Degradation detection of PV arrays using Extremum-seeking control based MPPT

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***Abstract*—The system operating costs and long-term reliability of the PV modules is significant in reducing the total lifetime cost of the PV system. In this context the diagnostic methods in identifying the degradation affecting PV array is important. Previous studies on degradation in PV modules showed that degradation leads to either decrease in shunt resistance or increase in series resistance of the PV module. With change in internal resistance of a PV array, the transient characteristics of array quantities (array voltage and current) may change. The effect of internal resistance of a PV array on transient characteristics was studied in this brief from the small signal model for a PV system with boost converter. The step responses for studying transient characteristics was obtained by implementing an extremum seeking control (ESC) based MPPT which injects a square wave dither signal into the duty ratio signal. The transient characteristics of array voltage signal were analyzed using suitable integral performance indices which helps in detecting degradation of PV array.**

Keywords—Degradation; PV modules; Extremum-seeking control; Maximum power point tracking;

I. INTRODUCTION

A major disadvantage of PV systems when compared with conventional energy systems is the higher cost of energy. In order to make PV power generation economically more competitive, maximizing the efficiency and reducing the maintenance cost are both important. Degradation of the PV modules is one of the reason which contributes towards reduced efficiency of a PV system [1]. The degradation in PV modules is due to the physical and/or chemical changes in various module components as it is constantly exposed to different environmental conditions. The different types of degradation of a PV module lead to either decrease in shunt resistance or increase in series resistance, and as a consequence power loss [1]. Several online and offline methods for degradation detection have been proposed earlier which are summarized in the remaining part of this section.

In [2] offline methods were employed in analyzing the degradation of PV modules are detailed. Some of the commonly used methods mentioned in [2] are light I-V curve measurement (to determine maximum power at STC by correction), dark I-V curve measurement (to determine cell diode saturation current, ideality factor, series and shunt resistance) and measurement of shunt resistance for individual cells by injecting an AC signal into PV module along with sequential shading of each cell in the module. Thus, the degraded modules will lower the PV system output until the offline methods are employed on the PV system. Also the power generation from PV system is shutdown whenever offline methods are employed.

In [3] three different PV systems were evaluated to compute degradation rates using four different methods, namely I-V measurement, metered raw kWh, performance ratio and performance index. Among the four methods of degradation rate evaluation except the metered raw kWh method, others needed irradiance data. I-V measurement is an offline method while others are online methods. I-V measurement method was ranked as the best method followed by performance index method which needs the local weather data. Metered raw kWh method was ranked third if the bad months with high irradiance variation were identified and eliminated. Performance ratio method was ranked the least as it does not have adjustments accounting for losses related to temperature, wiring, etc.

An autonomous I-V curve tracer using a SEPIC converter was designed in [4] which disconnects from the load (usually the grid) whenever the I-V curve is needed and the power generation from PV system is resumed when the I-V curve is measured. But, the autonomous I-V curve tracer was subjected to partial shading conditions only and not for the degradation conditions. In [5] the change in internal resistance of a PV system was detected by evaluating the transient characteristics performance of PV voltage. The MPPT scheme of PV system was based on extremum-seeking control (ESC) which is generally used for complex non-linear processes. The PV system considered in [5] is a string configuration where each string made of series connected PV modules is connected to a DC-DC converter (buck converter in this case) which is in turn connected to DC bus and an inverter at the next stage. A small-signal transfer function analysis was also performed for the PV buck system, which justified the impact of the internal resistance on the transient characteristics. The ESC based MPPT used in [5] used a square wave dither signal instead of a sinusoidal dither as used in conventional ESC to obtain step responses.

This paper's approach to degradation detection is similar to the method mentioned in [5]. The degradation detection in [5] considered a buck converter which is rarely used. Thus, in this paper a boost converter is considered which leads to a different small-signal analysis and a different transient characteristic performance. This paper has been organized as follows:

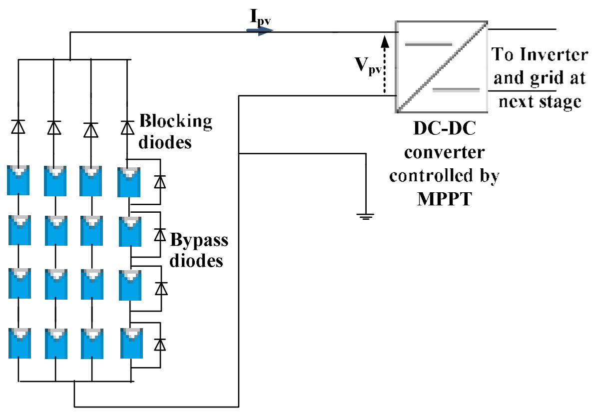

Fig. 1 Typical grid-connected centralized PV array

TABLE I
PARAMETERS OF PV MODULE

Parameters	Symbol	Value
Maximum power	P_m	100W
Open-circuit voltage	V_{oc}	50.5V
Short-circuit current	I_{sc}	3.3A
Maximum power voltage	V_{mp}	37.5V
Maximum power current	I_{mp}	2.65A

Section 2 gives an overview of types of the implementation of ESC based MPPT for PV system; Section 3 describes the derivation of small signal model of PV-boost converter system; Section 4 discusses the detection of internal resistance by calculating the performance of array voltage transient characteristics; Section 5 concludes the paper.

II. ESC BASED MPPT FOR PV SYSTEM

A grid-connected PV system with centralized inverter is used for the simulation as shown in Fig. 1. The bypass diodes connections in Fig. 1 is shown only for one PV string, but bypass diodes are connected to all PV modules. Table 1 shows the specifications of the PV module used in the PV system. The simulation model of PV module was adopted from [7].

ESC is a class of optimizing control strategies that can search for the unknown and/or time-varying optimal input parameter regarding a given performance index or an output from the non-linear plant. In this study the dither ESC scheme is used for the application to PV system's MPPT control. A common block diagram of dither ESC for any general non-linear process is as shown in Fig. 2. The blocks $F_I(s)$ and $F_O(s)$ denote the input and output dynamics of the non-linear process which may not be completely known. The measured noise is also denoted which gets added with the output of non-linear process. The block diagram of ESC comprises of high pass filter ($F_{HP}(s)$), demodulation signal ($d_1(t)$), a low pass filter ($F_{LP}(s)$), integrators (1/s), a dynamic compensator (K) and the dither signal ($d_2(t)$). The dither ESC can be used to extract the

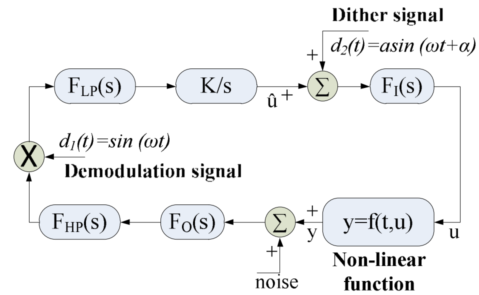

Fig. 2 Block diagram of ESC

TABLE II
PARAMETERS OF ESC FOR PV SYSTEM

Parameters	Value
Low pass filter	$\frac{s}{s+30}$
High pass filter	$\frac{5}{s+5}$
Dynamic compensator (K)	20
Dither amplitude	0.06
Dither frequency	10Hz

gradient information of a non-linear process which is proved in [8].

The design guidelines for ESC was derived in [8] by considering the non-linear function to be a general quadratic function. The low pass filter and high pass filter must be proper transfer functions, so that they can be implemented. These filters can be of first order or higher order depending on the accuracy need for the application. Linear time invariant (LTI) and linear time variant (LTV) stability test were performed for the generalized quadratic function in order to help with design of ESC. In each of these tests the state transition matrix was calculated. From the LTI and LTV tests the following points were observed.

a) The dither frequency must have sufficiently large difference with any noise frequency.

b) Phase difference between dither and demodulation signal depends on the input dynamics of the non-linear process.

c) The dither amplitude must be set so as to obtain a small steady state output error.

d) The dynamic compensator can be tuned to decrease the convergence rate.

Based on these design guidelines the ESC was implemented for PV system for the purpose of MPPT as shown in block diagram of Fig. 3. The parameters of ESC used for PV system is listed in Table 2. Initially a sinusoidal dither was used in the ESC for the MPPT of centralized PV system. The array power and array voltage waveforms for the ESC based MPPT of centralized PV system are plotted for different irradiances in Fig. 4 and Fig. 5. The ESC based MPPT was found to perform the function of tracking maximum power

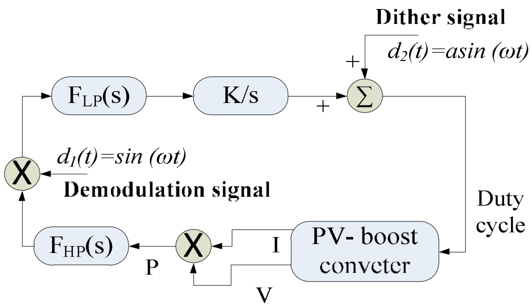

Fig. 3 Block diagram of ESC based MPPT for PV system

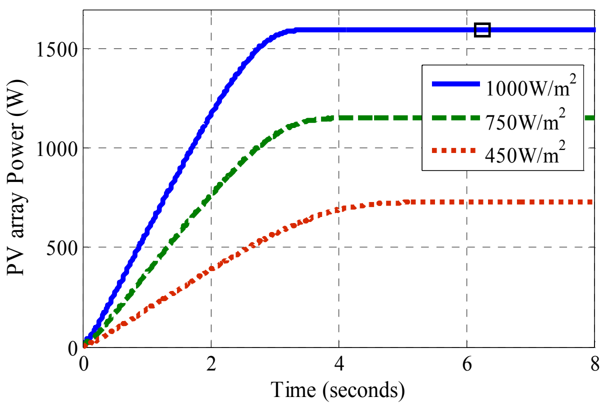

Fig. 4(a) Array power for ESC based MPPT

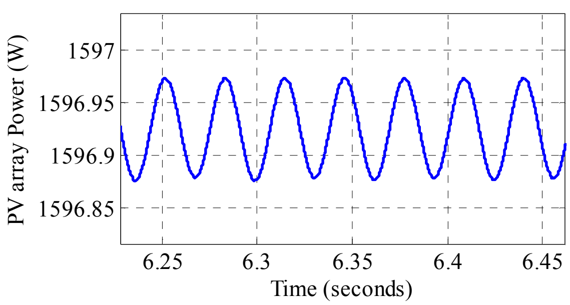

Fig. 4(b) Array power for ESC based MPPT

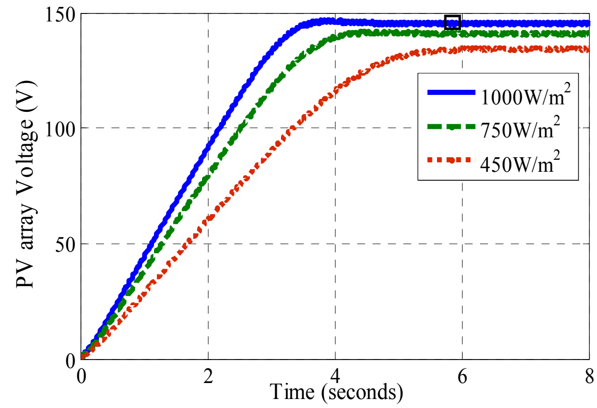

Fig. 5(a) Array voltage for ESC based MPPT

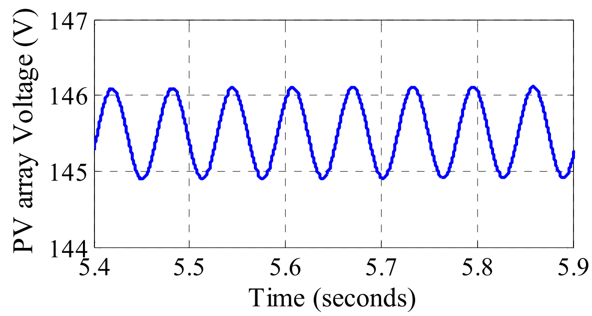

Fig. 5(b) Array voltage for ESC based MPPT

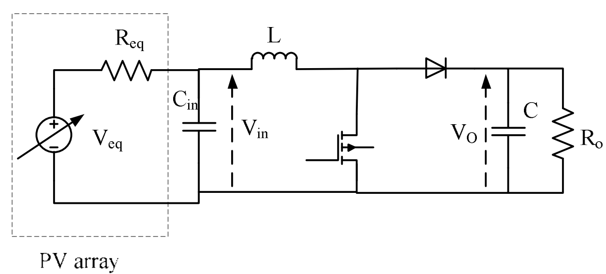

Fig. 6 Boost converter with averaged PV array

accurately under different irradiance. The zoomed waveform of power and voltage are plotted in Fig. 4(b) and Fig. 5(b) which is sinusoidal in nature due to the sinusoidal dither injected by ESC based MPPT.

III. Small-Signal Analysis for PV-Boost Converter System

Generally a PV system has a boost converter between the PV array and inverter so as to boost the array voltage to the required level of inverter. The transfer function ratio of input voltage to duty cycle is derived in this section in order to ascertain the effects of internal resistance of PV array on transient characteristics of array voltage. The internal resistance of the PV array may change with degradation in PV modules, which in turn may lead to changes in transient performance of array voltage signal. For any small signal analysis the procedure followed is the derivation of averaged model, derivation of ac equations, small signal model by taking Laplace transform and by calculating the desired transfer functions. The averaged model of PV array can be obtained by replacing it with an equivalent Thevenin voltage source V_{eq} and equivalent resistance R_{eq} as shown in Fig. 6.

The state variables considered for the small signal analysis of PV-boost system are output voltage (V_o), input or array voltage (V_{in}) and duty cycle (d).

By averaging the state equations for the condition open switch (MOSFET is non-conducting) and closed switch (MOSFET is conducting) the following equations were obtained.

$$-\frac{L}{R_{eq}}\frac{dv_{in}}{dt}=v_{in}-(1-\mathrm{d})v_o \tag{1}$$

$$C\frac{dv_o}{dt}=(1-\mathrm{d})\left(\frac{v_{eq}-v_{in}}{R_{eq}}\right)-\frac{v_o}{R} \tag{2}$$

The state variables were introduced with perturbations as shown in equation below in order to determine the state equations in ac form.

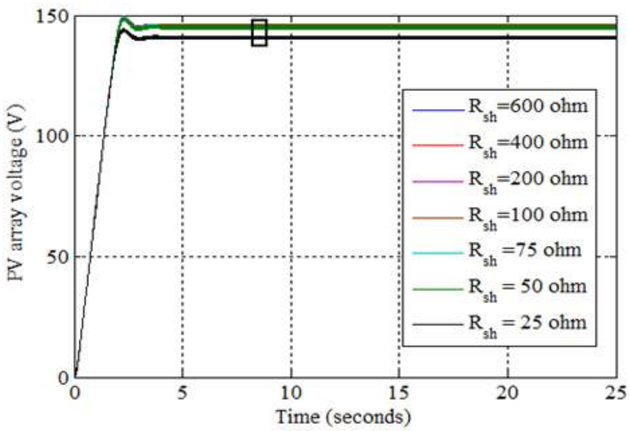

Fig. 7(a) Array voltage for ESC based MPPT with square wave dither

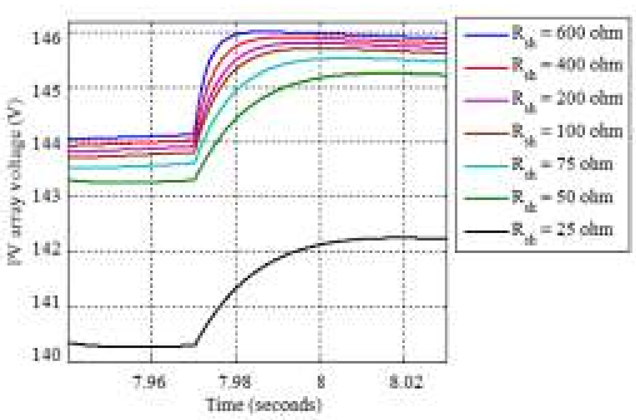

Fig. 7(b) Array voltage for ESC based MPPT with square wave dither

$$v_{in} = V_{in} + \hat{v}_{in} \qquad v_o = V_o + \hat{v}_o \qquad d = D + \hat{d} \tag{3}$$

After introducing the perturbations in state equations, the DC quantities equating to zero are removed and after neglecting the second order AC quantities the following equations were obtained

$$-\frac{L}{R_{eq}}\frac{d\hat{v}_{in}}{dt} = \hat{v}_{in} + V_o \hat{d} - (1-D)\hat{v}_o \tag{4}$$

$$C\frac{d\hat{v}_o}{dt} = (1-\mathrm{D})\left(\frac{-\hat{v}_{in}}{R_{eq}}\right) - \hat{d}\left(\frac{V_{eq} - V_{in}}{R_{eq}}\right) - \frac{\hat{v}_o}{R} \tag{5}$$

Performing Laplace transform of the above equations yields the following equations.

$$-s\frac{L}{R_{eq}}\hat{v}_{in}(\mathrm{s}) = \hat{v}_{in}(\mathrm{s}) - (1-D)\hat{v}_o(\mathrm{s}) + \mathrm{V}_o\hat{\mathrm{d}}(\mathrm{s}) \tag{6}$$

$$Cs\hat{v}_o(\mathrm{s}) = -(1-D)\left(\frac{-\hat{v}_{in}(\mathrm{s})}{R_{eq}}\right) - \hat{d}(\mathrm{s})\left(\frac{V_{eq} - V_{in}}{R_{eq}}\right) - \frac{\hat{v}_o(\mathrm{s})}{R} \tag{7}$$

Upon simplification the small signal transfer function of input voltage to duty ratio is obtained.

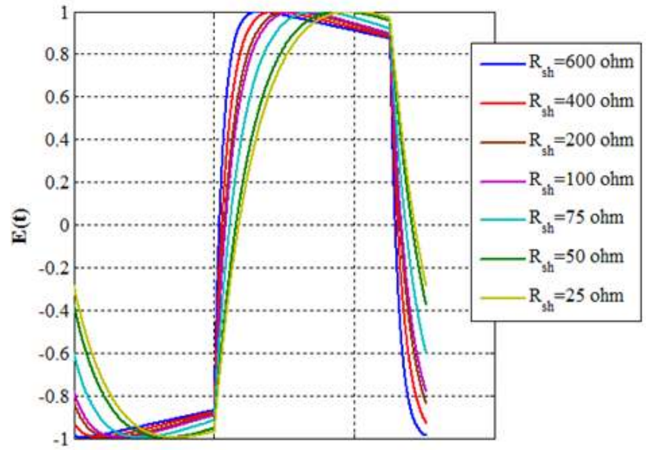

Fig. 8 Error signal E(t) for different shunt resistance in one PV module

$$G_{vd}(\mathrm{s}) = \frac{\hat{v}_{in}(\mathrm{s})}{\hat{d}(\mathrm{s})} = \frac{\left(\dfrac{sV_o R_{eq}}{L} - (1-\mathrm{D})(\mathrm{V}_{eq} - \mathrm{V}_{in})\right)}{s^2 + s\left(\dfrac{R_{eq}}{L} - \dfrac{R}{C}\right) + \dfrac{(1-D)^2}{LC}} \tag{8}$$

IV. Detection of PV Array Internal Resistance Using ESC Based MPPT

The sinusoidal dither in the simulation setup of ESC based PV system was replaced with a square wave dither and the simulation was done for different shunt resistance in only one PV module of the whole array. The array voltage for different shunt resistance is plotted in Fig. 7. The array voltage is zoomed according to the time period of dither signal which is shown in Fig. 7(b). The settling time of array voltage is found to be increasing with decrease in shunt resistance. The array voltage can change with change in irradiance, thus the normal transient performance indices mentioned in [9] need some changes so that the degradation detection is accurate.

The integral performance indices are certain parameters which are used as quantitative measures of the performance of designed control systems. The integral performance indices used for degradation detection are integrated square error (ISE) and integrated absolute error (IAE) which are given by the following formulae.

$$ISE = \int_{t_1}^{t_2} [E(\mathrm{t})]^2 \, dt \qquad IAE = \int_{t_1}^{t_2} |E(\mathrm{t})| \, dt \tag{9}$$

In the above formulae [t1, t2] is time period of dither signal and the error signal E(t) is given by the following formula.

$$E(\mathrm{t}) = \left(\frac{V(\mathrm{t}) - V_{avg}}{V_{\max}}\right) \tag{10}$$

The parameters V_{avg} and V_{max} are the calculated average and maximum value for the given voltage signal V(t) under the period [t_1, t_2]. The error signal for different shunt resistance in only one module from the whole PV array is plotted in Fig. 8 which shows that with decrease in shunt resistance the area

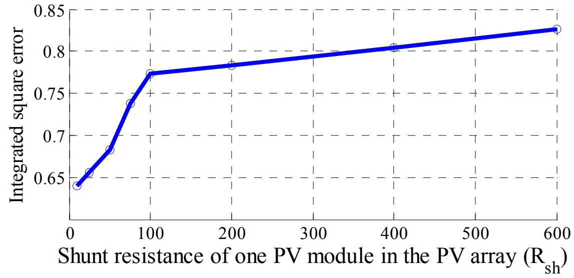

Fig. 9 Scatter plot of shunt resistance and ISE

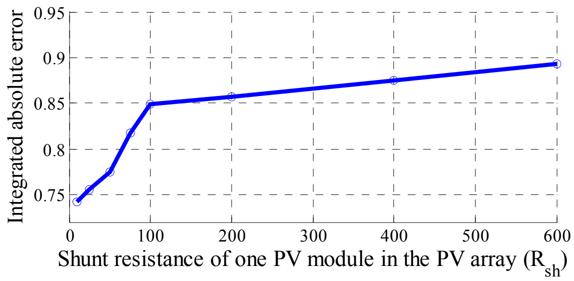

Fig. 10 Scatter plot of shunt resistance and IAE

under the signal also decreases. The integral performance indices ISE and IAE were calculated for different shunt resistance and they are plotted in Fig. 9 and Fig. 10 respectively. The plots of shunt resistance with the integrated square error shows that for normal range of shunt resistance (600 to 100Ω) the ISE also remains within a small range of 0.82 to 0.78. But for shunt resistance less than 100Ω the ISE drops steeply. Thus, if the ISE for the considered PV system at any time drops below 0.78 then it indicates that there is at least one degraded PV module in the array. The plot of shunt resistance and IAE shows that it can also be used to detect the degradation in PV array as the variation is similar to that of ISE.

V. Conclusion

Extremum seeking control (ESC) a class of optimizing control strategies was implemented as MPPT control for centralized inverter PV system. The ESC based MPPT was found to perform the function of tracking maximum power accurately under different irradiance. Also, upon deriving the small signal analysis model of PV-boost converter system it was found that the equivalent resistance of a PV array affects the settling time for a step input in duty ratio. Thus, in order to get a step input for the duty ratio signal the sinusoidal dither in ESC based MPPT was replaced with a square wave dither signal. Upon simulating ESC based MPPT with square wave dither the settling time of array voltage was found to be increasing with decrease in shunt resistance. The integral performance indices used for degradation detection were integrated square error and integrated absolute error which was used on the array voltage signal. The error signal in ISE and IAE were modified so that changes in irradiance does not affect the accuracy of degradation detection. The plot of shunt resistance with ISE and IAE showed that either of them can be used to detect the degradation in PV array.

The degradation detection proposed in this study is based on employing square wave dither extremum seeking control based MPPT. The proposed degradation detection method can be tested experimentally by modifying the MPPT controller. For a better supervision of the PV system even the short term failures like ground faults and arc faults can also be considered along with degradation of PV modules.

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