Deterministic Modeling of Inductive Motor Inrush Currents and Non-Coincident Load Stacking for Residential Backup Power Systems

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Abstract

Residential generator selection is often reduced to arithmetic addition of running and starting watts, a practice that can either oversize equipment substantially or overlook the voltage depression created by induction-motor acceleration. This paper develops a deterministic framework that separates continuous apparent-power demand from the largest credible non-coincident starting increment. The method derives locked-rotor current from motor slip, equivalent-circuit impedance, and NEMA locked-rotor kilovolt-ampere code ranges; represents electronic soft starters through an explicit inrush reduction coefficient; and screens generator transient performance using alternator direct-axis sub-transient reactance. Continuous loading is evaluated by vector summation of active and reactive power, while the startup envelope adds only the greatest motor delta to the aggregate running load unless a specified control sequence permits coincident starts. Fuel energy density, elevation, ambient temperature, and operating reserve are incorporated through multiplicative capacity-derating factors. A residential case study containing refrigeration, lighting, a furnace blower, a deep-well pump, and a three-ton heat pump demonstrates the distinction among conservative coincident summation, direct-on-line non-coincident sizing, and soft-starter-assisted sizing. For the stated assumptions, the optimized peak envelope is 11.275 kW, compared with 20.7 kW for direct-on-line non-coincident operation and 30.1 kW for deliberately conservative double-counting. The framework is intended as a transparent screening model rather than a substitute for manufacturer motor-starting curves, generator decrement data, protective-device coordination, or site-specific code review. Its equations map directly to a deterministic TypeScript implementation suitable for education, preliminary design, and reproducible field calculations. The approach exposes assumptions, supports sensitivity testing, and discourages unsupported universal sizing rules.

Index Terms—backup power systems, induction motors, locked-rotor current, motor starting, non-coincident loads, standby generators, sub-transient reactance, voltage sag, environmental derating, soft starters

1 Introduction

Residential electrification increasingly combines heat pumps, induction cooking, electric-vehicle supply equipment, and battery storage with standby generators or hybrid microgrids. Simplified sizing charts commonly make one of two errors: they add every starting demand as though all motors start simultaneously, or they consider running watts without checking the alternator response to a low-power-factor inrush event. The first approach inflates capital cost and worsens low-load operation; the second may permit contactor dropout, protective-device operation, or failed motor acceleration.

This paper formulates a deterministic screening method for residential backup-power sizing. It distinguishes continuous complex power from a specified startup sequence, calculates the governing non-coincident load envelope, estimates voltage dip from direct-axis sub-transient reactance, and adjusts rated output for fuel and environmental conditions. IEEE Std 446 supplies established emergency-power design practice, while NFPA 70 and NEMA MG 1 govern applicable installation and motor data considerations [1–3]. Final equipment selection must nevertheless use manufacturer-specific alternator decrement curves, engine recovery data, motor acceleration time, and local authority requirements.

2 Induction-Motor Starting Physics

2.1 Slip and Equivalent Impedance

For rotor speed n_r and synchronous speed n_s, induction-motor slip is

$$s = \frac{n_s - n_r}{n_s}. \tag{1}$$

At standstill, $n_r = 0$ and $s = 1$. A simplified per-phase starting impedance referred to the stator is

$$Z_{\text{start}} = \sqrt{\left(R_s + \frac{R'_r}{s}\right)^2 + (X_s + X'_r)^2}. \tag{2}$$

Table 1: Selected NEMA Locked-Rotor Code Ranges

Code	kVA/HP range	Midpoint	Representative application
A	0.00–3.14	2.5	Low-torque fans
C	3.55–3.99	3.8	Small blowers
E	4.50–4.99	4.7	Small compressors
G	5.60–6.29	5.9	Residential motors
J	7.10–7.99	7.5	Wells, older compressors
L	9.00–9.99	9.5	High-torque compressors

The locked-rotor current follows directly:

$$I_{\text{LRA}} = \left.\frac{V_\phi}{Z_{\text{start}}}\right|_{s=1}. \tag{3}$$

Because the starting impedance is low, across-the-line current commonly reaches several times rated full-load current. The exact multiple is equipment-specific and should be taken from nameplate or manufacturer data.

2.2 NEMA Code Letters and Starting kVA

When measured LRA is unavailable, a NEMA locked-rotor kVA code provides a screening estimate [3]:

$$S_{\text{start}} = \text{HP}\, K_{\text{NEMA}}, \tag{4}$$

where K_{NEMA} is expressed in kVA per horsepower. The corresponding currents are

$$I_{\text{LRA},3\phi} = \frac{1000 S_{\text{start}}}{\sqrt{3} V_{LL}}, \tag{5}$$

$$I_{\text{LRA},1\phi} = \frac{1000 S_{\text{start}}}{V_L}. \tag{6}$$

2.3 Soft-Starter Approximation

For preliminary sizing, a compatible electronic soft starter can be represented by

$$I_{\text{start,soft}} = \kappa_{\text{soft}} I_{\text{LRA}}, \qquad \kappa_{\text{soft}} \in [0.30, 0.40]. \tag{7}$$

This coefficient is not universal; the final value must come from measured data or the starter and compressor manufacturers.

3 Non-Coincident Load Envelope

3.1 Continuous Complex Power

The aggregate running active power is

$$P_{\text{run}} = \sum_{j=1}^{N_r} P_{r,j} + \sum_{k=1}^{N_m} P_{m,k}. \tag{8}$$

For motor power factor PF_k, reactive power is

$$Q_{\text{run}} = \sum_{k=1}^{N_m} P_{m,k} \tan\!\left(\cos^{-1} \text{PF}_k\right), \tag{9}$$

and the continuous apparent-power requirement is

$$S_{\text{continuous}} = \sqrt{P_{\text{run}}^2 + Q_{\text{run}}^2}. \tag{10}$$

3.2 Startup Delta and Governing Envelope

Define the incremental starting demand of motor k as

$$\Delta P_{\text{start},k} = P_{\text{start},k} - P_{\text{run},k}. \tag{11}$$

If controls or operating logic preclude coincident starts, the peak active-power envelope is

$$P_{\text{peak}} = P_{\text{run}} + \max_{1 \le k \le N_m} \left(\Delta P_{\text{start},k}\right). \tag{12}$$

Equation (12) is conditional, not probabilistic: it is valid only when the selected startup sequence is enforced or simultaneous starting is otherwise excluded. Where coincidence is credible, a scenario set $\mathcal{C}$ should be evaluated:

$$P_{\text{peak}} = P_{\text{run}} + \max_{c \in \mathcal{C}} \sum_{k \in c} \Delta P_{\text{start},k}. \tag{13}$$

4 Alternator Sub-Transient Response

The alternator is not an infinite bus. A low-power-factor motor-starting current produces an internal voltage drop governed initially by direct-axis sub-transient reactance X_d''. A first-order screening expression is

$$\Delta V_{\text{dip}}(\%) \approx \frac{S_{\text{motor,start}}}{S_{\text{alt,rated}}} X_d'' \times 100. \tag{14}$$

Typical screening values for four-pole brushless machines may lie near $X_d'' = 0.14$–0.18 p.u., but the manufacturer's decrement curve is authoritative. Allowable dip is load-dependent: sensitive electronic controls may require a tighter limit than motors or resistive loads. IEEE Std 446 provides design guidance but does not establish a single universal residential dip threshold [1]. Because induction-motor torque is approximately proportional to the square of applied voltage,

$$\frac{T_{\text{start,dip}}}{T_{\text{start,rated}}} \approx \left(1 - \frac{\Delta V_{\text{dip}}}{100}\right)^2, \tag{15}$$

so excessive sag can extend acceleration and sustain high current.

5 Fuel and Environmental Derating

Fuel conversion is represented by

$$P_{\text{fuel}} = P_{\text{nameplate}} \eta_{\text{fuel}}, \tag{16}$$

Table 2: Illustrative Fuel-Capacity Factors

Fuel	η_{fuel}	Use
Gasoline	1.00	Reference benchmark
Liquid propane	0.90	Preliminary screening
Natural gas	0.80–0.85	Preliminary screening

Table 3: Connected Essential Loads

Load	Run (W)	Start (W)	Delta (W)
Base loads	1,500	2,300	800
0.75-hp well pump	1,200	3,600	2,400
3-ton heat pump	3,500	18,000	14,500
Running total	6,200	–	–

with screening factors shown in Table 2. Actual ratings must use the manufacturer's fuel-specific data.

For elevation h in feet and ambient temperature T_a in degrees Fahrenheit, the manuscript's environmental model is

$$\delta_h = 0.035 \max\left(0, \frac{h-500}{1000}\right), \tag{17}$$

$$\delta_T = 0.010 \max\left(0, \frac{T_a-77}{10}\right), \tag{18}$$

$$\Phi_{\text{env}} = \max(0, 1-\delta_h-\delta_T). \tag{19}$$

With operating reserve factor κ_{margin}, usable continuous output becomes

$$P_{\text{usable}} = P_{\text{rated}}\eta_{\text{fuel}}\Phi_{\text{env}}\kappa_{\text{margin}}. \tag{20}$$

The example uses $\kappa_{\text{margin}} = 0.80$–$0.85$. The linear altitude and temperature coefficients are generic screening assumptions and should be replaced by the selected engine-generator derating chart.

6 Residential Case Study

Table 3 lists the essential loads. Starting watts are treated as input data; the heat-pump value corresponds to a 75-A, 240-V locked-rotor condition.

The deliberately conservative arithmetic that adds all run and all start values is

$$P_{\text{double}} = 6200 + 23900 = 30.1 \text{ kW}. \tag{21}$$

This expression double-counts each appliance's running component and is retained only to illustrate the defect in some consumer methods. Under enforced non-coincident direct-on-line starting,

$$P_{\text{peak,DOL}} = 6200 + 14500 = 20.7 \text{ kW}. \tag{22}$$

For $\kappa_{\text{soft}} = 0.35$, the heat-pump starting demand and delta are

$$P_{\text{HP,start,soft}} = 3500 + 0.35(14500) = 8575 \text{ W}, \tag{23}$$

$$\Delta P_{\text{HP,soft}} = 5075 \text{ W}. \tag{24}$$

Table 4: Case-Study Envelope Comparison

Method	Peak demand	Interpretation
Run-plus-start double count	30.1 kW	Overconservative
Non-coincident DOL	20.7 kW	Largest start delta
Non-coincident soft start	11.275 kW	$\kappa_{\text{soft}} = 0.35$

The optimized envelope is therefore

$$P_{\text{peak,soft}} = 6200 + 5075 = 11.275 \text{ kW}. \tag{25}$$

The continuous active-power requirement with 20% reserve is $6200/0.80 = 7.75$ kW before fuel and environmental correction. Nameplate selection must satisfy both continuous and transient constraints after derating; a product recommendation cannot be inferred from watts alone.

7 Deterministic Implementation

The governing algorithm maps to a pure-function implementation: sum running watts, compute each nonnegative starting delta, select the largest permitted coincident set, and divide continuous and peak requirements by fuel and environmental factors. The following compact pseudocode captures the core calculation.

Listing 1: Deterministic sizing kernel.

```
run = sum(load.runningWatts for load in loads)
deltas = [max(0, load.startingWatts
              - load.runningWatts)
          for load in loads]
peak = run + max(deltas)
alt = 0.035 * max(0, (elevation_ft-500)/1000)
temp = 0.010 * max(0, (ambient_F-77)/10)
env = max(0.60, 1-alt-temp)
continuous_kW = run/(margin*fuel*env*1000)
surge_kW = peak/(fuel*env*1000)
```

The online model is available at `https://www.powelab.org/home-energy/generator-size-calculator`. Reproducible implementations should retain units explicitly, distinguish kW from kVA, expose all derating assumptions, and accept measured LRA where available.

8 Limitations and Validation Requirements

The non-coincident envelope requires an enforceable operating sequence. It does not cover sustained coincident starts, nonlinear-load harmonic limits, phase imbalance, governor response, automatic-voltage-regulator ceiling current, cable voltage drop, breaker trip curves, or motor acceleration torque. Likewise, (14) is a screening approximation. Publication or field use should validate results against manufacturer data and coordinated protection studies. Relevant load, motor, and standby-system requirements remain subject to NFPA 70 Articles 220, 430, and 702 [2].

9 Conclusion

A defensible residential generator model must separate continuous complex power from the transient startup envelope. Adding the largest permitted motor-starting delta to aggregate running demand avoids automatic double-counting, while sub-transient reactance supplies a transparent first check on voltage recovery. Fuel, altitude, temperature, and reserve factors then translate rated output into usable site capacity. In the worked example, soft-start control materially reduces the peak envelope, but the result remains conditional on equipment data and startup sequencing. The framework is best used for reproducible screening, sensitivity analysis, and education, followed by manufacturer-specific verification and code-compliant design review.

References

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