Tuning of PID Controller with Differential Evolution Algorithm for LCC Resonant Converter

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Abstract. This paper deals with the optimization of LCC Resonant Converter based on Differential Evolution Algorithm. Closed Loop Analysis of LCC Resonant Converter have been Simulated by tuning PID Controller for different values of Kp, Ki and Kd values. Optimum Values of Kp, Ki and Kd were obtained using Differential Evolution Algorithm and these values were fitted to Obtain Maximum Output Voltage with LCC Resonant Converter. Initially three Variables namely Series Inductance, Series Capacitance and Parallel Capacitance were considered, out of which the Value of Series Capacitance was tuned with Differential Evolution.

1. Introduction

The Power Electronic Converters has proved to be more useful and efficient in almost all industries. Power electronics have gained so much of importance due to the switching characteristics of the converters. The technique of Optimization was initially used in Power Systems and later has been applied to Power Electronics and Power Converters. Power Electronics has boomed up to a higher level after the invention of various Switching Techniques. Various Power Converters have been employed according to the requirement of the applications. Resonant Converters are one of the prominent Converters for high voltage applications as they are capable of Switching in Zero Current and Zero Voltage [1]. Resonant Converters can be operated with different topologies namely LLC, LCC, CLL LCCL, etc...,[2]. Generally, system Performance can be improved using closed loop. Jimoh Pedro has tuned Resonant Converter manually through Differential Evolution (DE) Algorithm to minimize a Performance index which addresses parameters of Car Electro hydraulic Suspension [3].DE Algorithm has been used for tuning PID Controller in Automatic Voltage Regulator Systems. Integral Time Absolute Error (ITAE) and Integral Absolute Error (IAE) has been considered has objective function and Kp, Ki and Kd values have been calculated [4,5]. Mean Square Value (MSE) and Integral Absolute Error (IAE) has been set has objective functions and PID Controller tuned in both Genetic Algorithm and DE and compared with Ziegler-Nichols Method [6]. The Converter Controller Parameters have been designed based on Bacterial Foraging Optimization and Compared with Ziegler-Nichol’s techniques [7]. Optimization Technique has been used to minimize the losses for Electrostatic Precipitators considering the Resonant Tank elements as the parameters. Variable Frequency and Dual Control are different strategies used [8]. Optimal Converter Parameters have been determined by using a Boundary map for the modes such that higher efficiency can be obtained over the entire input voltage and load range [9]. Particle Swarm Optimization has been used to increase the Power and efficiency and
reduce the Voltage stress of Converter Components. The converter is switched in high frequency to reduce its weight and dimensions [10]. A good closed loop performance of the converter has been obtained using optimized digital compensations. But when resonant frequency increases, more design calculations are required for the converter to be stable [11]. Various Optimization Algorithms such as Differential Evolution, Genetic Algorithm and Bacterial Foraging Optimization have been used and compared with the traditional Ziegler-Nichols Technique. Different Optimization Algorithms also have been compared and Grey Wolf Optimization Algorithm has been proved to give minimum IAE, ITAE, ISE errors [12]. In this work, the Optimum value of series capacitance has been calculated after different iterations and also PID Controller is tuned by obtaining Kp, Ki and Kd values. This paper constitutes of Section I, II, III, IV with Introduction, System Overview and Analysis of the converter and Differential Evolution Algorithm respectively. The above sections are followed by Simulation of the Converter and conclusion.

2. System Overview

Resonant Converters are the Zero Voltage and Zero Current Switching Converters which are very suitable for High voltage applications. Different Topologies of Resonant Converters have been used namely LCC, LLC and CLL. A small output voltage is being boosted to a higher voltage with less conduction losses and Switching Losses. As the converter has less loss, it is used for X-Rays which require output voltage in the order of kilovolts. X-Rays are used for both Diagnostic and Therapeutic Measurements and it is one of the most important and essential requirements in the field of Medicine. Also, these X-Rays play a vital role in Mechanical, Electrical and Electronic Testing. LCC Resonant Converter characteristics appear to be more suitable for X-Rays. LCC Resonant Converters operate in both Continuous and Non-Continuous Mode in below and Above Resonant Frequencies. The variations in duty cycle of the converter can make variations in the output power according to the requirement.

![System Overview](image)

**Figure 1. System Overview**

The System Overview is shown in figure 1. An Input voltage of 540 volts is converted to a voltage in the order of kilovolts. The input voltage is initially fed to a Full bridge Inverter which has four MOSFET Switches and feeds to a LCC Resonant Converter after which is given to a step-up transformer. The Secondary Voltage of the Transformer is then given to a rectifier for conversion of ac voltage to dc voltage. A capacitor is connected parallel to the load on the output side as a filter.

3. Analysis of LCC resonant converter
The Equivalent Circuit of LCC Resonant Converter is given in Figure 2. The Space State Variable for LCC Resonant Converter is derived from the Equivalent Circuit.

\[ V_i(s) = sL_S I_1(s) + \frac{1}{sC_S} I_1(s) + \frac{1}{sC_P} [I_1(s)I_2(s)] \]  

(1)

\[ \frac{1}{sC_P} [I_2(s) - I_1(s)] + \frac{1}{sC_0} I_2(s) = 0 \]  

(2)

\[ V_0(s) = \frac{I_2(s)}{sC_0} Z_L \]  

(3)

Representing the Equations in Matrix Form,

\[
\begin{bmatrix}
V_i(s) \\
0
\end{bmatrix} =
\begin{bmatrix}
SL_S + \frac{1}{sC_S} + \frac{1}{sC_P} & -\frac{1}{sC_P} \\
\frac{1}{sC_P} + \frac{1}{sC_0}
\end{bmatrix}
\begin{bmatrix}
I_1(s) \\
I_2(s)
\end{bmatrix}
\]  

(4)

The Above Matrix is solved and the Output Voltage is obtained as,

\[ V_0(s) = \frac{I_1(s)}{s(C_0 + C_P)} Z_L \]  

(5)

4. Differential Evolution Algorithm

Differential Evolution is one of the famous Optimization Algorithm for solving Non-linear Problems. It was developed by Storn and Price in 1996. Optimization can be used to find local and Global operating point. This Algorithm consists of many steps namely Initialization, Mutation, Crossover and Selection.

**Initialization**

A Population of N size was considered for G generations. The First Population was generated randomly considering a range having lower limit and upper limit. The components of LCC Resonant Converter namely the Series Inductance, Series capacitance and the parallel capacitance were considered as parameters.

**Mutation**

For each value of the parameter three other vectors was selected randomly. The three vectors considered was Kp, Ki and Kd Values. The fitness value was calculated for each vector.

**Crossover**
The crossover Constant was assumed as a constant value as 0.2e-4. The fitness value is compared and the best optimum value was obtained as the solution.

Selection
The Solution is compared with the target and the entire Process is repeated for every generation and each Population.

Differential Evolution Algorithm was applied using pseudocodes in MATLAB and the different parameters of the PID Controller like Kp, Ki and Kd were calculated. Various cases of PID Parameters were generated by trial-and-error approach and output voltage and optimum Series capacitance values were obtained for all the cases. The problem was initially formulated for the objective function $f(x)$ to be maximized i.e., output voltage to be maximized. $g_i(x)$ represents the ith inequality constraint with $s$ is the number of constraints.

$$\text{Maximize } f(x)$$

(6)

$$g_i(x) \leq 0, i = 1, s$$

(7)

5. Simulation of Converter

LCC Resonant Converter was simulated in MATLAB Simulink. An input voltage of 540v was given and an output voltage of around 53 Kilovolts was obtained when simulated in closed loop. The PID Controller was tuned with Differential Evolution Algorithm initially to obtain the Value of Series Capacitance. The range considered for Series capacitance value as 0.2 and 0.6microfarad. The Optimum Value of Series Capacitance was found to be 36.02 Microfarad. The objective function was taken to obtain high output voltage as it is the requirement of X-ray. The PID Controller was tuned and optimum values were obtained for Kp, Ki and Kd using Differential Evolution Algorithm. The Parameters of the Simulation Circuit are

| Parameter            | Value           |
|----------------------|-----------------|
| Input Voltage        | 540V            |
| Series Inductor      | 42MicroHenry    |
| Series Capacitor     | 0.25 Microfarad |
| Parallel Capacitor   | 120nanofarad    |
| Switching Frequency  | 42KHz           |
| Load Capacitance     | 5.5Microfarad   |
| Output Voltage       | 53Kilovolts     |

Table 1. Converter Parameters
The Simulation Circuit of Tuning the PID Controller has been shown in the figure 3. The

Figure 3. Simulation Circuit

Primary and Secondary Voltage of the high Voltage transformer has been shown in the figure 4. The Primary Voltage of the transformer is about 300V and that of secondary voltage is in the range of kilovolts. The obtained output voltage has been enclosed in the Figure 4. The waveform is free from any disturbances as it is tuned by the PID Controller.

Figure 4. Primary & Secondary Transformer Voltage for the Optimum case

The waveform of the Circuit after tuning the PID Controller using Differential Evolution Algorithm is given in figure 5, 6 and 7. The Series Capacitance was tuned for five Generation of Population with a range of 0.2 to 0.6 Microfarad. The PID Controller was tuned with three variables namely Kp, Ki and Kd with 5 Generation of Populations. Different values of Kp, Ki and Kd were considered as three cases and the output voltage generated for all the below cases. The range of the variables were taken as
Kp=0.00001142 to 0.01142
Ki=0.0001539 to 0.01539
Kd=0.00001 to 0.001

Table 2. Optimized Coefficients of PID Controller

|        | Case1       | Case2       | Case3       |
|--------|-------------|-------------|-------------|
| Kp     | 0.0001142   | 0.0001142   | 0.0001142   |
| Ki     | 0.001539    | 0.001539    | 0.01539     |
| Kd     | 0.0001      | 0.00001     | 0.0001      |

Figure 5. Output Voltage of the Load for case 1

Figure 6. Output Voltage of the Load for case 2
Different time domain parameters were compared and results are tabulated in table 3.

**Table 3. Performance Comparison**

| Parameters/Systems      | Output Voltage (KV) | Output Current (A) | Output Power (KW) | Rise Time (sec) | Settling Time (sec) |
|-------------------------|---------------------|--------------------|-------------------|-----------------|---------------------|
| PID Controller          | 45.63               | 0.2395             | 10.93             | 4.18            | 5.77                |
| Tuned PID Controller    | 60                  | 0.3149             | 18.89             | 2.31            | 4.56                |

6. Conclusion

Differential Evolution Algorithm has been used for Single objective optimization to find the best value of Series Capacitance. LCC Resonant Converter has been used for X-Ray Generator after analysing its space state variable. The waveform of output voltage has been obtained in closed loop simulation after tuning the PID Controller for different values of Kp, Ki and Kd..

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