

# From Enumeration to Optimization: A Data-Driven Workflow for High-Continuous-Power Density Traction Motor Design

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# Background & Motivation

- **Challenge:** Permanent magnets (PMs) are expensive, but alternative topologies (e.g., SRM, induction, or ferrite-based machines) suffer from lower continuous power density and efficiency.
- **Approach:** Instead of abandoning PM technology, we **optimize PM motors** with **cost as the primary objective**.
- **Core Goal:** Achieve the lowest possible **total cost** while satisfying:
  - Continuous torque & peak torque
  - Continuous power & peak power at 10,000 rpm
  - Current density limits for EM, then verify in thermal analysis
- **Key Insight:** High-continuous-power density requires careful thermal-electromagnetic co-design – but full FEA thermal analysis is slow.

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# Key Requirements

| Performance Metric | Target |
|---|---|
| **Peak Torque 310A** | 450 Nm |
| **Peak Power** | 200 kW |
| **Continuous Torque 250A** | 350 Nm |
| **Max Speed** | 12000 rpm |
| **Continuous Power @ 10krpm** | 150 kW |
| **Max Voltage** | 650 V |
| **Max Length** | 230 mm |
| **Max Diameter** | 220 mm |
| **Cooling Method** | Water Jacket |
| **Max Winding/Magnet Temperature** | 160 C |
| **Coolant Temperature** | 50C |

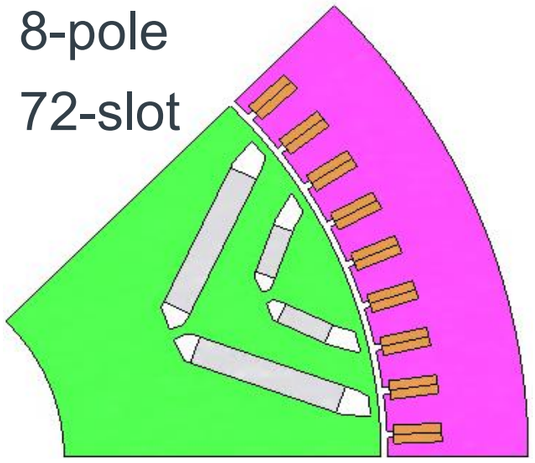
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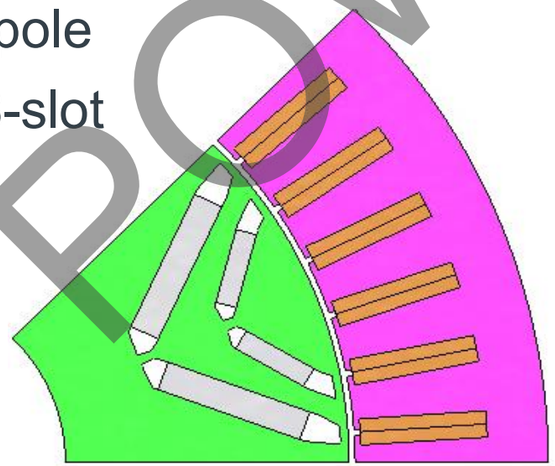
# Overview of Proposed Workflow

- **Define design space**
  - Slot/pole combinations, dimensions, current density and stress limits
- **ROM-based EM and structural analysis**
  - **2.x hours per slot- pole combination for ~3600 cases**
  - Fast screening of electromagnetic performance meeting the stress constraint
- **Select top 4 slot-pole combinations**
  - Based on lowest cost + meeting EM requirements
- **Detailed thermal analysis** (for each of the 5 candidates for each slot-pole combination)
- **Final selection** Winner = lowest total cost with thermal feasibility

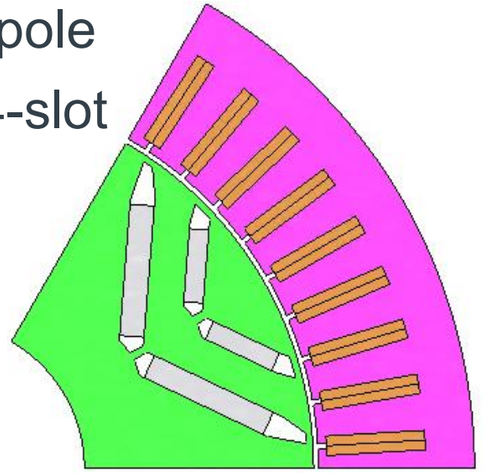
8-pole
72-slot



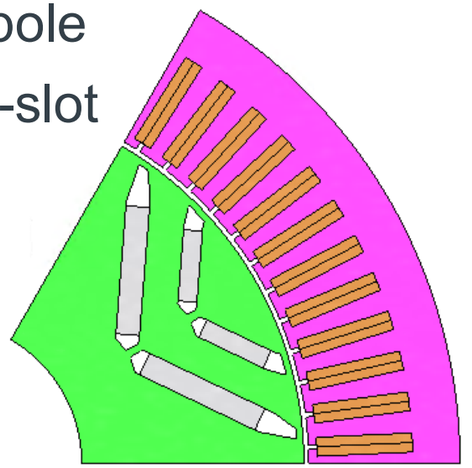
8-pole
48-slot



6-pole
54-slot



6-pole
72-slot



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# Define Design Space

- 19 Design Variables for 4 Slot-Pole Combinations

| | Combination #1 | Combination #2 | Combination #3 | Combination #4 |
|---|---|---|---|---|
| Number of Poles | 8 | 6 | 8 | 6 |
| Number of Slots | 48 | 54 | 72 | 72 |
| Stack Length | 200~250 | 200~250 | 200~250 | 200~250 |
| Stator Outer Diameter | 200~220 | 200~220 | 200~220 | 200~220 |
| Rotor Outer Diameter | 145~158 | 145~158 | 145~158 | 145~158 |
| Slot Width | 2.5~4.5 | 2~4.5 | 2~4.5 | 2~4.5 |
| Back Iron | 10~20 | 10~20 | 10~20 | 10~20 |
| Small Magnet Length | 6~18 | 6~20 | 6~15 | 6~20 |
| Small Magnet Width | 3~4.5 | 3~5 | 3~4.5 | 3~5 |
| Small Magnet Position 1 | 3~18 | 3~18 | 3~18 | 3~18 |
| Small Magnet Position 2 | 1~5 | 1~5 | 1~5 | 1~5 |
| Small Magnet Angle | 80~160 | 100~165 | 80~130 | 110~165 |
| Large Magnet Length | 18~27 | 20~35 | 20~27 | 20~35 |
| Large Magnet Width | 4~6 | 4~6 | 4~6 | 4~6 |
| Large Magnet Position 1 | 40~65 | 40~65 | 40~65 | 40~65 |
| Large Magnet Position 2 | 1.5~5 | 1.5~5 | 1.5~5 | 1.5~5 |
| Large Magnet Angle | 70~150 | 100~165 | 70~110 | 110~165 |
| Number of turns/Half Slot | 3,4,5 | 3,4,5 | 3,4,5 | 3,4,5 |
| Number of parallel branches | 2,3,4 | 2,3,4 | 2,3,4 | 2,3,4 |

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# ROM-based EM Analysis and Structural Analysis

- **Why ROM (Reduced Order Model) for the EM efficiency map?**
  - Traditional FEA-based optimization is too slow for large slot/pole search spaces.
  - 7 points (no-load, 50% and 100% peak current, [0,45,90] degrees)
- **Key benefit for this project:**
  - **Only 2~3 hours per (slot, pole) combination** → hours instead of weeks
  - Allows us to explore a large design space before committing to thermal analysis
- **Metrics extracted from ROM:**
  - Torque capability (continuous & peak) at 250Arms and 310Arms
  - Power at 10,000 rpm at 250Arms and 310Arms
  - Loss components (copper, iron, PM eddy current)
  - **Estimated active material cost** (magnets, copper, and laminations)

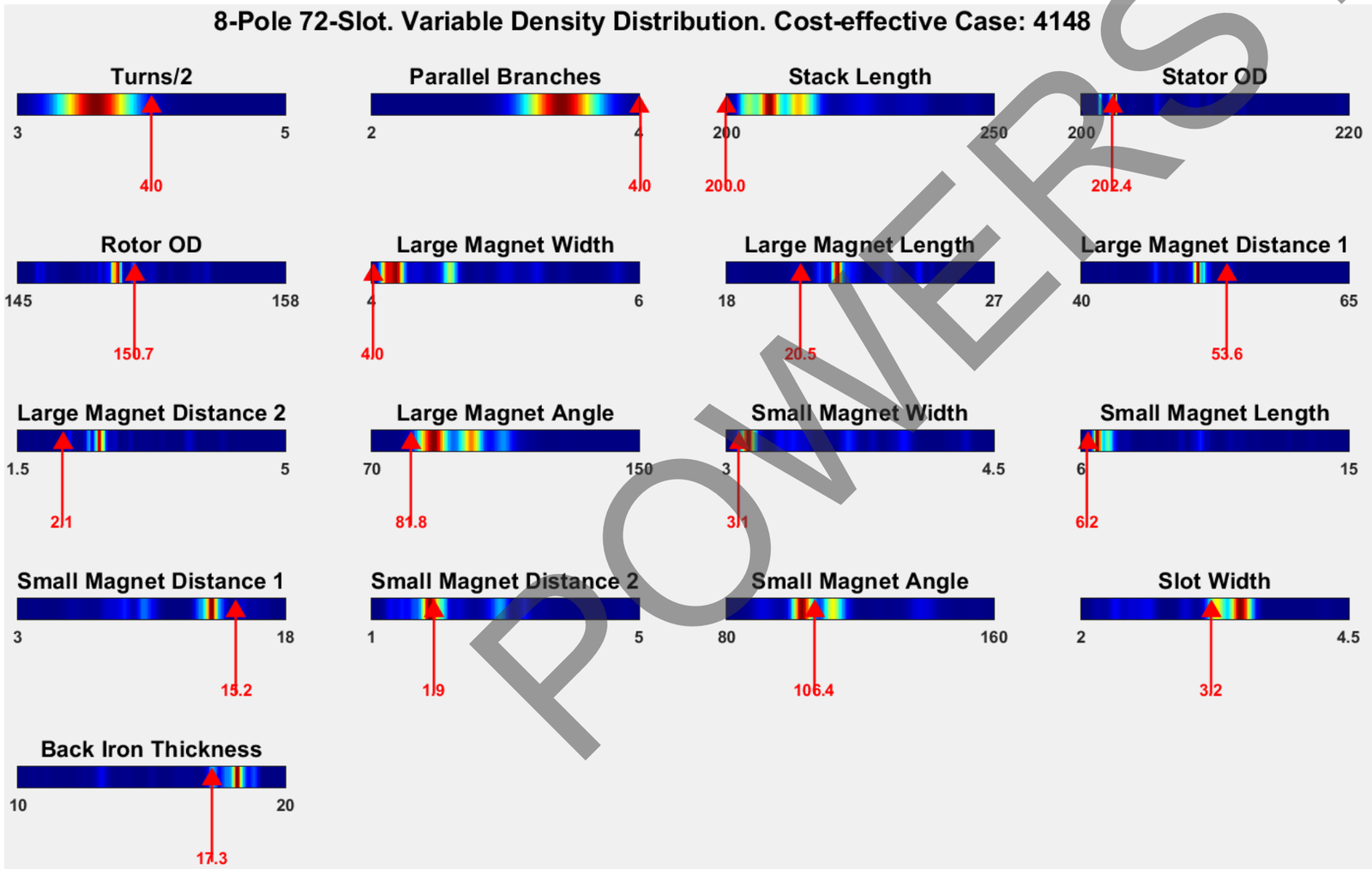
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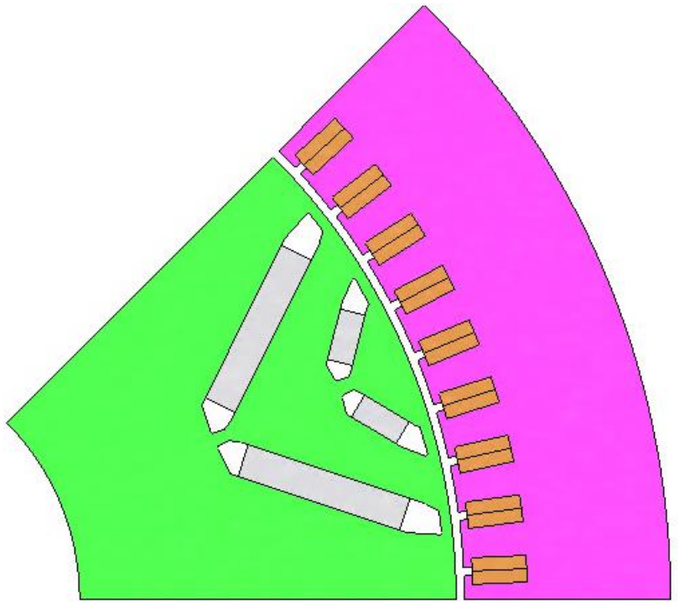
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# 8-Pole 72-Slot

- 4176 out of 4320 cases have valid geometries.
- 2070 cases meet torque, power, and stress requirements.

$416.2

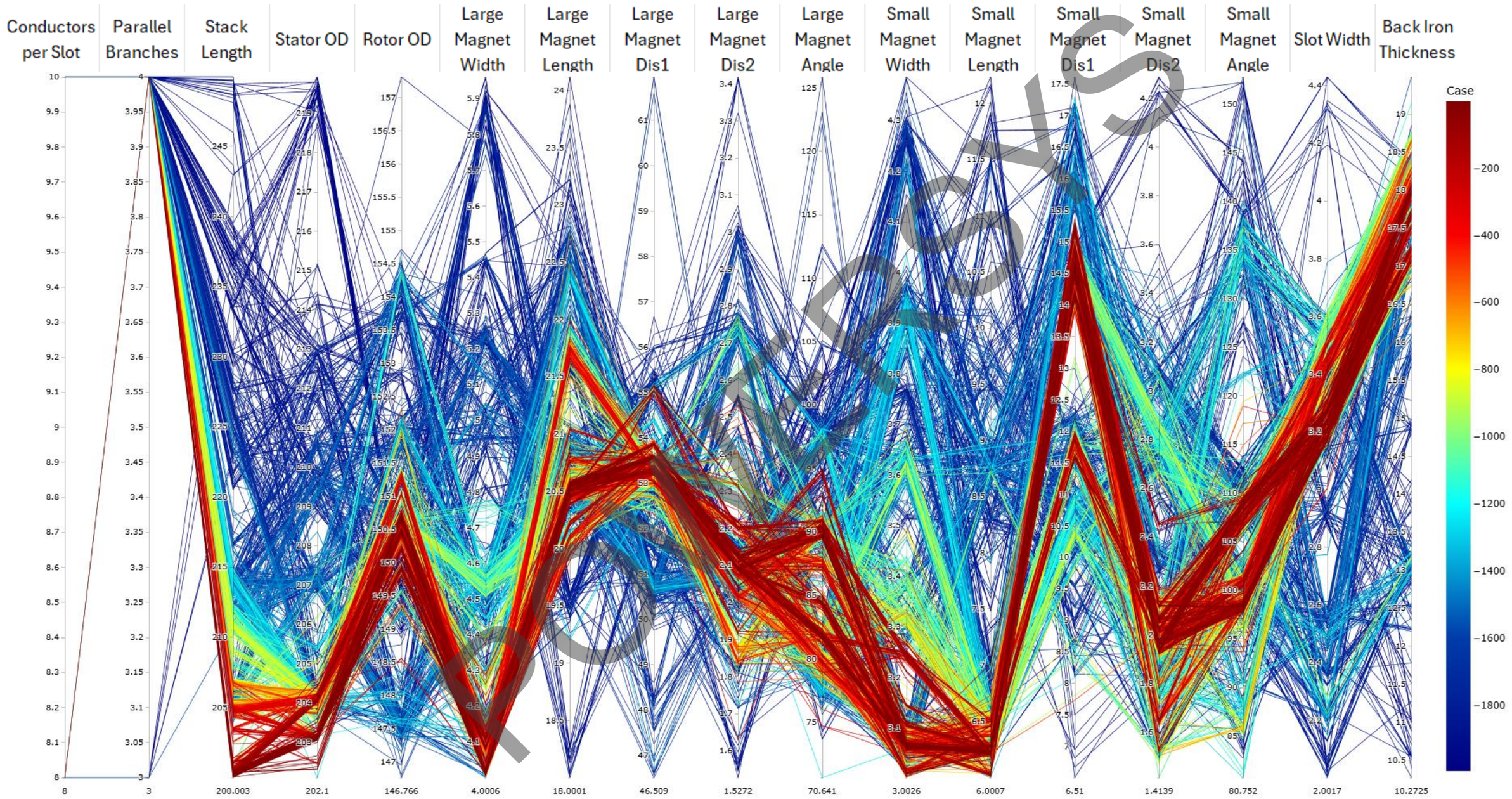


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# 8-Pole 72-Slot



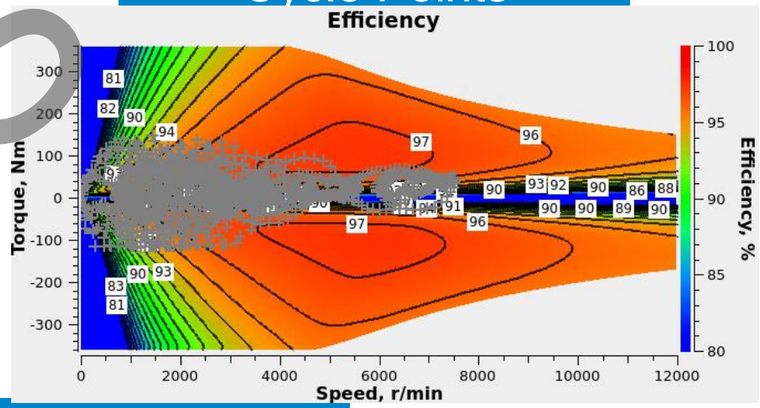

PROPOSAL

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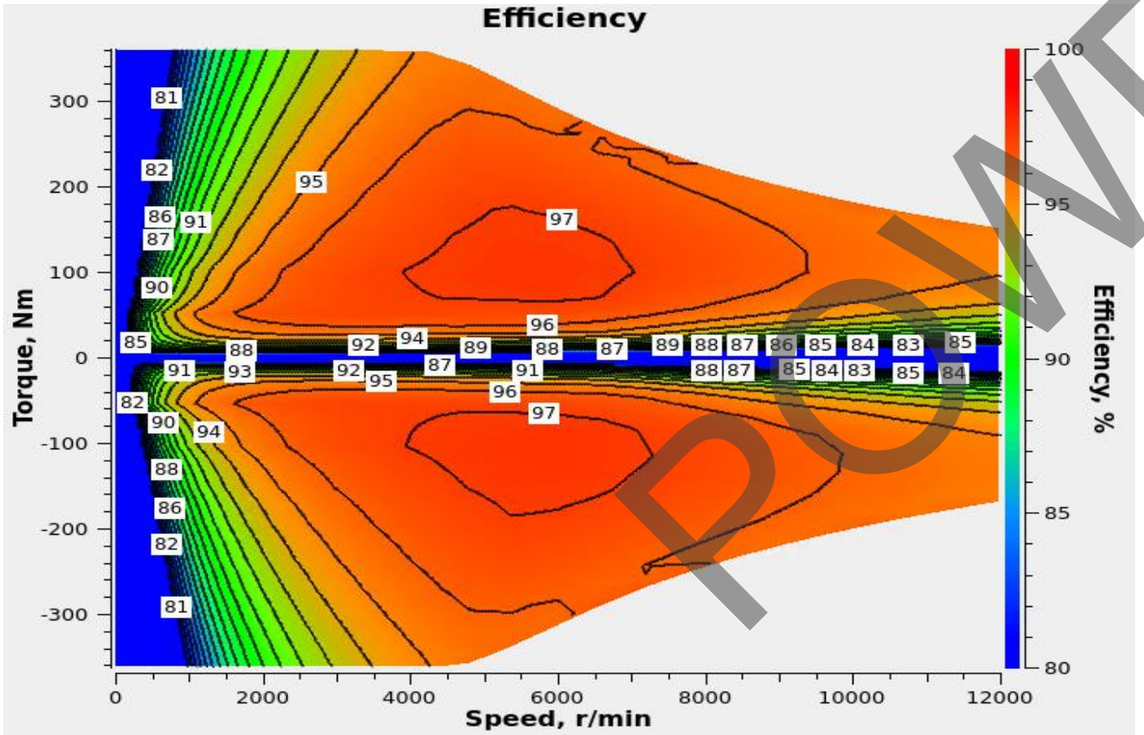
# 8-Pole 72-Slot

- Continuous map
  - 250Arms, 650Vdc
  - Max temperature for coil and magnets 160C
  - Coolant 50C

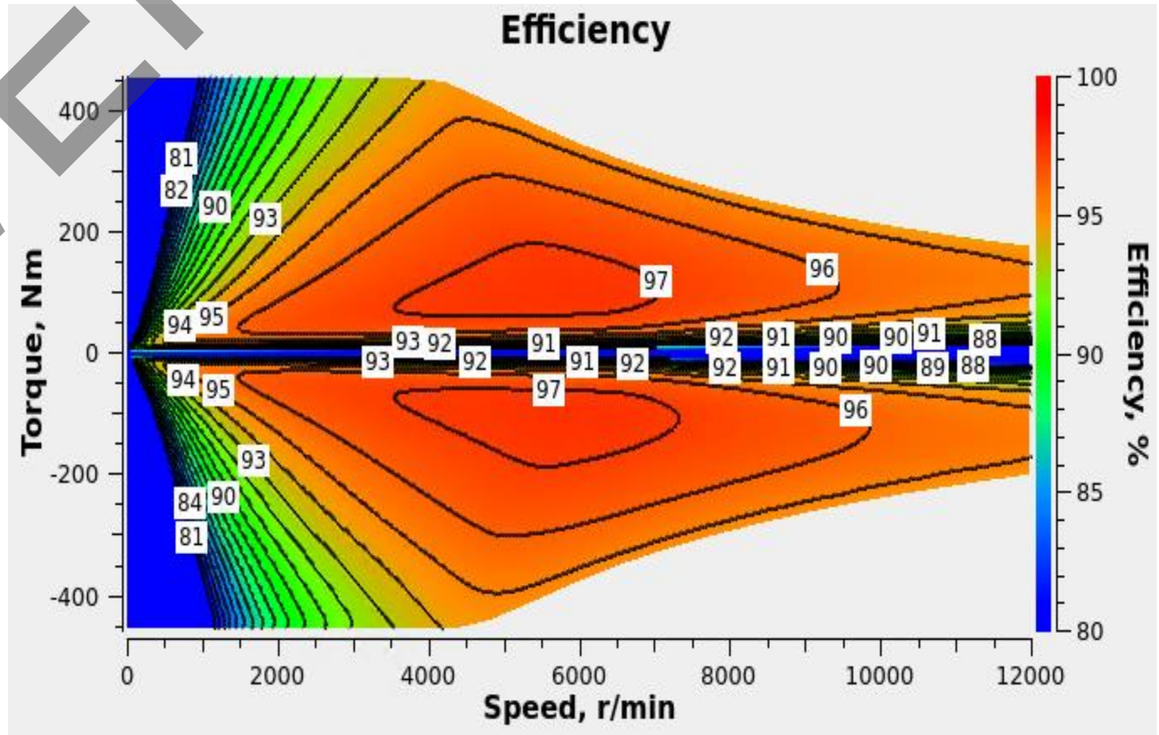
JMAG Built-in Drive Cycle Points




Continuous Operation Map




EM Map 310Arms



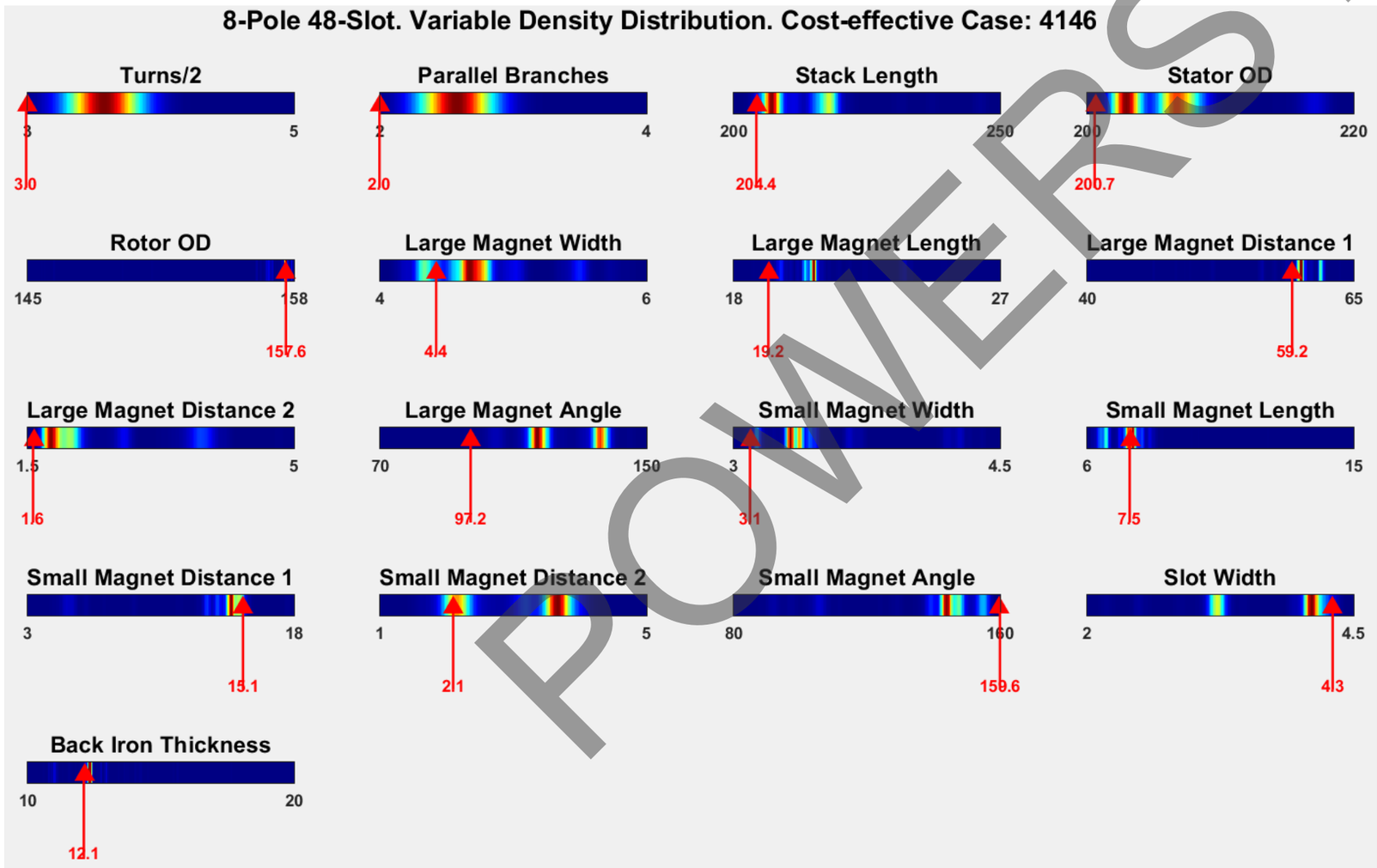

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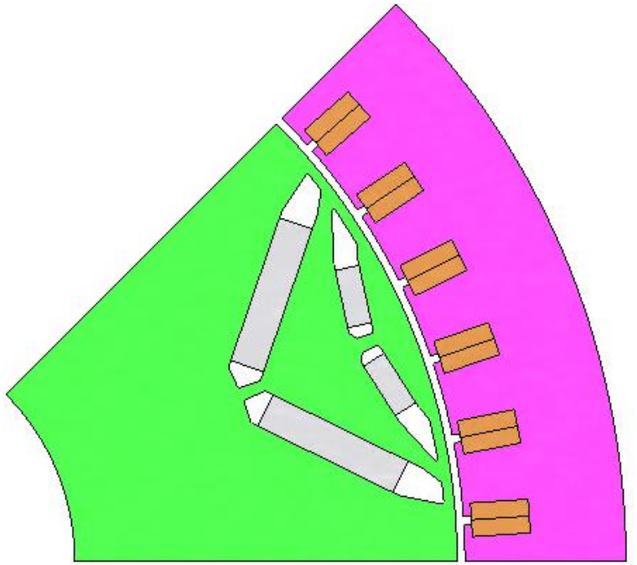
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# 8-Pole 48-Slot

- 4094 out of 4320 cases have valid geometries.
- 2246 cases meet torque, power, and stress requirements.

$440.36

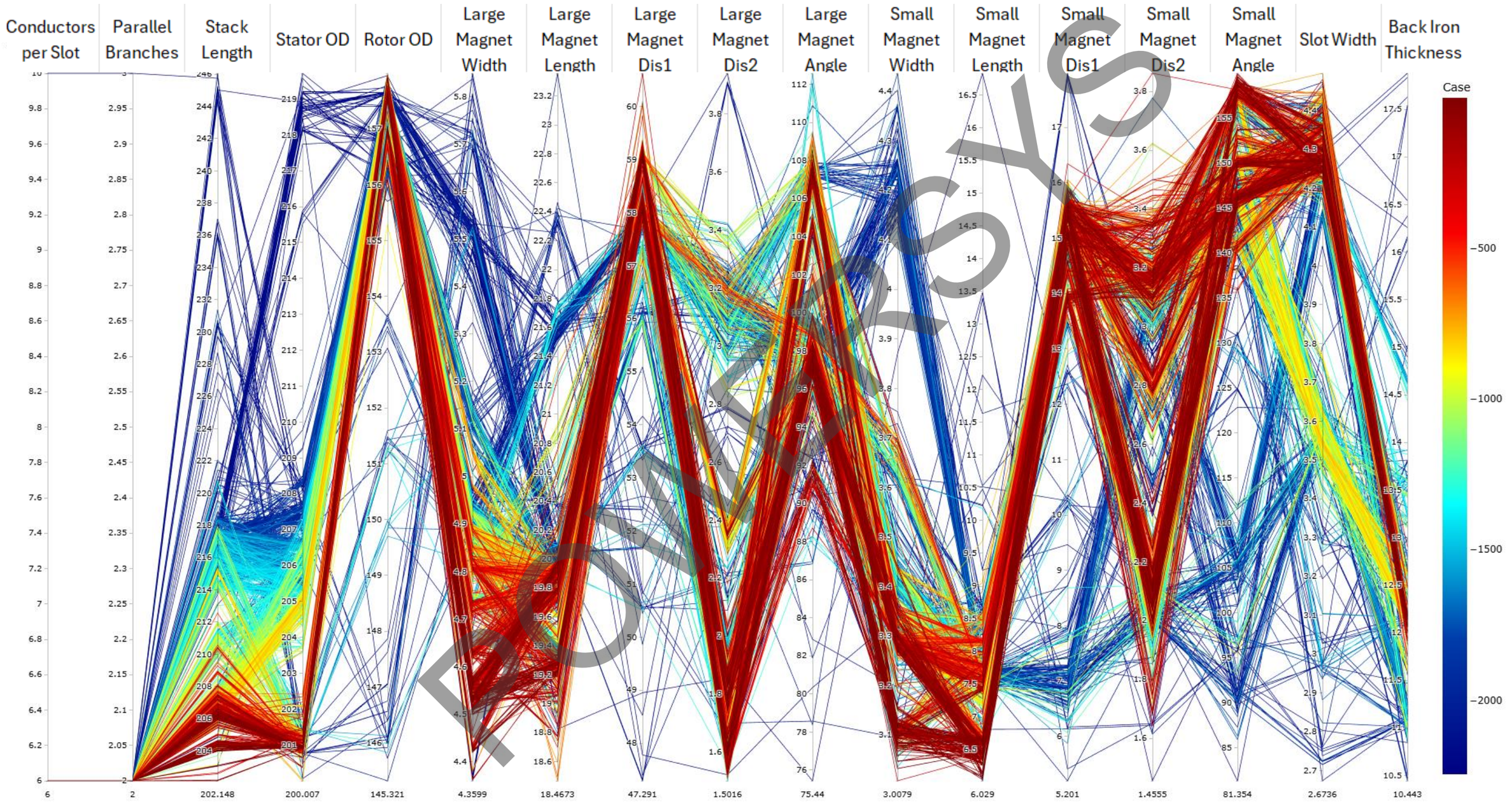


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# 8-Pole 48-Slot



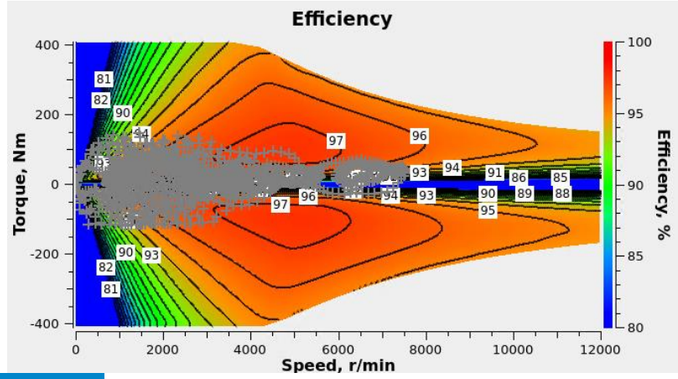

PROPRIETARY

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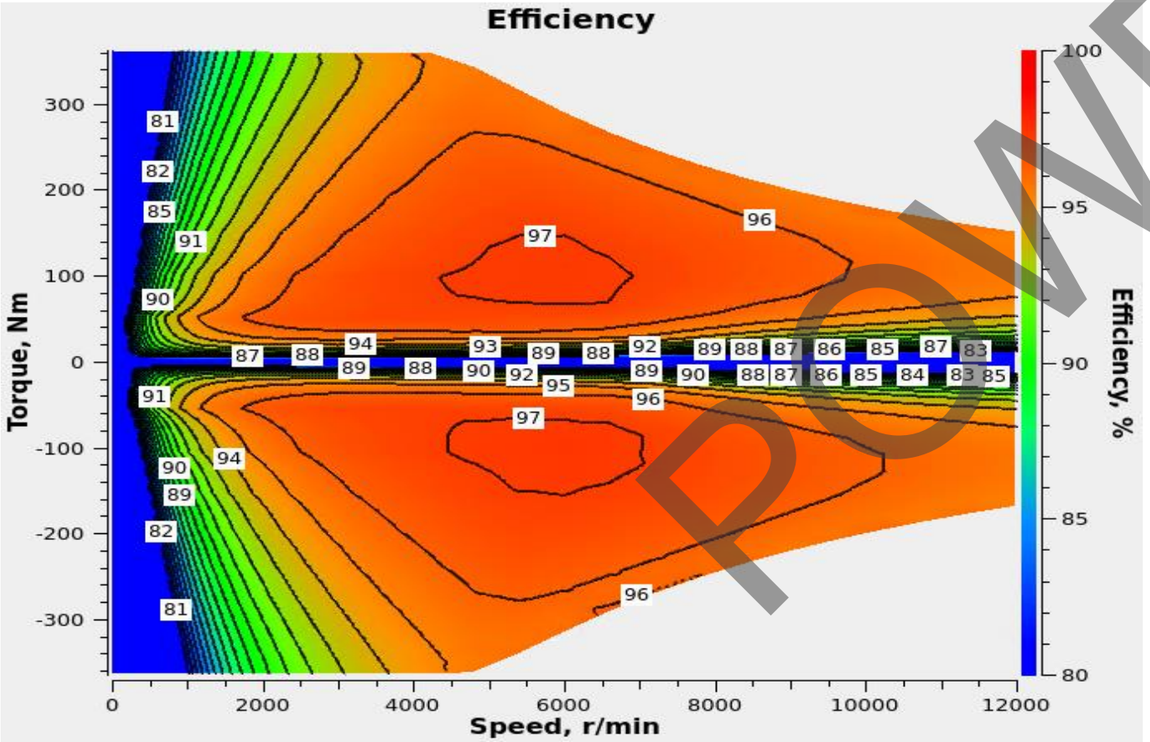
# 8-Pole 48-Slot

- Continuous map
  - 250Arms, 650Vdc
  - Max temperature for coil and magnets 160C
  - Coolant 50C

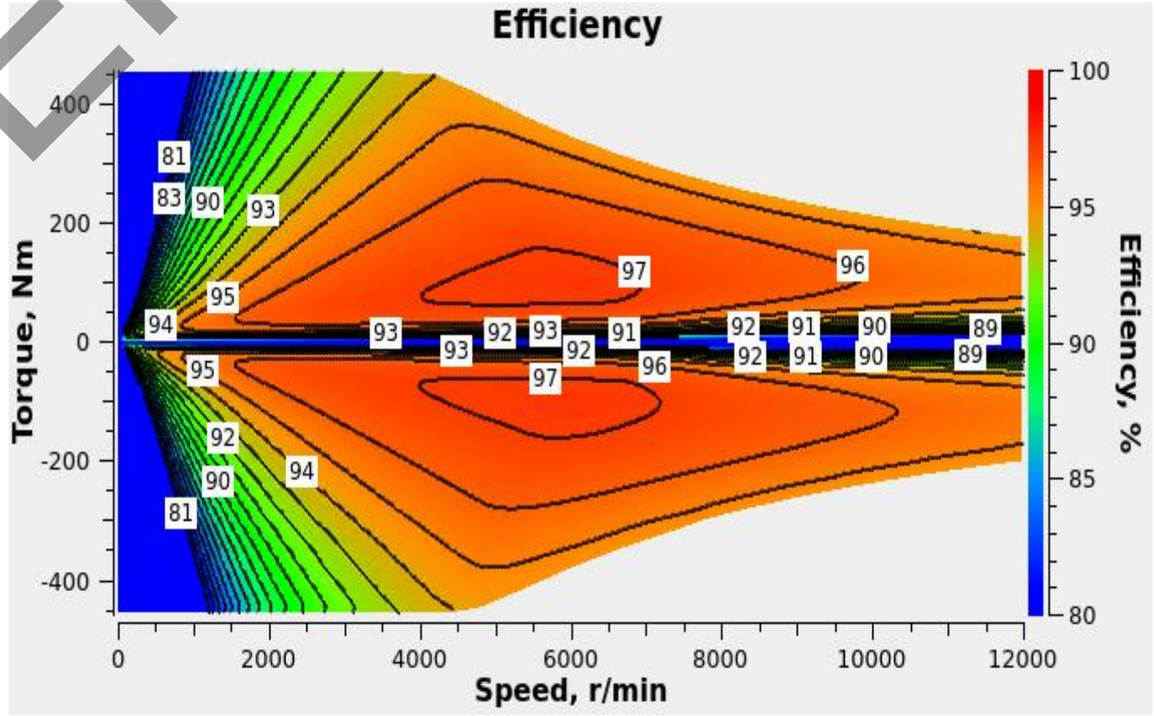
## JMAG Built-in Drive Cycle Points




## Continuous Operation Map




## EM Map 310Arms



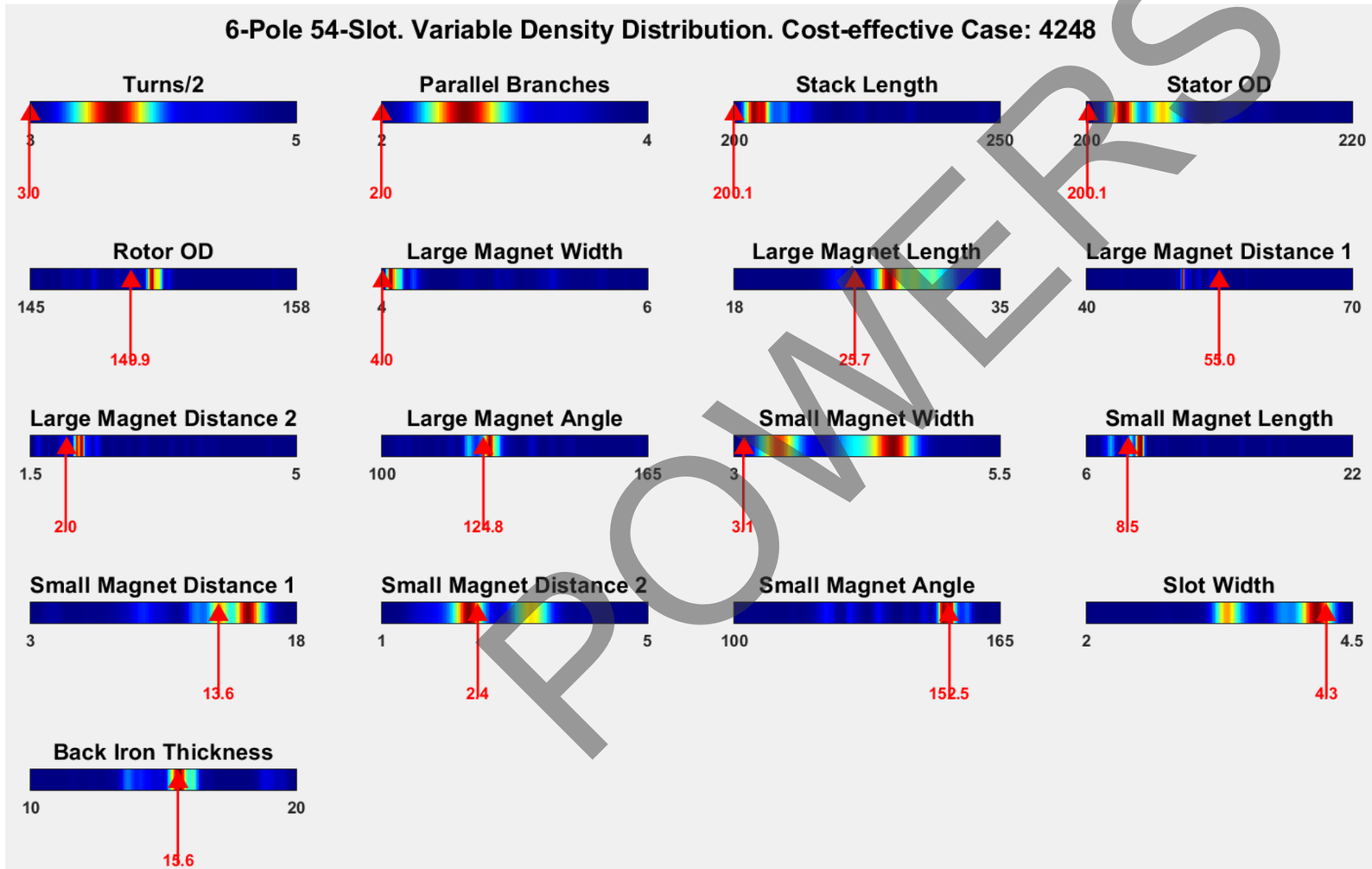

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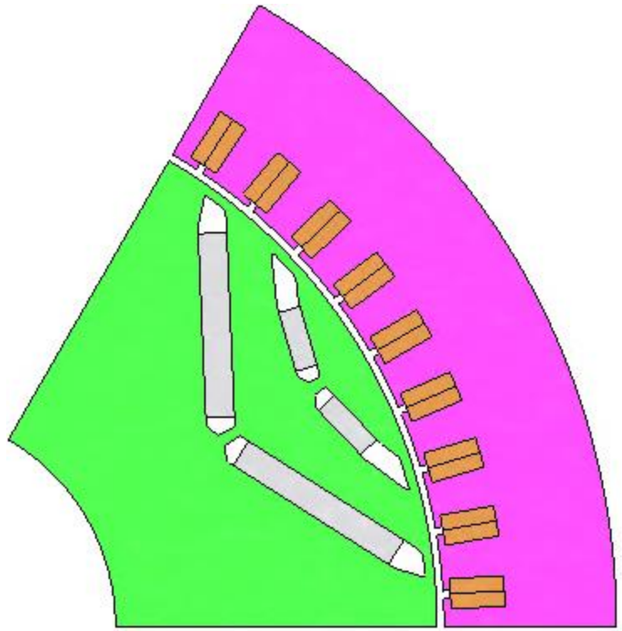
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# 6-Pole 54-Slot

- 4227 out of 4320 cases have valid geometries.
- 805 cases meet torque, power, and stress requirements.

$428.68

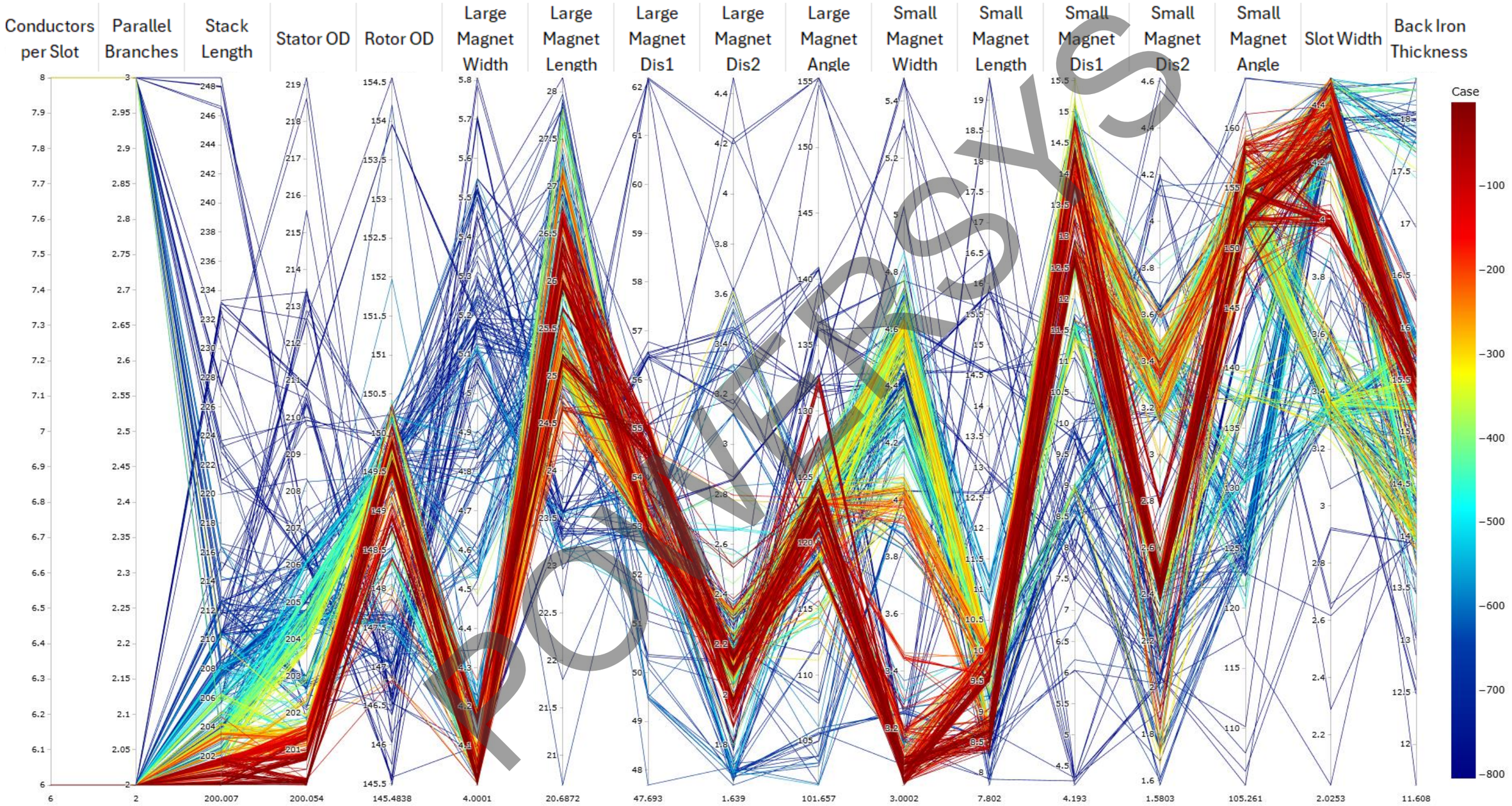


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# 6-Pole 54-Slot



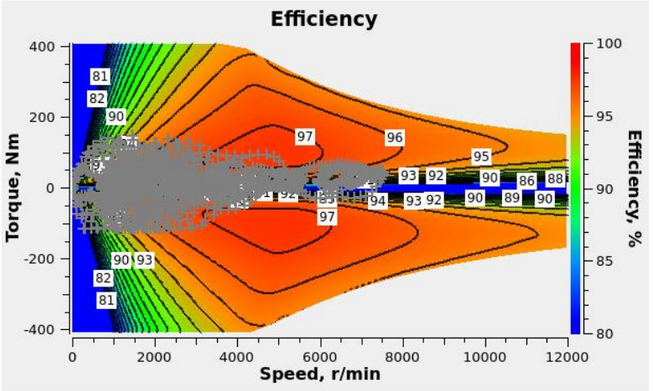

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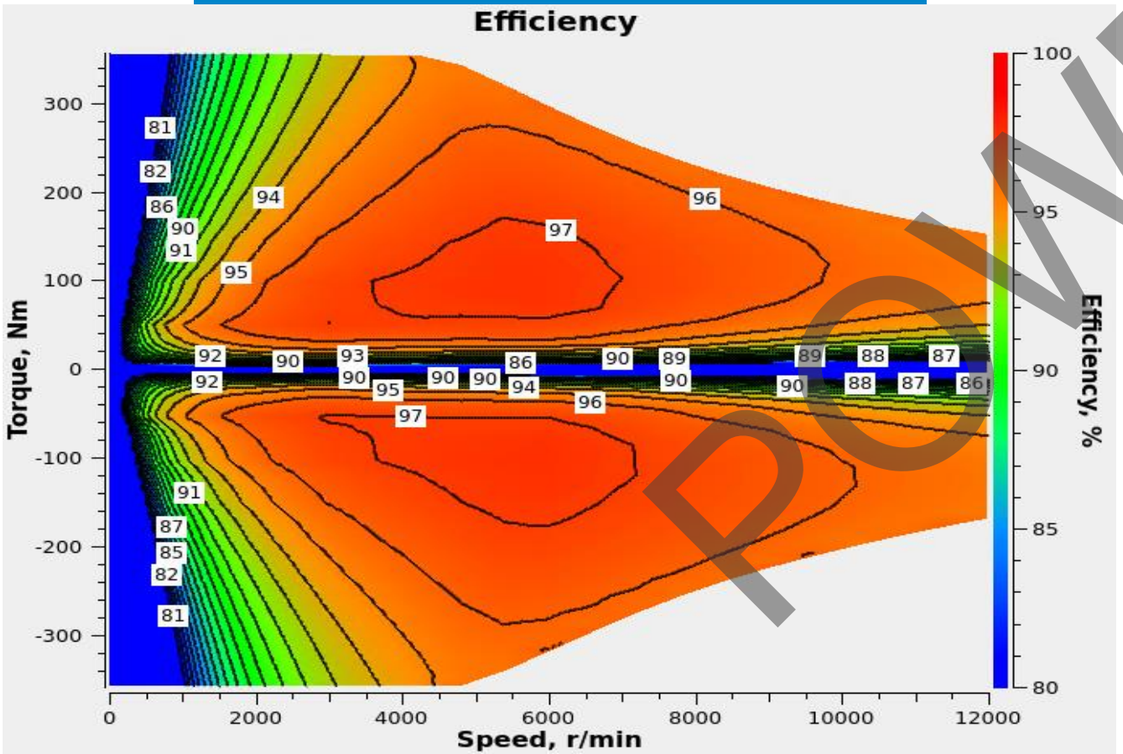
# 6-Pole 54-Slot

- Continuous map
  - 250Arms, 650Vdc
  - Max temperature for coil and magnets 160C
  - Coolant 50C

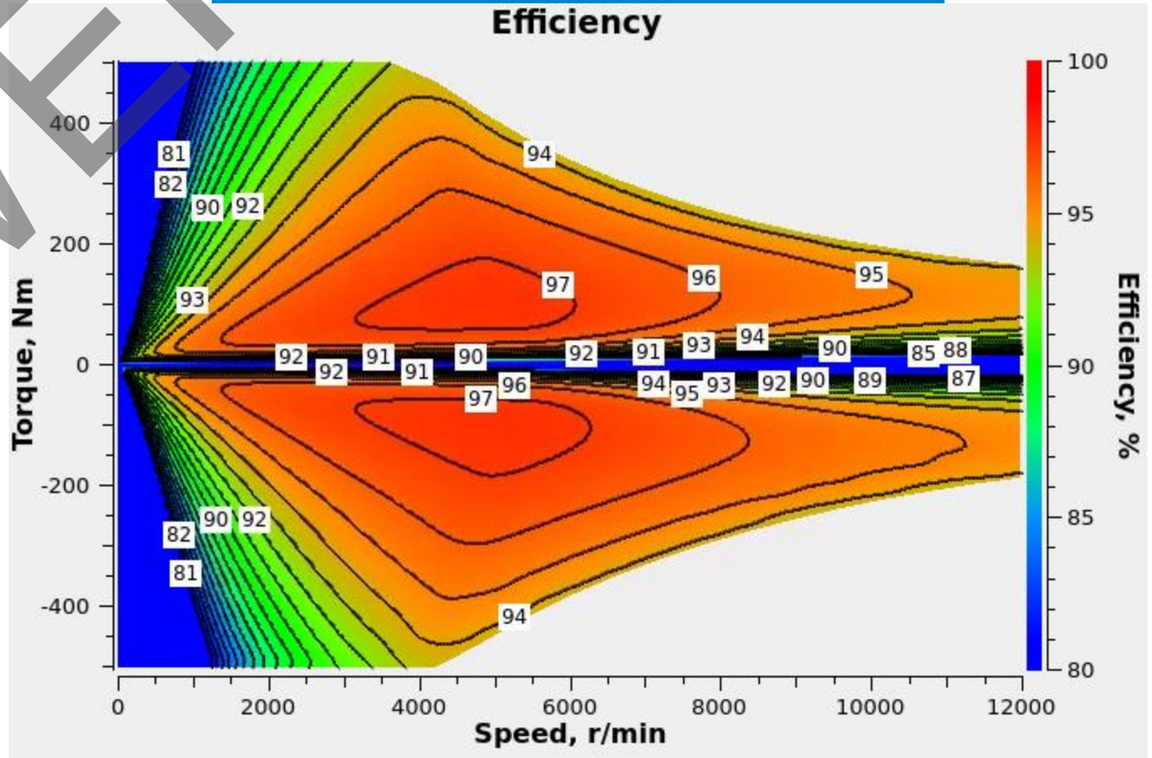
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## EM Map 310Arms

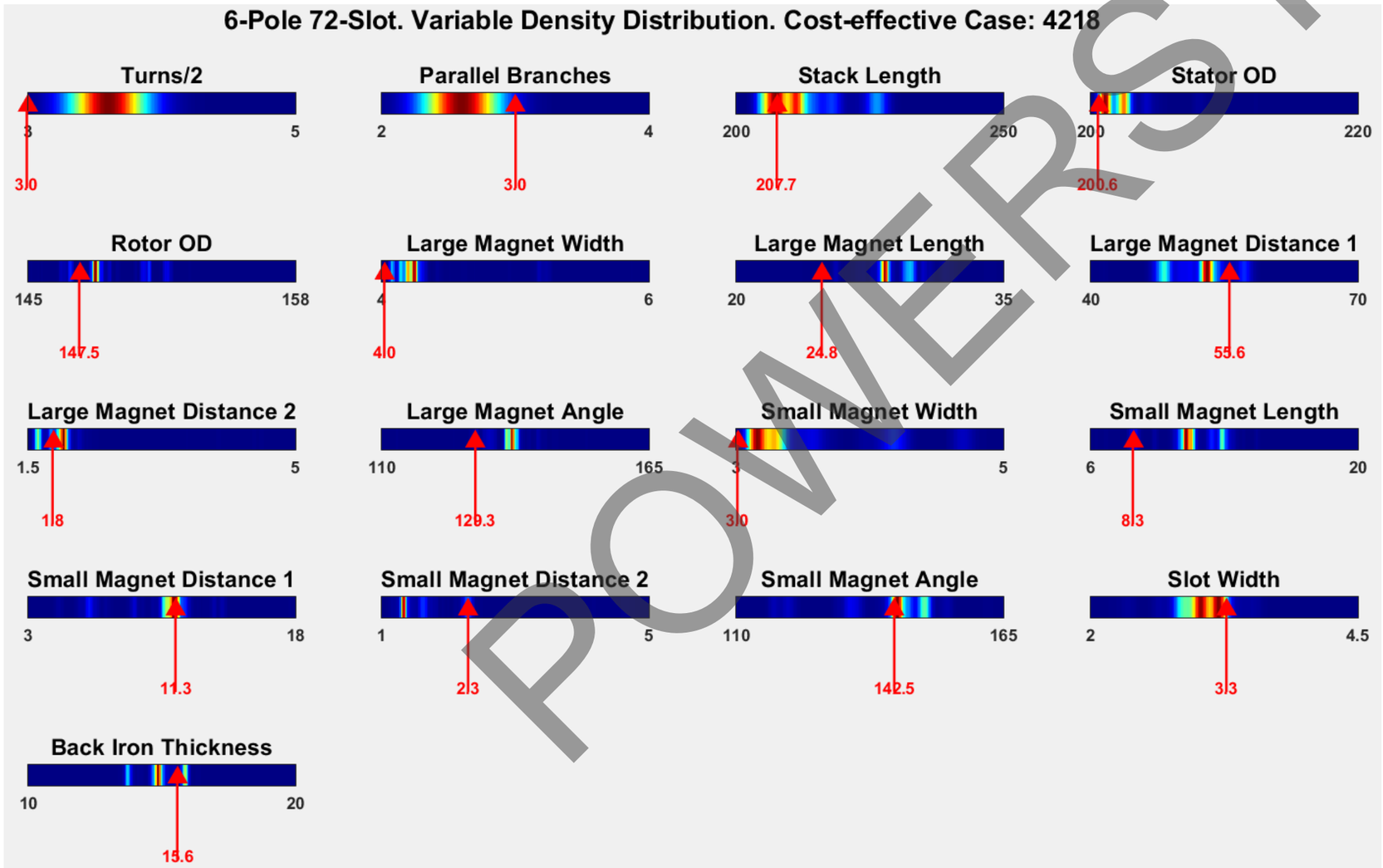



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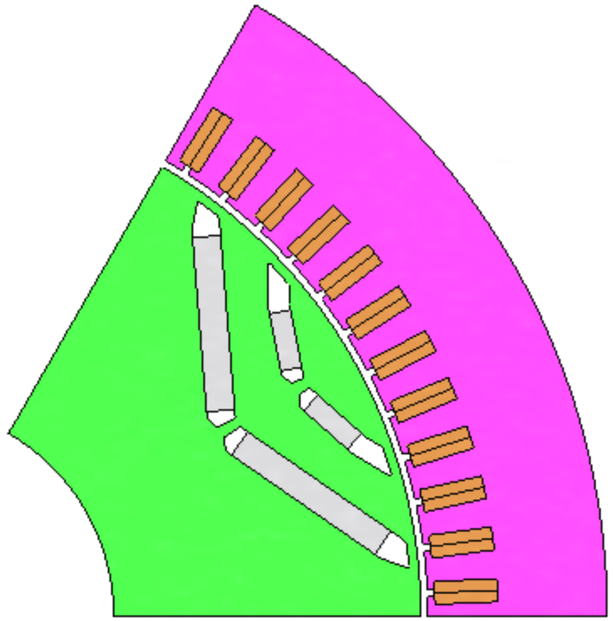
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# 6-Pole 72-Slot

- 4097 out of 4320 cases have valid geometries.
- 1377 cases meet torque, power, and stress requirements.



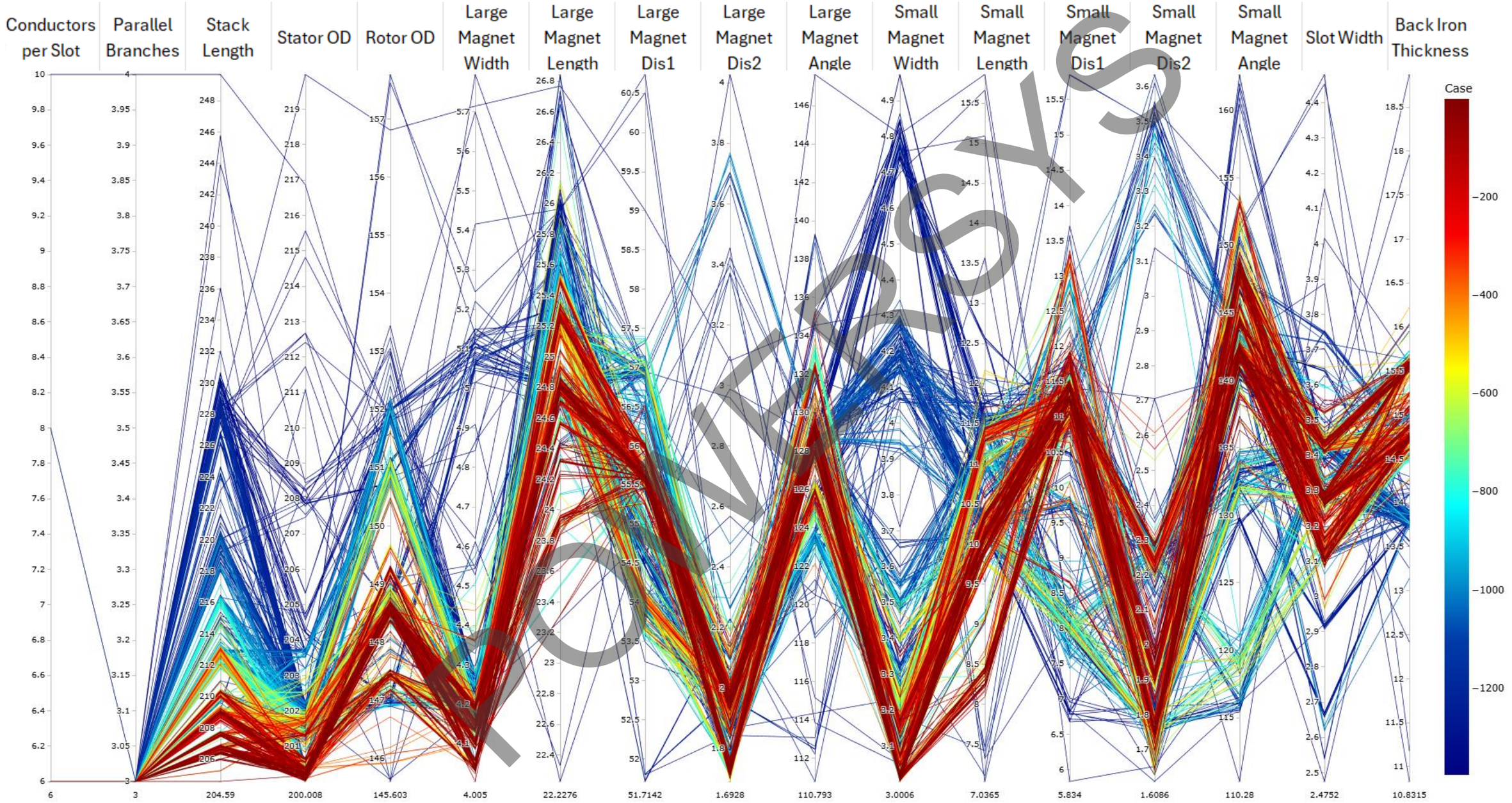

$432.72



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# 6-Pole 72-Slot



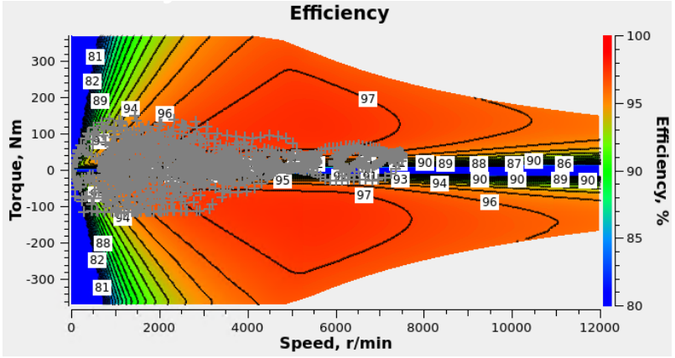

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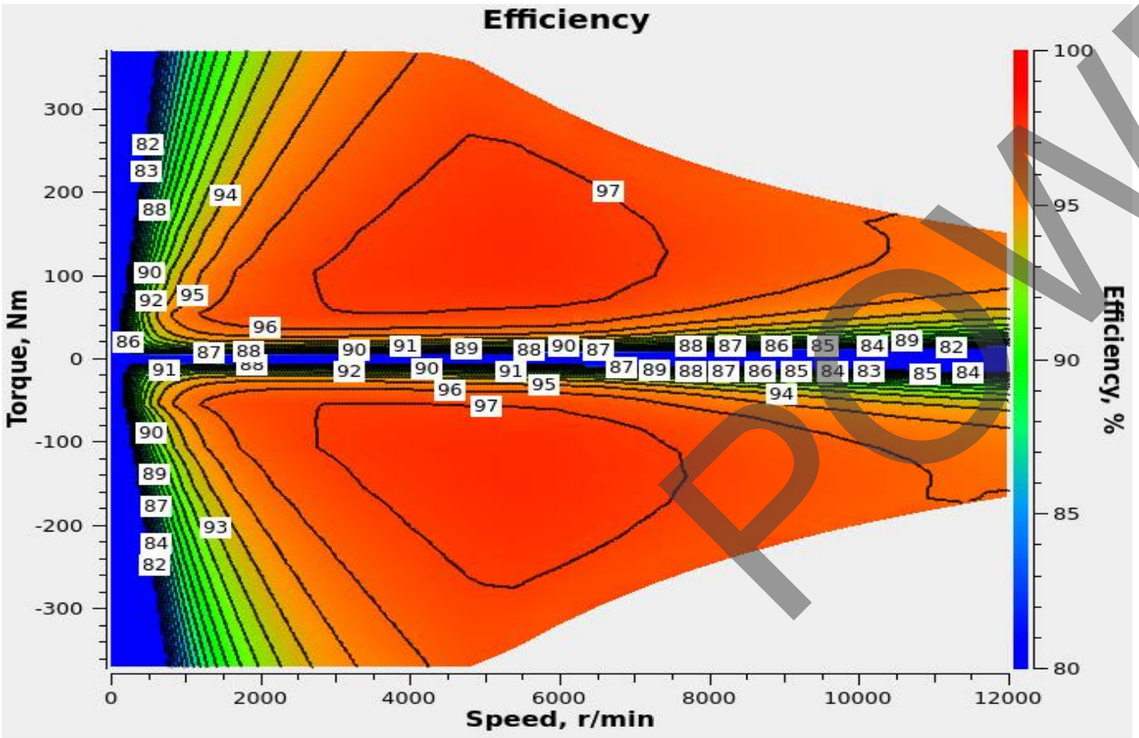
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- Continuous map
  - 250Arms, 650Vdc
  - Max temperature for coil and magnets 160C
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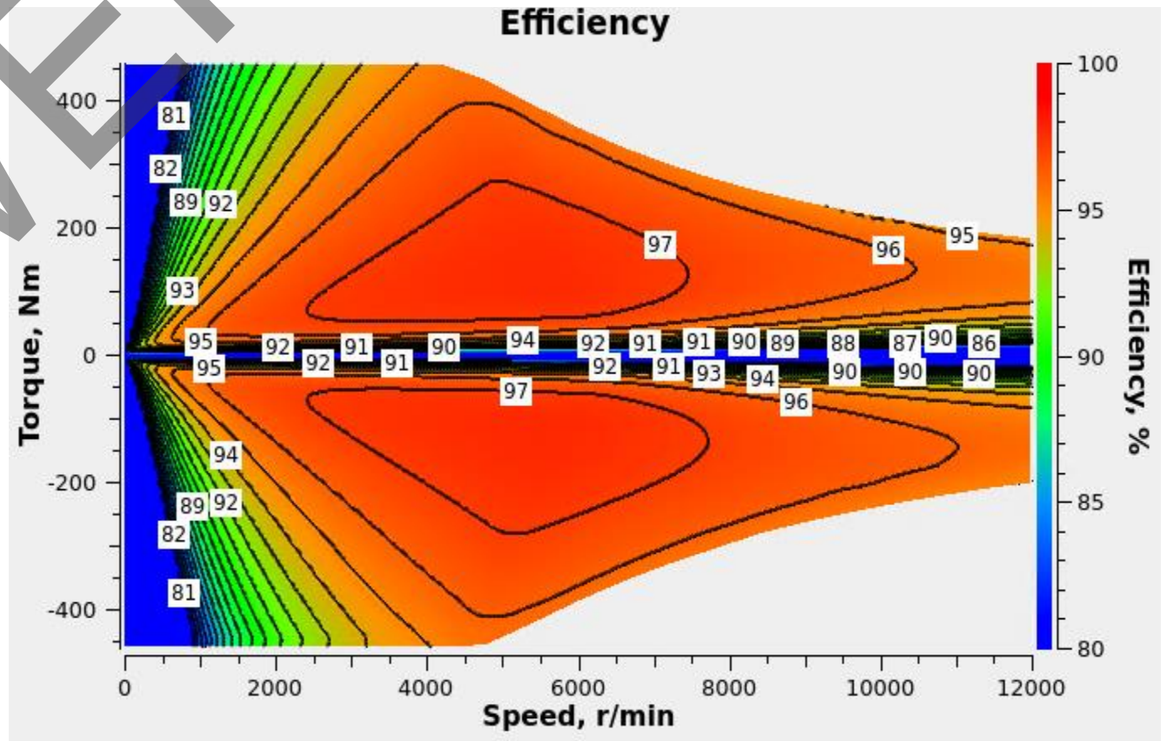
## JMAG Built-in Drive Cycle Points




## Continuous Operation Map




## EM Map 310Arms

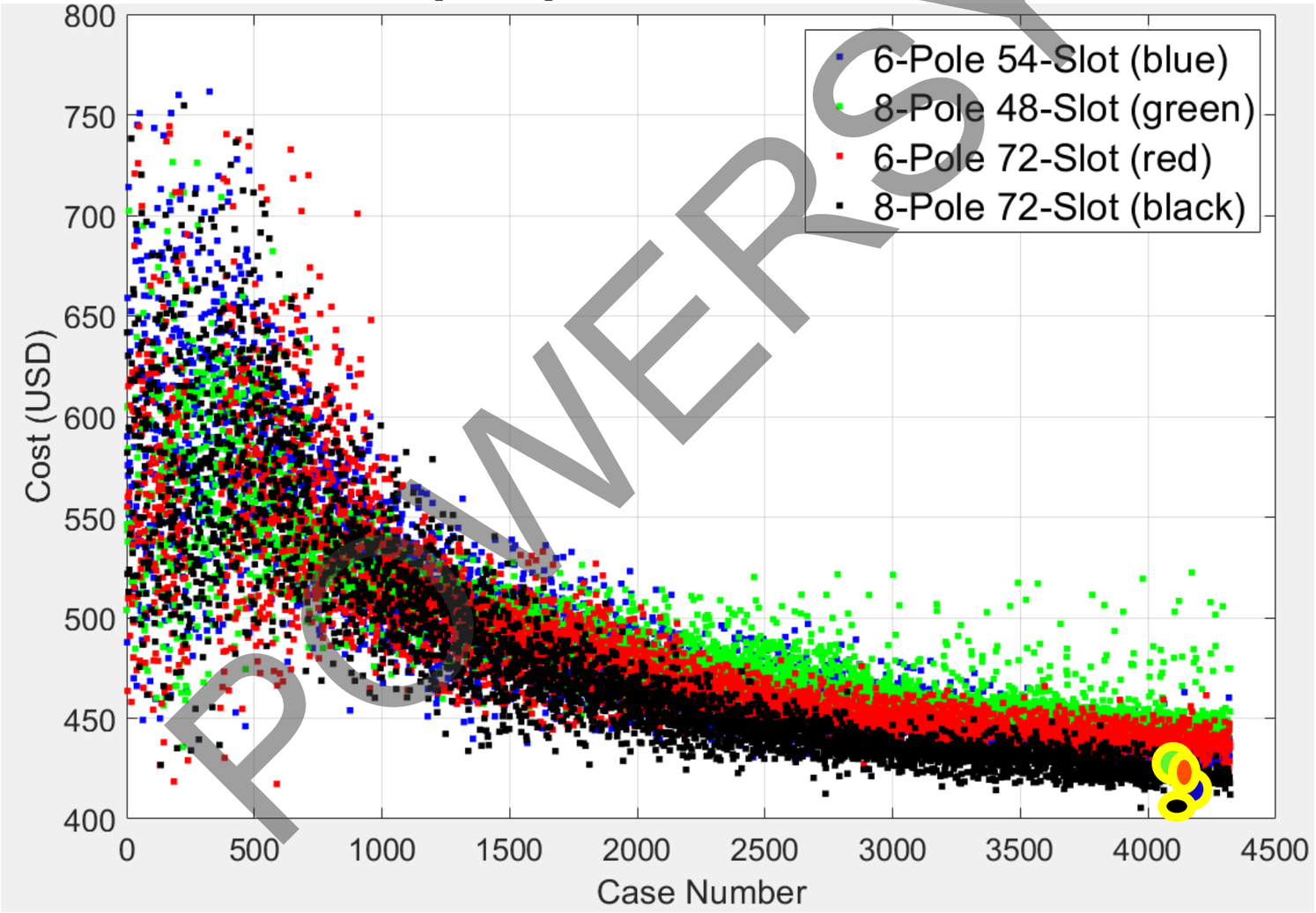



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# Selection of Top 4 Slot-Pole Designs

- Choose 4 best designs per slot-pole **combinations with the lowest cost** that meet the **requirements of torque, power, and maximum stress.**




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# 20 Best Designs

| | Conductors per Slot/2 | Parall Branches | Stack Length | Stator OD | Rotor OD | Large Magnet Width | Large Magnet Length | Large Magnet Dis 1 | Large Magnet Dis 2 | Large Magnet Angle | Small Magnet Width | Small Magnet Length | Small Magnet Dis 1 | Small Magnet Dis 2 | Small Magnet Angle | Slot Width | Back Iron Thickness | Tmax250 Arms | Tmax310 Arms | P10krpm 250Arms | P10krpm 310Arms | TotalLoss 10krpm 250Arms | TotalLoss 1krpm 310Arms | Current Density 250Arms | Mises | Cost | Best Case |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **6-Pole 54 Slot:** | 3 | 2 | 200.1 | 200.1 | 149.9 | 4.0065 | 25.722 | 54.99238 | 1.97706 | 124.82 | 3.0945 | 8.5159 | 13.6066 | 2.44284 | 152.51 | 4.2527 | 15.55341 | 396.543 | 490.103 | 189411 | 204081 | 9957.15 | 13162.9 | 29.52066 | 3E+08 | 428.684462 | 4248 |
| | 3 | 2 | 200.1 | 200.1 | 149.9 | 4.0035 | 24.677 | 55.05415 | 2.107095 | 122.45 | 3.0471 | 9.5987 | 14.2522 | 2.42308 | 150.97 | 4.3163 | 15.4294 | 397.128 | 489.279 | 187077 | 200530 | 9636.8 | 12751 | 28.57032 | 3E+08 | 429.4455 | 4103 |
| | 3 | 2 | 200.1 | 200.2 | 149.9 | 4.0152 | 25.711 | 54.99238 | 1.976762 | 124.82 | 3.0241 | 8.6205 | 13.8149 | 2.41264 | 152.26 | 4.254 | 15.43353 | 396.768 | 489.653 | 189567 | 201983 | 9870.7 | 12954.2 | 29.03317 | 3E+08 | 429.726075 | 4161 |
| | 3 | 2 | 200.6 | 200.1 | 148.9 | 4.0156 | 25.162 | 54.48819 | 2.103778 | 124.16 | 3.0479 | 8.6726 | 14.3313 | 2.3666 | 152.44 | 4.2571 | 15.52918 | 395.406 | 487.933 | 189233 | 200660 | 9457.81 | 12360 | 27.66316 | 3E+08 | 431.199861 | 3907 |
| | 3 | 2 | 200.1 | 200.1 | 149.7 | 4.1671 | 25.172 | 54.58703 | 2.160781 | 118.5 | 3.0725 | 8.6892 | 13.822 | 2.40589 | 154.41 | 4.2572 | 15.54994 | 396.706 | 490.955 | 189337 | 200867 | 9990.01 | 12944.4 | 29.02354 | 3E+08 | 431.583969 | 4284 |
| **8-Pole 48 Slot:** | 3 | 2 | 204.4 | 200.7 | 157.6 | 4.4225 | 19.198 | 59.20463 | 1.589086 | 97.207 | 3.0968 | 7.4693 | 15.1136 | 2.09907 | 159.64 | 4.2985 | 12.14947 | 381.475 | 450.153 | 193467 | 215202 | 7013.43 | 11339.1 | 29.88208 | 3E+08 | 440.357776 | 4146 |
| | 3 | 2 | 204.1 | 200.9 | 157.6 | 4.5362 | 19.284 | 59.09031 | 1.611414 | 97.878 | 3.1298 | 6.5776 | 15.3785 | 2.05809 | 145.86 | 4.2426 | 12.18128 | 389.145 | 458.163 | 192791 | 218901 | 7018.07 | 11343.7 | 29.9412 | 3E+08 | 440.955807 | 3962 |
| | 3 | 2 | 206.3 | 200.9 | 157.7 | 4.4212 | 19.225 | 59.20832 | 1.524797 | 97.711 | 3.0953 | 6.4345 | 15.6234 | 2.17101 | 157.55 | 4.3008 | 12.13435 | 382.72 | 450.287 | 193537 | 210034 | 6991.08 | 11286.9 | 29.53871 | 3E+08 | 441.188923 | 4170 |
| | 3 | 2 | 204 | 201 | 157.6 | 4.501 | 19.27 | 59.11188 | 1.823042 | 97.795 | 3.268 | 6.6156 | 15.3949 | 2.07019 | 149.27 | 4.3656 | 12.1804 | 382.821 | 451.692 | 194130 | 203109 | 6813.55 | 10987.8 | 28.98419 | 3E+08 | 442.070785 | 4300 |
| | 3 | 2 | 203.1 | 201 | 157.6 | 4.5117 | 19.982 | 59.10949 | 1.788415 | 97.72 | 3.0832 | 6.6529 | 15.6006 | 2.86541 | 158.71 | 4.2537 | 12.20698 | 387.461 | 454.112 | 186867 | 221930 | 6940.1 | 11281.8 | 29.88548 | 3E+08 | 442.164846 | 4065 |
| **8-Pole 72 Slot:** | 4 | 4 | 200 | 202.4 | 150.7 | 4.0146 | 20.5 | 53.61476 | 2.095504 | 81.84 | 3.0725 | 6.2323 | 15.208 | 1.93453 | 106.43 | 3.2166 | 17.25265 | 388.398 | 457.716 | 194031 | 210719 | 6840.13 | 10945.2 | 29.8506 | 3E+08 | 416.200017 | 4148 |
| | 4 | 4 | 200.3 | 203.1 | 150.7 | 4.0119 | 20.514 | 53.26755 | 2.091666 | 89.778 | 3.0706 | 6.2168 | 14.2229 | 2.19393 | 98.422 | 3.2423 | 17.66484 | 381.39 | 450.018 | 194663 | 205680 | 6575.04 | 10949 | 29.84517 | 3E+08 | 417.802335 | 4320 |
| | 4 | 4 | 200 | 203.1 | 150.7 | 4.0144 | 20.39 | 53.6134 | 2.129941 | 81.972 | 3.0661 | 6.2322 | 14.6346 | 2.06424 | 106.47 | 3.2146 | 17.51503 | 385.645 | 454.452 | 194485 | 205824 | 6739.53 | 10731.7 | 29.25746 | 3E+08 | 417.820163 | 4024 |
| | 4 | 4 | 200.3 | 203.1 | 150.7 | 4.012 | 20.495 | 53.8581 | 2.144613 | 89.612 | 3.0706 | 6.2166 | 14.4601 | 2.11972 | 98.409 | 3.2396 | 17.66423 | 387.429 | 457.419 | 193298 | 214792 | 6623.18 | 10960.6 | 29.87406 | 3E+08 | 418.303993 | 4159 |
| | 4 | 4 | 200 | 203.1 | 150.2 | 4.0173 | 20.387 | 53.85469 | 2.129341 | 89.643 | 3.0657 | 6.2181 | 14.6416 | 2.11801 | 109.54 | 3.24 | 17.6655 | 385.461 | 455.582 | 193953 | 215847 | 6438.54 | 10520.6 | 28.69233 | 3E+08 | 418.307549 | 4125 |
| **6-Pole 72 Slot:** | 3 | 3 | 207.7 | 200.6 | 147.5 | 4.0244 | 24.82 | 55.59893 | 1.835584 | 129.27 | 3.0164 | 8.2582 | 11.2831 | 2.29382 | 142.5 | 3.2717 | 15.59113 | 392.549 | 451.639 | 189175 | 224892 | 5711.15 | 8770.57 | 28.78432 | 3E+08 | 432.722852 | 4218 |
| | 3 | 3 | 206.4 | 200.1 | 148.7 | 4.1067 | 24.233 | 55.57542 | 1.934641 | 127.92 | 3.019 | 10.38 | 11.4898 | 1.74182 | 142.04 | 3.2728 | 15.10986 | 392.203 | 452.371 | 184053 | 230503 | 5752.04 | 9094.04 | 29.95332 | 3E+08 | 433.61761 | 3941 |
| | 3 | 3 | 207.6 | 200 | 148.7 | 4.1356 | 25.317 | 55.99238 | 1.954231 | 129.41 | 3.0197 | 8.2145 | 11.4953 | 1.76289 | 143.97 | 3.4658 | 15.54833 | 393.402 | 451.581 | 185174 | 229690 | 5852.61 | 9132.05 | 29.9715 | 3E+08 | 433.888668 | 4124 |
| | 3 | 3 | 206.8 | 200.2 | 149.2 | 4.0475 | 24.797 | 55.59772 | 1.738169 | 128.04 | 3.0022 | 9.9267 | 11.2241 | 1.74674 | 140.75 | 3.2631 | 14.89088 | 392.61 | 451.865 | 184723 | 230183 | 5768.21 | 9093.67 | 29.89113 | 3E+08 | 434.11427 | 4200 |
| | 3 | 3 | 206.5 | 200.1 | 149.3 | 4.04 | 24.763 | 55.59467 | 1.966826 | 128.37 | 3.072 | 10.108 | 11.7755 | 1.74412 | 140.85 | 3.2628 | 14.75581 | 391.99 | 450.73 | 183596 | 230540 | 5718.26 | 9070.88 | 29.84562 | 3E+08 | 434.214748 | 4131 |

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# Best design for each Slot-Pole Combination

- The Worldwide Harmonized Light vehicles Test Procedure (WLTP) is a global driving cycle standard for determining the levels of pollutants, CO2 emission standards, and fuel consumption of conventional internal combustion engine (ICE) and hybrid automobiles, as well as the all-electric range of plug-in electric vehicles.
- The built-in drive cycle WLTC Class3b in JMAG is used for the total energy calculation.
- 8-pole 48-slot design has the lowest energy consumption, but the cost is the highest.

| Case | Pole Slot | BOM Cost | Total Energy Consumption [MJ] |
|---|---|---|---|
| 4148 | **8-Pole 72 Slot** | $416.20 | 15.41486 |
| 4248 | **6-Pole 54 Slot** | $428.68 | 14.74378 |
| 4218 | **6-Pole 72 Slot** | $432.72 | 14.60329 |
| 4146 | **8-Pole 48 Slot** | $440.36 | 15.38888 |

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# Thermal Analysis & Final Selection

- **Why thermal matters:**
  - ROM EM assumes ideal cooling. Real continuous power is limited by **temperature rise**.
  - High power density → high losses in a small volume → thermal failure if not validated.
- **Thermal analysis on each of the 4 candidates:**
  - Steady-state temperature maps (windings, magnets, stator core)
  - Check if continuous torque/power limits are **thermally achievable**
  - Derate if necessary → recalculate **effective cost per usable power**
- **Final selection criteria:**
  - **Lowest total system cost** (material + cooling complexity) that meets **all continuous/peak requirements thermally**
- **Winner:** The slot-pole combination with the lowest cost AFTER thermal validation.

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# Simulation Time

- Hardware: AMD CPU 4.8GHz
- JMAG 25.0.01zzp
- 30 cases run in parallel
- ~ 1 hour/1200 cases (EM ROM efficiency map + structural analysis)
- ~ 15 min /case (EM + 2 thermal efficiency map analysis)

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# Conclusion

- During the design exploration phase, JMAG-Express is used due to its fast computation speed and 10× higher license availability, enabling efficient parallel design studies.
- This study shows that comparative evaluation of four slot–pole combinations is feasible on a standard workstation, with overnight simulations and a rapid screening workflow that integrates electromagnetic, structural, and thermal analyses within half a day.
- For confidentiality reasons, detailed rotor geometry is not included but can be added in future work.
- The workflow can be further accelerated by using surrogate models, AI-based methods, or database-driven optimization. However, due to time constraints, these approaches have not yet been implemented.
- The optimal design depends on the design requirements. Adding new requirements, such as NVH considerations or harmonic reduction targets, may change the preferred design, while the evaluation methodology remains valid.

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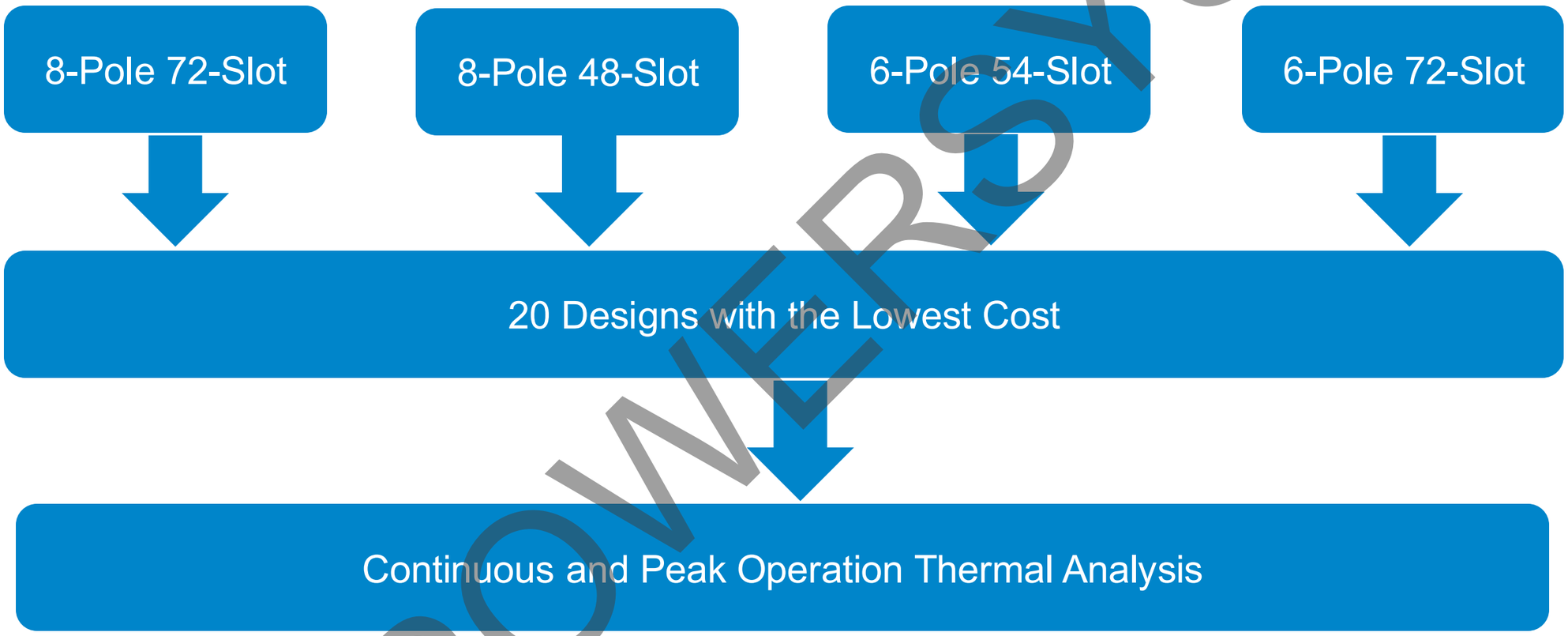
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# Workflow




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