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Automated Design of Slow Wave Structure of a Helix TWT using Multi-Objective NSGA-II Optimization Algorithm

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***Abstract*—In this paper, the design of the slow wave structure (SWS) of a helix traveling wave tube (TWT) using a meta-heuristic optimization algorithm has been presented. The design of the SWS using the large signal model (LSM)-based one-dimensional code, SUNRAY-1D, has been carried out as a multi-objective, multi-parameter global optimization problem. The non-dominated sorting genetic algorithm – II (NSGA-II) has been employed for optimization. In this automated optimization approach, the multiple pitches, lengths and the coating loss values in the various sections of a 2-section helix SWS have been optimized to meet the three objectives, namely, the required saturated output power, saturated gain and the 20-dB phase shift over the frequency range of 10.5-12.5 GHz. The Pareto-optimal front showing all the non-dominated solutions has been shown. The optimized parameter set and the corresponding output power, saturated gain and the 20-dB phase shift have also been shown.**

***Keywords*—helix, slow wave structure, TWT, optimization, NSGA-II, multi-objective, Pareto**

I. INTRODUCTION

An efficient design of the interaction structure is critical for the performance of a helix traveling wave tube (TWT). The interaction structure of a helix TWT is typically composed of a helix slow wave structure supported by dielectric rods and surrounded by a metal envelope. The helix SWS usually consists of multiple sections of different pitches and lengths. During the design of the SWS, the various dimensions of the helix and rods are to be optimized for maintaining near-synchronism between the electron beam and the RF signal, formation of electron bunches, gain growth and the transfer of power from the beam to the RF signal. Apart from the physical dimensions of the helix SWS, beam voltage, beam current and beam radius are some of the other parameters that are also considered in the SWS design. It can be seen that there is a large number of parameters to be optimized to meet the objectives such as target output power or gain. When such a multi-parameter optimization is done manually, it may become tedious and intervention is required to cycle through each of the parameter combination. It is not even guaranteed that the parameter set arrived at the end of the manual optimization process is the best possible solution. In addition to this, there is not a single solution set that would satisfy all the objectives. It is up to the designer to make an educated decision to select a parameter set which would closely satisfy one or few of the objectives without sacrificing the rest of the objectives too much. The motivation behind this work is to address these problems and demonstrate the process of helix SWS design as a multi-parameter, multi-objective optimization problem using a meta-heuristic global optimization algorithm, namely the non-dominated sorting genetic algorithm – II (NSGA - II).

There have been several papers on designing TWTs using optimization algorithms with most of the works focused on optimizing for the efficiency of the tube [1-5]. Design employing optimization algorithms have also been carried out in other vacuum microwave tubes and components [6-8]. In an earlier work by the authors [9], the helix SWS optimization using single-objective genetic algorithm was presented.

In this paper, the optimization has been carried out to meet three objectives, the targeted saturated output power, saturated gain and 20-dB phase shift. The NSGA-II optimization module, developed in MATLAB, has been interfaced with the large signal model (LSM)-based tool, SUNRAY-1D which is used for objective function evaluations.

II. METHODOLOGY

The SUNRAY-1D tool requires the cold circuit parameters, namely, the propagation constant (in rad/m), β, and the interaction impedance (in Ω), K as input parameters. These are determined for the required frequency range and the range of pitch values from an in-house code, GANGA. Over the course of optimization, the optimization module would automatically choose the corresponding β and K from the lookup table for a particular frequency and pitch value, thus eliminating the need for manual intervention. In this work, the inner and outer diameters of the helix, the dimensions and the relative permittivity of the support rods and the electron beam radius have been kept constant. The profile of the 2-section helix SWS to be optimized has been shown in fig. 1.

P1-P3 are the three pitches in the 2-section SWS. L1 and L2 are the lengths of the subsections in the input section of the SWS. L4-L7 are the lengths of the various subsections in the output section of the SWS. Connecting the input and output sections is the drift section of length L3. C1 and C2

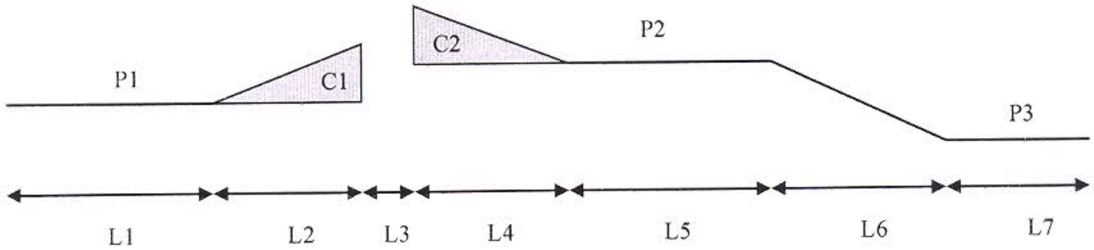

Fig. 1. A typical 2-section helix SWS.

are the loss values of the tip loss coating used to prevent oscillations due to reflections reaching the input side of the tube. P1-P3, L1-L7, C1, C2, beam voltage (V_0) and beam current (I_0) are the 14 parameters to be optimized.

A. NSGA-II Algorithm

The NSGA-II algorithm uses the concept of pareto dominance. A solution S_1 is said to dominate another solution S_2 if, for 'n' objectives [10],

- S_1 is better than S_2 in at least one of the objectives
- S_1 is better than or as good as S_2 in all of the objectives

If S_1 and S_2 do not dominate each other, then they are known as non-dominated solutions.

After the population is initialized, the members of the population are sorted in fronts based on non-domination. The first front consists of members which are completely non-dominant, the second front consists of members which are dominated only by those in the first front and so on. In order to retain diversity in the population, a parameter known as crowding distance (CD) is used. CD is a measure of how close a member of the population is to its neighbor. The key steps of the NSGA-II are as follows [11]:

1. The population, pop, of size 'npop' is initialized and each of the objectives is evaluated
2. Non-dominated sort is performed
3. CD is assigned front-wise and objective-wise
4. Individuals are sorted based on non-dominance and the CD and crossover operation is performed
5. Mutation is performed
6. The offspring population is appended with the current population and the entire new generation of members is again sorted based on non-domination and CD. Each front is filled with new generation.
7. The process is repeated for subsequent generations

B. Objective functions

The objective functions represent the goals to be achieved at the end of the optimization. In this work, the three objective functions used are to achieve the targeted saturated output power, targeted saturated gain and minimum 20-dB phase shift. The objective functions are defined as follows:

- Objective fn #1:

  Power cost: Minimize,

$$\left(\frac{\sqrt{\sum_{i=1}^{k}((P_{out,i}-P_{out,ref})^2)}}{k}\right) \qquad (1)$$

- Objective fn #2:

  Gain cost: Minimize,

$$\left(\frac{\sqrt{\sum_{i=1}^{k}((G_{sat,i}-G_{sat,ref})^2)}}{k}\right) \qquad (2)$$

- Objective fn #3:

  Phase cost:

$$\text{Minimize } (\max(\phi_1,\ \phi_2,\dots\ \phi_k)-\phi_{ref}) \qquad (3)$$

Here, i = 1…k represents the frequency point. $P_{out,i}$ and $G_{sat,}i$ represent the saturated output power and saturated gain at the i^{th} frequency point respectively. ϕ_i represents the 20-dB phase shift at the i^{th} frequency point. The reference values of output power ($P_{out,\ ref}\mathbf{P_{out_{ref}}}$), gain ($G_{sat,\ ref}$) and phase shift ($\phi_{ref}\ \boldsymbol{\Phi_{ref}}$) are 270 W, 55 dB and 80 degree respectively. The SWS has been designed to operate from 10.5-12.5 GHz.

III. RESULTS AND DISCUSSION

The pareto front consisting of all the non-dominated solutions at the end of 100 iterations is shown in fig. 2. Each of the red asterisks (*) represent a candidate non-dominant solution. One such solution which gives the minimum power cost has been shown using the tool tip. As can be seen from the figure, selecting any other candidate solution would have been a better choice in terms of gain or phase cost but with a tradeoff in terms of power cost. The synthesized parameter list corresponding to the selected candidate solution from fig. 2 is shown in table 1. The pitches, P1-P3 and lengths, L1-L7, have been normalized with respect to the maximum values. The saturated output power, saturated gain and 20-dB phase shift over the entire frequency range are shown in figs. 3 and 4.

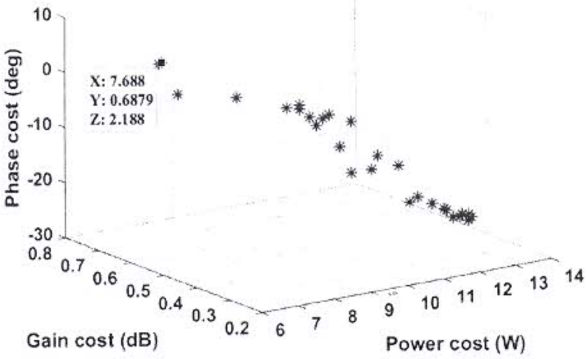

Fig. 2. Pareto front at the end of 100 iterations

TABLE I. THE OPTIMIZED PARAMETER LIST

Parameter	Value
P1	0.93
P2	1.00
P3	0.79
L1	1
L2	0.55
L3	0.06
L4	0.20
L5	0.84
L6	0.31
L7	0.12
C1 (dB)	26
C2 (dB)	40
V_0 (kV)	7.0
I_0 (mA)	131

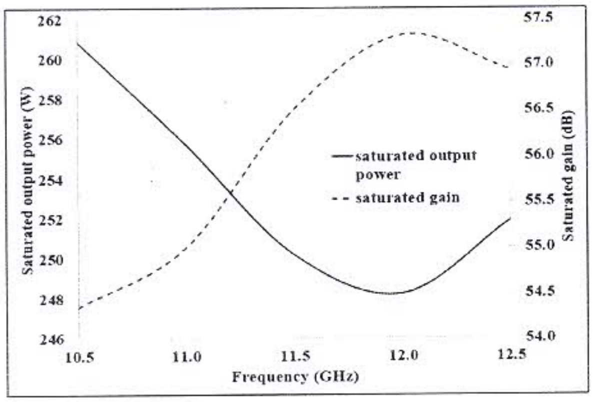

Fig. 3. Saturated output power and saturated gain Vs frequency

It can be seen from the figs. 3 and 4 that the saturated output power and saturated gain are close to their targeted values. The 20-dB phase shift is at its lowest at 53.450 at 10.5 GHz but approaches to 82.190 at 12.5 GHz. A lower phase shift could have been obtained by choosing another candidate solution although at the cost of sacrificing best optimum solution in terms of the other two objectives.

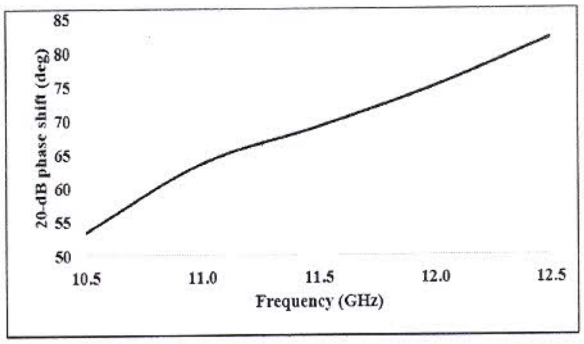

Fig. 4. 20-dB phase shift Vs frequency

IV. CONCLUSION

Thus, the automated design of a helix SWS using the multi-objective NSGA-II algorithm has been demonstrated. The pareto front depicting the list of possible candidate solutions has been shown. The synthesized parameters and the objective function values, namely, the saturated output power, saturated gain and 20-dB phase shift corresponding to one of the candidate solutions arrived at the end of 100 iterations have been shown. The pareto front allows the designer to examine the list of solutions and select the desired one with the complete knowledge of the trade-off among the objective function values.

REFERENCES

[1] T. K. Ghosh and R. G. Carter, "Optimization of multistage depressed collectors," IEEE Trans. Elect. Dev., vol. 54, no. 8, pp. 2031-2039, Aug. 2007

[2] H. X. Yi, P. K. Liu, and L. Xiao, "Numerical optimization of pitch profile for overall efficiency enhancement of a space TWT," Prog. Electromagn.Res. PIER C, 16, pp.37-50, 2010

[3] S. Coco, A. Laudani, G. Pucini, F. R. Fulginei and A. Salvini, "Shape optimization of multistage depressed collectors by parallel evolutionary algorithm," IEEE Trans. Magn., vol. 48, no. 2, pp. 435-438, Feb. 2012

[4] H-X Yi, L. Xiao. P-K Liu and F. Li, "Optimization design of slow wave structure using genetic algorithm," Proc. Int. Vac. Elect. Conf., Bangalore, India, pp. 215-216, Apr. 2011

[5] L. Xiao, Y-H. Dong, X-B Su and P-K Liu, "A multi-objective genetic algorithm for optimizing dispersion and coupling impedance in helix TWTs," Proc. Int. Vac. Elect. Conf., CA, USA, pp. 445-446, Apr. 2006

[6] J. Gong, X. Zhu, Q. Hu, Y. Hu and B. Li, "A fast optimized algorithm based on the NSGA-II for microwave windows," Proc. Int. Vac. Elect. Conf., London, UK, pp. 445-446, Apr. 2017

[7] W. Jiang, Y. Luo, R. Yan and S. Wang, "Genetic algorithm-based shape optimization of modulating anode for magnetron injection gun with low velocity spread," IEEE Trans. Elect. Dev., vol. 62, no. 8, pp. 2657-2662, Aug. 2015

[8] K. Dong, Y. Luo, W. Jian, H. Fu and S. Wang, "Numerical optimization of the cusp gun for a W-band second harmonic Gyro-TWTA," IEEE Trans. Elect. Dev., vol. 63, no. 11, pp. 4473-4478, Nov. 2016

[9] P. Narasimhan, V. Srivastava and S. K. Ghosh, "GA-based optimization of the interaction structure of an X-band helix travelling wave tube," IET Mic. Ant. Propn., vol. 12, no. 6, pp. 937-940, May 2018

[10] B. Y. Qu and P. N. Suganthan, "Constrained multi-objective optimization algorithm with an ensemble of constraint handling methods," Engg. Optimizn., vol. 43, no. 4, pp. 403-416, Apr. 2011

[11] K. Deb, A. Pratap, S. Agarwal and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," IEEE Transactions on Evolutionary Computation, vol. 6, no. 2, pp. 182-197, Apr. 2002