations and one linear equation, the first one, in which the terminal voltage V, that is assumed to be a known term, appears . Each non linear equation includes only two of the (N+1) unknowns, and the first one is always V_1. This choice has been made to simplify the expression of the Jacobian matrix needed to solve the non linear system by means of, for example, the Newton Raphson method.

Thanks to (10) it is possible to obtain each term of the Jacobian matrix J as a function of the unknowns. Moreover, the structure of the system has been properly chosen in order to simplify the structure of the Jacobian matrix that, as it is well known, needs to be inverted when using Newton Raphson iterative methods. The Jacobian matrix structure is reported in (12) which puts in evidence that it is sparse and with a pattern which is characteristic of doubly bordered and diagonal square matrices [2]. Moreover, the first row is composed by (N+1) constants, while all the other rows require the evaluation of dI_1/dV_1 and the calculation of just another derivative. As a whole, the evaluation of the system (11) requires N times the use of the equation (6) and one time the (1); the calculation of the Jacobian matrix requires N evaluations of (10) and one evaluation of (13).

Such features are useful both in terms of memory requirements during the simulation and of computation time.

In Section III the features of the method are described by means of a numeric example.

III. SIMULATION RESULTS

Simulations have been conducted by considering Kyocera KC120 PV panels, characterized by 36 series connected cells, each one of area 0.0225 m^2, R_s=0.006 Ω, $R_h=10^4$ Ω.

A string with two PV panels connected in series, and with the blocking diode has been simulated. In this case the order of the system is 3. The panels have been considered identical in terms of manufacturing parameters and working temperature (T=320K).

On the other hand, their irradiation level has been considered very different, namely S=1000 W/m^2 for the first panel and S=100 W/m^2 for the second one.

The whole simulation has been conducted in Matlab environment; it required 45.3 s (on an Intel Centrino 2.0 GHz platform) in order to calculate 100 linearly spaced points of the power-voltage characteristic of the PV array. The samples of the current in the series and of the voltage distribution over the three devices have been also stored during simulation. The curves are reported in figs.3 and 4. They put in evidence the effect of the panel that receives the lower irradiance level in terms of string current drop at high voltage values.

It is worth noting that the curve of fig.3, obtained under mismatching conditions of the PV string, exhibits two maxima at two different voltage levels, with that one occurring at about 44 V being characterised by a consistently lower value of the power with respect to the other one placed at about 18 V. This occurrence can compromise the energy conversion operated by the switching converter connected at the string terminals and responsible for the MPPT. This can be understood by comparing plots of fig.3, representing the mismatched string, with that one of fig.5, obtained by imposing a unique irradiance level S=1000 W/m^2 for both the panels. If the MPPT controller acts so that the string works at about 40 V under uniform irradiance, it ensures that the maximum power – about 260 W – is converted. If a sudden irradiance drop (from S=1000 W/m^2 to S=100 W/m^2) occurs on one panel and the MPPT algorithm is not able to perform a “global search” of the new maximum power point, the relative maximum placed at about 40 V (see fig.3) is the likely new operating point. This means that the MPPT controller is not able to track the real maximum power point and that about 90 W (the difference between the maximum power of the best operating point at about 18 V and the power of an operating point placed at about 44 V) are wasted due to MPPT algorithm limit.

Such considerations have been verified by means of a PSIM simulation of the PV field controlled by means of boost switching converter that performs the MPPT function and matches the PV field with a 48V battery (see fig.6). The layout puts in evidence two dynamic link libraries that implement the PV field (left) and the P&O based MPPT controller (bottom). It has been simulated a sun irradiance drop involving one of the two panels of the array: the steep transition between the characteristic of fig.5 and that one of fig.3 occurs at t=0.03s (see fig.7). The P&O controller tracks the lower maximum because the voltage at which it occurs (see fig.8) is close to the voltage corresponding to the unique maximum of the characteristic depicted in fig.5. Fig.7 also put in evidence the three-points behaviour at both steady states: this characterizes the hill climbing of the two maximum power points tracked at the two different conditions. This result is confirmed by the boost converter duty cycle variation shown in fig.9.

In conclusion, the model illustrated in this paper might be of great help in developing an improved MPPT algorithm that is robust with respect to this kind of conditions, since it allows to test the MPPT performances with respect to different shapes of the power-voltage characteristic of the PV generator.

IV. CONCLUSIONS AND FUTURE WORK

In this paper a non linear model of mismatched photovoltaic fields is introduced. It allows to simulate heterogeneous arrays, with subsections (cells, groups of cells, panels or groups of panels) characterized by different irradiation levels, temperatures, semiconductor materials, areas, operating parameters and so on. The model also allows to take into account manufacturing tolerances and drifts ascribable to aging effects.

Further work is in progress in order to use the simulator in order to develop and test a maximum power point tracking strategy able to ensure an efficient power conversion even if the photovoltaic field works in mismatched conditions.

REFERENCES

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[2] William H. Press, *Numerical Recipes in C, The Art of Scientific Computing*, Second Edition, Cambridge University Press, 2002.

[3] http://mathworld.wolfram.com/LambertW-Function.html

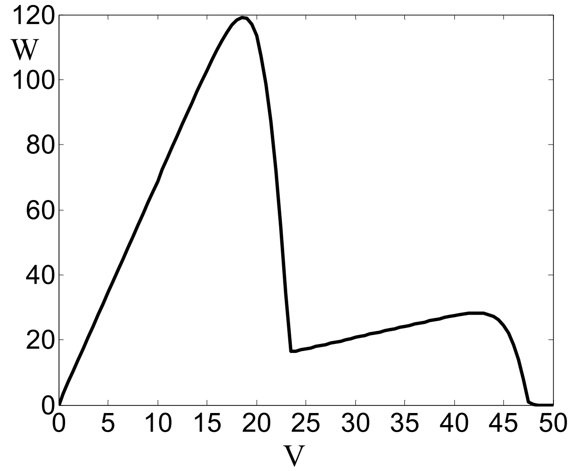

Fig 3. Power [W] vs. voltage [V] characteristic of the simulated mismatched PV field.

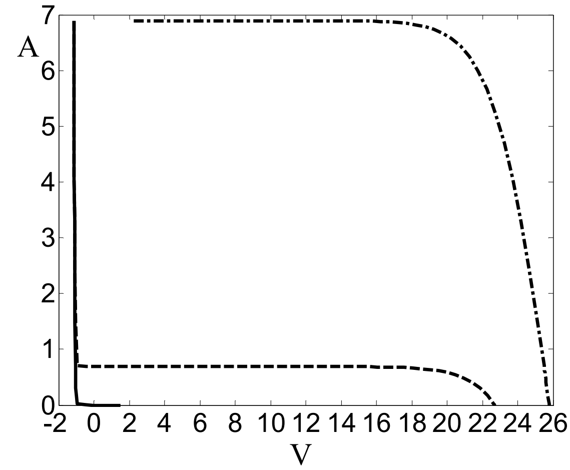

Fig.4 Current [A] vs. voltage [V] characteristic of the three devices in the simulated string. Continuous line = blocking diode curve, dashed line = curve of the panel with irradiation S=100 W/m^2, dash-dotted line = curve of the panel with irradiation S=1000 W/m^2.

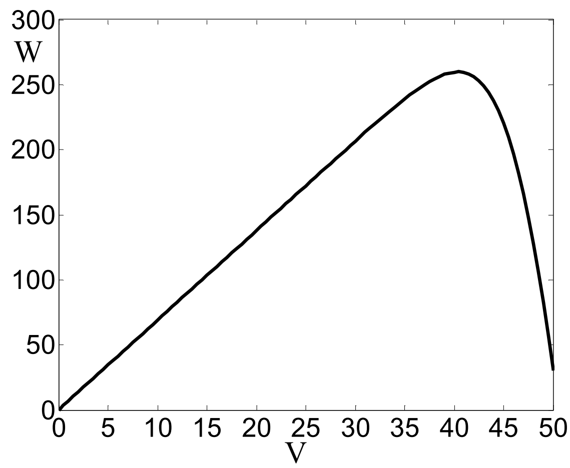

Fig 5. Power vs. voltage characteristic of the simulated matched PV field.

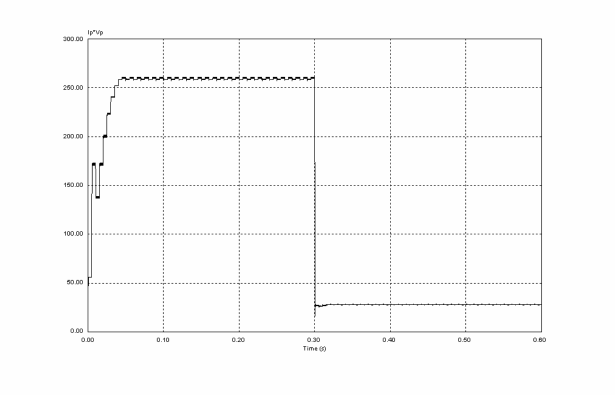

Figure 7. PV field output power.

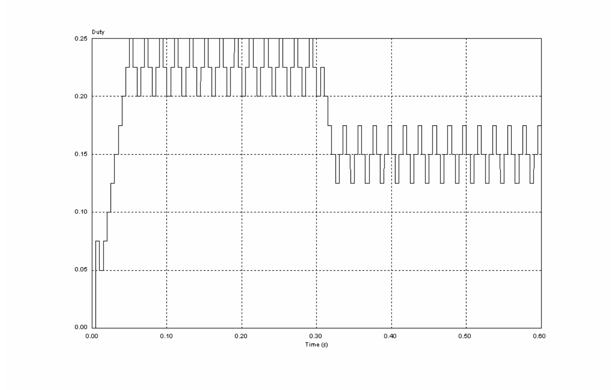

Figure 9. Duty cycle during transient.

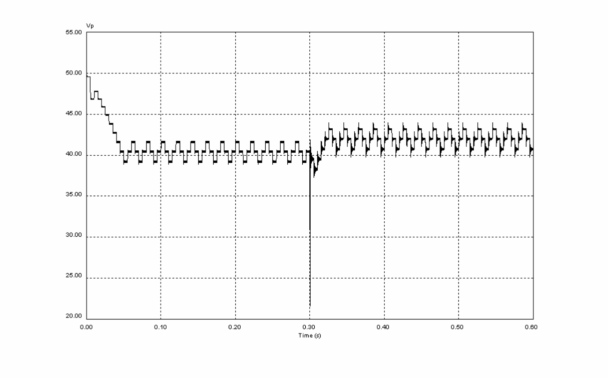

Figure 8. PV field voltage.

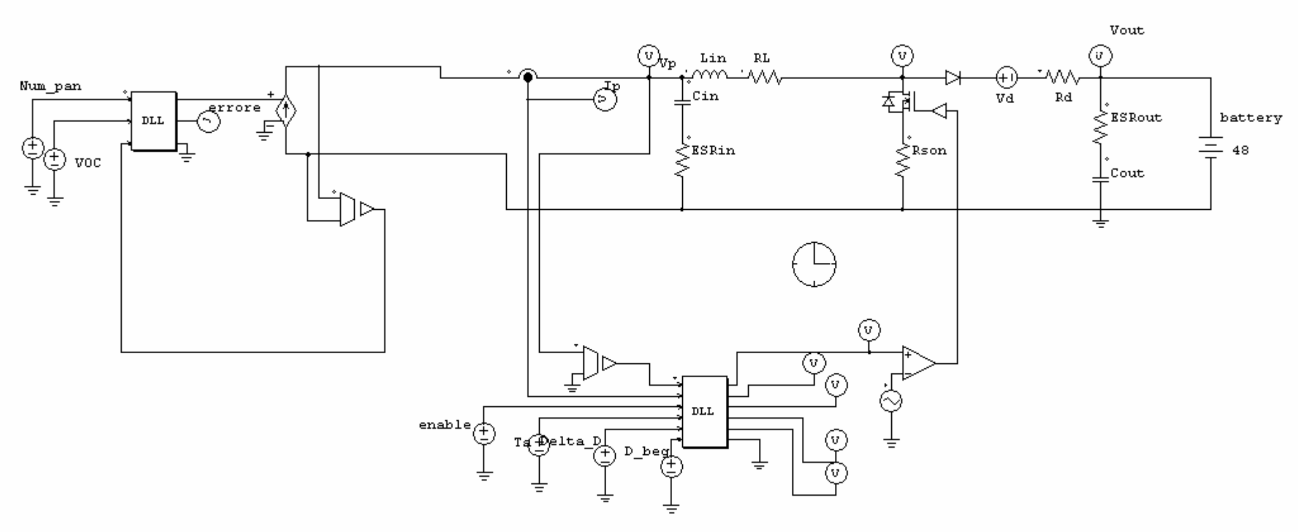

Figure 6. PSIM layout for the simulation of the MPPT controller.

$$I = \frac{\left[R_h \cdot \left(I_{ph} + I_{sat,d}\right) - V\right]}{\left(R_h + R_s\right)} + I_{sat,db} \cdot \left(e^{-\frac{V}{V_{t,db}}} - 1\right) - \frac{V_{t,d}}{R_s} \cdot \text{LambertW}(\theta) \tag{6}$$

$$\theta = \frac{(R_h // R_s) \cdot I_{sat,d} \cdot e^{\left[\frac{R_h \cdot R_s \cdot (I_{ph} + I_{sat,d}) + R_h \cdot V}{V_{t,d} \cdot (R_h + R_s)}\right]}}{V_{t,d}} \tag{7}$$

$$\frac{d}{d\theta}\text{LambertW}(\theta) = \frac{1}{[1 + \text{LambertW}(\theta)] \cdot e^{\text{LambertW}(\theta)}} = \frac{\text{LambertW}(\theta)}{[1 + \text{LambertW}(\theta)] \cdot \theta} \tag{9}$$

$$\frac{dI}{dV} = -\frac{1}{(R_h + R_s)} - \frac{I_{sat,db}}{V_{t,db}} \cdot e^{-\frac{V}{V_{t,db}}} - \frac{R_h}{R_s \cdot (R_h + R_s)} \cdot \text{LambertW}(\theta) \tag{10}$$

$$\begin{cases} V_1 + V_2 + \ldots + V_k + \ldots + V_{N-1} + V_N + V_{diode} - V = 0 \\ I_1(V_1) - I_2(V_2) = 0 \\ I_1(V_1) - I_3(V_3) = 0 \\ \ldots \\ I_1(V_1) - I_k(V_k) = 0 \\ \ldots \\ I_1(V_1) - I_{N-1}(V_{N-1}) = 0 \\ I_1(V_1) - I_N(V_N) = 0 \\ I_1(V_1) - I_{diode}(V_{diode}) = 0 \end{cases} \tag{11}$$

$$J = \begin{pmatrix} 1 & 1 & 1 & \ldots & 1 & \ldots & 1 & 1 & 1 \\ \frac{\partial I_1}{\partial V_1} & -\frac{\partial I_2}{\partial V_2} & & & & & & & \\ \frac{\partial I_1}{\partial V_1} & & -\frac{\partial I_3}{\partial V_3} & & & & & 0 & \\ \vdots & & & \ddots & & & & & \\ \frac{\partial I_1}{\partial V_1} & & & & -\frac{\partial I_k}{\partial V_k} & & & & \\ \vdots & & & & & \ddots & & & \\ \frac{\partial I_1}{\partial V_1} & & 0 & & & & -\frac{\partial I_{N-1}}{\partial V_{N-1}} & & \\ \frac{\partial I_1}{\partial V_1} & & & & & & & -\frac{\partial I_N}{\partial V_N} & \\ \frac{\partial I_1}{\partial V_1} & & & & & & & & -\frac{\partial I_{diode}}{\partial V_{diode}} \end{pmatrix} \tag{12}$$

$$\frac{\partial I_{diode}}{\partial V_{diode}} = -\frac{I_{sat,diode}}{V_{t,diode}} \cdot e^{\frac{V_{diode}}{V_{t,diode}}} \tag{13}$$