Received: 2 November 2021 | Revised: 26 February 2022 | Accepted: 20 March 2022

DOI: 10.1002/pip.3559

RESEARCH ARTICLE

PROGRESS IN PHOTOVOLTAICS WILEY

Sensitivity of accuracy of various standard test condition correction procedures to the errors in temperature coefficients of c-Si PV modules

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Funding information
Ministry of New and Renewable Energy of the Government of India, Grant/Award Number: 31/09/2015-16/PVSE-R&D

Abstract

The Standard Test Condition (STC) correction procedures are algorithms used for transforming the Photovoltaic (PV) module current-voltage (*I-V*) data measured at arbitrary conditions back to STC. The PV module Temperature Coefficients are used as inputs by various STC correction procedures and can significantly influence their accuracy. This paper presents the sensitivity analysis of accuracy of six STC correction procedures (IEC 60891-Procedure 1, Procedure 2, Modified IEC 60891-Procedure 1, IEC 60891-Procedure 4 (Voltage Dependent Temperature Coefficient (VDTC) Procedure), Anderson Procedure, and Standard Irradiance and Desired Temperature Procedure) to the errors in the temperature coefficients of P_{max}, V_{oc}, and I_{sc}. Experimentally measured as well as simulated *I-V* curves of six multi c-Si PV modules were used in this study. IEC 60891-Procedure 4 (Voltage Dependent Temperature Coefficient) that uses a Voltage Dependent Temperature Coefficient which can be calculated using a single measured *I-V* curve was found to be most robust against errors in the temperature coefficients.

KEYWORDS

accuracy, average percentage error, experiment, performance parameters, sensitivity, simulation, STC correction, temperature coefficient

1 | INTRODUCTION

Accurate estimation of the residual power of Solar Photovoltaic (PV) modules at Standard Test Conditions (STC) is necessary to calculate the degradation rates and decide the eligibility of PV modules for warranty returns. The following approaches are typically used to measure or estimate the residual power at STC and estimate the degradation rates of PV modules: (i) shipping of a limited number of modules to certified test labs for *I-V* measurements at STC with low uncertainty, (ii) on-site *I-V* measurements at STC using a mobile test lab equipped with solar simulators, and (iii) on-site *I-V* measurements in field using portable *I-V* tracers under uncontrolled environmental conditions followed by correction of *I-V* data to STC. Out of these methods, the first one offers the lowest measurement uncertainty; however, it is also the most expensive approach as far as measurement cost per module is concerned. In fact, the cost of shipping a module from an often remotely located PV plant to the test lab, followed by the measurement, often exceeds the cost of the module itself. These constraints limit the applicability of this approach to a small number of module samples. The second method brings the test lab to the PV plant site—thus eliminating shipping and possible damages that could be caused during shipping. However, the modules still need to be uninstalled from the structure and reinstalled after the measurement—which can lead to generation of new cell cracks or worsening of existing cracks. Also, the modules need to be stored indoors and cooled before performing the measurement at STC, which affects the throughput of measurements. Due to these constraints associated with the first two approaches, the third approach is often preferred for large-scale, periodic *I-V* studies as it offers the lowest cost and poses virtually no risk to the modules. However, the uncertainty in the estimated STC power is also the highest in the third approach. The accuracy of STC correction algorithms considerably impacts the overall uncertainty associated with the field I-V measurements. In the literature, various STC correction procedures are available such as: IEC 60891-Procedure 1, Procedure 2, and Procedure 3[1,2]; Modified IEC 60891-Procedure 1[3,4]; Anderson Procedure[5]; Standard Irradiance and Desired Temperature (SIDT) Procedure[6]; and IEC 60891-Procedure 4 (VDTC).[1,7,8] The comparison of accuracy of six STC correction procedures and the average percentage errors in STC correction of various performance parameters like P_{max}, V_{oc}, I_{sc}, and *FF* for different irradiance and temperature conditions were previously reported by the authors Golive et al.[9] for c-Si PV modules through experimental and simulation studies. It was shown that IEC 60891-Procedure 1 and Procedure 2 and IEC 60891-Procedure 4 (VDTC) deliver highest accuracies in STC correction in the range of 700–1,300 W/m^2, which is the range of interest for outdoor measurements as per IEC 60891 standard. The same conclusion was also valid in a broader range of 200–1,300 W/m^2 irradiance. Out of these procedures, the IEC 60891-Procedure 4 (VDTC) (the authors have used this name throughout this paper for IEC 60891-Procedure 4, to be consistent with our previous publication[9]) was deemed most appropriate for field applications due to its high accuracy and the requirement of only one *I-V* curve measured in the field. It should be noted that the VDTC procedure described in Hishikawa et al.[8] and the IEC 60891-Procedure 4 described in the standard have a minor difference. However, this difference does not lead to any considerable effect on the errors associated with this procedure. In this paper, the IEC 60891-Procedure 4 (VDTC) refers to the procedure described in the standard. Each of these, six procedures use at least one temperature coefficient for performing STC correction. High accuracy measurement of temperature coefficients usually requires an environmental chamber connected with the solar simulator. Since this is not possible during outdoor *I-V* measurements at a PV plant site, the temperature coefficients given in the module datasheet are often used for STC correction. The uncertainties in PV module Temperature Coefficients (TC) could arise from the measurement and/or due to technology specific variations. The measurement uncertainties in TC are due to the following reasons: (i) non-uniformity of temperature across the module, (ii) difference between the actual cell temperature and measured backsheet temperature, and (iii) variation in the spectrum of solar simulators used. The round robin measurements of temperature coefficients at different certified test labs have also shown considerable variation in each of the temperature coefficients for not only the same technology but also for the same PV modules.[10–13] Even though the magnitude of Short Circuit Current temperature coefficient (α) is very low compared to Open Circuit Voltage and Maximum Power temperature coefficients (β and γ), the uncertainty associated with its measurement can be significantly high.[10,14]

Uncertainty in the values of temperature coefficients of Short Circuit Current (I_{sc}), Open Circuit Voltage (V_{oc}), and Maximum Power (P_{max}) (α, β, and γ, respectively) used by the STC correction procedures affect the accuracy of correction. As often the temperature coefficient values mentioned in the datasheet are used in STC correction, since neither the exact procedure of temperature coefficient measurement nor the uncertainty is mentioned in the PV module datasheet, there is a risk of introducing significant error in the STC correction. In cases where no information about the temperature coefficients is available (e.g., lack of datasheets), one has to depend on the technology specific values mentioned in the literature. This will further add to the uncertainty in the temperature coefficients. Thus, this paper focuses on the estimation of sensitivity of accuracy of six STC correction procedures to the errors in all the temperature coefficients (α, β, and γ). The following STC correction procedures are considered in this paper: IEC 60891-Procedure 1 and Procedure 2, Modified IEC 60891-Procedure 1, IEC 60891-Procedure 4 (VDTC), Anderson Procedure, and SIDT Procedure. Brief description of these six STC correction procedures and the equations used by them in the STC correction are mentioned in Data S1. The sensitivity of all the STC corrected performance parameters (P_{max}, V_{oc}, I_{sc}, and *FF*) has been estimated and reported.

2 | METHODOLOGY

The *I-V* curves of six multi-c-Si PV modules (three each from the two major tier-1 module manufacturers[15]) were experimentally measured at STC and at other irradiance and temperature conditions using the SPIRE 5600SLP BLUE system. Based on these measurements and the simulation models discussed in previous studies,[9,16–18] the *I-V* curves at desired temperature and irradiance values were generated. The irradiance conditions for the experimentally measured *I-V* curves range from 200 to 1,100 W/m^2 with a step of 100 W/m^2, while the temperature conditions range from 25°C to 70°C with a step of 5°C. The *I-V* curves generated through simulation have the same temperature range and step size; however, they are generated over a slightly broader irradiance range of 200 to 1,300 W/m^2 with the same step size. The Average Root Mean Square Error (ARMSE) was computed by comparing the experimentally measured *I-V* curves with those that were generated through simulation.[9] The average percentage errors in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and *FF*) for the entire range of measured and simulated irradiance and temperature conditions for all the six STC correction procedures were predicted and reported.[9] The reported average percentage errors in STC correction in Golive et al.[9] are predicted with an assumption that we know the true values of temperature coefficients. However, in reality, the temperature coefficients given in the module datasheets could have high uncertainty. Figure 1 shows the I_{sc}, V_{oc}, and P_{max} temperature coefficients (α, β, and γ) of mono and multi c-Si PV modules mentioned in the datasheets of 26 modules inspected during All-India Survey (AIS) of PV module reliability 2018.

Figure 1 shows that the outliers in V_{oc} and P_{max} temperature coefficients (β and γ) deviate up to ±15% to ±20% from the mean value for multi c-Si PV modules, and the deviation in I_{sc} temperature coefficient (α) is even more (up to 70% in rare cases). Similar observations were found in literature[10–13] where the deviation in V_{oc} and P_{max} temperature coefficients (β and γ) was found up to ±10% to ±15% from mean value in the round robin testing among the certified test labs. In

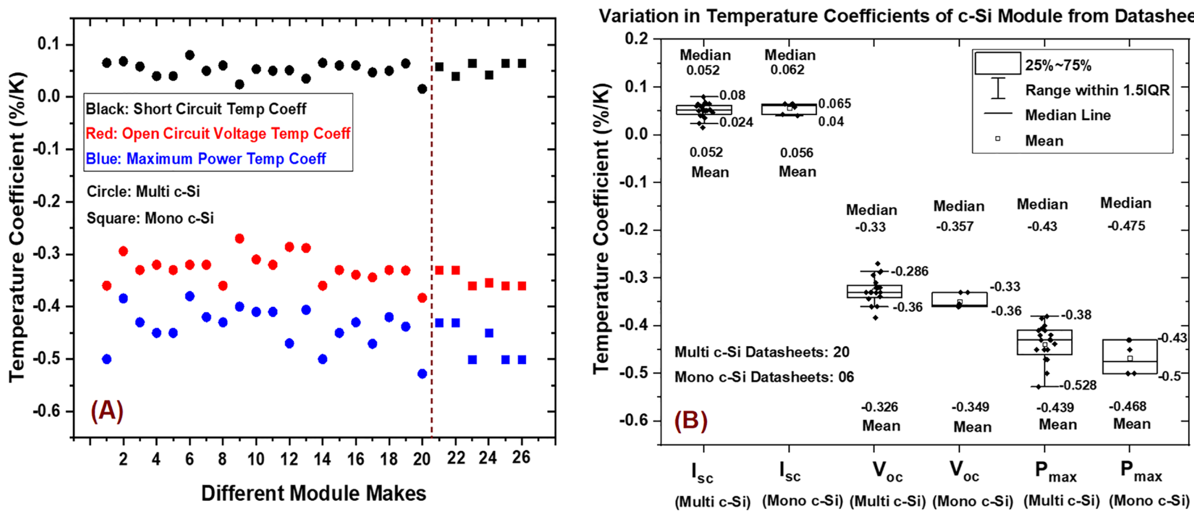
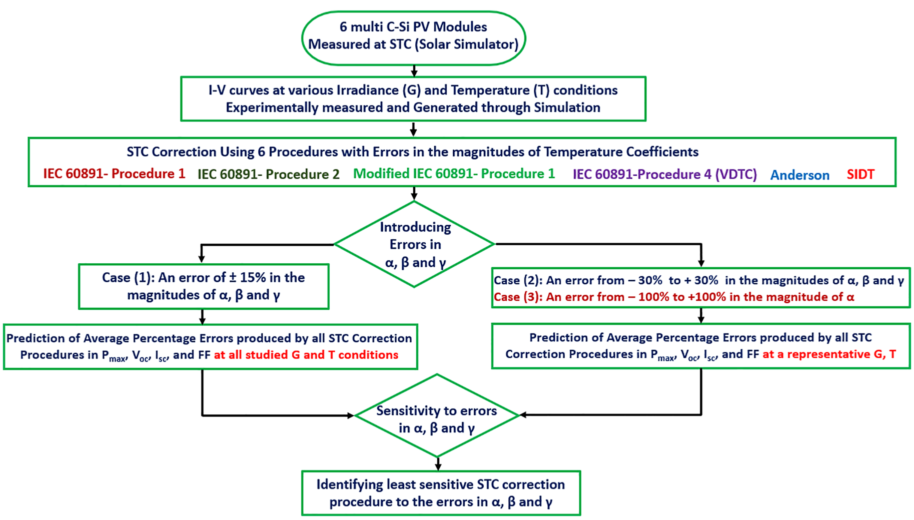


FIGURE 1 Temperature coefficients (α, β, and γ) of c-Si PV modules mentioned in the datasheets of modules inspected during AIS 2018 (A) Scatter Plot and (B) Box Plot

TABLE 1 True and erroneous (±15% in magnitude) temperature coefficients of six c-Si PV modules of both module makers (tier-1; three modules from each) used in this study

Temperature coefficient	Datasheet values	Error (+15%)	Error (−15%)	Datasheet values	Error (+15%)	Error (−15%)
	Module Make-1			Module Make-2		
α (%/K)	+0.05	+0.0575	+0.0425	+0.06	+0.069	+0.051
β (%/K)	−0.32	−0.368	−0.272	−0.30	−0.345	−0.255
γ (%/K)	−0.41	−0.472	−0.349	−0.40	−0.46	−0.34

FIGURE 2 Flowchart for predicting the least sensitive STC correction procedure for errors in all the temperature coefficients (α, β, and γ) with experimental and simulation input data



this paper, to account for uncertainties associated with measurement/datasheet values/choosing representative technology specific values of temperature coefficients from the literature, the following cases are considered: (i) an error of ±15% in the magnitude in all the three (α, β, and γ) temperature coefficients (Table 1; Case 1); (ii) an error of −30% to +30% in the magnitude in all the three (α, β, and γ) temperature coefficients (Case 2); and (iii) an error of −100% to +100% in the magnitude of only I_{sc} temperature coefficient (α) (Case 3). For each of these cases, the errors produced by various STC correction procedures in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and FF) as a

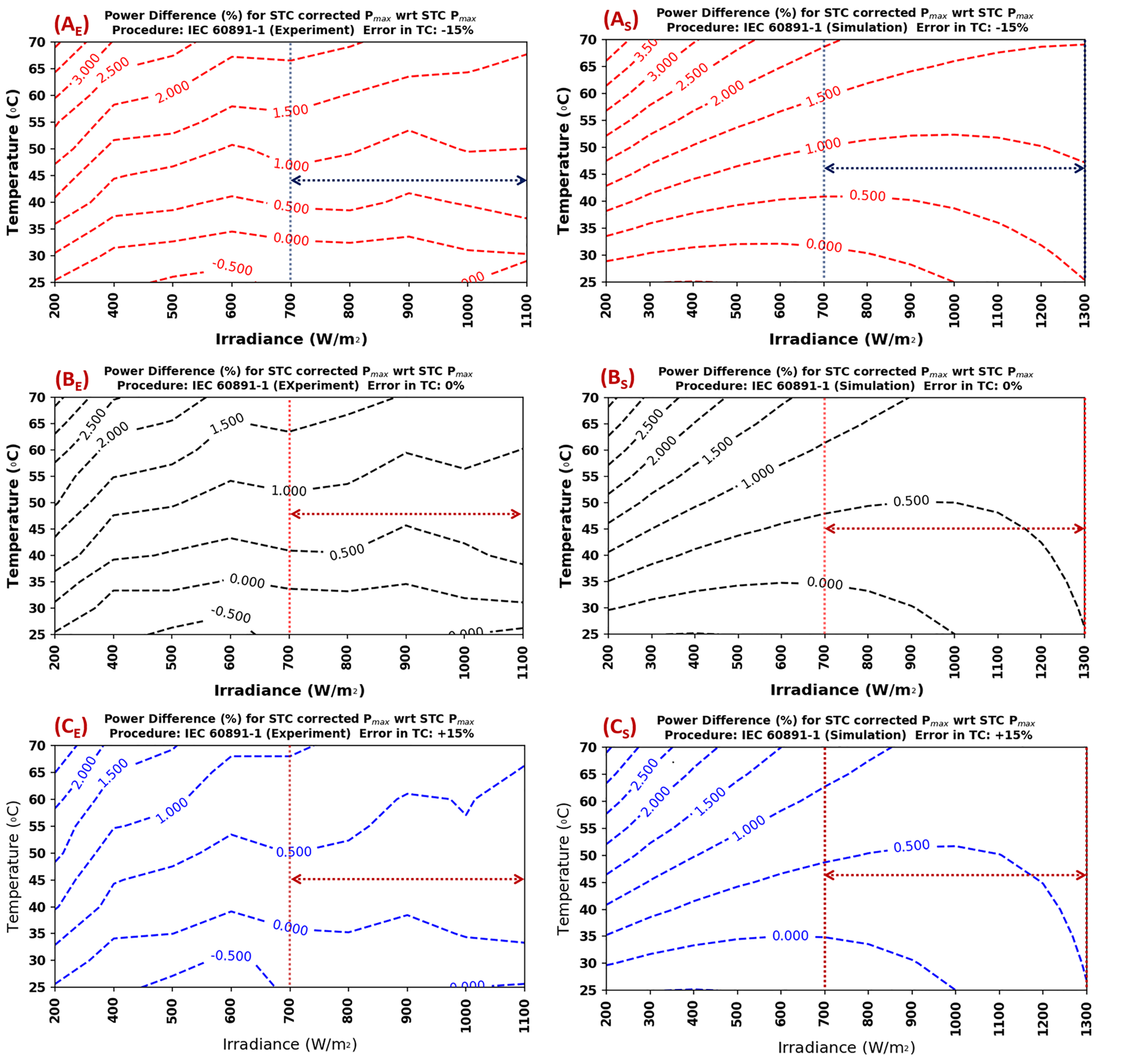


FIGURE 3 Contour plots of average percentage errors in P_{max} obtained in STC correction by IEC 60891-Procedure 1 with -15% (A_E, A_s), 0% (B_E, B_s),[9] and $+15\%$ (C_E, C_s) errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

result of uncertainty in the temperature coefficients were analyzed. For this error estimation, the experimentally measured and simulated *I-V* curves of six multi-c-Si PV modules from two major tier-1 module manufacturers (three from each) were given as input to all the STC correction procedures considered in this study. Figure 2 shows the end-to-end flow chart of the methodology followed in this study for identifying the least sensitive STC correction procedure when high uncertainty in the values of the temperature coefficients is present.

3 | RESULTS

The contour plots of average percentage errors in all the performance parameters produced by all the six STC correction procedures for the errors in the magnitudes of temperature coefficients (±15%) were generated with respect to irradiance and temperature for the experimental and simulated data. Percentage error in STC correction of any performance parameter can be calculated using Equation 1, and then, it was averaged for six PV modules as discussed in Golive et al.[9] to give the average percentage error. The changes in average percentage errors in all the performance parameters with respect to temperature at any irradiance condition for -15% and for $+15\%$ errors in all the temperature coefficients (Case 1) were estimated. The average percentage errors in all the performance parameters for an error of -30% to $+30\%$ with a step of 5% (Case 2) in all the temperature coefficients and for an error in only I_{sc} temperature coefficient (α) (-100% to $+100\%$ with a step of 10%; Case 3) were also estimated at a representative irradiance and temperature condition observed in the field.

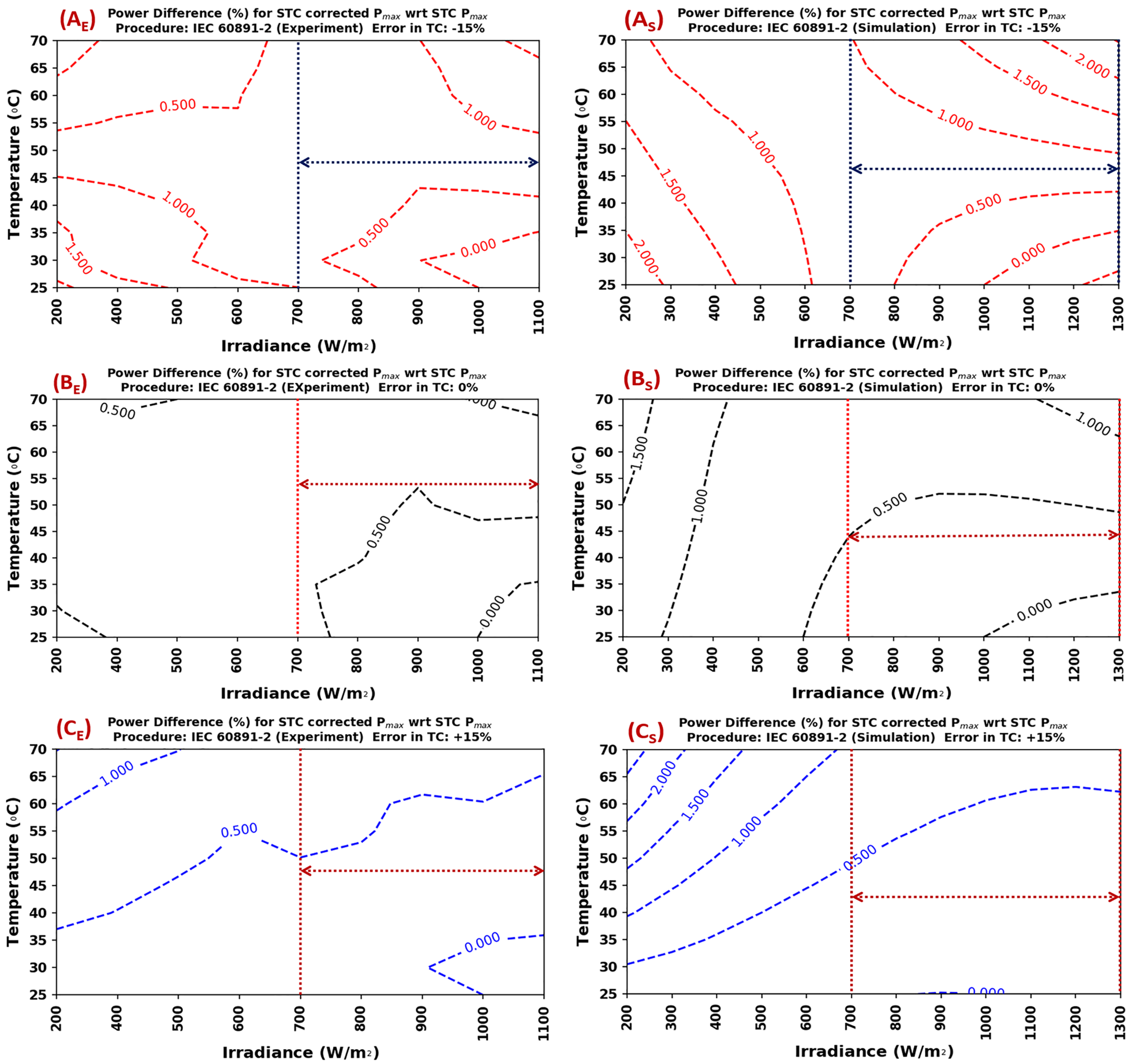


FIGURE 4 Contour plots of average percentage errors in P_{max} obtained in STC correction by IEC 60891-Procedure 2 with −15% (A_E, A_s), 0% (B_E, B_s),[9] and +15% (C_E, C_s) errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

$$\text{Percentage Error}(\%) = \left(\frac{\text{Value after Corrected to STC} - \text{Actual Value at STC}}{\text{Actual Value at STC}}\right) \times 100. \tag{1}$$

3.1 | Case 1: STC correction errors for the ±15% error in all the three temperature coefficients

The average percentage errors in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and FF) produced by all the six STC correction procedures for the errors in the magnitudes of temperature coefficients (±15%, Table 1) were plotted in the form of contour plots. Figures 3–8, S1–S6, S7, and S8–S13 show the contour plots of average percentage errors in P_{max}, V_{oc}, I_{sc}, and FF. For all performance parameters, the contour plots of errors for experimental and simulation input data were found to be comparable. Figures 3–8 show the contours plots of errors in STC correction of P_{max} for experimental and simulation data. The demarcation lines for experimental and simulation contours (700 to 1,300 W/m^2) represent the range of irradiation conditions recommended by IEC 60891 Standard (Edition 3.0, 2021-10),[1] to measure the I-V curve to apply the STC correction procedures for both irradiance and temperature correction. The contour plots of average percentage errors in STC correction of V_{oc} (Figures S1–S6) and FF (Figures S8–S13) are shown for both experimental and simulation input data. But the contour plots of errors in STC correction of I_{sc} were shown only for simulation input data (Figure S7) since it covers a

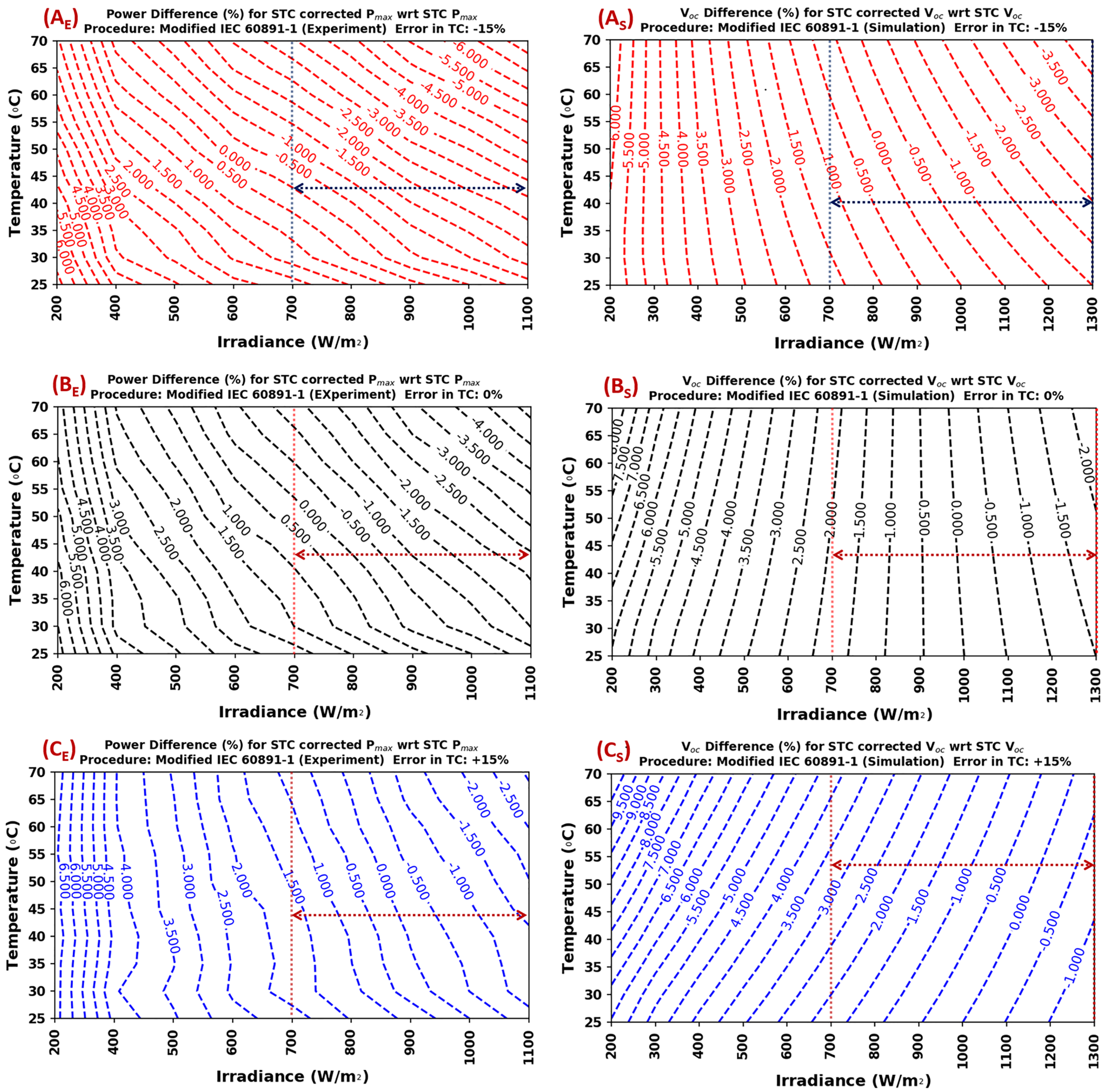


FIGURE 5 Contour plots of average percentage errors in P_{max} obtained in STC correction by Modified IEC 60891-Procedure 1 with -15% (A_E, A_s), 0% (B_E, B_s),[9] and $+15\%$ (C_E, C_s) errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

wider irradiance range (200 to 1,300 W/m^2) than the experimental (200 to 1,100 W/m^2) data. The percentage errors produced by all the six STC correction procedures in I_{sc} are similar for a given error in temperature coefficient. Therefore, only the contour plots for IEC 60891-Procedure 1 are shown, which could be considered as representative for all the procedures (Figure S7).

IEC 60891-Procedure 1 and Procedure 2 show relatively low sensitivity in P_{max}, but moderate to high sensitivity in V_{oc} and *FF* correction. Along with the sensitivity to erroneous temperature coefficients, the requirement of multiple measured *I-V* curves make these procedures less attractive to high throughput field *I-V* measurements.[9] Modified IEC 60891-Procedure 1 shows relatively high sensitivity in P_{max} and V_{oc} correction, and Anderson and SIDT procedures show the highest sensitivity in P_{max} and V_{oc} correction. IEC 60891-Procedure 4 (VDTC) shows the least sensitivity in P_{max}, V_{oc}, and *FF* correction, and it is also the most suitable procedure for high throughput field *I-V* measurements of conventional c-Si PV modules.[9] The analysis of the observed sensitivities of all the six STC correction procedures for erroneous temperature coefficients is presented in section 4.1.

3.2 | Change in STC correction errors with respect to temperature for Case 1

The change in average percentage errors in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and *FF*) produced by all the six STC correction procedures with ±15% error in all the three (α, β, and γ) temperature coefficients were plotted with respect to temperature (Figure 9).

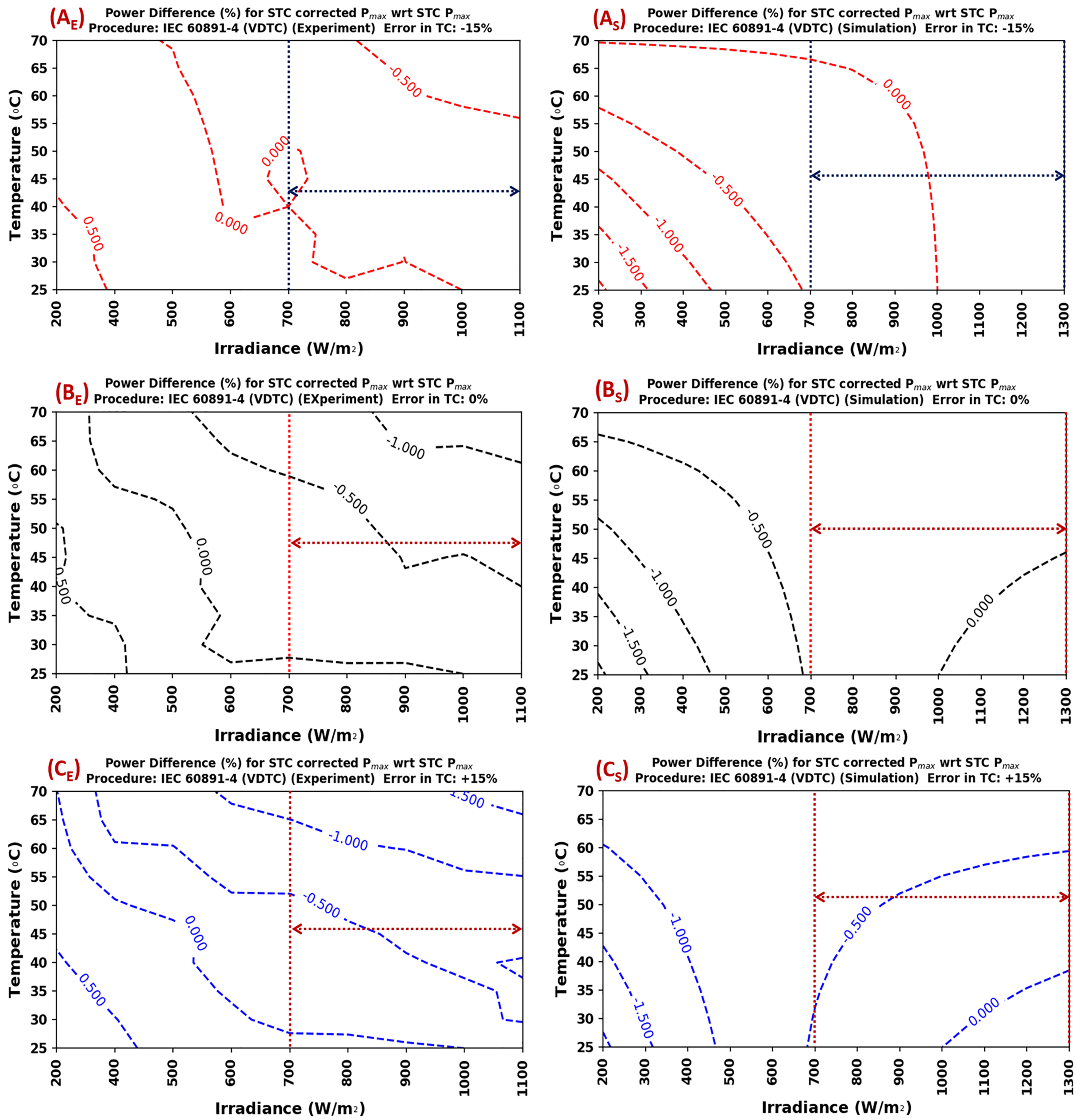


FIGURE 6 Contour plots of average percentage errors in P_{max} obtained in STC correction by IEC 60891-Procedure 4 (VDTC) with −15% (A_E, A_s), 0% (B_E, B_s),[9] and +15% (C_E, C_s) errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

The change in STC correction error was calculated using Equation 2. The obtained change in STC correction errors with respect to temperature are almost independent of irradiance, so Figure 9 was plotted at a single irradiance (1,000 W/m^2; similar results were observed for all the irradiance conditions used in this study).

$$\text{Change in STC Correction Error}\,(\%) \\ = \text{Error with Erroneous TC}\,(\%) - \text{Error with True TC}\,(\%). \quad (2)$$

IEC 60891-Procedure 4 (VDTC) produce the least change in average percentage error in P_{max}, V_{oc}, and FF correction, compared to the remaining five STC correction procedures at all the temperature conditions. But all the six STC correction procedures including IEC 60891-Procedure 4 (VDTC) similar change in average percentage error in I_{sc} correction, and the details are discussed in Section 4.1.

3.3 | Case 2: STC correction errors for an error of −30% to +30% in all the three temperature coefficients

The average percentage errors produced by all the six STC correction procedures in all the performance parameters with an error (−30% to

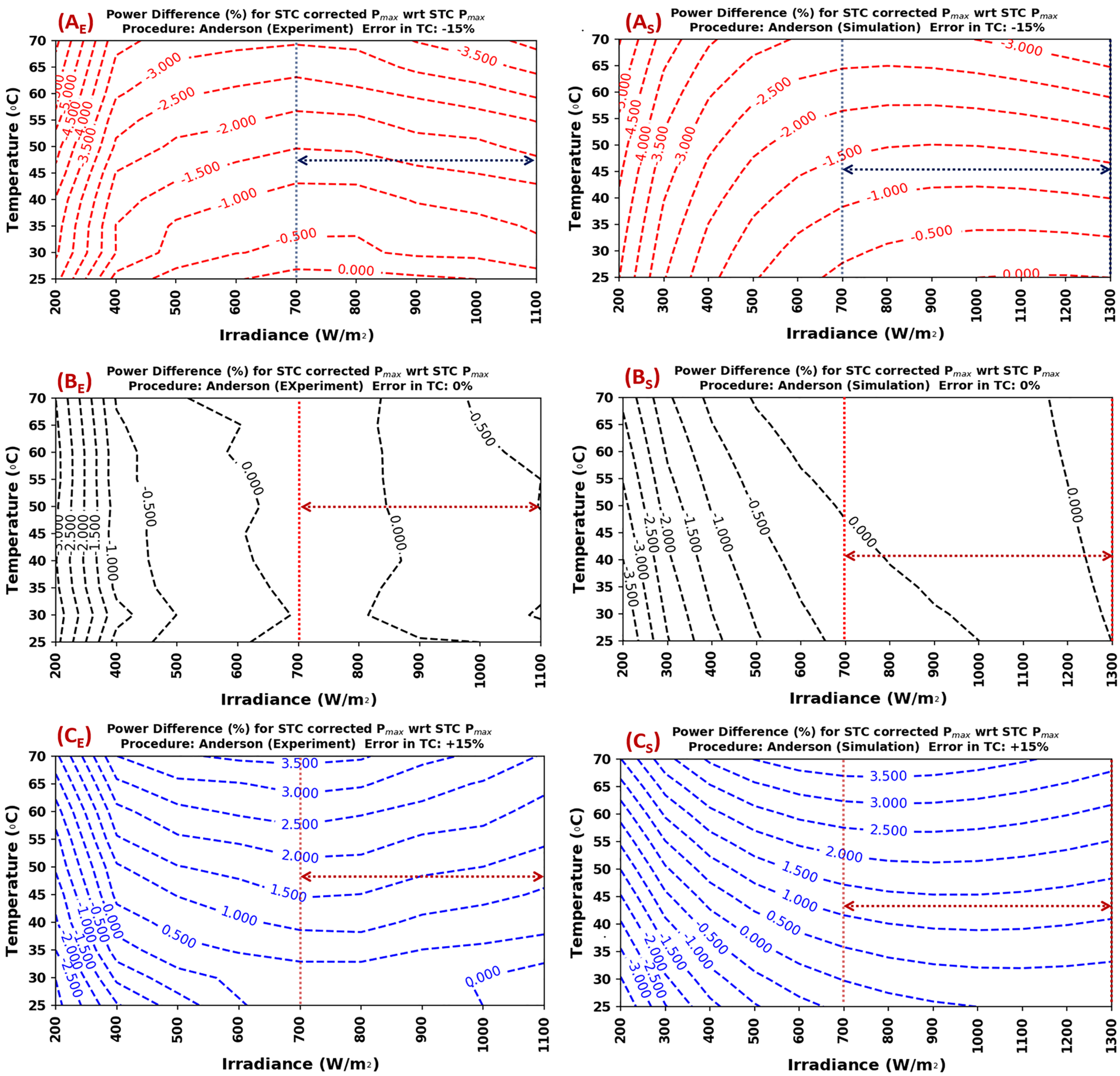


FIGURE 7 Contour plots of average percentage errors in P_{max} obtained in STC correction by Anderson procedure with (A_E, A_s) -15%, (B_E, B_s) 0%,[9] and (C_E, C_s) $+15\%$ errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

+30%, with a step of 5%) in all three temperature coefficients (α, β, and γ) were also estimated. To plot the STC correction errors with an error of −30% to +30%, with a step of 5% in the three temperature coefficients, a representative measured irradiance (G_m) and cell temperature (T_c) condition was obtained from the analysis of measurement conditions in All India Survey (AIS) of PV module reliability performed in 2018. Figure 10 shows the histograms of measured irradiance and cell temperature during the survey, and it was observed that the likelihood of occurrence of the conditions of 900 W/m^2 and 63°C was maximum in the field. Figure 11 shows the STC correction errors in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and FF) with error of −30% to +30% in the temperature coefficients at the closest condition (900 W/m^2 and 65°C; from experimental and simulation data) to the representative condition observed in AIS 2018. Similar numbers are likely to be encountered in several other locations with hot/sunny climates.

Even for the case of varying magnitudes of all the temperature coefficients to a wider range (from −30% to +30%), similar observations were made as that of Section 3.1. IEC 60891-Procedure 4 (VDTC) shows least sensitivity at the mentioned representative conditions. The details are discussed in Section 4.2.

3.4 | Case 3: STC correction errors for an error in only I_{sc} temperature coefficient

Among the three temperature coefficients, the I_{sc} temperature coefficient (α) is reported to have highest uncertainty.[10,14] The reasons for

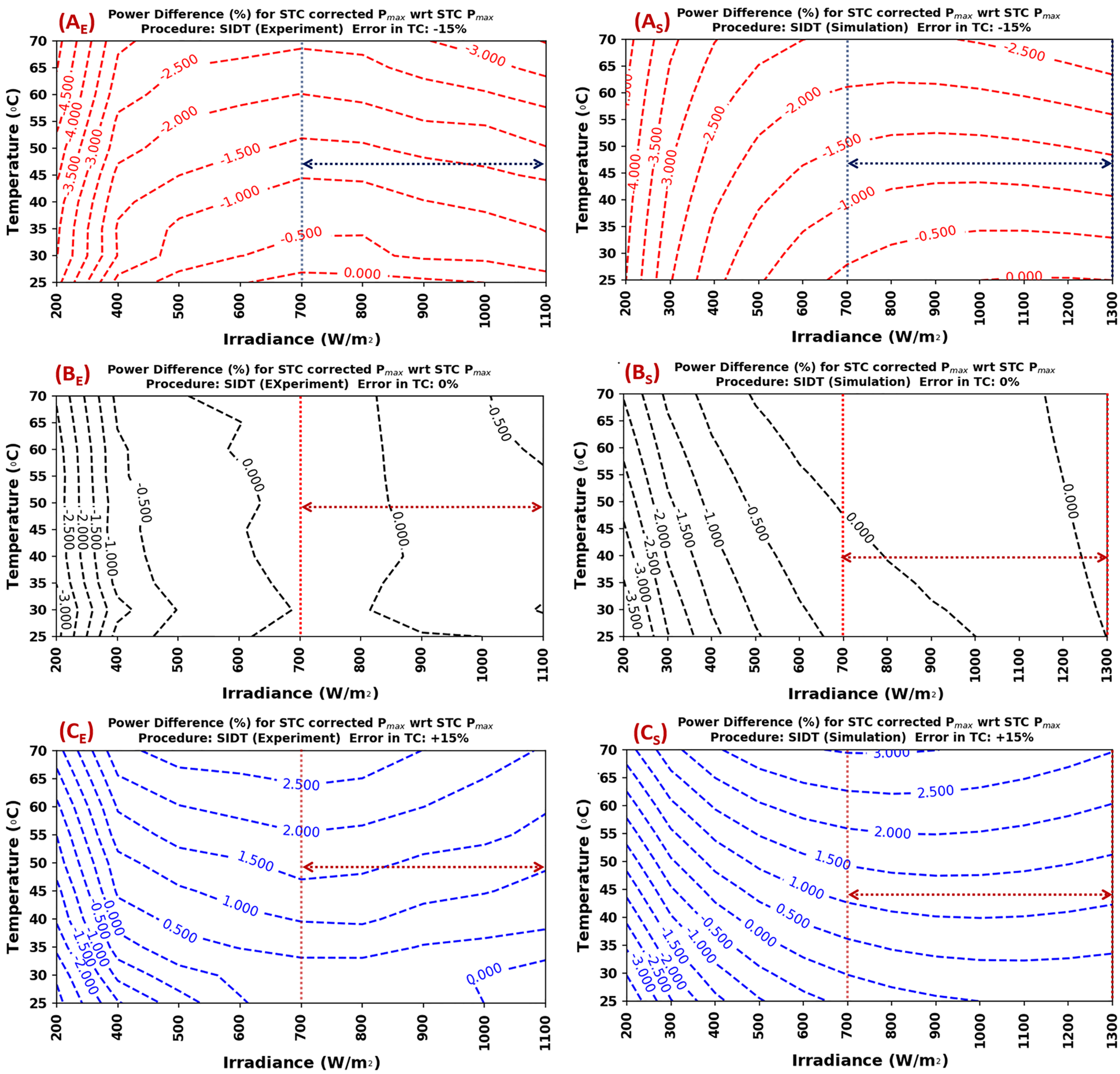


FIGURE 8 Contour plots of average percentage errors in P_{max} obtained in STC correction by SIDT procedure with (A_E, A_s) -15%, (B_E, B_s) 0%,[9] and (C_E, C_s) $+15\%$ errors in all three TC (α, β, and γ) for experimental (left) and simulation (right) data

possible occurrence of highest uncertainty in the measurement of I_{sc} temperature coefficient (α) compared to other two temperature coefficients (β and γ) are the following: (i) mismatch in spectral irradiance of solar simulator with respect to the reference AM1.5G spectrum,[14] (ii) variation of spectrum in the solar simulators used across various test labs,[10] and (iii) mismatch in spectral responses of reference device and the device under test with temperature.[14] To estimate the effect of error in the temperature coefficient of I_{sc} (α) on the STC corrected parameters, the following calculation was performed: The error in the I_{sc} temperature coefficient (α) has been varied from -100% to $+100\%$ (with a step of 10%), and no error is assumed in the temperature coefficients of V_{oc} and P_{max} (β and γ). Detailed description of the findings is mentioned in Data S2, and the change in STC correction errors in all the performance parameters (P_{max}, V_{oc}, I_{sc}, and FF) with respect to the error in I_{sc} temperature coefficient (α) are shown in Figure S14. It was observed that Modified IEC 60891-Procedure 1 and IEC 60891-Procedure 4 (VDTC) show highest sensitivity in P_{max} correction (but the change in error is still within ±1% even at 50% error in α); Anderson and SIDT procedures show least sensitivity. For the error in only I_{sc} temperature coefficient (α) in V_{oc} correction, all the six STC correction procedures have negligible sensitivity. All the six STC correction procedures show similar sensitivity in I_{sc} correction, and Modified IEC 60891-Procedure 1 and IEC 60891-Procedure 4 (VDTC) have low sensitivity in FF correction.

4 | DISCUSSION

Estimation of average percentage errors in all the performance parameters produced by all six STC correction procedures with true

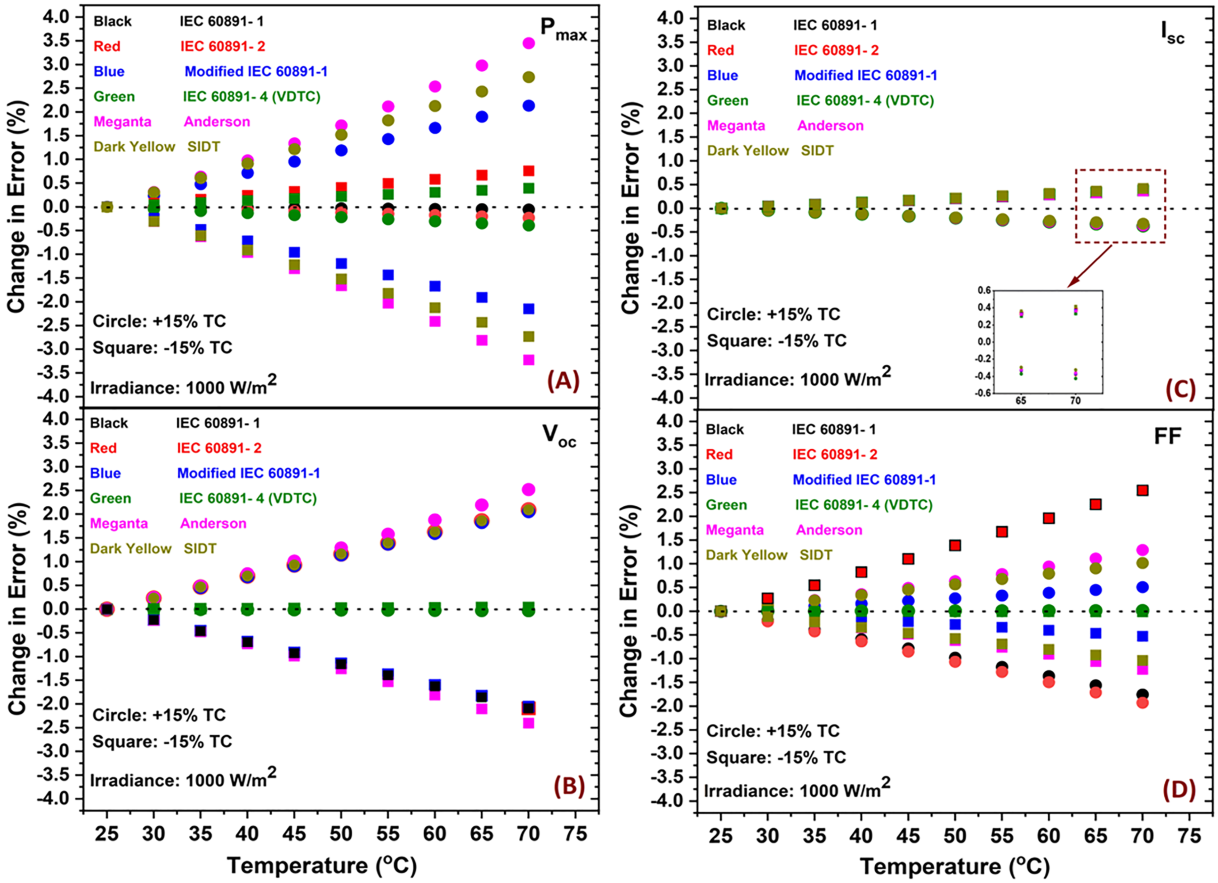


FIGURE 9 Change in average percentage error in (A) P_{max}, (B) V_{oc}, (C) I_{sc}, and (D) FF produced by all six STC correction procedures with erroneous (±15%) TC with respect to temperature at 1,000 W/m^2 irradiance condition (similar for other irradiances also)

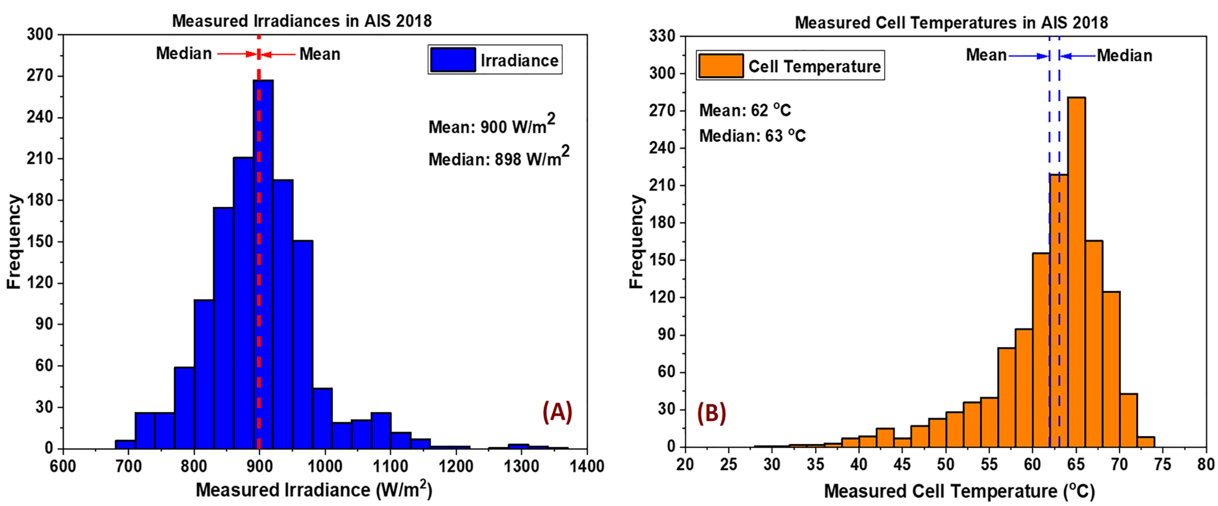


FIGURE 10 Histograms of measured (A) irradiances (G_m) and (B) cell temperatures (T_c) during All India Survey (AIS) of PV module reliability 2018

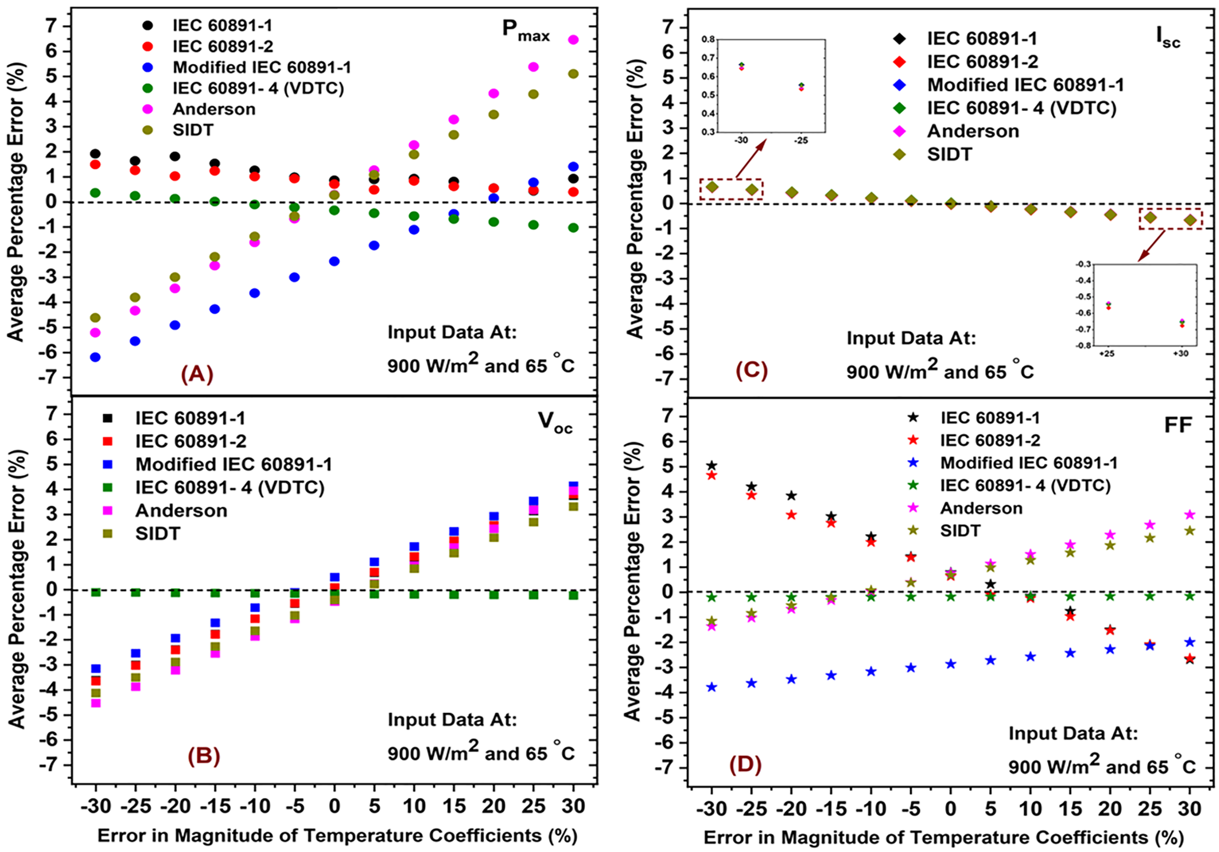


FIGURE 11 Average percentage error in (A) P_{max}, (B) V_{oc}, (C) I_{sc}, and (D) FF produced by all six STC correction procedures with respect to an error (from −30% to +30% with a step of 5%) in all three TC at an irradiance (G_m) and temperature (T_c) condition closest to the representative of AIS 2018

temperature coefficients was reported in Golive et al.[9] In this study, sensitivity of accuracy of six STC correction procedures was analyzed for three different cases of errors in temperature coefficients.

4.1 | An error of ±15% in all the three temperature coefficients (Case 1)

IEC 60891-Procedure 1 and Procedure 2 show relatively low sensitivity (within ±1%) in estimating P_{max} (Figures 3 and 4), and the reasons are as follows: (i) These procedures use only two temperature coefficients (α and β), of which the magnitude of I_{sc} temperature coefficient (α) is considerably small (~0.04%/°C to 0.06%/°C for c-Si technology). (ii) IEC 60891-Procedure 1 uses Series Resistance (R_s); IEC 60891-Procedure 2 uses Series Resistance (R_s') and Irradiance correction factors (B_2, and B_1) for V_{oc}. All these three parameters are independent of temperature coefficients. (iii) Even though Curve Correction Factor (K or K') used in these procedures depends on temperature coefficients, its value is computed in accordance with the values of temperature coefficients (α and β) which ensures that these procedures are less sensitive. (iv) Error in V_{oc} temperature coefficient (β) contributes significantly to the observed sensitivity in P_{max} estimation. Modified IEC 60891-Procedure 1 also uses only two temperature coefficients (α and β), but it assumes the values of R_s and K as zero. The error in V_{oc} temperature coefficient (β) and zero value of K are important sources of observed relatively high sensitivity of P_{max} (Figure 5) estimation (up to ±2.2%) by this procedure. Anderson and SIDT procedures perform similarly and their sensitivity to the errors in all the temperature coefficients is the highest. They use all three temperature coefficients (α, β, and γ), and error in P_{max} temperature coefficient (γ) is directly responsible for observed high sensitivity of P_{max} (Figures 7 and 8) estimation (up to ±3.5% for Anderson and up to ±2.75% for SIDT). Out of all the six STC correction procedures, IEC 60891-Procedure 4 (VDTC) is least sensitive to errors in temperature coefficients in estimating P_{max} (Figure 6) (within ±0.5%), due to the following reasons: (i) This procedure uses only I_{sc} temperature coefficient (α), and its value is considerably small (~0.04%/°C to 0.06%/°C for c-Si technology). (ii) Instead of using V_{oc} temperature coefficient (β), it uses Voltage Dependent Temperature Coefficient (VDTC) which can be calculated from the single measured *I-V* curve itself. (iii) Error in I_{sc} temperature coefficient (α) is the only significant contributor for observed sensitivity of P_{max} estimation using IEC 60891-Procedure 4 (VDTC).

The contour plots of average percentage errors in V_{oc} by all STC correction procedures are shown in Figure S1–S6 for the experimental and simulation input data. It is evident that all the procedures

TABLE 2 Maximum change in error (MCE) of performance parameters at the highest temperature (70°C) used in this study for all the STC correction procedures with erroneous (±15%) temperature coefficients

Parameter	Maximum change in error (MCE) (%)								AAE
	P_{max}		V_{oc}		I_{sc}		FF		
Error in TC (α, β and γ)	−15%	+15%	−15%	+15%	−15%	+15%	−15%	+15%	
IEC-60891-1	+0.07	−0.77	−2.07	+2.07	+0.37	−0.37	+1.76	−2.55	5.02
IEC-60891-2	+0.58	−0.72	−1.82	+1.82	+0.39	−0.39	+2.00	−2.10	4.96
Modified IEC-60891-1	−2.13	+2.15	−2.05	+2.05	+0.37	−0.38	−0.51	+0.53	5.09
IEC 60891–4 (VDTC)	+0.40	−0.40	+0.04	−0.04	+0.37	−0.37	−0.02	+0.02	0.83
Anderson	−3.47	+3.25	−2.52	+2.40	+0.36	−0.37	−1.37	+1.30	7.52
SIDT	−2.73	+2.73	−2.09	+2.09	+0.37	−0.42	−1.02	+1.04	6.25

except IEC 60891-Procedure 4 (VDTC) are quite sensitive to errors in all the temperature coefficients in V_{oc} estimation (IEC 60891-Procedure 1 (Figure S1): up to ±2.1%, and Procedure 2 (Figure S2): up to ±1.8%, Modified IEC 60891-Procedure 1 (Figure S3): up to ±2.1%, Anderson procedure (Figure S5): up to ±2.5%, SIDT procedure (Figure S6): up to ±2.1%, and IEC 60891-Procedure 4 (VDTC) (Figure S4): within ±0.05%). The key reason behind superior performance of IEC 60891-Procedure 4 (VDTC) with respect to others is that all the other STC correction procedures use V_{oc} temperature coefficient (β) while IEC 60891-Procedure 4 (VDTC) uses Voltage Dependent Temperature Coefficient as mentioned earlier in this section. The error in V_{oc} temperature coefficient (β) is responsible for high sensitivity of V_{oc} estimation by all other procedures. Among all six STC correction procedures, IEC 60891-Procedure 4 (VDTC) not only estimates the most accurate V_{oc}[9] but it is also the least sensitive (within ±0.05%) to errors in temperature coefficients.

The estimation of average percentage errors in I_{sc} by IEC 60891-Procedure 1 is shown in contour plots in Figure S7 (it was found to be similar for all other STC correction procedures). All the STC correction procedures show low sensitivity to errors in all the temperature coefficients in I_{sc} estimation. The reason behind this is all the six procedures including IEC 60891-Procedure 4 (VDTC) use I_{sc} temperature coefficient (α) and the error in it is the only contributor for observed sensitivity (within ±0.4%). As the magnitude of α is much less than that of β and γ for c-Si technology, for the same amount of percentage error (±15%) in all the temperature coefficients, sensitivity in I_{sc} estimation is lowest for all the STC correction procedures.

The estimations of average percentage errors in *FF* by all STC correction procedures are shown in contour plots in Figures S8–S13 for errors in all the temperature coefficients. It was observed that IEC 60891-Procedure 1 (Figure S8) and Procedure 2 (Figure S9) are most sensitive (up to ±2.5%), and then Anderson (Figure S12) and SIDT (Figure S13) procedures (up to ±1.4%) followed by Modified IEC 60891-Procedure 1 (Figure S10; up to ±0.5%) and IEC 60891-Procedure 4 (VDTC) (Figure S11; within ±0.05%). Equation 3 was used for the calculation of Fill Factor (*FF*). The percentage degradation in P_{max} is equal to the sum of percentage degradations in V_{oc}, I_{sc}, and *FF*, and similarly, the error in P_{max} in STC correction is equal to the sum of the errors in V_{oc}, I_{sc}, and *FF* in STC correction.

$$\text{Fill Factor}\,(FF) = \frac{\text{Maximum Power}\,(P_{max})}{\text{Open Circuit Voltage}\,(V_{oc}) \times \text{Short Circuit Current}\,(I_{sc})}. \tag{3}$$

The change in errors with respect to temperature plotted in Figure 9 shows that for all the procedures, the Maximum Change in Error (MCE) or highest sensitivity in all performance parameters occurs at the maximum temperature. Effect of any error in temperature coefficient will show up at their peak when the temperature is furthest from STC, which happens to be 70°C in this study. Table 2 shows the maximum change in errors of performance parameters at the highest temperature (70°C) used in this study for all the STC correction procedures with erroneous (±15%) temperature coefficients. To simply understand the sensitivity of all the six STC correction procedures, a parameter called "Average Absolute Error (AAE)" was introduced, and it was calculated by using Equation 4.

$$AAE = \sum \frac{|\text{MCE for each performance parameter for} \pm 15\% \text{ error in all TC}|}{2}. \tag{4}$$

The calculated "Average Absolute Error (AAE)" show that (Table 2) IEC 60891-Procedure 4 (VDTC) is least sensitive (AAE is 0.83) and Anderson (AAE is 7.52) and SIDT (AAE is 6.25) procedures are most sensitive to errors in all the temperature coefficients.

4.2 | An error from −30% to +30% in all the temperature coefficients (Case 2)

The observations made for Case 2 (for an error of −30% to +30% with a step of 5% in all the temperature coefficients) in estimating the average percentage errors in the STC correction of all the performance parameters (Figure 11) were the same as that of Case

1 (Section 4.1). The only difference is that magnitudes of these errors will change based on the magnitudes in the errors of temperature coefficients and Case 1 is a subset of Case 2. IEC 60891-Procedure 4 (VDTC) shows the least sensitivity in the STC correction of all performance parameters (except I_{sc}) compared to the other five STC correction procedures. All the STC correction procedures perform similarly including the IEC 60891-Procedure 4 (VDTC) in STC correction of I_{sc}.

5 | CONCLUSION

The sensitivity of accuracy of six STC correction procedures (IEC 60891-Procedure 1 and Procedure 2, Modified IEC 60891-Procedure 1, IEC 60891-Procedure 4 (VDTC), Anderson procedure, and SIDT procedure) to the three different cases of errors in the magnitude of the temperature coefficients are estimated. For this study, experimentally measured as well as simulated *I-V* data of six multi-c-Si PV modules at various Irradiance (*G*) and Temperature (*T*) conditions were used. The average percentage errors in the STC correction of all the performance parameters (P_{max}, V_{oc}, I_{sc}, and *FF*) and change in those errors for all the STC correction procedures with erroneous temperature coefficients (for all three cases) were estimated. For Case 1 (±15% error in all three temperature coefficients [α, β, and γ]) and for Case 2 (-30% to $+30\%$ with a step of 5% error in all three temperature coefficients [α, β, and γ]), it was observed that the IEC 60891-Procedure 4 (VDTC) is least sensitive in P_{max}, V_{oc}, and *FF* correction. One of the key reasons behind this finding is that the IEC 60891-Procedure 4 (VDTC) does not use V_{oc} and P_{max} temperature coefficients (β and γ) in its curve correction equations; instead, it uses Voltage Dependent Temperature Coefficient (VDTC). IEC 60891-Procedure1 and Procedure 2 are less sensitive in P_{max} correction but moderately sensitive in V_{oc} and highly sensitive in *FF* correction. IEC 60891-Procedure1 and Procedure 2 use I_{sc} and V_{oc} temperature coefficients (α and β), Series Resistance (R_s or R_s'), and Curve Correction Factor (K or K') in their curve correction equations. The computation of K or K' value in accordance with temperature coefficients makes these procedures less sensitive in P_{max} estimation, but the error in V_{oc} temperature coefficient (β) is the reason behind observed sensitivities in V_{oc} and *FF* correction. Modified IEC 60891-Procedure 1 is highly sensitive in P_{max} and in V_{oc} correction and moderately sensitive in *FF* correction as it uses α and β in its curve correction equations but assumes R_s and K as zero. Both Anderson and SIDT procedures perform similarly, and they are most sensitive in P_{max} correction and highly sensitive in V_{oc} and in *FF* correction. Anderson and SIDT procedures use all three (α, β, and γ) temperature coefficients in their point correction equations, and the errors in them are the direct contributors to the observed sensitivities in the discussed performance parameters. As all the six STC correction procedures uses I_{sc} temperature coefficient (α), the error or uncertainty in it directly contributes to sensitivity in I_{sc} estimation for all procedures.

For Case 3 (-100% to $+100\%$ with a step of 10% error or uncertainty in only I_{sc} temperature coefficient (α)), all six STC correction procedures showed almost similar sensitivity in I_{sc} correction. Modified IEC 60891-Procedure 1 and IEC 60891-Procedure 4 (VDTC) were found to be the most sensitive among the six procedures in P_{max} correction, but the magnitude of the change in error is less than ±2.5% even at ±100% error in α. IEC 60891-Procedure1 and Procedure 2 showed moderate sensitivity. Anderson and SIDT procedures are least sensitive in P_{max} correction as they are point correction procedures and do not use α in P_{max} correction. All the six procedures have low sensitivity in V_{oc} correction; maximum observed change is ±0.3% even at ±100% error in α at the representative condition. Modified IEC 60891-Procedure 1 and IEC 60891-Procedure 4 (VDTC) are insensitive in *FF* correction, Anderson and SIDT procedures showed moderate sensitivity, and IEC 60891-Procedure 1 and Procedure 2 showed highest sensitivity.

Thus, for outdoor *I-V* measurements of c-Si PV modules, IEC 60891-Procedure 4 (VDTC) procedure not only provides least errors in P_{max} (within ±2%), V_{oc} (within ±0.25%), and *FF* (within ±2%) in the STC correction for the 200–1,300 W/m^2 irradiance range when true temperature coefficient values are used,[9] but it also has the advantage of being least sensitive to errors in all the three temperature coefficients. The change in average percentage error in P_{max} correction is still within ±1% even at ±50% error in the value of only I_{sc} temperature coefficient (α). Therefore, out of all the procedures considered in this study, IEC 60891-Procedure 4 (VDTC) is recommended for high accuracy, high throughput field *I-V* measurements of c-Si PV modules even when high uncertainty in the temperature coefficients is suspected.

ACKNOWLEDGEMENTS

The authors would like to acknowledge Prof. Juzer Vasi, Prof. B M Arora, Prof. K L Narasimhan, and Dr. Hemant Kumar Singh for their inputs during the discussions. The authors would also like to thank Mr. Rambabu Sugguna, Mr. Ajeesh Alath, and Mr. Ritesh Ingle for helping during the experiments. This work was supported by NCPRE funded by the Ministry of New and Renewable Energy of the Government of India through Project No. 31/09/2015-16/PVSE-R&D, dated June 15, 2016.

CONFLICT OF INTEREST

The authors confirm that there is no conflict of interest in this study.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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How to cite this article: Golive YR, Kottantharayil A, Shiradkar N. Sensitivity of accuracy of various standard test condition correction procedures to the errors in temperature coefficients of c-Si PV modules. *Prog Photovolt Res Appl*. 2022; 30(9):1087-1100. doi:10.1002/pip.3559