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A Method Selection Framework for Operating-Profile Assessment and Sensitivity Analysis of DC/AC Inverters in Photovoltaic Plants

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Motivation: why inverter operating profiles matter

The inverter is not only a DC/AC converter; it is an active monitoring and control node.

Operational complexity

Irradiance, temperature, DC inputs, grid conditions, control settings and alarms interact over time.

Decision problem

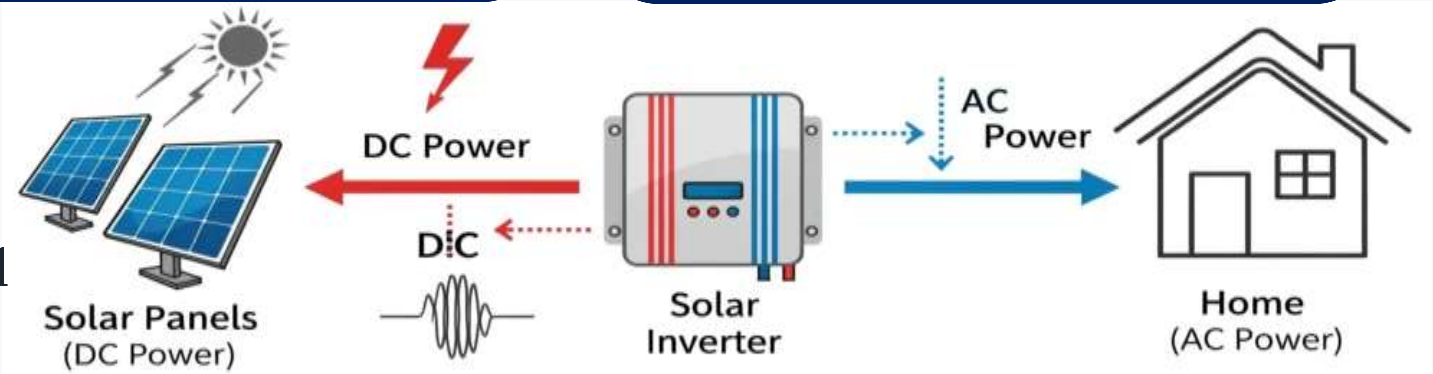
Many assessment and sensitivity methods exist, but their suitability depends on data quality and purpose.

Research contribution

A formal framework selects the method family that best supports monitoring, diagnostics and sustainable control.

Three guiding questions

1. How to formalize the operating profile mathematically?
2. Which methods fit different data and model maturity levels?
3. How to translate sensitivity results into O&M actions?



Goal: $\mathcal{D} \rightarrow KPI \rightarrow Sensitivity \rightarrow O\&M\ decision$

Key message: Method selection comes before detailed engineering actions

Mathematical object: the inverter operating profile

Observation interval

$$\mathcal{T} = [t_0, t_N], t_k = t_0 + k\Delta t, \ k = 0, 1, \dots, N \quad (1)$$

t_0 is the starting time of observation
t_N is the ending time
Δt is the sampling time interval

In discrete form, the work profile is represented as a set of observations

$$\mathcal{D} = \{\mathbf{u}_k, \mathbf{x}_k, \mathbf{y}_k, \mathbf{m}_k\}_{k=0}^{N} \quad (2)$$

u_k is the vector of input quantities at time t_k
x_k is the vector of internal states of the inverter
y_k is the vector of output indicators
m_k is a vector or label of the operating mode

Structured definition

$$\mathcal{OP} = (\mathcal{T}, \mathrm{U}, \mathrm{X}, \mathrm{Y}, \mathrm{M}, \theta, \Omega, \mathrm{K}) \quad (3)$$

$\mathcal{T}$ is the observation time interval
$\mathrm{U} = \{u_k\}_{k=0}^{N}$ is the input data matrix
$X = \{x_k\}_{k=0}^{N}$ is the matrix of internal states
$Y = \{y_k\}_{k=0}^{N}$ is the matrix of output indicators

$M = \{m_k\}_{k=0}^{N}$ is the sequence of operating modes
θ is the vector of inverter parameters
Ω is the area of permissible work
K is the vector of aggregated KPIs

Mathematical object: the inverter operating profile

Inputs U
$G, T_a, T_c, V_{DC}, I_{DC}, V_g, f_g,$ controls

States X
thermal and internal states

Outputs Y
$P_{AC}, Q, \eta, PF, THD, \varepsilon_{MPPT}, T_j$

Modes M
MPPT, clipping, derating, curtailment, fault

KPIs K
energy, power quality, thermal, reliability

This formal object links measured time series, physical constraints and decision indicators in one notation.

KPI apparatus: from measurements to indicators

Power and efficiency

$$P_{dc}(t) = V_{dc}(t)I_{dc}(t) \quad (4)$$

$$\eta(t) = \frac{P_{ac}(t)}{P_{dc}(t)}, P_{dc}(t) > 0 \quad (5)$$

$P_{ac}(t)$ is the active AC power
$V_{dc}(t)$ is the DC voltage at the inverter input
$I_{dc}(t)$ is the DC input current
$P_{dc}(t)$ is the DC input power
$\eta(t)$ is the instantaneous conversion efficiency of the inverter

Energy-weighted efficiency

$$E_{ac} \approx \sum_{k=0}^{N} P_{ac,k}\Delta t\,, E_{dc} \approx \sum_{k=0}^{N} P_{dc,k}\Delta t \quad (6)$$

$$\bar{\eta}_E = \frac{E_{ac}}{E_{dc}}, \qquad E_{dc} > 0 \quad (7)$$

E_{ac} is the AC energy produced
E_{dc} is the DC input energy
$\bar{\eta}_E$ is the average energy efficiency

KPI apparatus: from measurements to indicators

Loss separation

$$E_{clip} \approx \sum_{k=0}^{N} \max\left(0, P^{*}_{ac,k} - P_{rated}\right) \Delta t \quad (8)$$

$$E_{der} = \sum_{k=0}^{N} \left(P^{ref}_{ac,k}(t) - P_{ac,k}(t)\right)_{+} \Delta t \quad (9)$$

E_{clip} is the clipping loss
E_{der} is the derating energy

Indices

$$CI = \frac{E_{clip}}{E_{ac} + E_{clip}} \quad (10)$$

$$DI = \frac{E_{der}}{E_{ac} + E_{der}} \quad (11)$$

CI is the clipping index
DI is the derating index

Interpretation: clipping, derating and curtailment must be separated before diagnosing inverter faults.

KPI families
Energy · MPPT · limitation · power quality · thermal · reliability · sustainability

Mode-dependent interpretation: same number, different meaning

$$\mathcal{M} = \{M_0, M_1, M_2, M_3, M_4, M_5, M_6, M_7\} \qquad (12)$$

M_0: off mode or night mode
M_1: start
M_2: normal MPPT operation
M_3: clipping
M_4: thermal derating
M_5: curtailment by external command
M_6: network limitation or deviation
M_7: failure, alarm or protective shutdown

Conditional sensitivity

$$S_i^{Y|M_q} = S\left(Y, X_i \middle| M = M_q\right) \qquad (13)$$

Estimate sensitivity within the relevant operating mode, not across mixed modes.

Mode-dependent interpretation: same number, different meaning

During MPPT

Low $\frac{\partial P_{AC}}{\partial G}$ may indicate MPPT, string, shading or soiling issues.

During clipping

Low $\frac{\partial P_{AC}}{\partial G}$ is expected because AC output is limited by Prated.

During curtailment

Low $\frac{\partial P_{AC}}{\partial G}$ reflects external power command or grid constraint, not necessarily a fault.

$$S_G^{P_{AC}|M_{clip}} \approx 0 \nRightarrow MPPT\ fault \qquad (14)$$

Data quality as a mathematical gatekeeper

$$Q_{\mathcal{D}} = w_1 C_{\mathcal{D}} + w_2 A_{\mathcal{D}} + w_3 S_{\mathcal{D}} + w_4 K_{\mathcal{D}} + w_5 M_{\mathcal{D}} - w_6 E_{\mathcal{D}} \qquad (15)$$

C	A	S	K	M	E
completeness	accuracy	synchronization	calibration	metadata/modes	bad records

Eligible method classes by data maturity

Level	Typical condition	Suitable methods
Low	missing irradiance or unsynchronized channels	QA/QC, limited KPI review
Medium	basic SCADA: P, V, I, G, T; incomplete flags	KPI, regression, benchmarking
High	timestamps, mode labels, metadata and alarms	local sensitivity, Morris, fleet monitoring
Very high	calibrated model and distributions	Sobol/Saltelli, Monte Carlo, ML, digital twin

$$\mathcal{M}_{feas} = \{M_m : Q_D \geq q_{min}(M_m)\} \qquad (16)$$

Method-selection framework: score, feasibility, hierarchy

$$Score_m = w_A A_m + w_I I_m + w_D D_m + w_R R_m + w_{OM} OM_m + w_S S_m - w_C C_m \quad (17)$$

$$M^* = \arg\max_{M_m \in \mathcal{M}_{feas}} Score_m \quad (18)$$

Practical hierarchy

QA/QC → KPI → Regression → Local SA → Morris → Sobol → ML / DT

Scenario-to-method examples

Scenario	Recommended method
Commissioning	KPI + residual analysis + local sensitivity
Many uncertain factors	Morris screening before expensive global analysis
Global risk analysis	Sobol/Saltelli + Monte Carlo
Large inverter fleet	ML/SHAP + fleet benchmarking, only with enough history

Sensitivity analysis toolbox: local, screening, global

Local sensitivity

Best for commissioning and control tuning near one operating point.

Morris screening

Finds important factors at low computational cost when the factor list is long.

Sobol/Saltelli

Explains output variance and interactions for calibrated models.

$$S_i^Y = \frac{X_i}{Y}\frac{\partial Y}{\partial X_i} \approx \approx \frac{X_i}{Y}\frac{F(X_i+\Delta X_i)-F(X_i)}{\Delta X_i} \quad (19)$$

$$EEi = \frac{F(X_1,\dots,X_i+\Delta,\dots,X_n)-F(X_1,\dots,X_i,\dots,X_n)}{\Delta}$$

$$\mu_i^* = \frac{1}{r}\sum_{q=1}^{r}\left|EE_i^{(q)}\right| \quad (20)$$

$$S_i = \frac{Var_{X_i}(E[Y|X_i])}{Var(Y)}$$

$$S_{T_i} = 1 - \frac{Var_{X_{\sim i}}(E[Y|X_{\sim i}])}{Var(Y)} \quad (21)$$

Interpretation rule: If $S_{T_i} \gg S_i$, the factor contributes mainly through interactions.

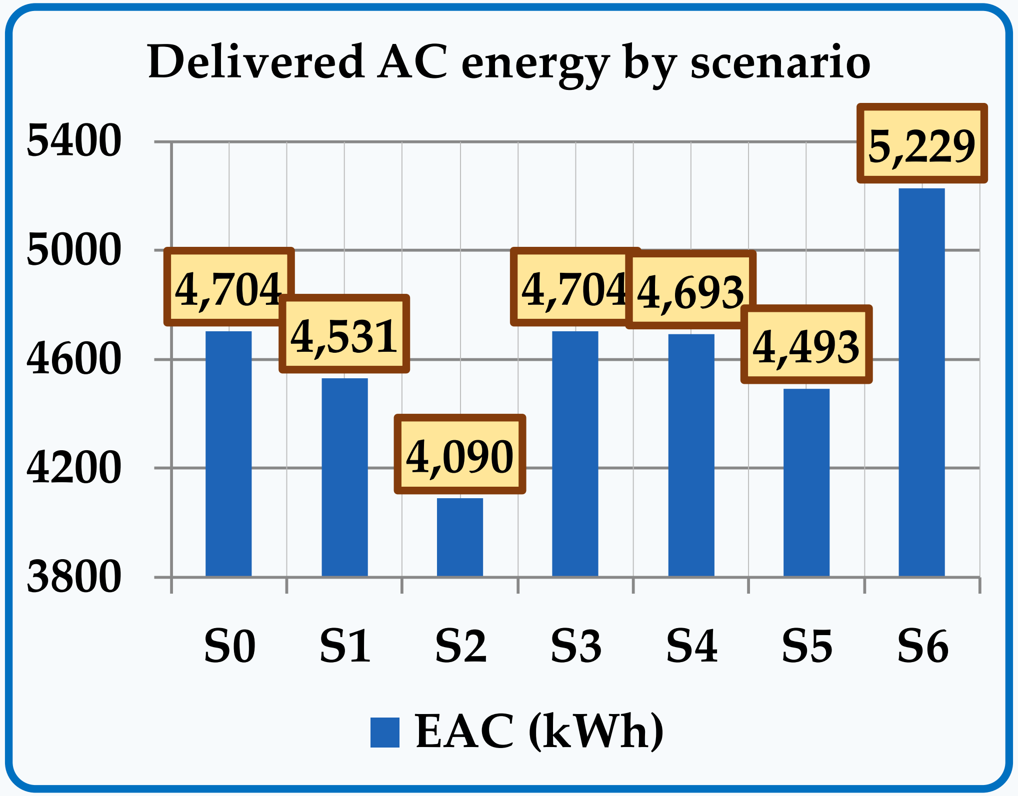
Factor groups for O&M communication

$$X = [X_{clim}, X_{DC}, X_{grid}, X_{thermal}, X_{ctrl}] \quad (22)$$

Climate → resource and thermal variability
DC side → MPPT and string behavior
Grid → PF, reactive power and THD
Thermal/control → derating, lifetime and settings

Numerical workflow: scenario diagnostics for a 100 kW inverter

$$P_{AC,rated} = 100kW, P_{DC,inst} = 120/135kWp, \Delta t = 5min, N = 2016$$



Scenario	Diagnostic signal	Interpretation
S1	Tjmax = 92.9 ˚C; DI = 0.48%	Thermal/cooling risk
S2	EAC = 4090.3 kWh; PR = 74.09%	Shading/soiling or MPPT degradation
S3	PFw = 0.977; THDw = 2.43%	Grid-voltage stress
S5	CuI = 4.49%; ηE = 93.58%	Curtailment, not inverter fault
S6	EAC = 5229.1 kWh; CI = 1.51%	Higher ILR, but clipping appears

The workflow separates loss mechanisms before ranking influential factors.

Global sensitivity ranking: Sobol total indices

Total Sobol indices S_{T_i} from the illustrative model

Factor	P_{AC}	η	THD	T_j	PF
G	0.970	0.113	0.648	0.505	0.000
T_a	0.029	0.340	0.020	0.480	0.000
V_g	0.000	0.000	0.045	0.000	1.000
r_{DC}	0.000	0.420	0.241	0.001	0.000
R_{eq}	0.000	0.000	0.000	0.023	0.000
f_{sw}	0.000	0.122	0.051	0.000	0.000

Interpretation

P_{AC} is dominated by irradiance G.

η is driven by DC ripple r_{DC}, temperature T_a and switching frequency f_{sw}.

THD is mainly load/irradiance plus ripple.

T_j is explained by G and T_a.

PF is almost entirely controlled by grid voltage V_g.

$S_{T_i} \gg S_i \Rightarrow interaction\ effect$

Relevant factors depend on the selected output indicator — there is no universal ranking.

From mathematical sensitivity to O&M action

$$Risk_l = a_1 DI_l + a_2 \overline{THD}_l + a_3(1 - \overline{PF}_l) + a_4(1 - HI_l) + a_5 N_{alarm,l} \quad (23)$$

$$\left|S_i^{K_j}\right| > \lambda_{i,j} \Rightarrow O\&M\ Action_{i,j} \quad (24)$$

Sensitivity pattern	Likely cause	Recommended action
High $S(\eta, T_a)$	Cooling degradation or increased losses	Inspect fans, heat sinks, airflow and derating logic
High $S(THD, ripple)$	DC-link degradation or filter issue	Check capacitors, ESR and output filter condition
Low $S(P_{AC}, G)$ in normal mode	MPPT problem, shading or soiling	Inspect strings and MPPT channels
High $S(PF, V_g)$	Grid-voltage effect or Q/PF setting issue	Verify $Q(V)$ and power-factor control parameters

Actionability is the final criterion: a sensitivity index is useful only if it can trigger a meaningful technical decision.

Conclusions

Sustainable control objective

$$J = w_1(1-\eta_E) + w_2 THD + w_3 \max\left(0, T_j - T_{lim}\right) + w_4 DI + w_5 CI - w_6 E_{AC} \quad (25)$$

Recommended practical sequence

$$KPI + Conditional\ Regression + Local\ Sensitivity + Morris + Sobol + ML/Hybrid \quad (26)$$

1
Define OP formally: inputs, states, outputs, modes, constraints and KPIs.

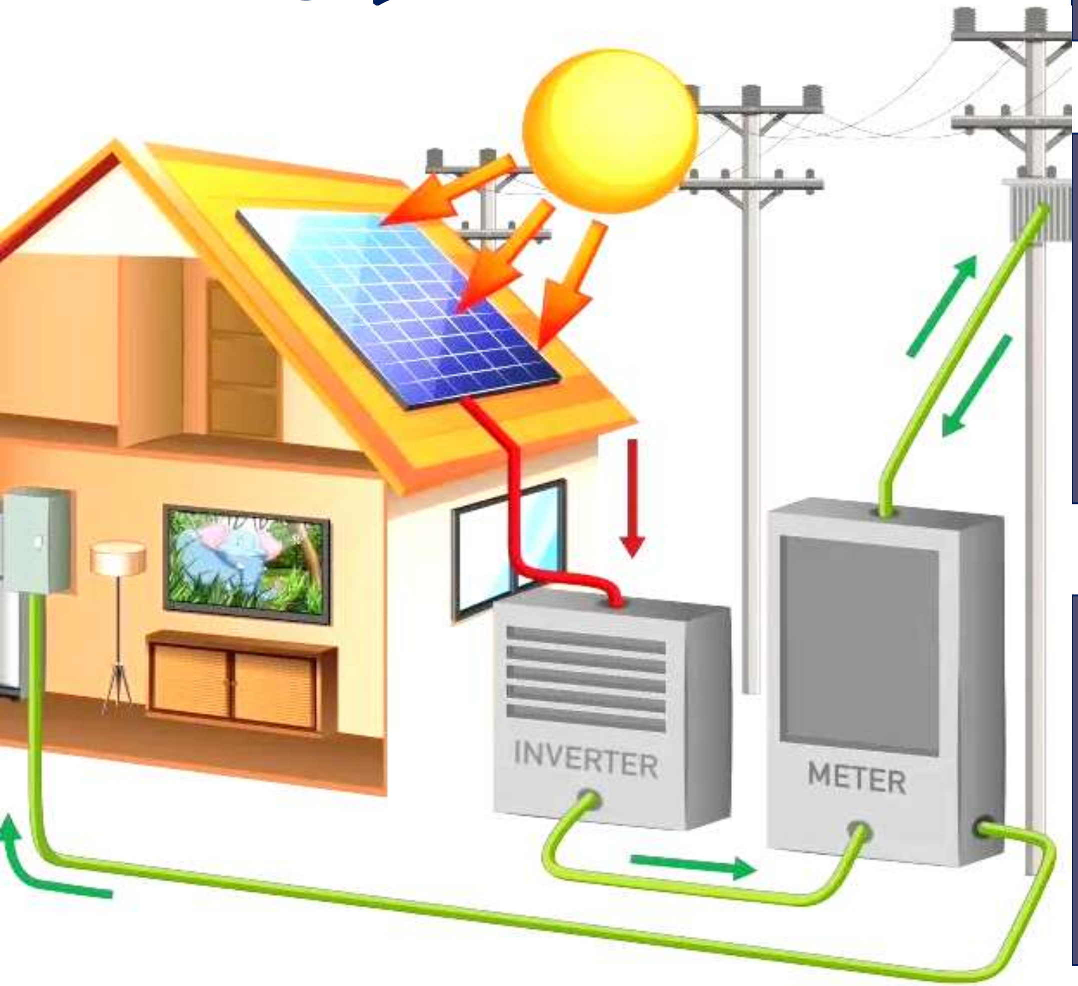
2
Filter by data quality before applying complex models.

3
Interpret sensitivities conditionally by operating mode.

4
Translate rankings into diagnostics, maintenance and control tuning.

5
Balance yield, power quality, thermal risk, reliability and lifetime.

THANK YOU FOR YOUR ATTENTION!



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