Generator Simulator — Operator & Technical Manual (Complete)

> **Purpose**: This manual explains, in plain language first and then in technical detail, how the simulator's parts fit together, what every control and indicator means, and exactly how each displayed value is calculated.

Part A — Simple Overview (Plain-English)

A1) What this simulator models

- A hydro **turbine/governor** that opens **gates** (think "throttle"). More gate → more mechanical power → the generator's **frequency (Hz)** rises off-grid, or **MW** increases when on the grid.
- An **excitation/AVR** (field breaker 41 + AVR) that controls generator **voltage (kV)**. AVR ON holds a set kV; AVR OFF is manual.
- A **synchronization** step: match **voltage, frequency, and phase** to the grid, then close the **generator breaker (52G)**.
- **Power flow** once paralleled: MW follows gates; **reactive power (MVAR)** follows the voltage difference between generator and bus.
- **Protections** (reverse power, over/undervoltage, over/underfrequency, loss of field) that alarm or trip and drive the unit safely down.

A2) The 5 key things to watch

1) **Gate %** (how hard you're feeding the turbine) 2) **Hz (and RPM)** 3) **Generator kV** 4) **Syncscope needle + twin lamps** (phase/voltage agreement) 5) **MW, MVAR, AMPS, PF** (what the grid "sees" when you're on line)

A3) The basic flow (start → sync → run → stop)

1) **Master Start** → gates ramp to ~20% over a few seconds. 2) With 52G **open**: frequency rises with gates; close **41 (field)** and bring kV where you want it (AVR ON = holds setpoint). 3) Turn **Sync** ON → use the needle and lamps to match the grid: kV ≈ bus, Δf small, phase crossing near "12 o'clock". 4) When **sync-check** permissive shows, **close 52G** → you're paralleled: Hz locks to 60, MW/MVAR become meaningful. 5) **Run**: Gates change **MW**; AVR/manual voltage changes **MVAR/PF**. 6) **Normal Stop**: Master Stop ramps gates to 0; unit coasts down; breakers open; "Unit Stopped" latches. 7) **Trip Stop**: a protective trip drives gates faster to 0, then opens 41 and 52G and latches 86G.

Part B — Everyday Use (Operator)

B1) Quick-Start Checklist

1) **86G** permissive (not tripped) and **Master Start** → watch gates move toward ~19–20%. 2) **41 (Field)** close → generator kV ramps to a target (AVR ON: ~13.8 kV; AVR OFF: nominal off-grid value). 3) **Sync switch ON** → confirm lamps dim near in-phase; needle approaches top. 4) **Match**: kV within ±3%, $|\Delta f| \leq 0.15$ Hz, $|\Delta\theta| \leq 10°$. 5) **52G close** (sync-check glow present) → online. AVR ON holds kV; manual droop applies if AVR OFF.

B2) Normal Running

- **Raise MW**: increase **Gate** (Knob 65). On line, Hz stays at 60; MW climbs.
- **Adjust PF/MVAR**: tweak **Voltage** (Knob 90) or use **AVR ON** for fixed kV. Higher gen-kV than bus → **lagging (+Q)**; lower → **leading (−Q)**.

B3) Stopping

- **Normal Stop**: Master Stop → gates ramp to 0 (slower ramp); when nearly stopped, breakers open and “Unit Stopped” latches.
- **Trip Stop**: protection event → fast gate drive-back, then 41/52G open and 86G trips (requires reset once stopped).

B4) Syncing Tips

- Dim **lamps** + needle passing the top **slowly** → press 52G.
- Lamps **full bright all the time** → voltage badly mismatched; fix kV first.
- Needle whipping around fast → frequency mismatch too big; trim gates.

Part C — Controls, Indicators, Gauges

C1) Switches & Knobs

- **Master Start/Stop**: Arms a start ramp or a stop ramp; stop is slower, trip stop is faster.
- **Knob 65 (Gate)**: Past ±20° angle → nudges gate setpoint continuously (fast when on-line, slow when off-grid).
- **41 (Field breaker)**: Close to energize the field and begin a controlled kV ramp; open to ramp kV to zero.
- **AVR ON/OFF**: ON → generator kV tracks the setpoint with AVR slew; OFF → you control kV manually (with droop when paralleled).
- **Sync ON/OFF**: Shows lamps and sync needle and enables sync-check logic.
- **52G (Gen breaker)**: Requires sync-check permissive; closes to parallel; opens to island.
- **86G (Lockout)**: Trip latches the unit out; reset only when fully stopped.

Angle thresholds: Most knobs act when deflected $\geq$ **+20°** (upper) or $\leq$ **−20°** (lower). 86G permissive is > −1°.

C2) Gauges & Readouts

- **Gate %** (0–100)
- **Hz** (with RPM text)
- **Gen kV** (0–16 kV scale, top around 15 kV)
- **Syncscope** (needle = phase; lamps = voltage/phase agreement)
- **Digitals**: MW, MVAR, AMPS, PF (signed PF: + lagging, − leading)

C3) Glows (status & permissives)

- **52G Permissive**: lit when 52G is **open** (you may close).
- **86G Permissive**: lit when lockout knob not tripped (> −1°).
- **Speed Permissive**: true once running above a small RPM threshold.
- **Excitation Permissive**: lit when 41 is closed.
- **Sync-Check**: white when in window (voltage, frequency, phase).
- **Status**: red/green for 41 and 52G (closed vs open).

Part D — Tuning & Configuration (How to Adjust Behavior)

D1) Rated & Limits

- **Rated**: 13.8 kV line-line, 25 MVA, nominal MW ≈ 23.5, MVAR limits ≈ +15.5 (lag), −19.4 (lead).
- **Voltage limits**: 0…16 kV (display clamp).
- **Slew rates**: AVR ≈ 1.2 kV/s; Manual ≈ 2.0 kV/s; Gate normal ≈ 20 %/s; Gate trip ≈ 80 %/s.
- **Ramp durations**: Start ≈ 3.0 s to ~19.7% gate; Normal stop ≈ 2.0 s to 0%; Trip stop ≈ 0.5 s to 0%.

D2) Sync-Check Window

- $|Vg - Vb| \le$ **3%** of Vb, $|fg - fb| \le$ **0.15 Hz**, $|\Delta\theta| \le$ **10°**.

D3) Manual Droop (Voltage)

- When paralleled with AVR **OFF**, the target kV is reduced slightly with effective load:
  `kvTarget = SP − k_droop · effGatePU`.

D4) Reactive Gain Shaping

- MVAR gain increases with load so vars stay tame near close:
  `qGain = q_min + (q_max − q_min) · (effGatePU^n)`.

D5) Loss-of-Field (LOE) Targets

- On-line with 41 open → blend quickly (≈250 ms) toward small **reverse MW** and inductive **+Q** import.

D6) No-Load Calibration

- On 52G close, the simulator stores an offset so that your typical close gate (~18–20%) corresponds to ~0 MW. This stabilizes MW around zero at close.

Part E — Detailed Calculations (Engineer)

E1) Frequency & RPM (Off-grid vs On-grid)

- **Off-grid** (52G open):
- If gate < 20%: `Hz = 3.0 · gate%`
- Else: `Hz = 0.375 · gate% + 52.5`
- Falling frequency is rate-limited (≈3 Hz/s above 20 Hz; slower below 20 Hz). Clamp to 0…94 Hz.
- **On-grid** (52G closed): `Hz = 60`.
- **RPM**: `RPM = 1.667 · Hz` (display convenience).

E2) Gate Dynamics

- **Gate_Setpoint** moves via Master ramps and Knob 65.
- **Gate_Pos** (actual) slews toward setpoint with capped rates (normal or trip). Per-frame step is limited to `rate · dt`.

E3) Voltage Setpoint & Tracking

- **Knob 90** nudges **SP** (setpoint) when deflected beyond ±20°.
- **41 CLOSE** starts a 3 s **kV ramp** from current to SP (AVR ON → 13.8 kV when paralleled; otherwise off-grid nominal).
- **41 OPEN** ramps kV to 0 in ≈3 s.
- **Paralleled + AVR ON**: actual kV tracks SP with AVR slew.
- **Paralleled + AVR OFF**: actual kV tracks `SP − k_droop · effGatePU` with manual slew.
- **Islanded**: with 41 closed, track SP; with 41 open, decay to 0 (manual slew). Always clamp to 0…16 kV.

E4) No-Load Calibration & MW Mapping

- On 52G close, compute and store **NoLoadGateCal** so that effective gate above this offset maps to MW linearly.
`MW_pu = clamp( slope · effGate% / 100, MW_min_pu, 1 )` → `MW = MW_pu · RatedMW`.

E5) Reactive Power (Q)

- Compute voltage deviation `dv = Vg − Vb`.
- Compute `effGatePU` (0…1) from gate above the no-load calibration.
- Gain: `qGain = q_min + (q_max − q_min) · (effGatePU^n)`.
- **MVAR**: `Q = clamp( dv · qGain , −Q_lead_max , +Q_lag_max )`.

E6) Apparent Power, Amps, Power Factor

- `S = √(MW² + Q²)` (MVA)
- `AMPS = (S·1e6) / (√3 · 13.8e3)`
- `PF = sign(Q) · (|MW|/S)` with **+** for lagging (Q≥0), **−** for leading (Q<0).
  Near zero load, display may coerce to ±1.00 to avoid noisy PF.

E7) Phase, Syncscope Needle, and Lamps

- **PhaseTracker** integrates `df = fg − fb` each frame, normalizes **Δθ** to (−180°, 180°], and exposes a **snapshot** {vb, vg, fb, fg, Δθ}.
- **Needle**:
- Clamp to 0° if Sync OFF, 52G closed, or fg≈0.
- Else rotate to Δθ mapped into 0…360° (svg rotation).
- **Lamp brightness**:
- Vector difference: `Vr = |Vg∠θg − Vb∠θb| = √(Vg² + Vb² − 2VgVb cosΔθ)`.
- Normalize to pu, apply gain/gamma → brightness 0…1.
- If Vg out of nominal band, force full-bright (teaching aid).

E8) Oscilloscope (Waveforms)

- **Bus**: 4 cycles across the scope window at fixed amplitude (drawn once).
- **Generator** (redrawn): amplitude ∝ `Vg/Vnom`; cycles across window ∝ `fg/fb`; phase offset = 0 when paralleled, else Δθ.
  The plotted polyline uses dense samples for smooth curves.

E9) Stopped Latch & Online State

- Latches **Unit Stopped** only after genuine coast-down: gates ≤0.5% and Hz ≤0.2, with intent to stop present. Clears start/stop ramps and marks offline.

Part F — Protections (Alarms & Trips)

Protection logic only evaluates when **on line** (52G closed), except where noted. A “Master Stop mask” suppresses nuisance alarms during orderly shutdown.

F1) Alarms (Self-Reset)

Code	Condition (examples)	Delay/Persistence	Effect
32 (Reverse Power)	`MW/Rated < −0.01`	≥0.2 s	Alarm only
55 (Low PF)	`|PF| < 0.90`	≥0.2 s	Alarm only
27 (Undervoltage)	`Vpu < 0.96`	Immediate	Alarm only
59 (Overvoltage)	`Vpu > 1.06`	Immediate	Alarm only

Code	Condition (examples)	Delay/Persistence	Effect
81 (Freq dev)	Hz < 59.8 or > 60.2	≥5 s	Alarm only

Post-close inhibit: After 52G closes, **32 alarm/trip** is inhibited ~15 s to avoid false reverse power during settling.

F2) Trips (Latched, Drive-Back)

Code	Condition (examples)	Delay/ Persistence	Action
32 (Reverse Power)	`MW < −0.02 · RatedMW`	≥0.5 s (after inhibit)	Drive gates to 0 (fast) → when ≤20% sustained, **open 41 & 52G**, latch **86G**
40 (Field/LOE)	41 open while 52G closed	~50 ms	Same drive-back → 86G
27/59 (Under/ Over V)	`Vpu < 0.90` or `> 1.10`	≥0.5 s	Same drive-back → 86G
81 (Under/ Over f)	Hz < 59.0 or > 61.5	≥0.5 s	Same drive-back → 86G (over-f logs “Overspeed”)

Reset: 86G can reset only when **Unit Stopped** is true.

Part G — Calibration & Re-Calibration

1) On **52G close**, the simulator captures **NoLoadGateCal** so **0 MW** occurs near your customary close gate.
2) If you change how you close (e.g., a very different gate), open 52G and close again to refresh the calibration.
3) Opening 52G clears the calibration so next close re-establishes it.

Part H — Limits, Clamping, Display Rules

- **kV**: Always limited to 0…16 kV for display; slews use AVR or Manual rates.
- **Hz**: Off-grid limited to 0…94; on-grid forced to 60.
- **Gate**: 0…100% (ramps and slews enforce rates).
- **MW/Q**: Clamped to rated envelopes; **PF** sign reflects Q (+ lag, − lead). At very small S, PF display may be coerced to ±1.00.
- **Lamps**: Full-bright override if Vg far from nominal (to signal mismatch clearly).

Part I — Troubleshooting Guide

Lamps never dim - Likely kV mismatch: set generator kV within ±3% of bus; ensure Sync ON and 41 closed.

Needle spins fast - Frequency mismatch: adjust gates until the needle crawls; target $\Delta f \leq 0.15$ Hz.

Cannot close 52G (no permissive) - Check: Sync ON, 41 closed, V/Hz/Δθ within window.

PF reads weird at tiny load - Normal: near zero S, PF is noisy; display may coerce to ±1.00 until S grows.

Trip occurred immediately after closing - Reverse-power inhibit wasn't long enough or close conditions were poor. Re-sync carefully; verify calibration and AVR state.

On-line but Q goes strongly + or − - AVR OFF with manual droop: your SP may be off; raise/lower kV relative to bus to tune Q toward target.

Voltage collapses on 41 open while on-line - Expected: LOE behavior blends to small reverse MW and inductive Q import, then trips if configured.

Part J — Data Dictionary (UI Variables)

Variable (UI/State)	Meaning	Units	Typical Range
`Gate_Setpoint`	Target gate from ramps/knob	%	0…100
`Gate_Pos_Var`	Actual gate (slewed)	%	0…100
`Gen_Freq_Var`	Generator frequency	Hz	0…94 (island), 60 (on-line)
`Gen_RPM_Var`	Display RPM	rpm	0…157 (island), 100 at 60 Hz
`Gen_kV_SP`	Voltage setpoint	kV	0…16+ (floored at 0)
`Gen_kV_Var`	Terminal kV (tracked)	kV	0…16
`MW`	Real power	MW	−small … ≈Rated
`MVAR`	Reactive power (+lag, −lead)	MVAR	−lead limit … +lag limit
`AMPS`	Line current	A	0…≈1050
`PF`	Power factor (signed)	—	−1.00…+1.00
`Δθ`	Phase angle difference	°	−180…+180
`SyncCheck_Perm`	Close permissive	bool	true/false
`Speed_Perm`	Speed permissive	bool	true/false

Variable (UI/State)	Meaning	Units	Typical Range
`GeneratorOnline`	Paralleled state	bool	true/false
`NoLoadGateCal`	Stored gate offset at close	%	0…≈30

Part K — Version, Assumptions, Notes

- **Rated system**: 13.8 kV, 25 MVA.
- **Teaching aids**: full-bright lamps when Vg far from nominal; PF coercion at tiny S; clean phase clamp when paralleled.
- **Simplifications**: Linearized governor, linear Q-gain shaping, fixed reactance proxy via Q-gain, fixed AVR/Manual slews, discrete thresholds.

Part L — Glossary

- **AVR**: Automatic Voltage Regulator (voltage controller)
- **Field / 41**: DC excitation breaker for the generator field
- **52G**: Generator breaker to the grid
- **86G**: Lockout relay (trip latch)
- **LOE**: Loss of Excitation (field open while online)
- **Lagging (+Q)**: Generator voltage set higher → current lags → import vars
- **Leading (−Q)**: Generator voltage set lower → current leads → export vars
- **Δθ**: Phase angle difference between generator and bus

Part M — Worked Example (At Close)

1) **Before close**: Gate ≈ 20%, Hz ≈ 60, Gen kV ≈ 13.8, lamps dimming, needle near top. 2) **Close 52G**: Hz locks to 60; **NoLoadGateCal** captured so MW ~ 0. 3) **Raise gates**: effGatePU increases → **MW** rises. 4) **Bump kV up** (AVR ON or manual): generator kV > bus → **+Q lagging** increases; PF moves positive toward lag.

Part N — HTML & SVG Panel (Structure & Bindings)

N1) Document skeleton & load order

- Keep **one** HTML root only: `<!DOCTYPE html>`, a single `<html>`, one `<head>`, one `<body>`.
- Load scripts with `defer` so `Script.js` runs after the DOM is parsed:

```
<script src="Script.js" defer></script>
```

- Place the main **SVG panel** inside a container (e.g., `#sim-wrap`) that controls sizing; avoid inline `width/height` on the SVG that fight responsiveness.

N2) Required containers & attributes

- `#sim-wrap` (block-level container) — owns layout, padding, and max-width.
- `svg#panel` (or equivalent) — main UI surface; include a `viewBox`; use `preserveAspectRatio="xMidYMid meet"`.
- Background/decoration elements should be marked `role="presentation"` and `aria-hidden="true"`.

N3) SVG coordinate system & responsiveness

- The `viewBox` defines the internal coordinate system (e.g., `0 0 1600 900`).
- Scale the SVG via CSS (e.g., `width: 100%; height: auto;`) so it fits different screens without distorting.
- Keep gauge math independent of pixel size—the script uses element bounding boxes and/or transforms to locate rotation centers.

N4) DOM bindings (IDs the script reads/writes)

Do not rename these without updating the selectors in `Script.js`.

Controls (knobs/switches) - `#Knob_65` (Gate), `#Knob_90` (Excitation/Voltage) - `#Knob_Master`, `#Knob_41`, `#Knob_52G`, `#Knob_AVR`, `#Knob_Sync`, `#Knob_86G`

Indicators / Glows - `#Glow_SyncLeft`, `#Glow_SyncRight` - `#Glow_52G_Green`, `#Glow_52G_Red`, `#Glow_41_Green`, `#Glow_41_Red` - `#Glow_Perm_Speed`, `#Glow_Perm_52G`, `#Glow_Perm_Exc`, `#Glow_Perm_86G`, `#Glow_Perm_SyncCheck`

Needles / Gauges - `#Needle_Gate`, `#Needle_Hz`, `#Needle_GenKV`, `#SyncScope_Rotation`

Digital readouts - `#Value_MW`, `#Value_MVAR`, `#Value_AMPS`, `#Value_PF`

(If your IDs differ, keep a one-to-one table and update selectors in `Script.js` accordingly.)

N5) Accessibility

- Decorative vectors: `aria-hidden="true"`, `role="presentation"`.
- If any controls become keyboard-accessible, add focus order and ARIA labels (`aria-label`) and ensure pointer/keyboard parity.

N6) Performance & assets

- Prefer a single, inline SVG (no external `<image>` references) for reliability.
- Avoid heavy filters/shadows on frequently updated elements (needles/lamps) to keep frame times smooth.

- Keep animation work in `Script.js`; no inline SMIL/`<animate>`.

N7) Safe-edit rules

- **Never duplicate the HTML root** (no nested `<!DOCTYPE html><html>` blocks).
- **Do not** move or remove IDs bound by the script without updating the JS.
- If you must rename an ID: (1) change it in HTML, (2) change the corresponding selector in `Script.js`, (3) update this Manual's ID list.

N8) Embedding & theming

- To embed the simulator in another site:
- Copy `index.html` and `Script.js`; keep IDs unchanged.
- Wrap `#sim-wrap` in the host page and set container width; the SVG will scale.
- Theming (colors/labels): edit SVG fills/strokes/text styles; keep IDs and transforms intact.

N9) SEO & metadata (index.html)

- Keep `<title>`, `<meta name="description">`, canonical link, and Open Graph/Twitter tags.
- Retain JSON-LD (`SoftwareApplication`) if present; update fields (name, description, url, image) when you rebrand or relocate.

N10) Validation & smoke test

1) Open `index.html` in a browser → no console errors. 2) Resize window → panel scales; nothing overlaps or crops. 3) Toggle **Sync** → lamps and needle appear; lamps dim near in-phase. 4) Close **52G** → Hz clamps to 60; MW follows gate; MVAR follows kV. 5) Open **41** while on-line → LOE behavior (reverse MW, +Q) until trip sequence.

(Chapter end.)