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Optimum Design of a Thyristor Assembly for Pulsed Power Applications

- Optimization via Computational Intelligence Technology

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Contributors

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Felix O. Heimes, M.S.E.E.
BAE SYSTEMS *Controls, Inc.*
600 Main Street
Johnson City, NY
Felix.o.heimes@baesystems.com

Mike Elmore, M.S.E.E.
BAE SYSTEMS *Controls, Inc.*
600 Main Street
Johnson City, NY
mike.elmore@baesystems.com

Scott Ragon, Ph.D.
Center for Power Electronics Systems
Virginia Polytechnic Institute and State University
340 Whittemore Hall
Blacksburg, VA 24060-6373
ragon@vt.edu

Douglas K. Lindner, Ph.D.
Center for Power Electronics Systems
Virginia Polytechnic Institute and State University
340 Whittemore Hall
Blacksburg, VA 24061
lindner@vt.edu

Dushan Boroyevich, Ph.D.
Center for Power Electronics Systems
Virginia Polytechnic Institute and State University
340 Whittemore Hall
Blacksburg, VA 24061
dusan@vt.edu

Zafer Gürdal, Ph.D.
Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University
322 Norris Hall
Blacksburg, VA 24061
zgurdal@vt.edu

Thyristor Assembly for Pulsed Power

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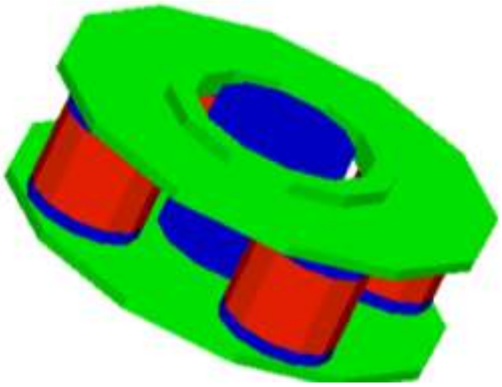
- The Air Force Office of Scientific Research (AFOSR) has sponsored efforts in the "Control and Optimization of Regenerative Power Flow in 21ST Century Airlifters"
- Power demands from electrical weapons systems require switch assemblies that can control very high peak currents
- These assemblies are large and add to aircraft weight
- The design must be optimized to minimize size and/or weight, while constraining inductance, power dissipation, current density, junction temperature, Lorentz forces and other performance parameters

  - The assembly consists of 4 parallel stacks of 4 thyristors in series
  - Current enters through the top disk (green), flows down through the thyristor stacks to the bottom disk (green) and returns to the top through a center conductor (blue)



A Multi-Disciplinary Approach to Optimization

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- Complex electro-mechanical power systems require design optimization of
  - Power conversion circuits to maximize efficiency, reduce power consumption, meet regulatory standards and guarantee functional compliance
  - Control functions for robust stability and performance
  - Thermal characteristics for heat rejection and temperature rise
  - Mechanical packaging for vibration and shock tolerance and size and weight reduction
- Design optimization can be achieved with Computational Intelligence Technology (CIT)
  - Commercially available tools to simulate the local performance of power sub-system functions
  - CIT performs global optimization using local simulations to achieve system level optimization

What is Computational Intelligence?

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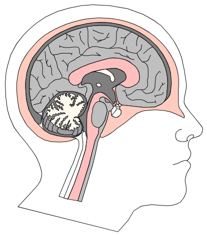
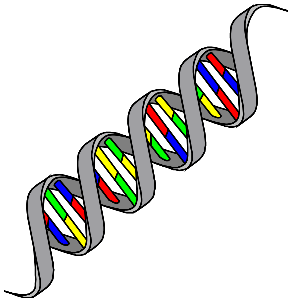
- CIT imitates intelligent life to enhance computational capabilities (learning, adaptability)

- Neural Networks
  - Mimic how the nervous system processes information to create algorithms that learn from data, represent complex information, recognize patterns, and process data efficiently.



- Evolutionary Strategies
  - Mimic the process of evolution for developing optimum solutions to difficult problems. Utilizes a population of solutions that compete against each other. The fittest individuals survive to create new individuals and improve the overall strength of the population.



Neural Networks – Key Features

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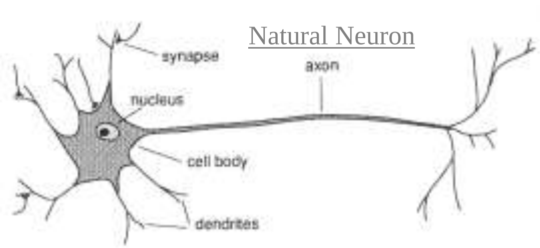

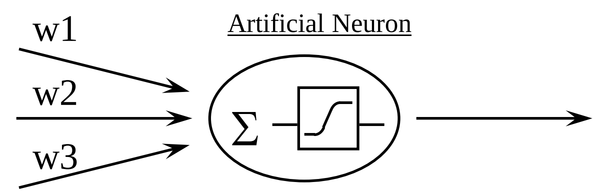

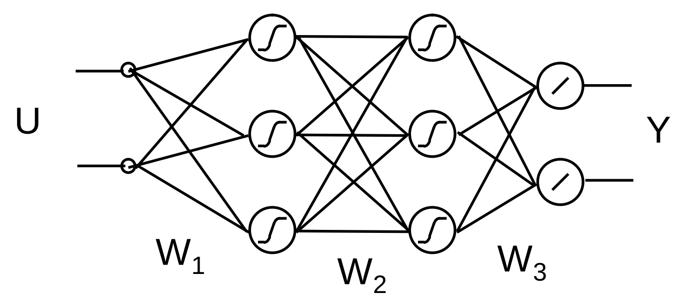

$$Y = F\left[F\left(W_1 U\right) W_2\right] W_3$$

• Key Features

- Realizes complex non-linear mappings in a compact generic structure (static and dynamic)
- Universal approximator
- Learns from data by minimizing $(Y_{desired} - Y)^2$
- Applications:
    - Modeling
    - Optimization
    - Control
    - Pattern Recognition (Diagnostics)

Evolutionary Strategies – Key Features

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- Each individual is defined by 2 *vectors in* $\Re^n$
  - ***X:*** parameters that define the solution (object parameters)
  - σ**:** mutation step size (strategy parameters)
- The ES algorithm is implemented as follows:
  - Initialize a population of *p* individuals ($X_i\ \sigma_l$) for $i=1..p$
  - Calculate the fitness, $f(i)$, for each individual
  - Select the μ individuals with the best fitness
  - Create λ new offspring (where $\mu < \lambda$, and $\mu + \lambda = p$) as follows**:**
    - Recombination: randomly select two individuals *j* and *k* from μ and create a new individual *l* as follows:
      - $X_l = ½ * (X_j + X_k)$
      - $\sigma_l = ½ * (\sigma_j + \sigma_k)$
    - Mutate: modify the new individual according to:
      - $\sigma_l'(j) = \sigma_l(j) \exp(\tau' N(0,1) + \tau N_j(0,1))$
      - $X_l'(j) = X_l(j) + \sigma_l'(j)\delta_j$

Note: *N(0,1) is a random number drawn from a normal distribution with mean 0 and standard deviation 1.* δ *is a random number drawn from a Cauchy distribution with t =1.* τ *and* τ' *are constants*

Thyristor Assembly Structure

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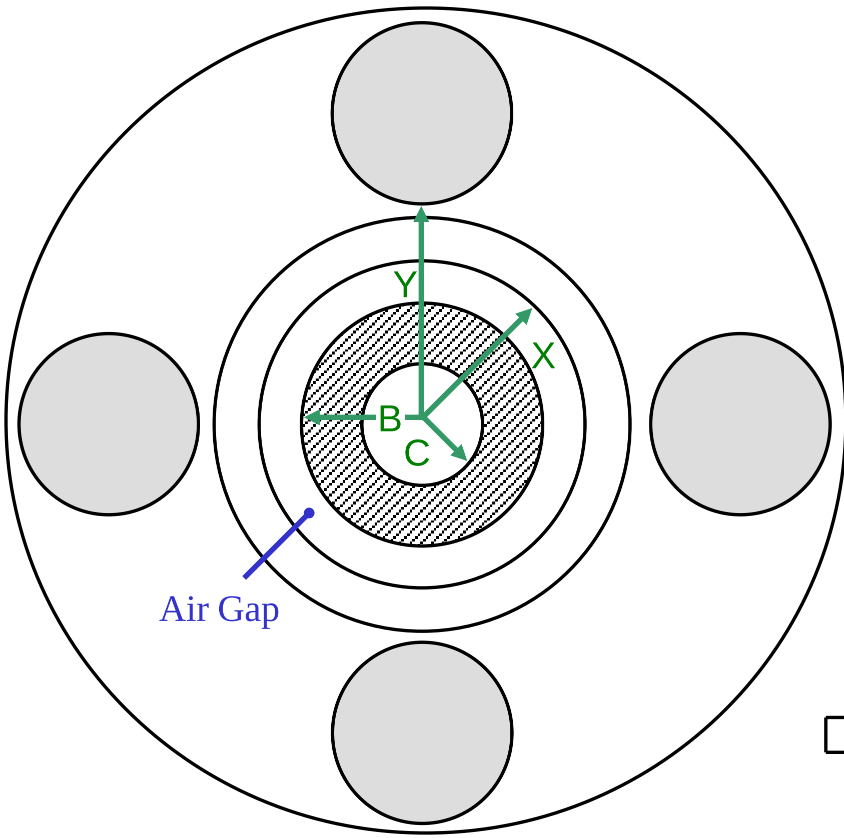

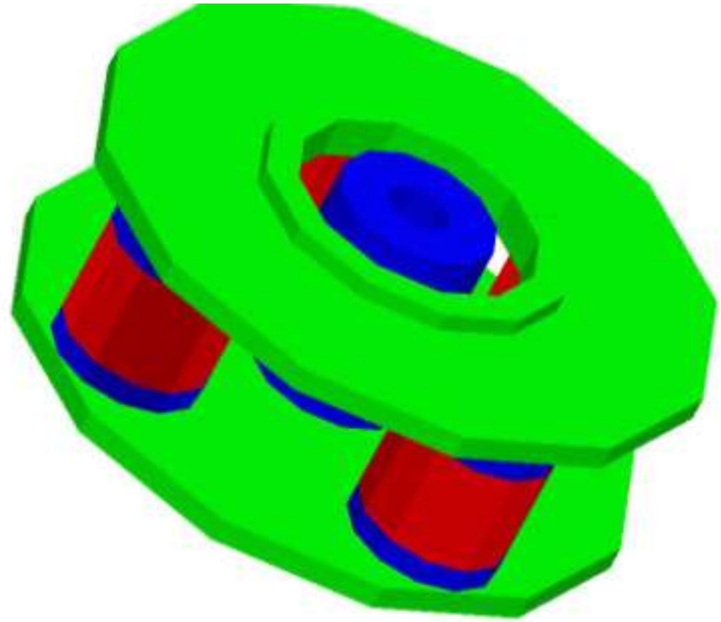

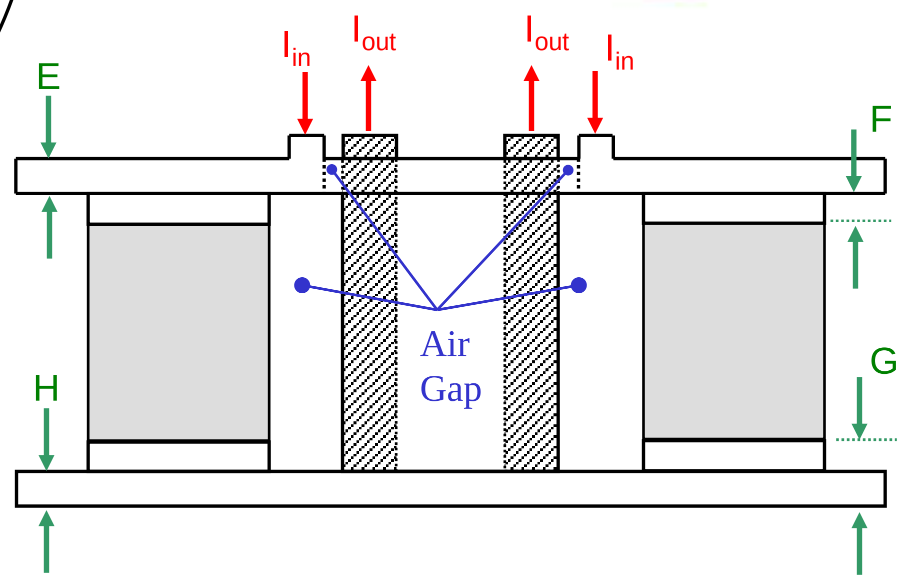

Note: E = H, F = G

Evolutionary Strategy for this Application

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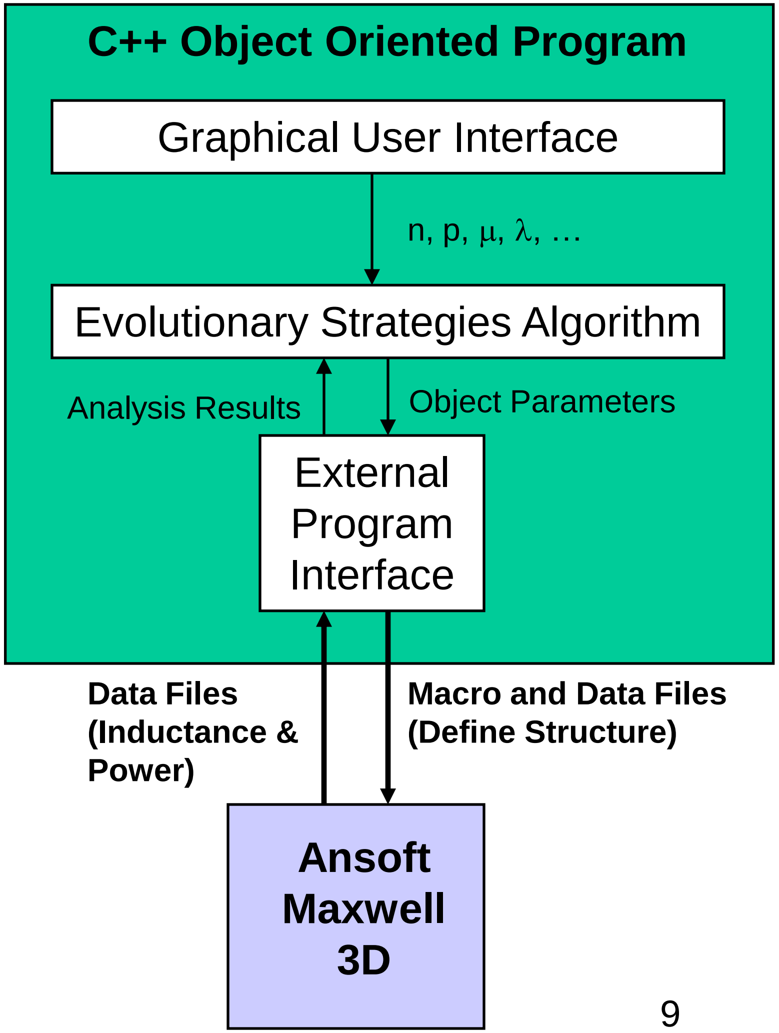
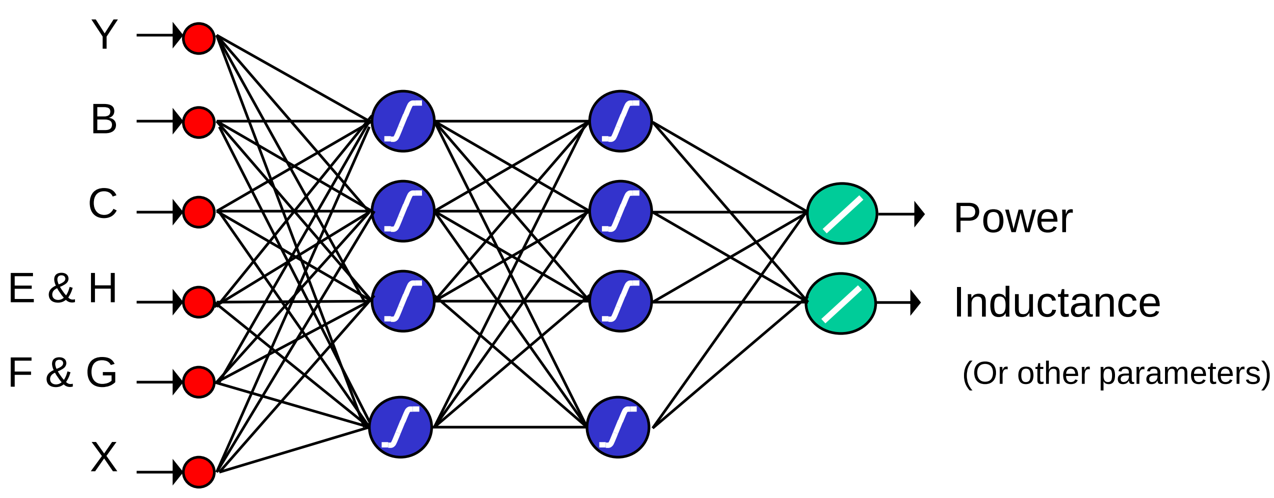
- An Evolutionary Strategies algorithm is coded as a C++ object
- The ES algorithm interfaces to an external analysis package via the External Program Interface
- Ansoft Maxwell 3D is used to analyze circuit performance (one analysis takes 1 to 3 minutes)
- *Execution of one ES optimization run takes about 500 to 1,000 circuit evaluations in about **10 hours*** on a 1 GHz Pentium III



Neural Networks for this Application

- Each time a circuit is analyzed by Maxwell 3D the parameters and performance are stored to a data file
- Using the saved data, Neural Networks are trained to model the effect of the geometry variables on the performance of the circuit
- Neural Networks can then be used in place of Maxwell by the ES optimization algorithm



Optimization Using Neural Networks

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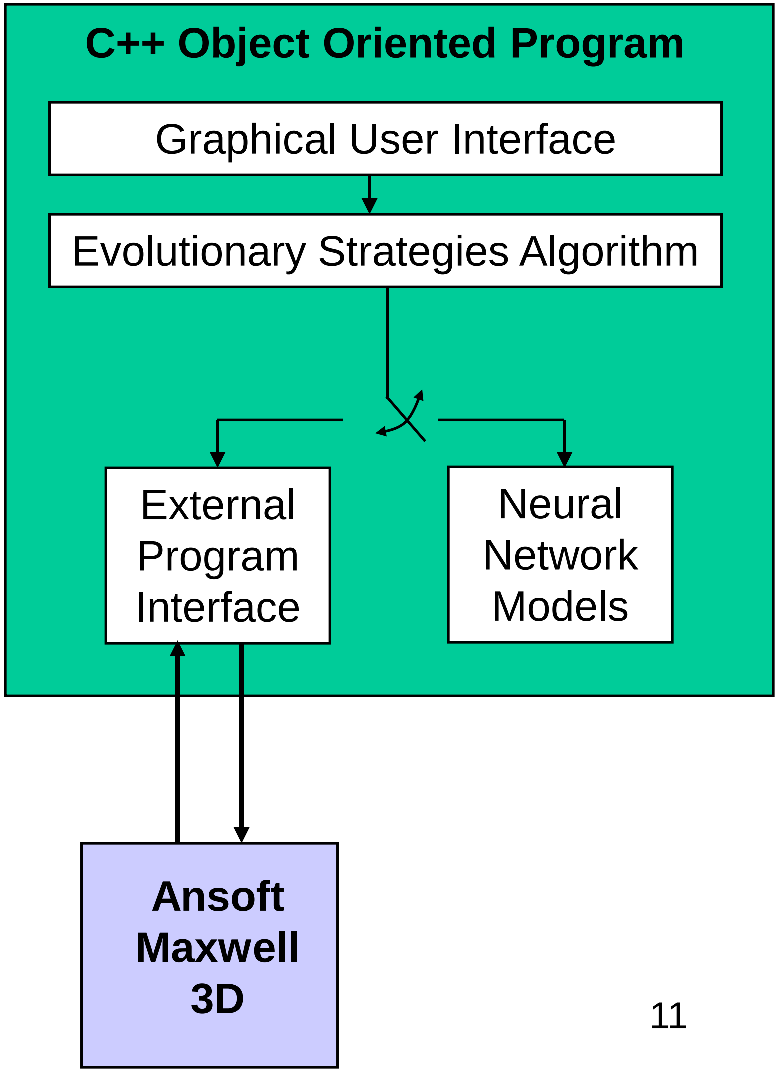
- The Neural Network algorithm is coded as a C++ object and easily integrated into the C++ program
- Neural Network models can be used instead of Ansoft Maxwell 3D to analyze circuit performance (one analysis takes several milliseconds)
- With the Neural Network models, *execution of one ES optimization run takes about 500 to 1,000 circuit evaluations in about **10 seconds*** on a 1 GHz Pentium III



CIT for Multidisciplinary Optimization

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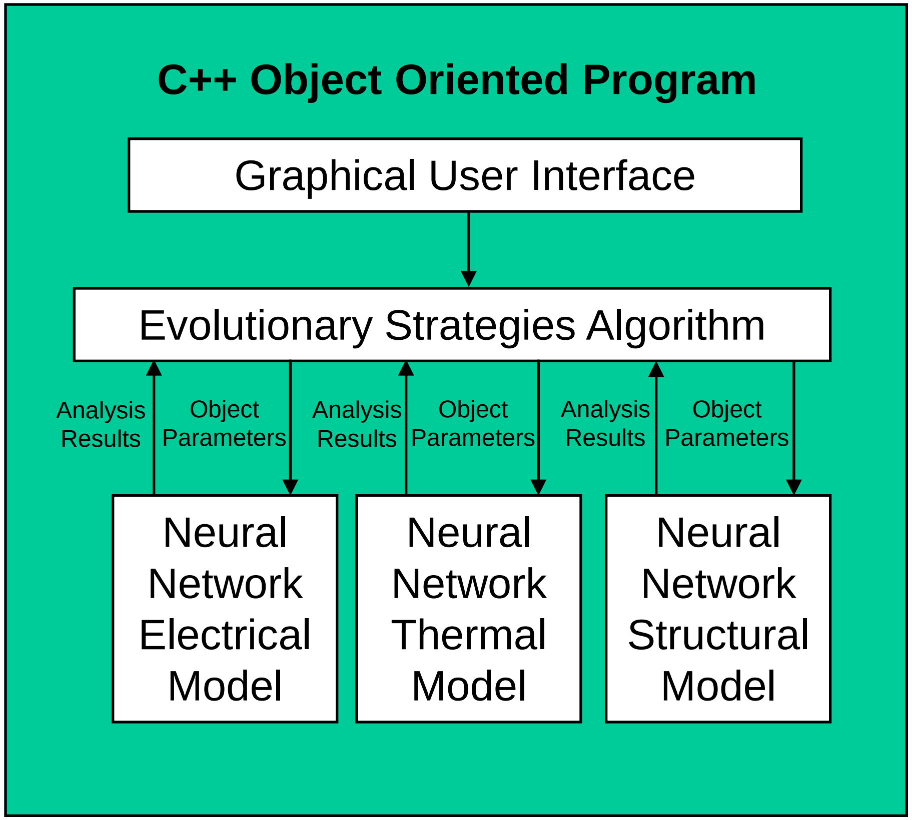
- Neural Network models can be used to model most characteristics of a power system
  - **Electrical**
  - **Thermal**
  - **Structural**
  - **And More**

- Using Neural Networks we have produced a generic optimization package (any system that can be modeled by a Neural Network can be optimized)

- Multidisciplinary Optimization can be performed



Evolutionary Algorithm Objective Function

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- Objective: Minimize volume (volume is in the range of 5000 – 20,000 cm^3) without exceeding constraints

- Evolutionary algorithms require a objective function to minimize, *J*
  - *Volume appears explicitly in objective function*
  - *Constraints are added to objective in the form of a penalty times a constant*

$$J = Volume + Penalties$$

- Constraints:
  - Geometry must be realizable
  - Power < 750 W
  - Inductance < 18 nH

- Penalties
  - P_1 = *f(realizable structure)*

$$if\ \ (\text{Structure Not Realizable}),\ \ then\ \ P_1 = 40{,}000,\ \ else\ P_1 = 0$$

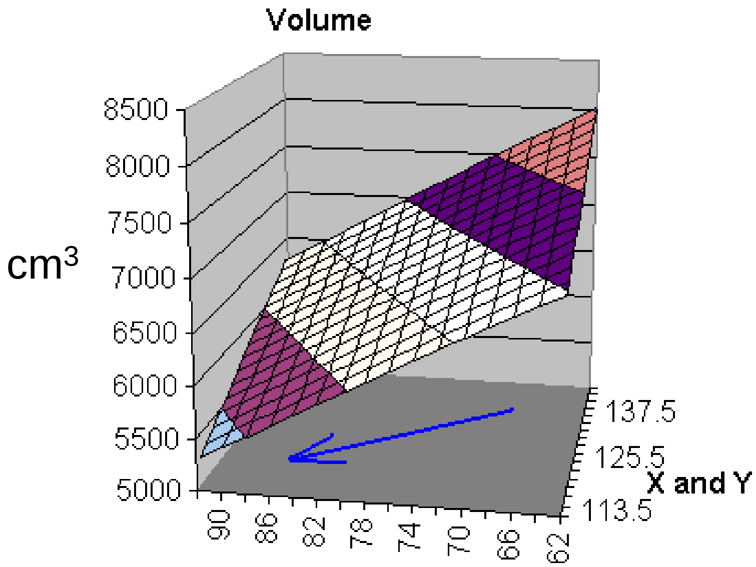
  - P_2 = f (Power)

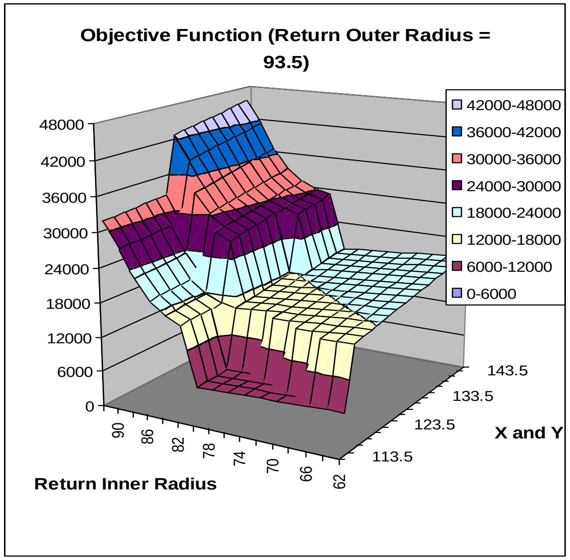
$$if\ \ (P > 750\,Watts),\ \ then\ \ P_2 = 10{,}000 \cdot \left(1 + \frac{(Power - 750\,Watts)}{750\,Watts}\right),\ else\ P_2 = 0$$

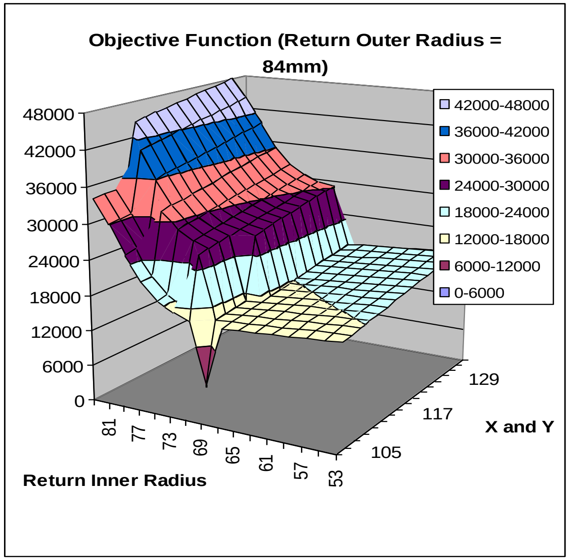
  - P_3 = *f*(Inductance)

$$if\ (L > 18nH),\ \ then\ \ P_3 = 10{,}000 \cdot \left(1 + \frac{(L - 18nH)}{18nH}\right),\ else\ \ P_3 = 0$$

Objective Function







- Volume is a smooth function
- Objective function is discontinuous due to constraint penalties
- Upper and lower objective function plots show movement towards the optimum

First Optimization Run - Constraints

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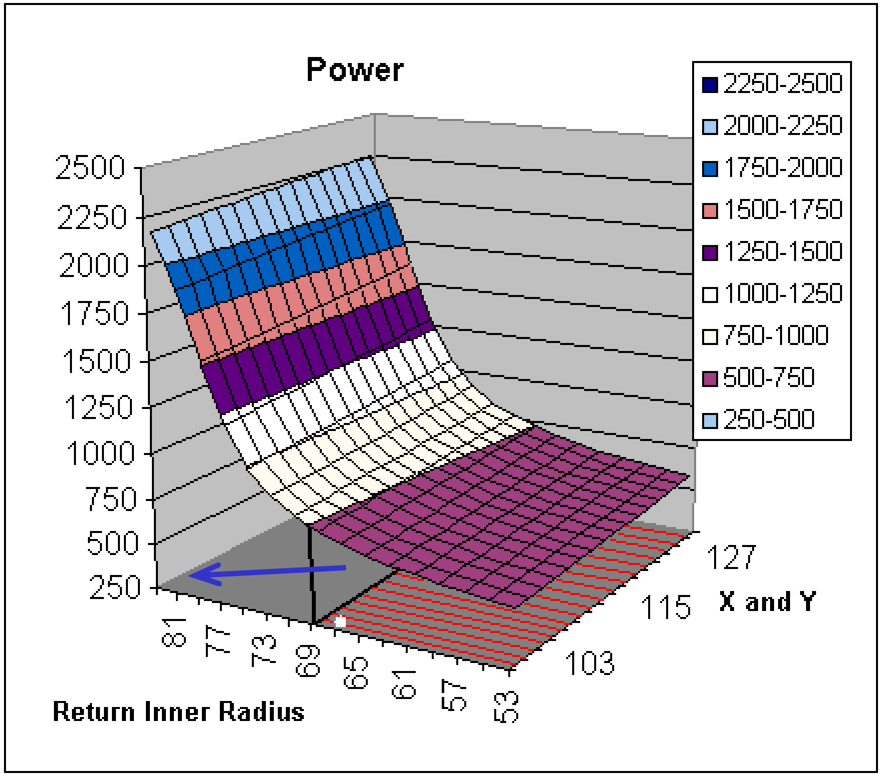
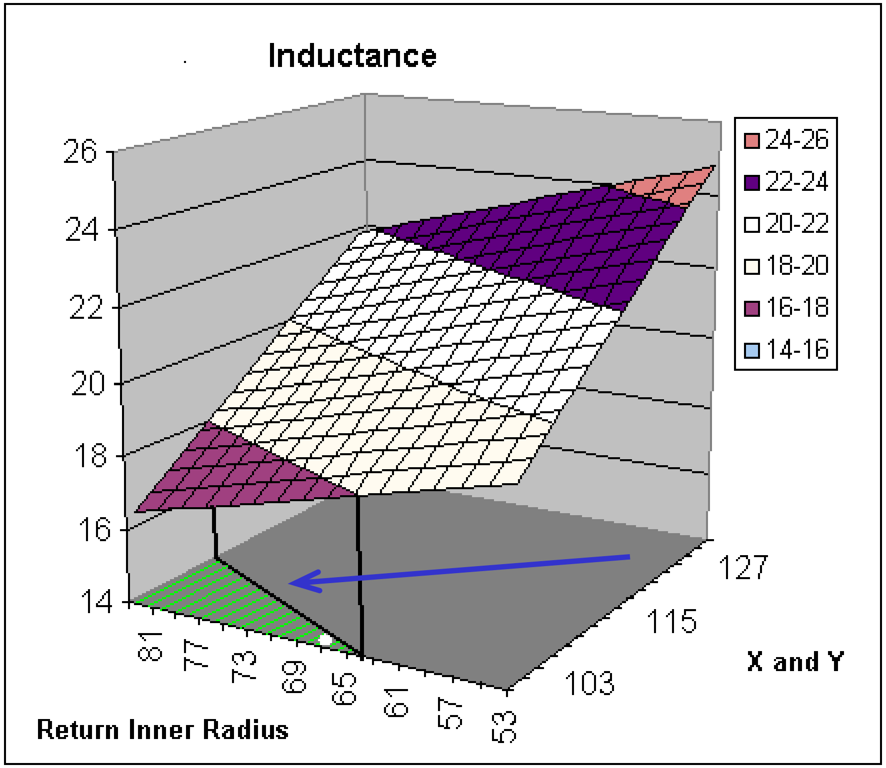
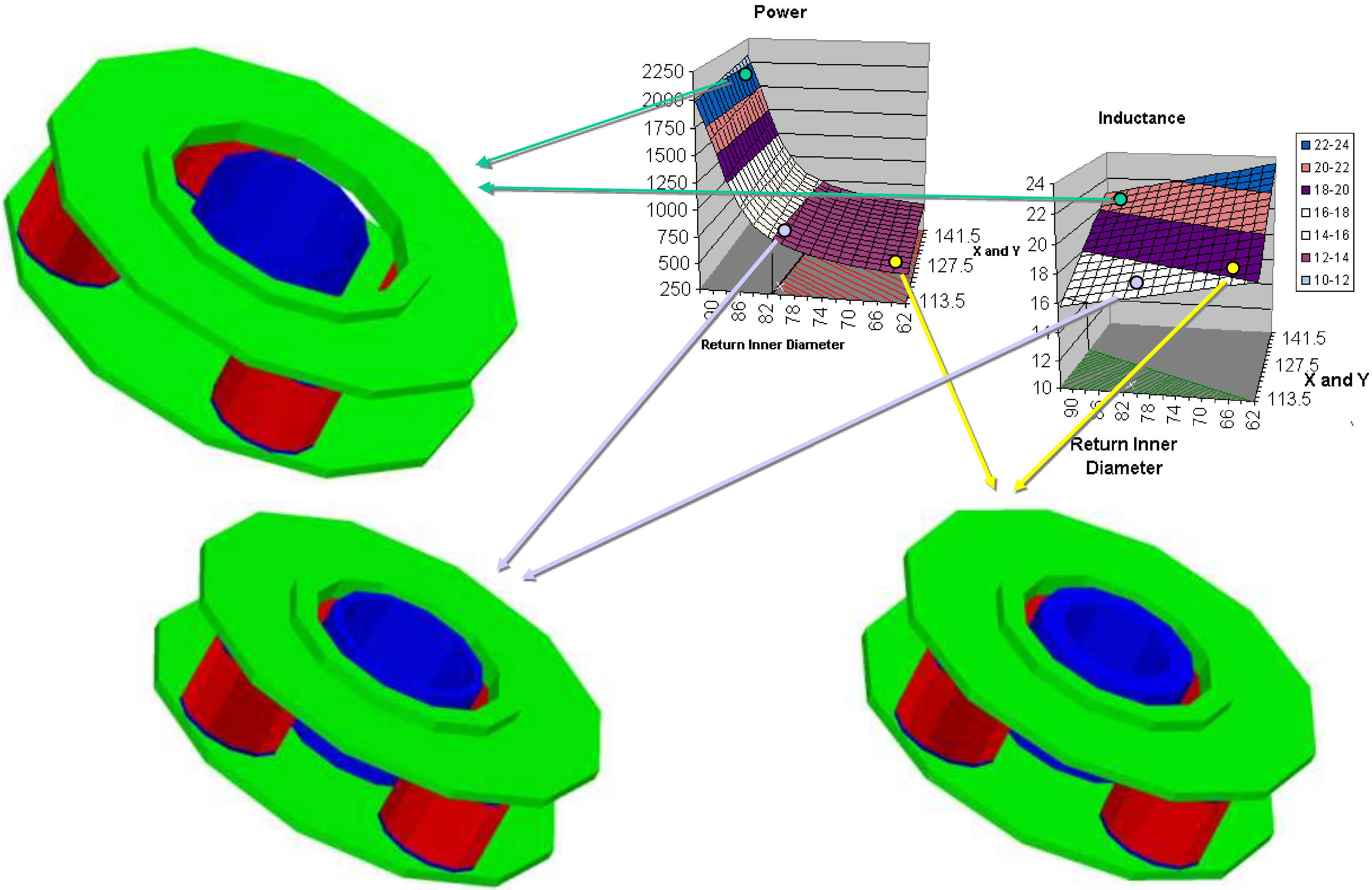
- Plots below show the effect of constraints (active)
  - Power < 750 Watts (red shaded region satisfies constraint)
  - Inductance < 18nH (green shaded region satisfies constraint)
- Minimum volume solution found using Neural Network models is shown by white dot (5662 cm^3)





First Optimization Run – Sample Structures



Second Optimization Run - Constraints

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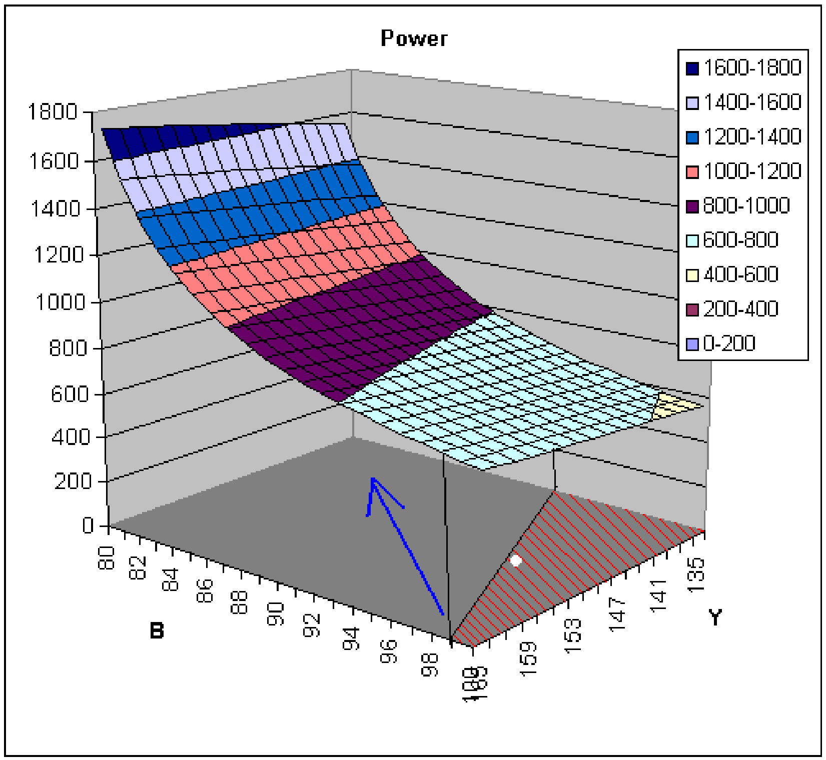
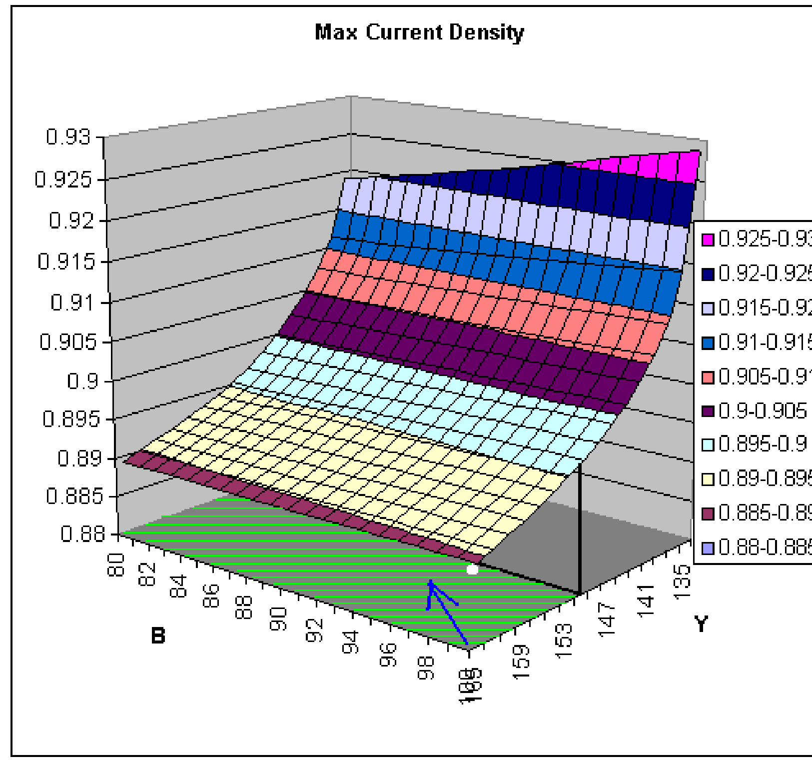
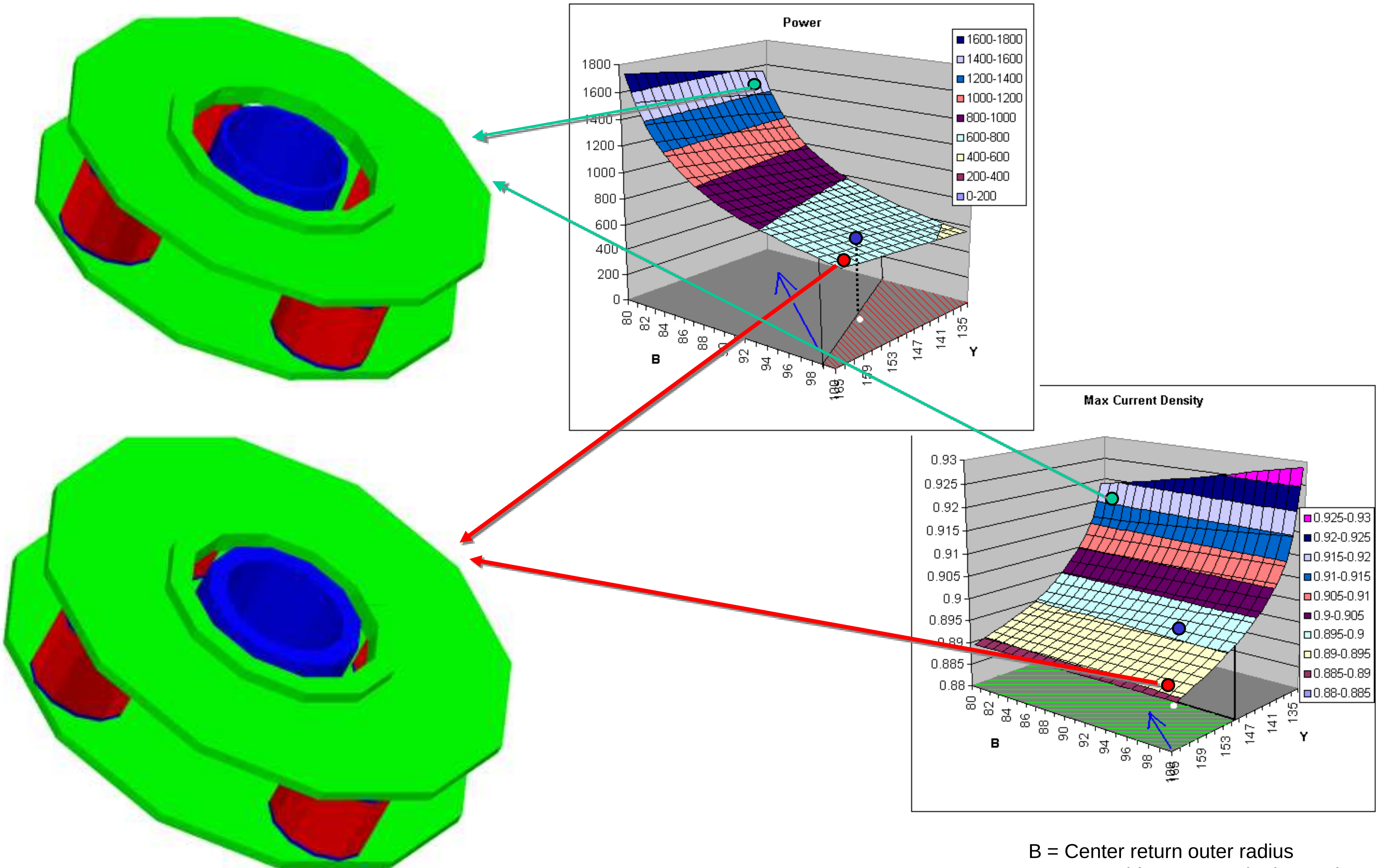
- Thyristor Conductivity was increased
- Constraints:
  - –Power < 750 W (red shaded region satisfies constraint)
  - –Max Current Density < 0.896 A/mm^3 (green shaded region satisfies constraint)
- Minimum volume solution is shown by white dot (8070 cm^3)





B = Center return outer radius
Y = Assembly center to thyristor edge

Second Optimization Run – Sample Structures



B = Center return outer radius
Y = Assembly center to thyristor edge

Second Optimization Run – Current Density

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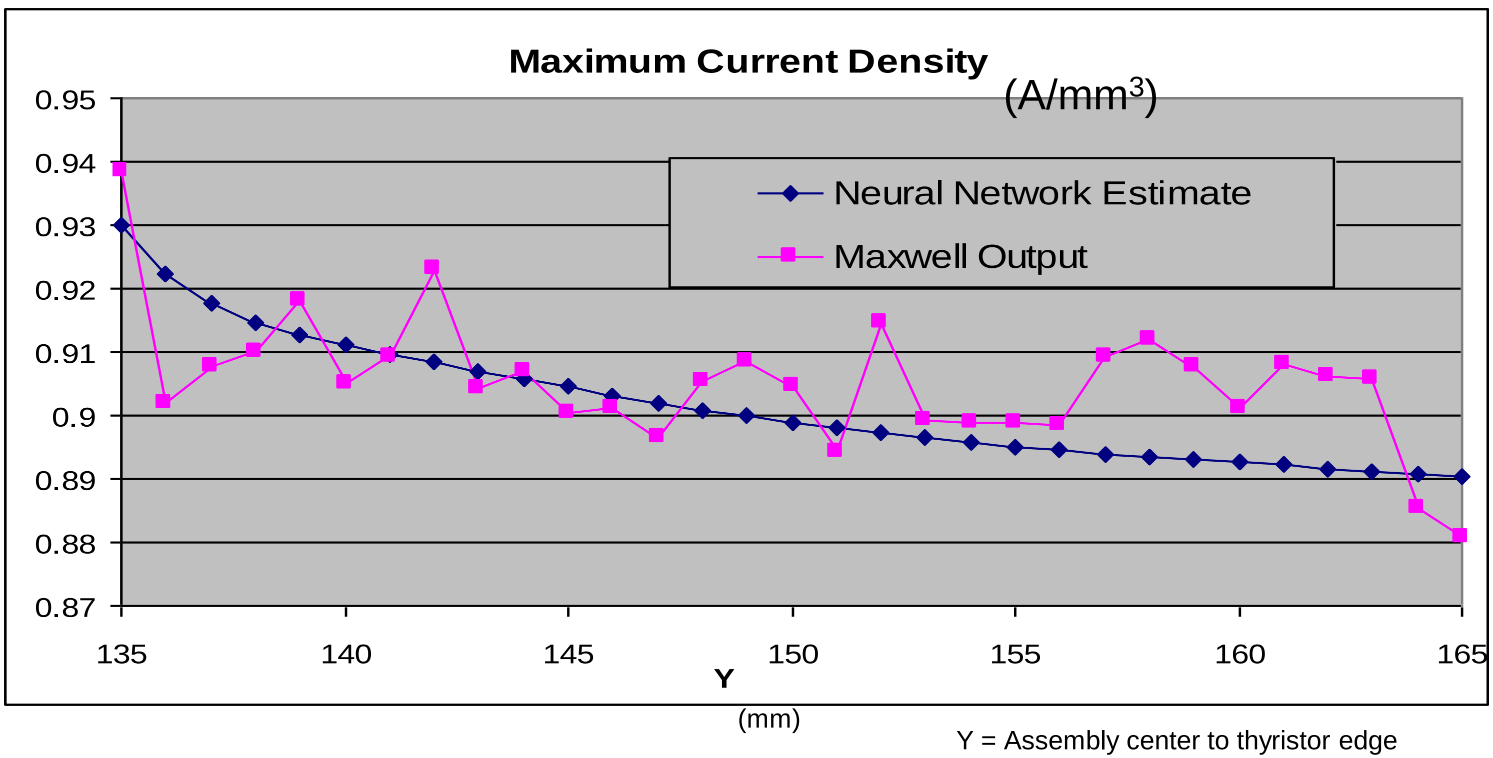
- Plot below shows the current density as modeled by the Neural Network versus the output of Maxwell 3D
  - Maxwell 3D current density is noisy
  - Neural Network filters noise and produces a better estimate



Thyristor Assembly Optimization - Conclusions

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- Biggest trade-off is in inner cylinder thickness to balance inductance and power dissipation
- Keep thyristors close to the center to minimize size, weight, and inductance

  This result was anticipated, given the small number of constraints. As the geometry becomes more complex and more constraints are added, this conclusion may not hold up.

- The discs between the thyristors and top and bottom plates do not seem beneficial (they are always set to the minimum).

  Originally, these were added to spread current flowing from the plates into the thyristors, but the optimization showed that the current density gradient is small.

  However, these disks may still be required for thermal optimization.

Work in Progress and Future Work

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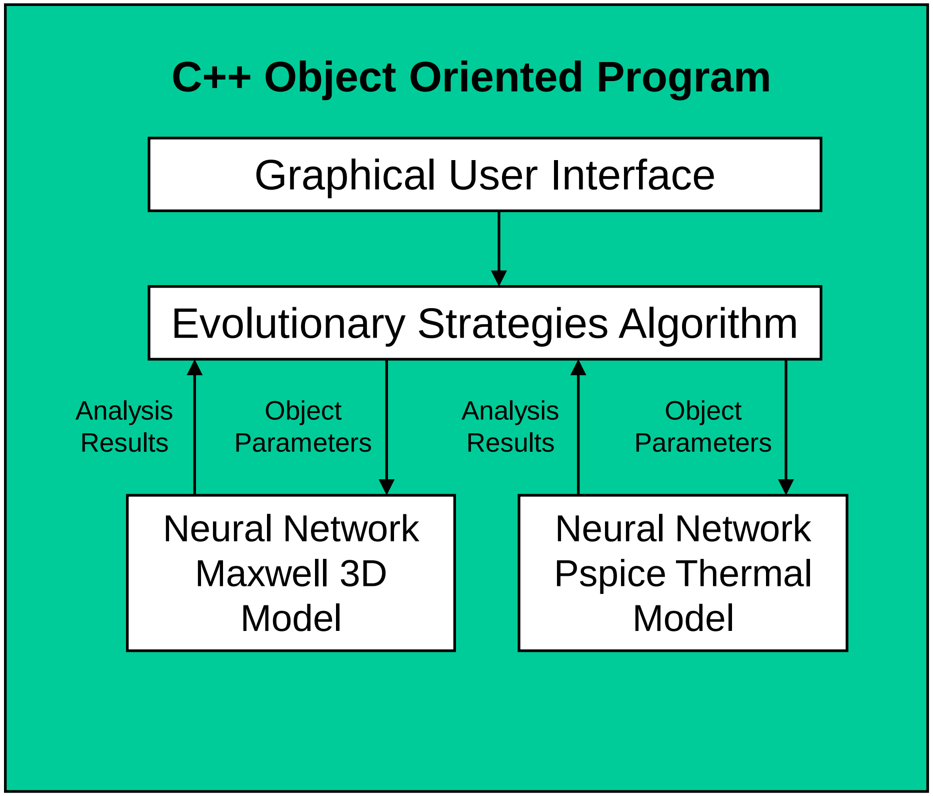
- Transient EM Model
  - Ansoft currently has a 3D transient EM simulation tool in development
  - When this tool becomes available, transient EM effects will be investigated (e.g., current density gradient due to skin and proximity effects)
- Transient Thermal Model
  - A transient thermal circuit model of the thyristor assembly is currently in development
  - Orcad Pspice is used to simulate heat flow through the assembly
  - Thyristor junction temperatures are constrained below a maximum acceptable value
  - Thermal conductivities are calculated for varying component geometries and materials outside of the Pspice simulation.
- Additional models will be added to the optimization software in the form of Neural Network Models

Optimization with Maxwell 3D and Pspice

- Maxwell and Pspice optimizations are run independently from each other
- Each optimization is modeled as a Neural Network
- The thermal conductivity/geometry relationship provides the link between the Maxwell 3D and Pspice simulations.



Transient Thermal Circuit Model

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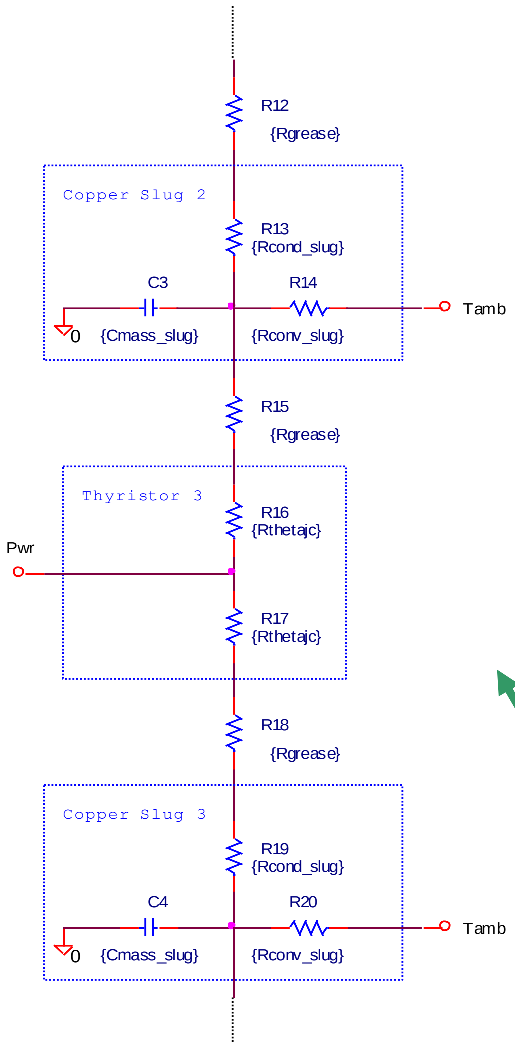

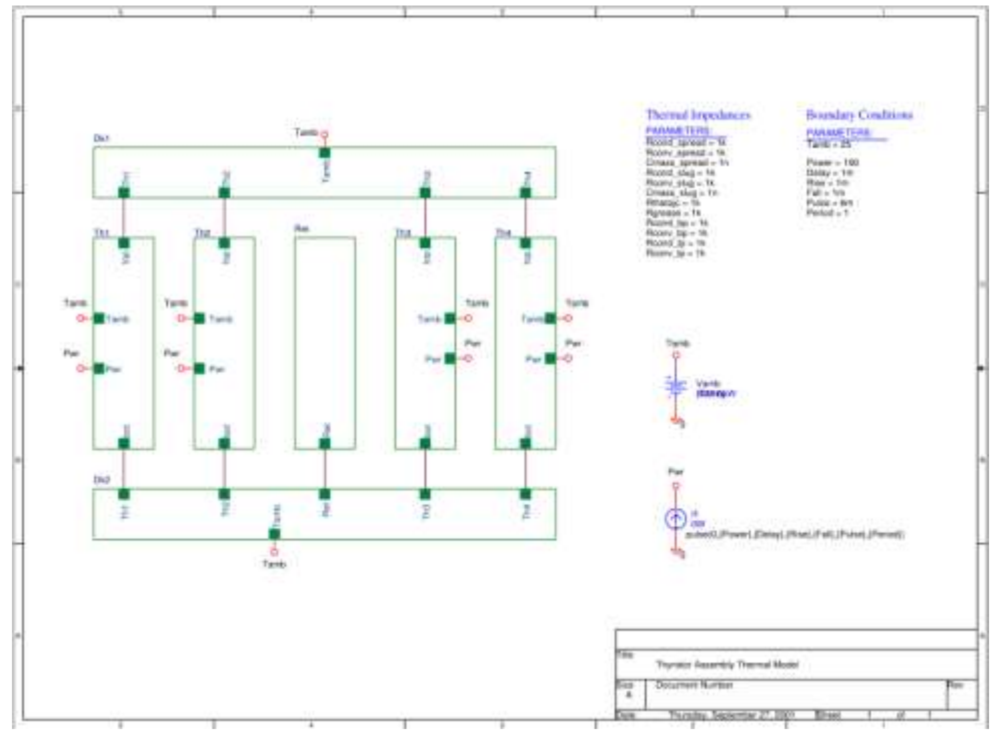

Each thyristor leg contains a stack of 4 thyristors

Thyristors are sandwiched between copper slugs

Summary

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- Demonstrated a practical methodology for implementing multi-disciplinary optimization through the integration of Evolutionary Strategies and Neural Networks

- Evolutionary Strategies and Neural Network models discovered an optimum solution that minimized volume of a pulsed power thyristor assembly that meets performance constraints.

- Neural Networks provide a valuable tool for modeling power system performance
  - Model development is fast and requires little effort
  - Common software structure to implement any model
  - Allows for plotting of performance to learn basic characteristics

Final Comments

- The methodology utilized in the optimization of this thyristor assembly is applicable to many Multi-Disciplinary Optimization (MDO) problems.
- For Electric Launcher Technology this includes optimization of the launch package, launcher, rotating machine, power converter and control for any set of design variables and constraints.
- If the multi-disciplinary aspects of the Electric Launcher can be simulated or actual test data is available, this methodology can be used to optimize them.