Using Photovoltaic Systems to Improve Voltage Control in Low Voltage Networks

J. M. Rodrigues, F. O. Resende

***Abstract*-- This paper describes technical solutions based on advanced control functionalities for photovoltaic systems aiming to prevent voltage rise above technical limits in low voltage MicroGrids by limiting the injected active power. Due to the action of Maximum Power Point Tracking (MPPT) systems, it is expected that the output power of photovoltaic systems tracks the maximum value according to both solar and temperature conditions. Hence, limiting the active power to be injected into the low voltage network requires the accommodation of the generation surplus. An innovative approach is proposed for this purpose, exploiting a modified MPPT algorithm that finds a proper operation point considering also the grid operating conditions. The technical feasibility of this approach is evaluated through numerical simulations performed in the *Matlab®/Simulink®* simulation tool using the detailed models of the power electronic converters.**

***Index Terms*-- MicroGrids, Maximum Power Point Tracking, Photovoltaic Systems, Power Electronic Converters, Voltage Control, Low Voltage Networks.**

I. Nomenclature

DG – Distributed Generation
IGBT – Insulated Gate Bipolar Transistor
LC – Load Controllers
LV – Low Voltage
MC – Microsource Controller
MG – MicroGrid
MGCC – Micro Grid Central Controller
MPP – Maximum Power Point
MPPT – Maximum Power Point Tracking
MV – Medium Voltage
NOTC - Nominal Operation Temperature of the Cell
NTC – Normal Test Condition
PI – Proportional Integral
PLL – Phase Locked Loop
P&O – Perturb and Observe
PV – Photovoltaic
PWM – Pulse Width Modulation
RES – Renewable Energy Sources
STC – Standard Test Condition
THD – Total Harmonic Distortion
VSI – Voltage Source Inverter

II. Introduction

FOLLOWING the increasing penetration of Distributed Generation (DG) in Medium Voltage (MV) distribution networks, the dissemination of small size and modular microgeneration systems connected to the Low Voltage (LV) networks will provide an important contribution to face demand growth, taking into account the common concerns about fossil fuel scarcity, security of supply and reduction of greenhouse gas emissions. Thus, technological developments related with the improvement of systems efficiency and the possibility of exploiting Renewable Energy Sources (RES) are important issues that are contributing for the deployment of small scale generation systems, i.e. microgeneration systems, in LV networks [1]-[3]. However, an effective integration of increasing levels of microgeneration requires tackling several technical issues regarding mainly the active management and control of LV networks. For this purpose, the MicroGrid (MG) concept has been pursued in several researches to face these challenges and to best profit the potential benefits arising from an effective integration of microgeneration systems [2]-[6].

The MG concept, developed within the framework of the EU MICROGRIDS Project [7], comprises a LV distribution network with loads (some of them being controllable), small modular generation units and storage devices connected to it through power electronic interfaces. The two level hierarchical type management and control scheme allows the MG operation as a coordinated entity both in interconnected and islanded mode of operation. The MG is centrally controlled and managed by the MG Central Controller (MGCC) installed at the MV/LV secondary substation, which is responsible to head the MG hierarchical control system. For this purpose the MGCC includes several key functions that support adequate technical and economical management policies and allow providing set points to the second control level comprising Microsource Controllers (MC) and Load Controllers (LC), in order to control locally the controllable microgeneration units and the responsive loads, respectively [4]-[7].

However, in spite of the active MG control and management capabilities, the control of voltage profiles in LV distribution networks will become a difficult task. Since this kind of networks are characterized by having high R/X ratios,

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high voltage problems can arise from the active power flow in the opposite direction as a result of the injected active power from the microgeneration systems, especially in radial grids with long branches and low load density [8], [9]. Under this context, a special attention should be given to microgeneration systems exploiting RES, such as photovoltaic systems, due to both its potential widespread and the limited control capability of the active power generation, since PV systems are usually equipped with Maximum Power Point Tracking (MPPT) systems in order to increase efficiency. Thus, when the generation levels are high during periods of low local consumption, rise voltage problems can arise and therefore the microgeneration system can be switched-off by means of their own maximum voltage protection systems [8], [10]. In order to overcome this problem in scenarios of large deployment of PV systems, innovative control strategies need to be developed to control the voltage profile in LV networks based on the injected active power control.

Thus, in this paper, a commonly used MPPT system based on the Perturb and Observe (P&O) algorithm [11] is exploited to implement additional features aiming to control the active power supplied by PV systems into LV grids in order to keep the voltage levels within acceptable limits. The MG concept is exploited for this purpose, so that the proposed approach aims providing capability for supporting two complementary control philosophies:

1. Local control, being the active power supplied to the grid adjusted autonomously based on the voltage level measured locally;
2. Hierarchical/centralized control in which the active power supplied to the grid follows a given set-point sent by the MGCC to the corresponding MC.

The local control provides an autonomous and fast response regarding voltage control, but it may be not sufficient to assure the MG management and control in optimum operating conditions. A suitable coordination involving both control philosophies is thereby required. However, since the scope of this research is focused on the performance evaluation of the proposed technical solutions, only the local control is addressed, thus demonstrating that the proposed approach can provide benefits to the current LV networks without advanced control and management systems.

III. Dynamic Modeling of Grid Connected Photovoltaic Systems

Grid connected PV systems require power electronics based interfaces with specific capabilities to convert the dc power generated by PV arrays into ac power to be injected into the utility network. Since power electronic converters of several RES perform similarly, the development of scalable, modular, low cost and highly reliable power electronic based interfaces has been a matter of concern recently, attempting to reduce the overall cost and reliability of DG systems based on RES, in the spite of the potential benefits they can provide by exploiting the power electronics control capabilities, such as system ancillary services [4]-[6]. Reducing costs of power electronic based interfaces is mandatory to reduce investments (capital costs) while increase reliability will contribute to reduce operation costs [12].

Therefore, this research focus on modular power electronics topologies leading to low cost and reliable interfaces intended for application in PV systems. These topologies can be grouped based on the number of power processing stages, location of power decoupling capacitors, utilization of transformers and types of grid connected inverters [13]-[15]. To avoid low frequency transformers, which have been commonly regarded as poor components due to their large sizes and low efficiency, multiple stage conversion systems are widely used in grid connected PV systems [16]. Although some solutions have been proposed in the literature to reduce the number of power processing stages [17], grid connected PV systems usually employ two stages [18] and the most common topology comprises a dc-ac grid connected single phase Voltage Source Inverter (VSI) along with a dc-dc boost converter [12]. Then the power electronics based interfaces accept dc power from the PV system and convert it to single-phase ac power with the required grid voltage and frequency. Besides the typical configuration, the MPPT control for PV array, the Phase Locked Loop (PLL) to track the fundamental component of the grid voltage, the dc-link voltage controller and the grid current controller were also considered, being the typical configuration together with the control structures illustrated in Fig. 1.

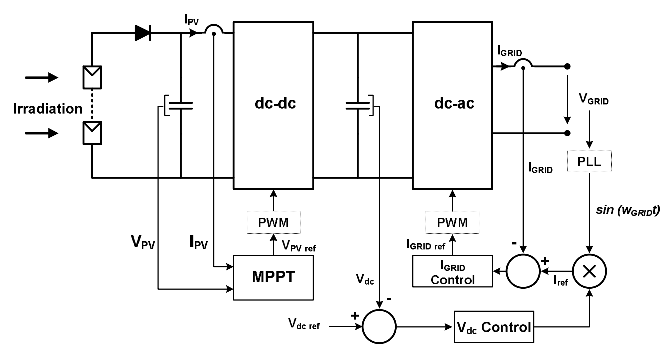

Fig. 1. Typical configuration of a single-phase grid connected PV system and control structures.

In general, as it can be observed from Fig. 1 the MPPT and the voltage boost are performed by the dc-dc converter controller while the power flow control to the utility as well as the common sinusoidal unity power factor current injection are performed through the dc-ac inverter controller [9], [12], [19]. Then, the dc-dc boost converter is controlled to achieve MPPT [20]. Regarding the grid connected converter, there are two basic control modes: PQ control and VSI control. Although the current IEEE 1547 Standard [21] does not allow DG to actively regulate voltage, industrial trend suggest that voltage regulation has positive impact on the grid [22], so that the dc-ac converter is controlled as VSI. Pulse Width Modulation (PWM) techniques were used to generate the switching signals that control the switching devices of both dc-dc conversion stages. A brief description of mathematical models representing the grid connected PV system main components is followed presented.

A. The solar cell and PV array model

PV systems directly convert sunlight into dc power by means of the solar cells, which are connected in series and parallel to increase voltage and current, respectively, to suitable values for PV modules and arrays. This section addresses the modeling of PV arrays, since manufacturers are usually interested on that [23]. A solar cell is basically a semiconductor diode whose *p-n* junction generates a dc current junction when exposed to sunlight. The single-diode model has been extensively used since it offers a good compromise between simplicity and accuracy [23]-[25], so that it was also adopted in this paper. The typical equivalent circuit is represented in Fig. 2.

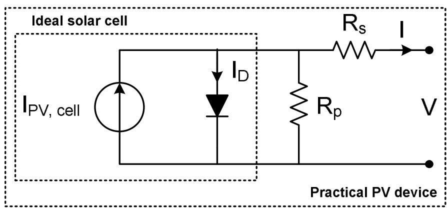

Fig. 2. Single-diode model of the theoretical solar cell and equivalent circuit of the practical solar cell, including series and parallel resistances [23].

The basic equation describing the I-V characteristic of the ideal solar cell arises from the semi-conductor theory [26] and is given by:

$$I_{cell} = I_{PV,cell} - I_D = I_{PV,cell} - I_{0,cell}\left(e^{\frac{qV}{nKT}} - 1\right) \qquad (1)$$

Here, $I_{PV,cell}$ is the current generated by the sunlight, $I_{0,cell}$ is the diode reverse saturation current, q is the electron charge $\left(1.6\times10^{-19}C\right)$, K is the Boltzmann constant $\left(1.38\times10^{-23}J/C\right)$, T (in Kelvin) is the temperature of the *p-n* junction and n is the ideality constant.

Practical PV arrays comprise several connected solar cells and the additional parameters R_p and R_s (Fig. 2), being the corresponding I-V characteristic given by [23], [26] as:

$$I = I_{PV} - I_0\left(e^{\frac{V+R_sI}{nV_T}} - 1\right) - \frac{V+R_sI}{R_p} \qquad (2)$$

where $I_{PV} = N_p \times I_{PV,cell}$ is the photovoltaic current and $I_0 = N_p \times I_{0,cell}$ is the saturation current of the array with N_p solar cells connected in parallel. $V_T = \left(N_s KT\right)/q$ is the thermal voltage of the array with N_s cells connected in series.

A practical model is based on experimental data provided by manufacturers in the data sheets, which usually bring basic information referred to the Standard Test Conditions (STC) of temperature and irradiance, $T_n = 25^{o}C$ and $G_n = 1000\,W/m^2$, respectively [23]. In practice, the operating conditions of the PV systems differ from the STC, so that under actual operating conditions, T (in Kelvin) and G (in Watts per square meter), the temperature in the surface of the PV system is given by:

$$T_{PV} = T + G\frac{NOTC - 20}{800} \qquad (3)$$

where NOTC is the Normal Operating Temperature of the Cell, which is defined as the cell temperature under a solar irradiance of 800 W/m^2, ambient temperature of 20*ºC* and a wind speed lower than 1 *m/s*, known as Normal Test Conditions (NTC).

Therefore, the thermal voltage in equation (2) referred to the temperature on the surface of the PV system is obtained as $V_T = \left(N_s KT_{PV}\right)/q$. The PV array is then represented in this work by a current source, being the driven current controlled according to equation (2) for the simulated conditions of temperature and irradiance.

B. The dc-dc boost converter and control scheme with MPPT

Since the dc-link voltage of the photovoltaic array terminals is a variable dc voltage, depending on temperature and irradiance conditions, the boost converter is responsible to adapt the output voltage of the PV array in order to match the corresponding reference provided by the MPPT system, so that the PV system is operated at the MPP. For this purpose, the duty-cycle of the boost converter is automatically adjusted, modifying the firing angle accordingly, as suggested in [27]. The basic control scheme of the dc-dc boost converter in a standard unidirectional topology is presented in Fig. 3.

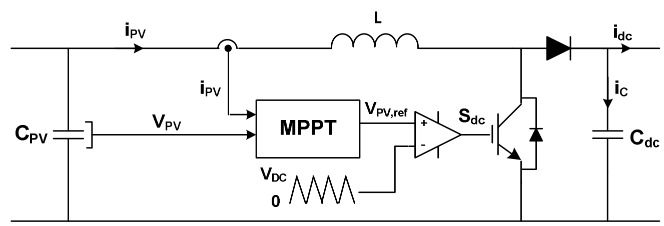

Fig. 3. Basic control scheme of the dc-dc boost converter with direct duty ratio control.

The common MPPT strategies aim to find the voltage or current for which the PV system provides the maximum output power. For this purpose, many MPPT methods have been proposed and reported on the available literature [11], [24]-[31]. In [29] a comparative study of the performance of MPPT algorithms is presented and it was concluded that the direct algorithm usually called P&O is the most widely used method in commercial PV systems, because it is easy to implement and requires few measured parameters. Therefore, the P&O method based on [32] was followed on this research, acting in real time on the voltage reference variable corresponding to the maximum power extracted from the PV array. By perturbing the operation voltage and observing the power variation the proper direction of evolution is found in order to give the voltage reference.

C. The single-phase dc-ac converter and control scheme

The grid side converter, operating at the grid frequency (50 Hz) involves a single phase full bridge Insulated Gate Bipolar Transistor (IGBT) inverter together with the control scheme presented in [9], [33], as depicted in Fig. 4.

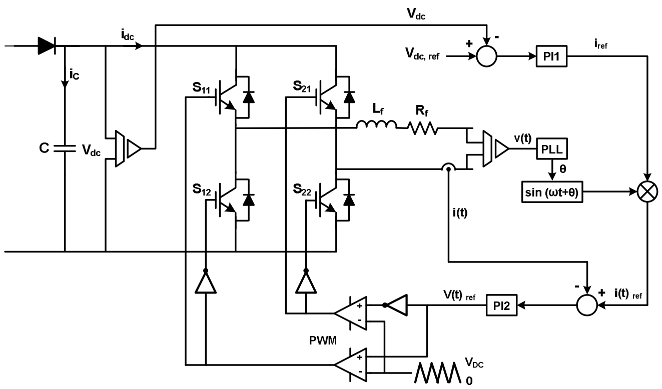

Fig. 4. Inverter topology and control structure.

As already mentioned previously, the adopted control strategy aims basically to regulate the dc-link voltage at the input terminals of the VSI and to operate the PV system with a unitary power factor, which has been a common procedure in LV networks. The sinusoidal current mode control [34], [35] was also adopted to reduce the Total Harmonic Distortion (THD) of the system output current. The controller is implemented with constant switching frequency imposed by the triangular carrier signal in order to perform selective harmonic elimination, thereby reducing the harmonic spectrum of the output current and also the system losses [9], [33].

According to this control scheme, the active power control is performed by regulating both the magnitude and phase of the fundamental output current such that it tracks a sinusoidal reference current which is in phase with the grid voltage. The sinusoidal reference current is regulated by means of Proportional Integral (PI) controllers, PI1 and PI2, as it can be observed from Fig. 4, by providing a sinusoidal voltage reference that is used on the PWM generator to define proper pulse signals to control the IGBT switching.

IV. Advanced Control Features to Improve Voltage Control in LV Distribution Systems

As already mentioned previously, increasing levels integration of PV systems in LV networks will contribute to voltage rise, especially in weak systems comprising feeders with low X/R ratio and during periods with high generation levels and low consumption. Since these systems are usually controlled for MPP operation, they can be tripped out by their own overvoltage protection systems under the above mentioned operating conditions. Thus, advanced control features should be included in the control systems of power electronic based interfaces aiming to provide additional control capabilities of PV systems, allowing them to control/limit the active power injected in LV networks when voltage rises above acceptable technical limits. These features will contribute to improve the LV network operating conditions by providing a dynamic local control based on the following approach:

1. The grid voltage LV is measured and its value compared with the maximum technical limit or with a proper reference value, which will be computed centrally and sent by the MGCC to the MC, yielding an error signal;
2. Based on the error value, a coordinated control scheme takes action, halting the MPPT algorithm and enabling the additional control features by decreasing system efficiency.

The modified control schemes focus basically the dc-dc boost converter of the PV systems, so that a more detailed description regarding its control system as well as the modified MPPT method is provided in the sections followed.

A. The dc-dc boost control scheme

In order to integrate the above mentioned control functions the MPPT algorithm includes the grid voltage, V_{GRID}, as an additional input, as it can be observed from Fig. 5.

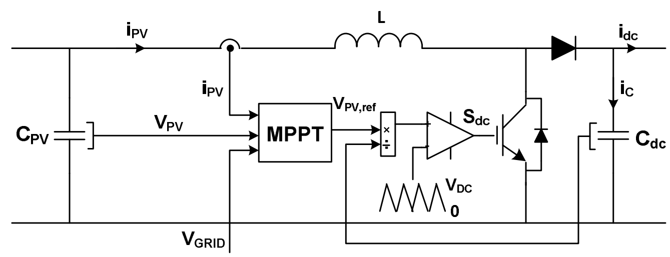

Fig. 5. The modified dc-dc boost control scheme.

Since the dc-link voltage of the VSI side is controlled according to the corresponding reference value by the grid connected inverter, as described in section III, the direct duty ratio control can e simplified, being performed according to the scheme represented in Fig. 5.

B. The modified P&O method

The advanced control features followed whenever the grid voltage is higher than the corresponding maximum technical limit are implemented through an additional path that will be performed by the modified MPPT algorithm based on the P&O method.

As it can be observed from Fig. 6, when the terminal voltage level at the LV network is within acceptable maximum limit, the MPPT algorithm follows the common procedure, which is implemented through the common basic steps of the P&O methods from 1 to 6, according to the decision conditions allowing to find the direction of the PV array reference voltage. Otherwise, if the grid voltage rises above the maxim acceptable limit, the step 7 is performed within the modified P&O algorithm aiming to move the operating point from the MPP in order to decrease the PV system efficiency, without losing stability.

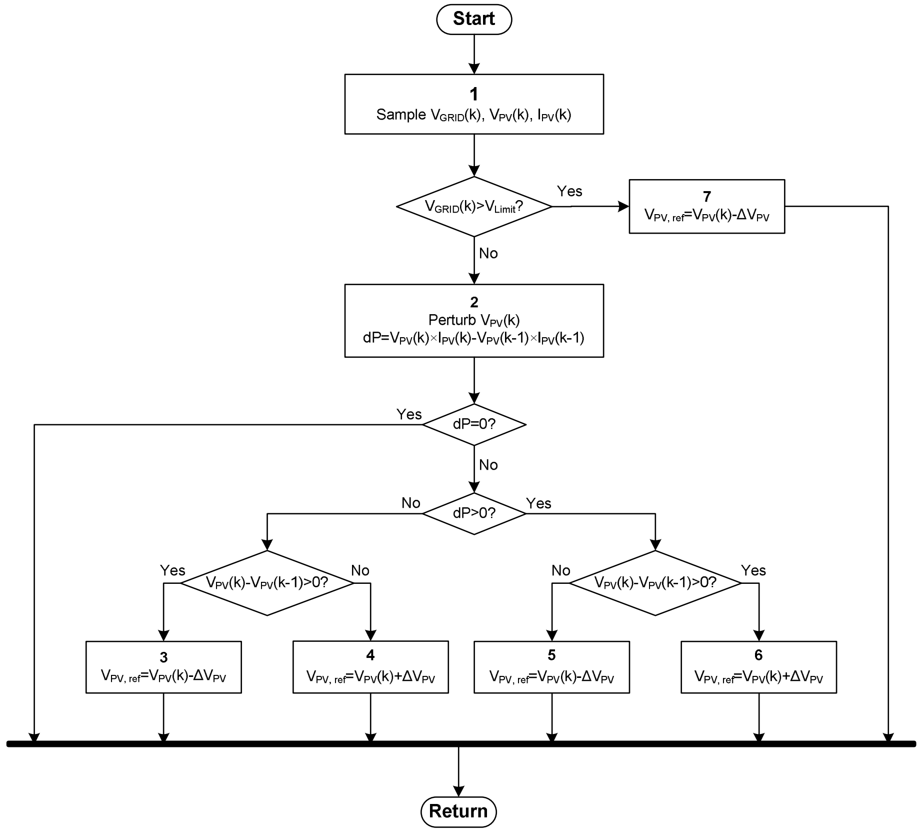

Fig. 6. Flow chart of the modified P&O method.

V. Simulation Results and Discussion

In order to evaluate the performance of the proposed additional control features to prevent voltage rise above acceptable technical limits in LV networks, a small test system was implemented in *Matlab®/Simulink®*, comprising a photovoltaic array and the corresponding power electronic interfaces together with the control schemes described previously, being the single-phase VSI connected to a 400 V network with a low X/R ratio. The single-phase photovoltaic system is connected to the phase *a* of the LV network operating under unbalanced conditions. This test system is presented in Fig. 7.

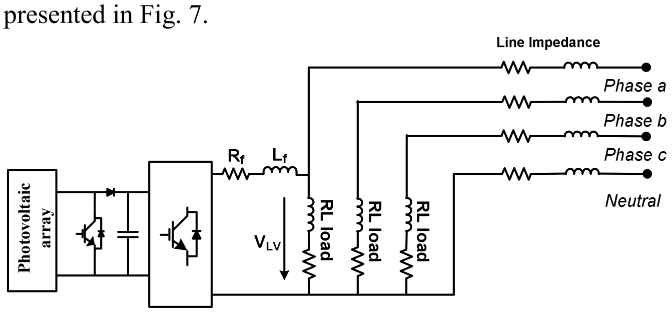

Fig. 7. The single-phase PV system connected to the LV grid.

The PV array comprises 24 modules BP4161 connected in series-parallel along with three strings of 8 PV modules, resulting in 3960 Watt of peak power at STC. For simulation purposes it was also considered that the PV system is subjected to the irradiance behavior, which is represented in Fig. 8. It was assumed that the maximum allowable voltage per phase is 1,1 p.u (253 V).

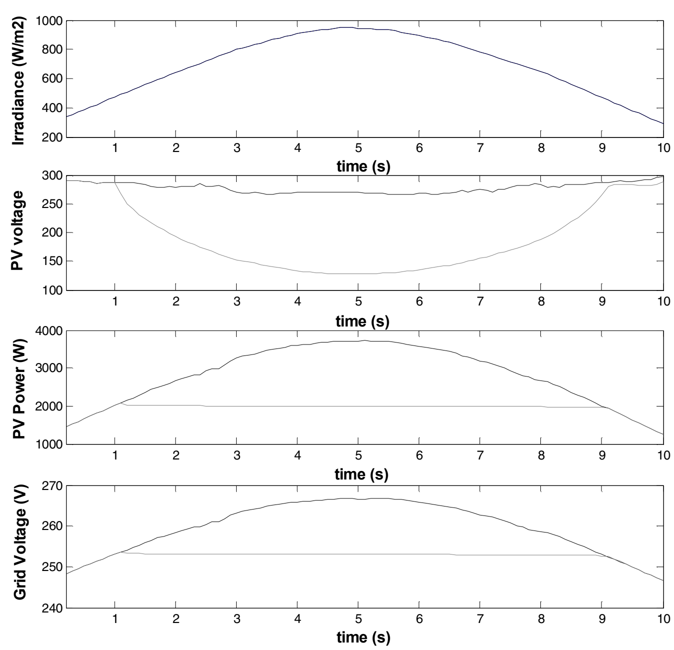

Fig. 8. Dynamic behavior of the PV system with voltage control (grey curves) and without voltage control (black curves). From top to down: System irradiance; PV array voltage; behavior of the active power output injected into the LV grid; behavior of the LV grid voltage at PV system terminals.

The simulation results demonstrate the effectiveness of the proposed additional control features focusing PV systems in order to prevent high voltage problems that can arise from active power flows in the opposite directions by limiting the injected active power.

VI. Conclusions

Following the increasing integration levels of PV systems in LV networks high voltage problems can arise. In order to keep local voltage levels within acceptable limits, the active power output should be limited to prevent DG systems to trip out by means of their maximum voltage protections. For this purpose additional control features were proposed for PV systems, focusing on the MPPT algorithm, and therefore on the dc-dc boost converter control system, aiming to reduce the system efficiency when grid voltage tends to rise above the maximum technical limit. The performance of the proposed approach was evaluated through numerical simulations performed in *Matlab*® *Simulink*® environment. The results obtained demonstrate its technical feasibility as well as its contribution to improve the operating conditions of LV distribution systems when operated according to the current practices as well as within the framework of the MG concept.

VII. Acknowledgment

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