THE UNIVERSITY of WISCONSIN MADISON

WEMPEC

Machine Design Optimization Based on Finite Element Analysis using High-Throughput Computing

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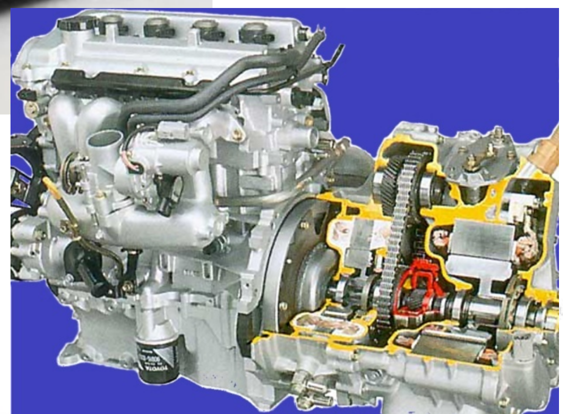
Project Objectives

To develop software that efficiently optimizes the design of various types of machines using *finite element (FE) analysis* in a *high throughput computing (HTC) environment* to achieve the best possible performance results in the least amount of computing time

Hybrid and Battery Electric Vehicles



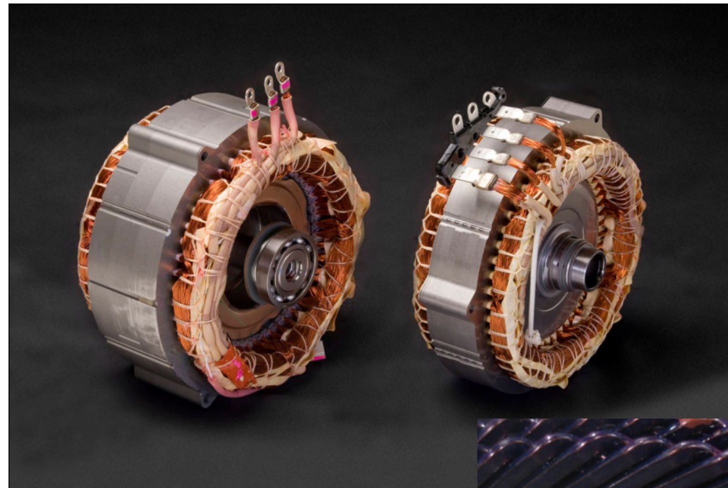
Toyota Prius

Chevy Volt

Nissan Leaf

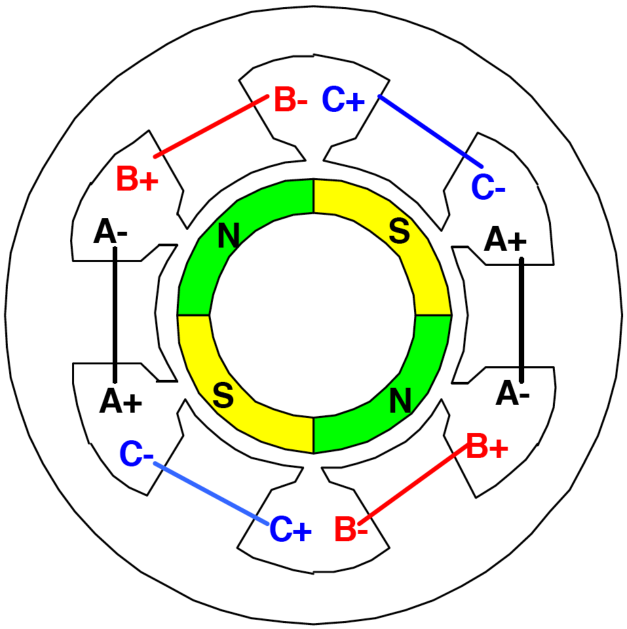
- Wide variety of vehicles available with innovative drivetrains to achieve high fuel economy

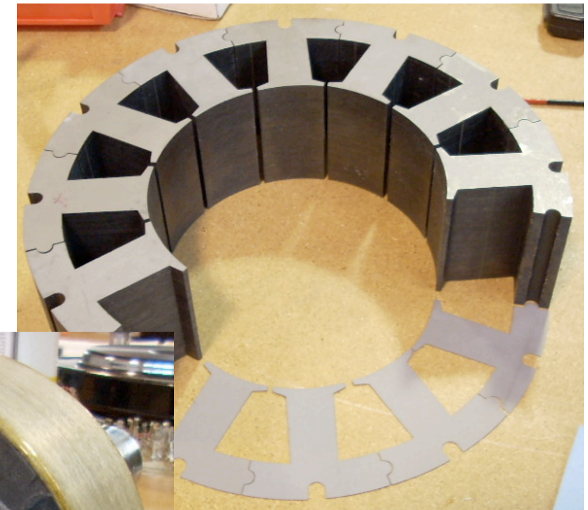
EV Electric Machine Requirements

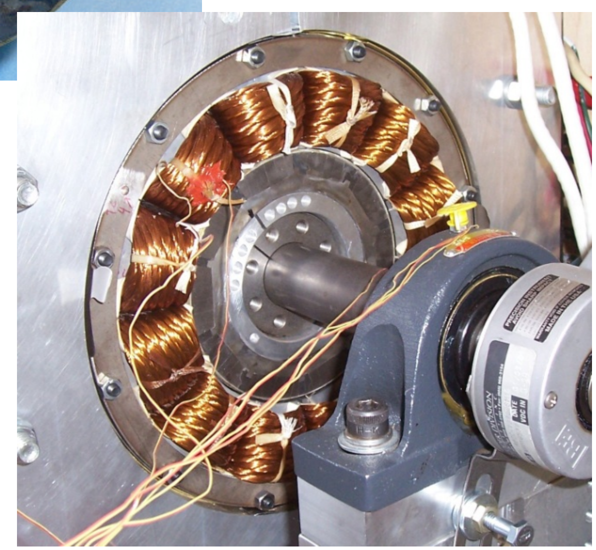


- High Volumetric Power Density
- High Mass Specific Power
- High Efficiency
- High Peak Torque
- High Maximum Speed
- Wide Constant Power Speed Ratio
- High Maximum Temperature
- High Reliability
- Low Ripple Torque

Fractional-Slot Concentrated-Winding Surface PM Machine



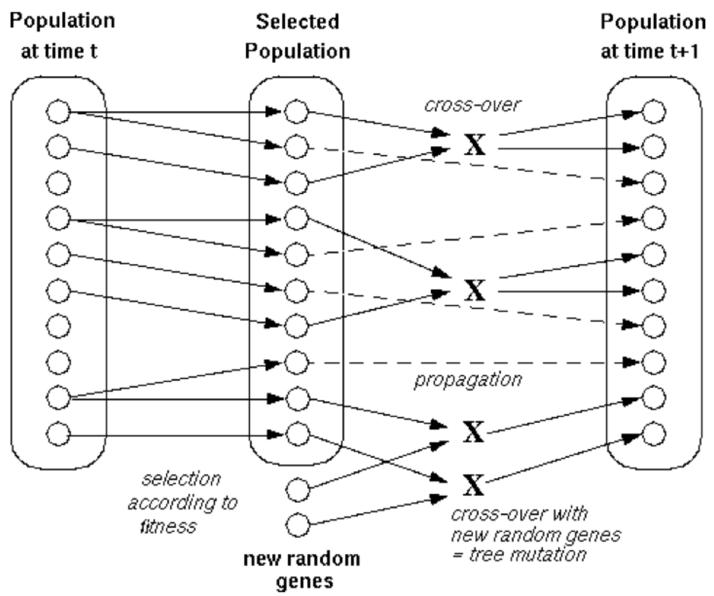




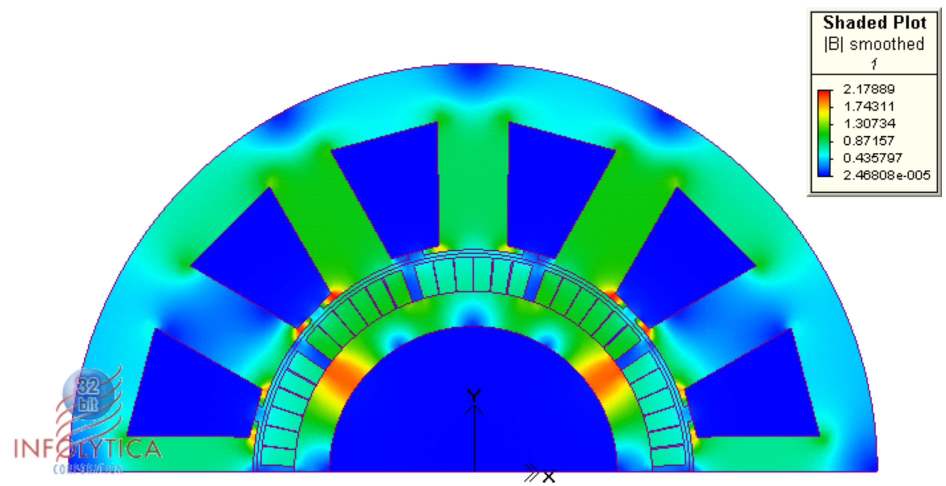
- FSCW-PM machine offers attractive performance features for EV applications
- Challenging to develop optimal design for this type of machine

Machine Design Optimization using Genetic Algorithm Technique

Genetic Evolution



Electromagnetic Finite Element Analysis



- Differential evolution provides an effective means of optimizing design of FSCW-SPM machine
  - Typically requires analysis of thousands of candidate designs
- Challenge is aggravated by the need for time-consuming electromagnetic finite element analysis to evaluate each design

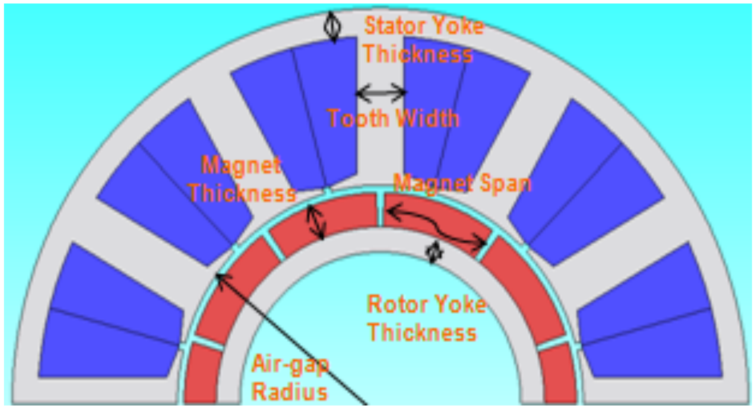
Performance Requirements for 55kW (Peak) / 30kW (Cont.) PM Machine

PM Machine Performance Requirements

Parameter/Metric	*Value*
Peak Power @ 2800 r/min	55 kW
Maximum Speed	14,000 r/min
Continuous Power	30 kW
Mass Power Density for Total Machine	>1.6 kW/kg
Vol. Power Density for Total Machine	>5.67 kW/l
Constant Power Speed Ratio	5:1
Maximum Phase Current	400 Arms
Peak Line-Line Back-EMF @ 2800 r/min	600 V
Efficiency at 20% Rated Torque up to the Max. Speed	>95%

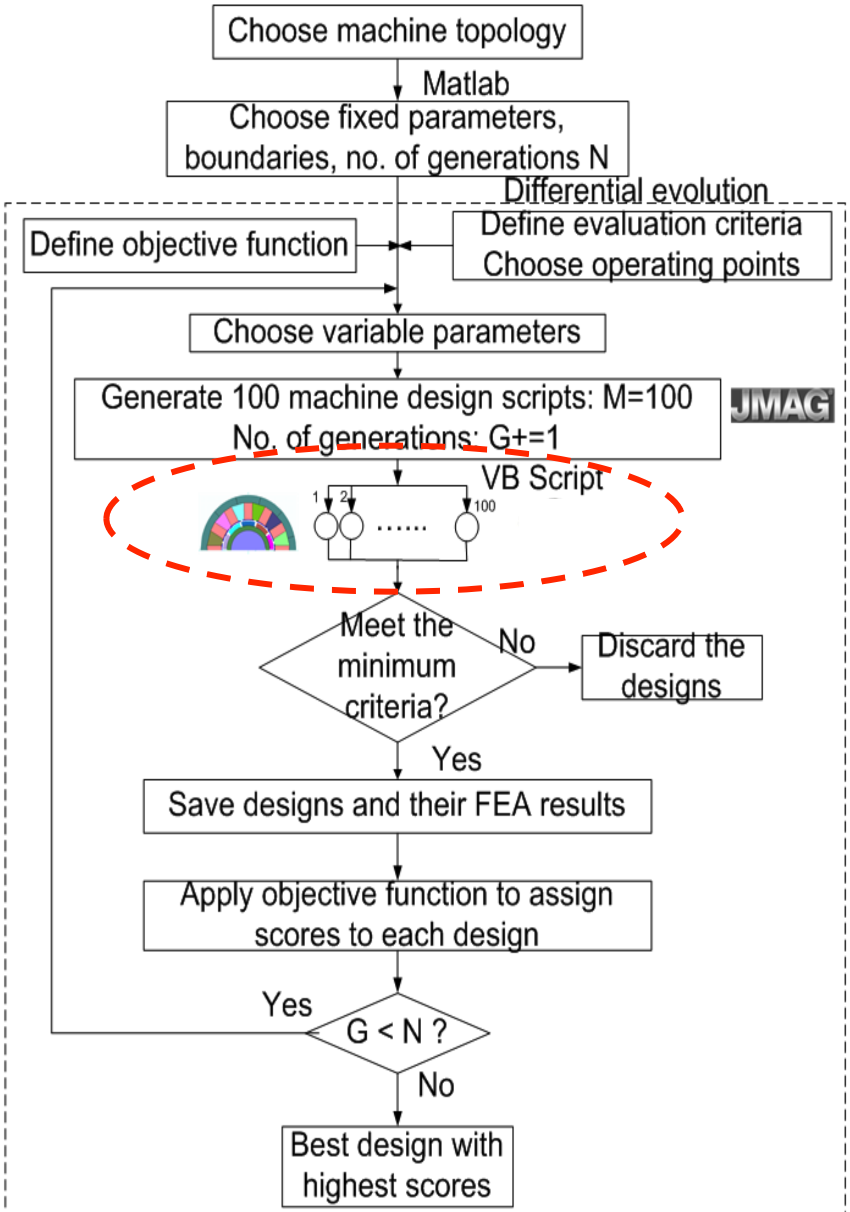
- Requirements provided by U.S. DRIVE partnership between gov't & automakers
- 6 machine dimensional ratios chosen as most important for finding optimal design
- Attention focused on a particular geometry with 12 stator teeth and 10 magnet poles

SPM Machine Design Variables



Tooth width to slot pitch ratio	[0.1, 0.8]
Stator yoke thickness to tooth width ratio	[0.1, 0.8]
Magnet span to rotor pole pitch ratio	[0.5, 0.95]
Rotor yoke thickness to rotor pole pitch ratio	[0.1, 0.6]
Magnet thickness to air-gap thickness ratio	[1, 7]
Air-gap radius to stator outer radius ratio	[0.3, 0.75]

Machine Design Optimization Flowchart

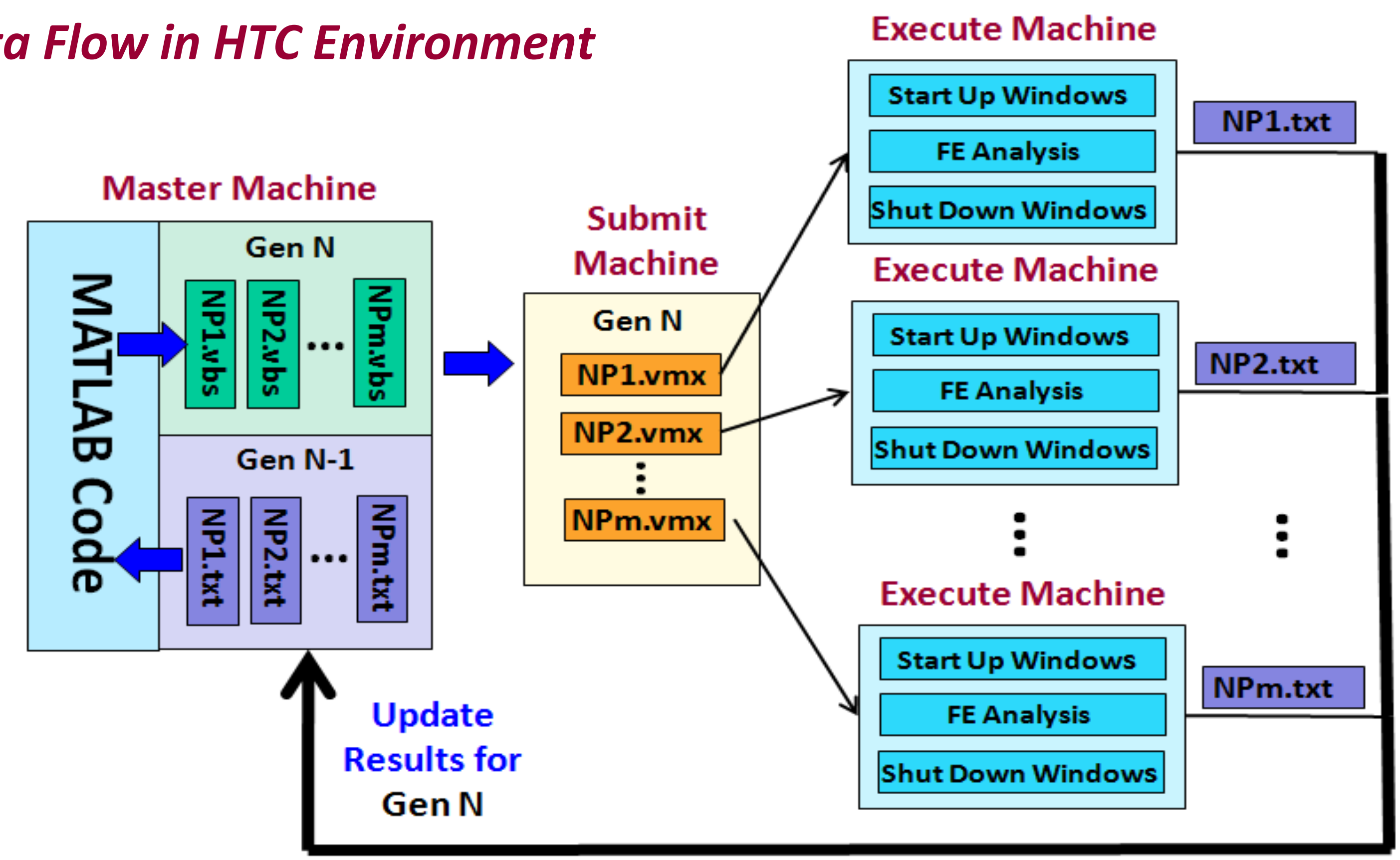


Implementation of FE Analysis-Based Machine Design Optimization

- Differential evolution algorithm launches up to 100 candidate designs in each generation
  - Algorithm is designed to search out and focus on most promising regions of parameter space
  - *Opportunity for parallel analysis of all designs within generation*
- A user-defined objective function is used to evaluate performance metrics of all candidate designs
- Algorithm uses objective function results to formulate choices for next generation of designs

Implementation of Design Optimization in HTC Environment

Data Flow in HTC Environment



- Project Condor adopted as means of implementing parallel processing of all candidate design analysis within generation
- Made possible by JSOL Corporation donation of 100 JMAG licenses.

Comparison between Condor and Single Computer Optimization

Rated Operating Condition Design Point

Rotor speed:
$n = 2800$ r/min

Output mechanical power:
$P = 30$ kW

Torque:
$T = 102.3$ Nm

Torque Density Objective Function

$$OF_1 = \frac{Calculated\ Active\ Mass\ to\ Produce\ Required\ Torque}{Base\ Machine\ Active\ Mass}$$

Differential Evolution Control Parameters

Convergence tolerance (**Tol**): 1E-6 *-> Threshold for terminating optimization*

No. of population members (**NP**): 85 *-> No. of parallel design per generation*

Crossover probability (**Cr**): 0.8 *-> Determine mutation aggressiveness*

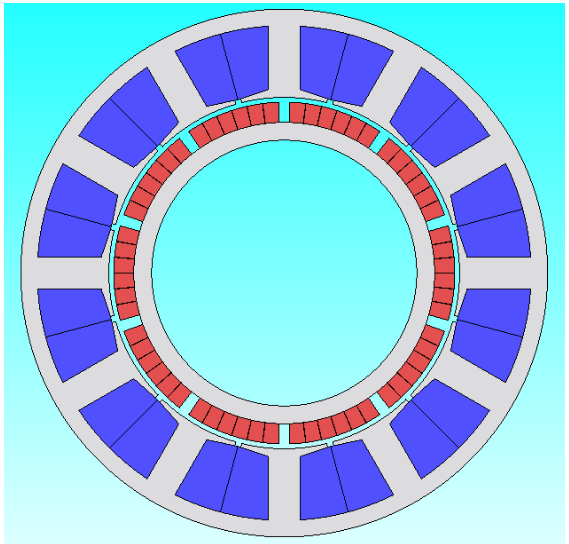
Scale factor (**F**): 0.8 *-> Controls the rate of evolution*

Baseline Machine: *Existing prototype 12/10 FSCW-SPM machine designed for FreedomCar specifications with an active mass of 27.8 kg including the stator and rotor electromagnetics*

- Same software has been applied to optimize the PM machine torque density using both the Condor HTC resources and a single computer
- Single computer was chosen from the Condor pool in order to provide a fair comparison.

Design Results of Condor and Single Computer Optimization

Optimal Design for
Maximum Torque Density



Both optimizations converged at the 50th generation, with a total number of 4250 evaluated designs

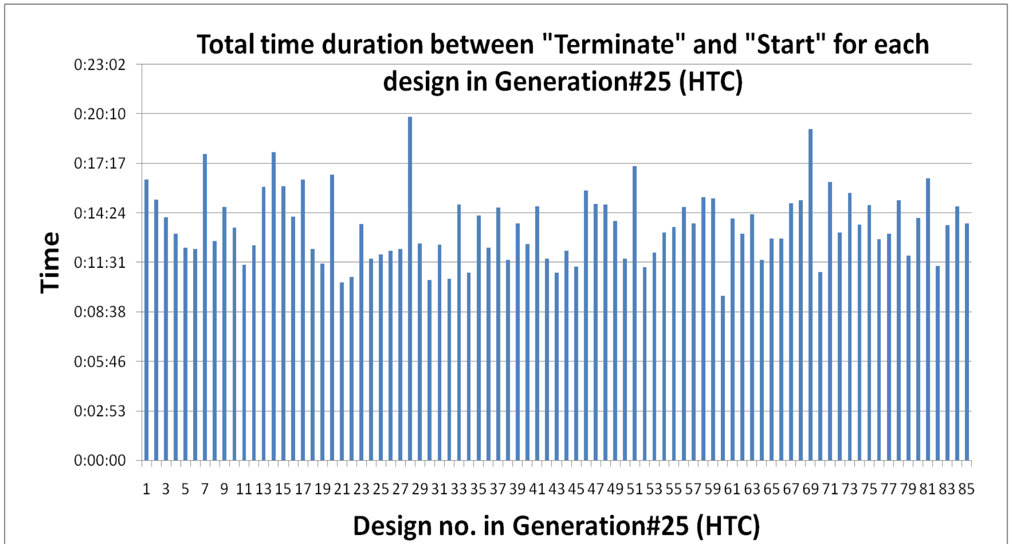
Performance Metrics

Volume (m^3)	0.0025
Copper mass (kg)	10.108
Iron mass (kg)	8.4722
Magnet mass (kg)	2.0658
Total mass (kg)	**20.646**
Cost ($)	172.6318
Torque ripple	0.0524
Power factor	0.9107
Magnet loss (W)	59.4385
Core loss (W)	282.3898
Copper loss (W)	609.6436
Efficiency	0.9693

The machine optimized for maximum torque density exhibits a mass reduction of 25.7% compared to the baseline machine

Comparison of Computation Times for Single Generation

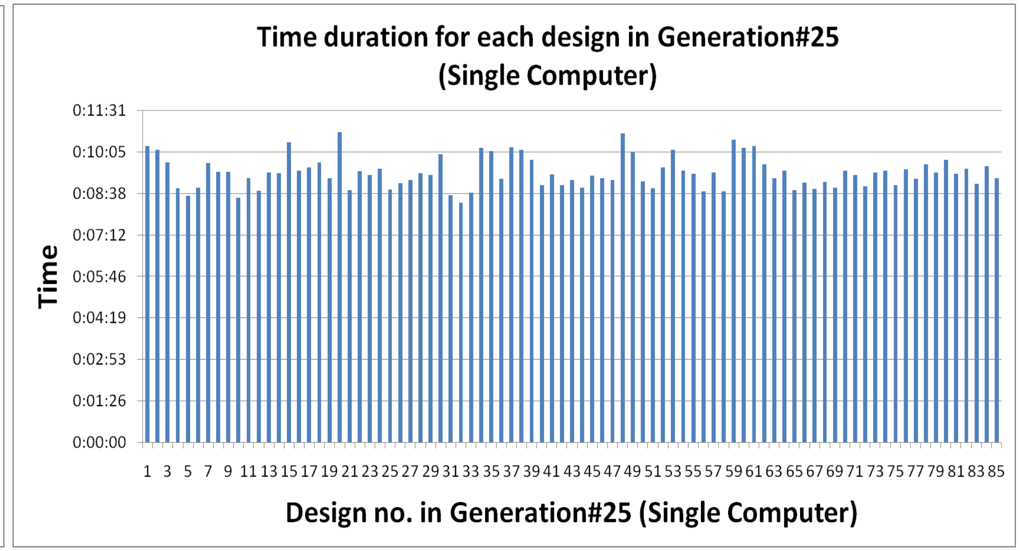
Condor (HTC)



Min: 9 min 35 sec **Max:** 20 min 0 sec

Total: 20 min 0 sec

Single Computer



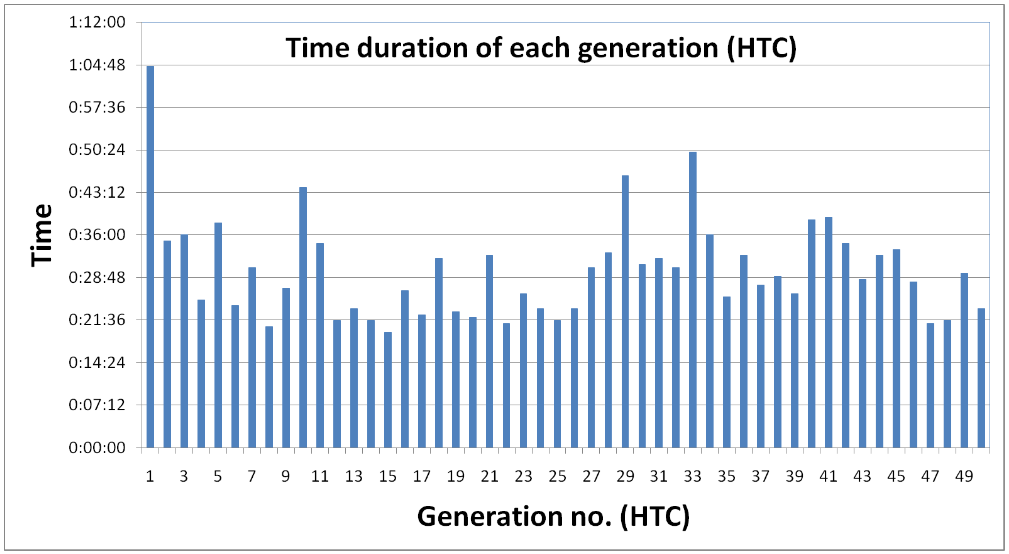
Min: 8 min 19 sec **Max:** 10 min 46 sec

Total: 13 hr 16 min 52 sec

- Condor exhibits acceleration factor of 39.8 for Generation #25
- Several designs have much longer computation times in Condor, preventing acceleration factor from being significantly higher

Comparison of Total Computation Times for Design Optimization

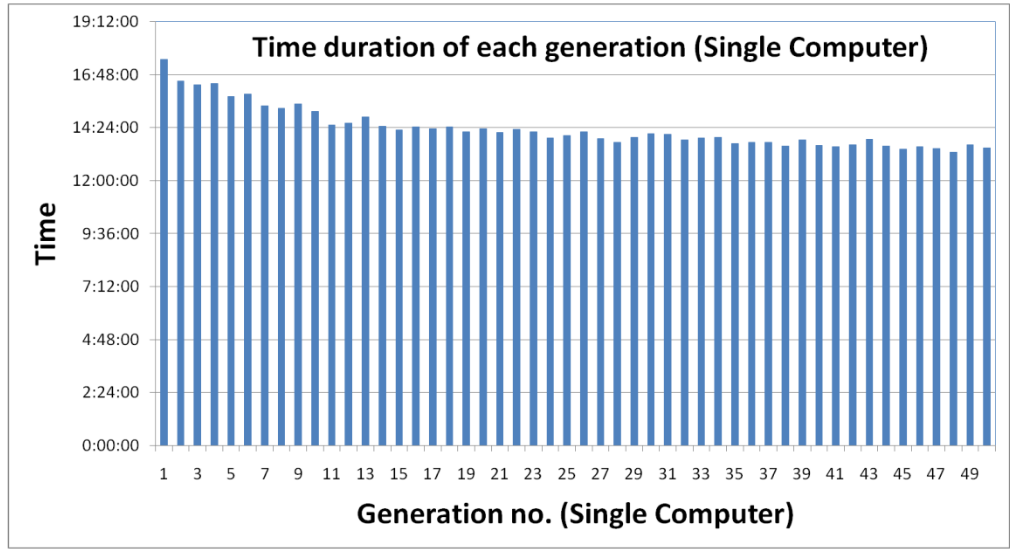
Condor (HTC)



Min: **19 min 32 s** **Max:** **1 hr 4 min 34 s**

Total: **25 hr 0 min 26 sec**

Single Computer



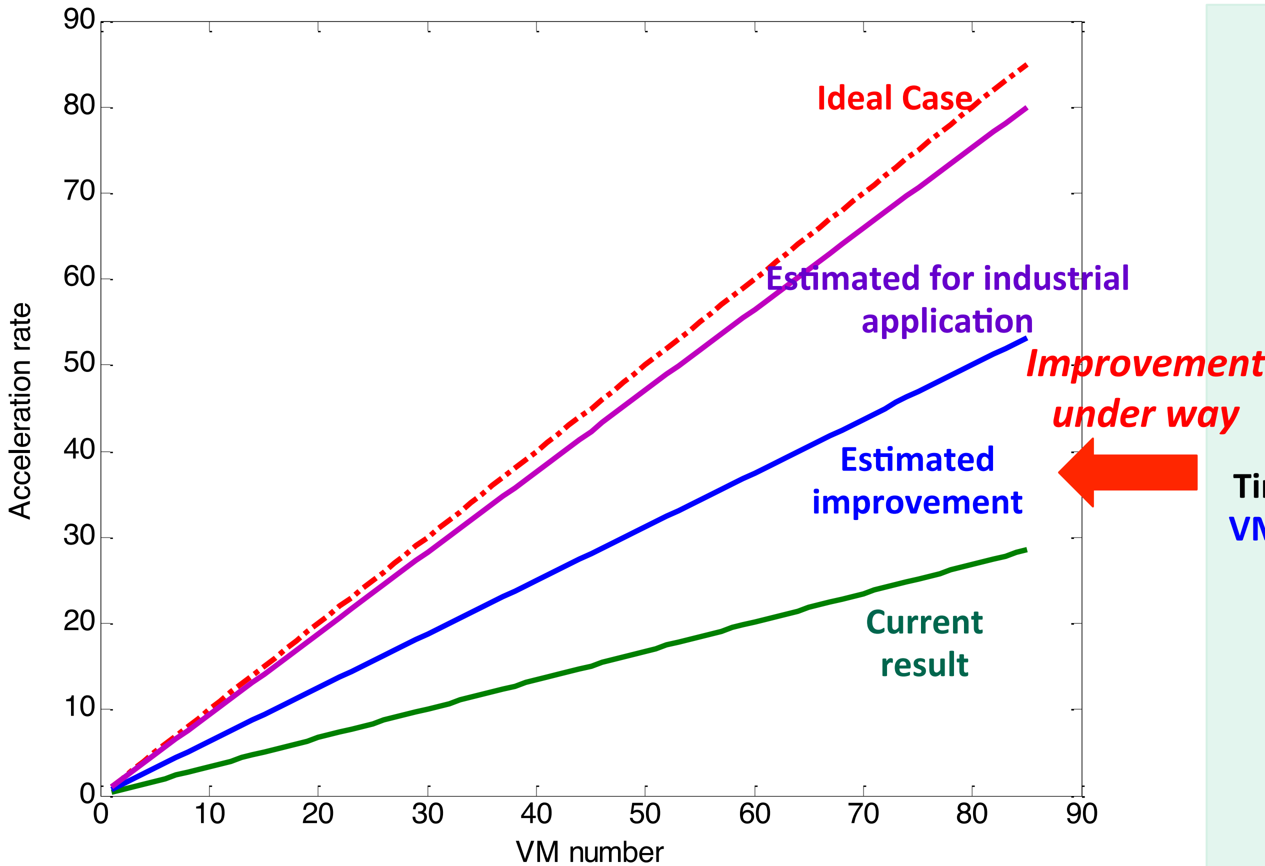
Min: **13 h 17 m 10 s** **Max:** **17 h 29 m 18 s**

Total: **29 days 22 hr 17 min 8 sec**

- Total computation time has been accelerated by approx. 30:1 using HTC environment compared to single computer

Computation Time Breakdown and Acceleration Factor Improvements

Acceleration Factor as Function of the Number of Designs per Generation



Condor Time Breakdown for One Design Analysis

Time for MATLAB to create scripts
(~1 sec)

Encapsulate script into VM format
(~1 min)

Waiting to be submitted
(~2 min)

Time between "execute" and "submit"
(~10 sec)

Time between "terminate" and "execute"
VM start time, JMAG simulation time, fault time, VM shut down time
(~13 min)

Extract txt result from VM
(~40 sec)

Time for MATLAB to read results
(~1 sec)

The achievable acceleration factor for a dedicated industrial HTC network (Window OS) is estimated to be 80 for 85 computers

Conclusions and Future Work

- HTC environment enables major acceleration of machine design optimization using differential evolution algorithm
- Efforts are currently under way to significantly reduce the current overhead time in Condor environment
  - Current goal is to improve the acceleration factor to >50 with 85 designs in each generation
- Project is being expanded to integrate FE-based thermal analysis into the optimization program
  - Major step towards the ultimate objective of multi-physics based machine design optimization that eventually includes structural analysis as well.