Loss Minimization in Parallel & Series Induction Heating Inverters Using Genetic Algorithm

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Abstract: - In this paper induction heating system is modeled and effective factors on induction heater system losses are represented. Respective to the intensive importance of capacitor losses and its potential ability of being harmful, furnace parameters must be designed in a way to minimize capacitor losses and maximize the transmitted power into the load. The effective parameters are the number of turns of work coil and the value of capacitor used for power factor correction. In this paper the optimal capacitance is calculated by the use of genetic algorithm to minimize the capacitance losses and maximize the transmitted power into the load for induction heaters with series and parallel resonances. Furthermore, the effect of capacitance change on the load and impedance matching transformer impedances are considered theoretically and experimentally.

Key-word: - Induction Heating, Capacitor loss, Optimization, Genetic algorithm, Modeling, Frequency changes

1 Introduction

Nowadays inductive heaters are widely being used in the industry and fossil heaters are being replaced by induction heaters rapidly. Induction heaters have numerous capabilities rather than the other types of heater which the most prominent of them are high efficiency, high output rate and cleanness [1,2]. Inductive heaters never pollute the environment, and additionally their maintenance and usage are much cheaper rather than fossil fuel heaters. The basic idea used in this type of heaters is ohmic loss of inducted current in the work piece. Based on this, the set of the load and the inductive heater coil are attached to the output of a voltage source or current source inverters. In order to correct power factor of inverter, one capacitance is located in series or parallel with induction heater load. Fig.5 shows proposed scheme for such structures. In the case with series structure switching frequency of the inverter can be more or less than the resonance frequency of capacitor and inductor. If the switching frequency is chosen below the resonance frequency, the load will be capacitive and if not the load will be inductive. In the parallel structure for the load commutation, the load current must be lead respect to the voltage. This means that in parallel structure it is possible for switching frequency only to be more than the resonance frequency. Circuit losses consist of capacitance loss, switching loss, transformer loss and coil losses. Among these losses, capacitance loss is of great importance of difficulty and complexity of cooling. If capacitor loss is not damped well, the internal temperature of capacitor will increase and this may cause damages. Consequently the heater design must be carried on in a way to reach minimum capacitor loss. Controllable parameters in order to decrease capacitance loss are capacitance and load coil parameters such as number of turn. In reference [3] minimization of capacitance loss for parallel structure is performed using Lagrange method and finding the suitable size for the capacitance assuming that the load impedance is constant. In this paper minimization of capacitor loss is performed via Chue Beasly genetic algorithm stated in appendix 1 for both series and parallel structures in order to choose the suitable capacitance considering variations in load impedance versus switching frequency variations. As discussed before it is possible to be effective on capacitor loss by changing coil parameters such as number of coil turn. Therefore generally we are encountering a two variable optimization problem which genetic algorithm is a very powerful tool in this case. In this paper effect of capacitance on capacitor loss is investigated in both series and parallel inductive heaters.

In section 2 of this paper equivalent circuit for the load is introduced and the effect of switching frequency on it is discussed which has never shown in the previous papers [3-5]. the mentioned theory in this section is proved by experimental results, and the theoretical and experimental results are in a good agreement. In the third section power loss in the capacitor and total power losses in the induction heating system are calculated using mathematical equations for both series and parallel schemes based on switching frequency variations.

2 Equivalent circuit of induction heating load

Induction heater load is modeled in different ways in publications [3,4]. In this paper series model of reference [6] is used. As we can see in Fig.1 the load is modeled as two work piece and heating coil resistors and three inductances include heating coil and air gap and work piece in series together. Relevant parameters are presented in equations below:

$$Z = (R_W + R_C) + j(X_g + X_C + X_W) \tag{1}$$

$$R_W = K(\mu_r\, p A_W) \tag{2}$$

$$R_{COIL} = K\left(\frac{k_r \pi\, d_C \delta_C}{2}\right) \tag{3}$$

$$X_g = K(A_g) \tag{4}$$

$$X_W = K(\mu_r q\, A_W) \tag{5}$$

$$X_{COIL} = K\left(\frac{K_r \pi\, d_C\, \delta_C}{2}\right) \tag{6}$$

$$K = \left[2\pi\, f\, \mu_\circ \frac{N_C^{\ 2}}{L_C}\right] \tag{7}$$

As it can be inferred from the equation (8) that equivalent resistance of the load consists of the work piece and the coil resistances is related to the square root of the switching frequency. Fig.2 shows experimental results to prove the equation (8).

$$R = 2\pi f \mu_0 \frac{N_C^2}{L_C}(\mu_r p A_W + \frac{K_r \pi d_C \delta_C}{2}) = K\sqrt{f} \tag{8}$$

Changes in capacitance size will result in the resonance frequency change. Assuming that the switching frequency of the inverter is a constant multiplication of the resonance frequency, the resistance value will change with variation of the capacitance and will decrease with larger capacitance. As implied by equations (1) to (7) maximum value of the load inductance is a result of the air gap and therefore the equivalent inductance of the load is being assumed independent of the switching frequency. Moreover, the transformer will be modeled as a set of leakage inductance and conductive resistance (Fig.3). The transformer resistance varies by changes in the size of capacitor as a result of skin effect. As we can conclude from the equation (9), the value of transformer resistance is proportional with square root of the switching frequency value.

$$R_T = \frac{r_1^{\ 2}}{2\pi\delta r_1 - \delta^2} R_{1TDC} + \frac{r_2^2}{2\pi\delta r_2 - \delta^2} R_{2TDC} \cong K' \sqrt{f} \tag{9}$$

As shown in Fig.4 the capacitor will be modeled as a composition of one resistor and one ideal capacitor [7, 8]. Series model and parallel one are suitable for low and high frequencies respectively. When several capacitance banks are used in parallel, the resistance of capacitor is approximately $\frac{K''}{C}$ in which K'' is a constant [3].

Equivalent circuit of the heater for two parallel and series cases are shown in Fig.5. As we can see in Fig.5, modeling is performed for transformer and load as two inductive-resistive impedances which resistance is variable with switching frequency.

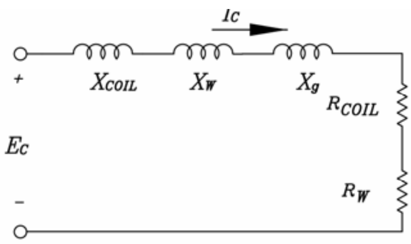

Fig.1 Load model for induction heating

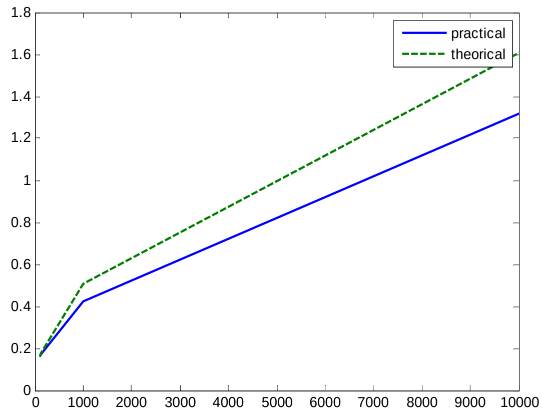

Fig.2
Theoretical and experimental diagram of load resistance variations (Ohm) vs. frequency variations (Hz)

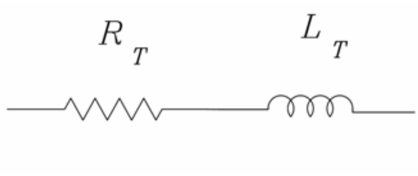

Fig.3
Model of impedance matching transformer

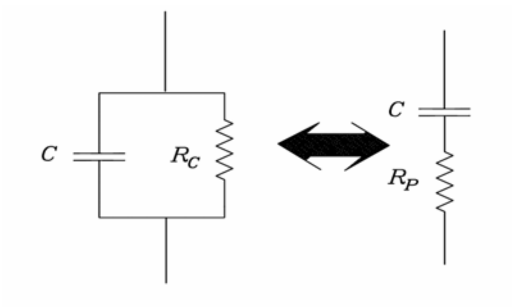

Fig.4
Parallel and series equivalent circuits of capacitance

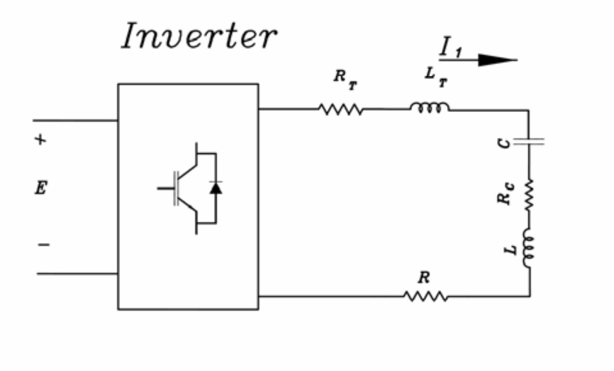

Fig.5 a
Model of induction heater with series connection of load and capacitor

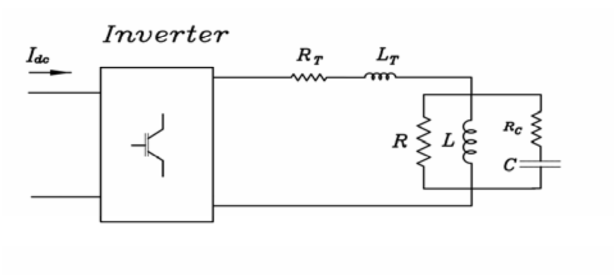

Fig.5 b
Model of induction heater with parallel connection of the load and the capacitor

3 Power equations

In this section, equations for the transmitted power into the load are shown for both series and parallel schemes considering the effect of frequency variations on the impedance of the inverter.

3.1 Series resonance inverter

In this case equivalent circuit of heater is as shown in Fig.6. Equivalent resistance consists of load resistance, transformer, switches and the capacitance series altogether. Also equivalent inductance of inverter consists of leakage inductance of impedance matching transformer and load inductance.

$$R_{eq} = R + R_T + R_C + 2R_{SW} = = (n^2 K + K')\sqrt{f} + \frac{K''}{C} + 2R_{SW} \tag{10}$$

$$L_{eq} = (L_W + L_g + L_{COIL})n^2 + L_T = L + L_T \tag{11}$$

In the mentioned equations n is the ratio of impedance matching transformer and R_{SW} is the resistance of switch which is on. Because of the low damping factor of the resonant load in the induction heating systems the current could be assumed as a sinusoidal one [9] and transmitted power into the load could be calculated easily using first harmonic approximation as equation (12).

In order to use first harmonic approximation, only we use first component of voltage harmonics existing in square voltage of inverter output; Then, the first component of the current could be found using equation (12).

$$I_{1rms} = \frac{2\frac{\sqrt{2}}{\pi}V_d}{\sqrt{R_{eq}^2 + X_{eq}^2}} = \frac{2\frac{\sqrt{2}}{\pi}V_d}{\sqrt{((n^2K + K')\sqrt{f} + \frac{K''}{C} + 2R_{SW})^2 + (2\pi f L_{eq} - \frac{1}{2\pi f C})^2}} \tag{12}$$

Consequently for transmitted power into the load we have:

$$P_{out} = n^2 K \sqrt{f} \times \frac{\frac{8}{\pi^2}V_d^2}{((n^2K + K')\sqrt{f} + \frac{K''}{C} + 2R_{SW})^2 + (2\pi f L_{eq} - \frac{1}{2\pi f C})^2} \tag{13}$$

In which V_d is DC part of the voltage.

Total loss is formed of capacitance, coil, switches and impedance matching transformer losses. Therefore for conduction losses we will have:

$$P_{LOSS} = (K^{/}\sqrt{f} + \frac{K^{//}}{C} + 2R_{SW})\frac{8}{\pi^2}\times \frac{V_d^2}{((n^2K+K^{/})\sqrt{f}+\frac{K^{//}}{C}+2R_{SW})^2+(2\pi f L_{eq}-\frac{1}{2\pi f C})^2} \quad (14)$$

Also capacitor losses could be obtained using equation (15).

$$P_{LOSSC} = R_C \times I_{1RMS}^2 = \frac{K8}{C\pi^2}\times \frac{V_d^2}{((n^2K+K^{/})\sqrt{f}+\frac{K^{//}}{C}+2R_{SW})^2+(2\pi f L_{eq}-\frac{1}{2\pi f C})^2} \quad (15)$$

In which P_{LOSSC} is capacitor loss.

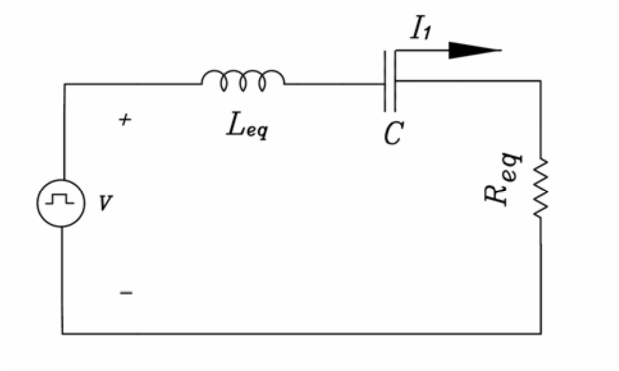

Fig.6
Equivalent circuit of the heater in the series scheme of load and the capacitor

Empirically switching frequency is assumed proportional to resonance frequency. Here switching frequency is assumed in two cases above and below resonance frequency:

$f = 1.1 f_0$

$f = 0.9 f_0$

Where f_0 is the resonance frequency of the system.

$$f_0 = \frac{1}{2\pi\sqrt{L_{eq}C}} \quad (16)$$

In the case that the resistor is in series with the capacitor, increasing capacitance will result in increase of transmitted power into the load. In series structure in position to parallel one capacitor losses would be maximum for a specific value of capacitance.

Of course it is important to consider financial considerations, resonance frequency and voltage and current constraints of the capacitance.

Maximum voltage constraint on the capacitor

$$V_C = (\frac{L_{eq}}{(1.1 or 0.9)^2 C} + R^2{}_C)^{0.5} I_{1RMS} < V_{\max} \quad (17)$$

Maximum current constraint

$$I_{1RMS} < I_{\max} \quad (18)$$

3.2 Parallel resonance inverter

Equivalent circuit for heater with parallel resonance load is illustrated in Fig.6. Based on the fact that this kind of inverter is being modeled as a current source, hence heater model will be simplified as Fig.7. Resonance tank impedance stated as Z_{Leq} could be achieved as equation (19).

$$Z_{Leq} = \frac{(Z_C + R_C).(Z_L + R)}{Z_L + R + Z_C + R_C} = \frac{(\omega_s K''R + \omega_s L) + j(\omega_s{}^2 LK'' - R)}{\omega_s(CR + K'') + j(\omega_s LC - 1)} \quad (19)$$

In which we will have $Z_L = j\omega_s L$, $Z_C = 1/j\omega_S C$, $R = (R_{COIL} + R_W)n^2$ and $L = (L_g + L_{COIL} + L_W)n^2$.

Indeed, the impedance of inverter consists of matching transformer impedance and tank circuit impedances. It should be mentioned that I_S is the first order harmonics of square wave inverter output current. Therefore we will have $I_S = 4I_{dc}/\pi$. Which I_{dc} is input current of inverter.

$$Z_{eq} = Z_T + Z_{Leq} \quad (20)$$

It can be seen from Fig.7 that current in R and R_C are shown as i_L and i_C respectively which will be obtained as below:

$$I_L = \frac{V_C}{Z_L + R} = \frac{Z_C + R_C}{Z_L + R + Z_C + R_C} I_s \quad (21)$$

$$I_C = \frac{V_C}{Z_L + R_C} = \frac{Z_L + R}{Z_L + R + Z_C + R_C} I_s \quad (22)$$

In these equations V_C and I_S are capacitor voltage and i_S phasors and also V_C equals $Z_{Leq}.I_S$.

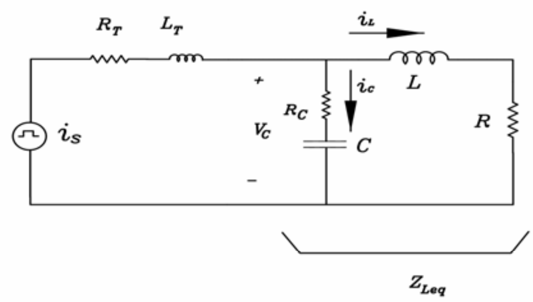

Fig.7
Equivalent circuit of heater in the case that load and capacitance are parallel

In this paper P_{Out} is the power (heat) generated in R (sum of resistances of coil and work piece) which will be referred as output power. Also the power (heat) generated in R_C is P_{LOSSC} and will be called capacitor loss. Both could be calculated using equations (4) and (5). Switching frequency is chosen as $\omega_s = 1.1/\sqrt{L_{eq}C}$.

$$P_{out}(C) = (\frac{I_L}{\sqrt{2}})^2 R = \frac{1}{2}\left|\frac{Z_C + R_C}{Z_L + R + Z_C + R_C}\right|^2 I_s{}^2 R = \frac{8I^2{}_{dc}}{\pi^2}\left|\frac{\omega K'' - j}{\omega C(K\sqrt{f} + \frac{K''}{C}) + j(\omega^2 CL - 1)}\right|^2 K\sqrt{f} \tag{23}$$

$$P_{LOSSC}(C) = (\frac{I_C}{\sqrt{2}})^2 R_C = \frac{1}{2}\left|\frac{Z_L + R}{Z_L + R + Z_C + R_C}\right|^2 I_s{}^2 R_C \tag{24}$$

$$\frac{8I^2{}_{dc}}{\pi^2}\left|\frac{\omega C(R + j\omega L)}{\omega C(R + \frac{k''}{C}) + j(\omega^2 CL - 1)}\right|^2 \frac{K''}{C}$$

We will have $I_L = |I_L|$ and $I_C = |I_C|$. As apparently we can see, P_{Out} and P_{LOSSC} are functions of capacitance. Therefore changing capacitance will result in variations in the power transmitted into the capacitor and dissipated in it. The target is to minimize capacitance loss and to maximize transmitted power into the load which is obtainable through maximizing the difference between power transmitted into the load and the power dissipated in the capacitor.

Circuit loss is composed of capacitor, coil, and impedance matching transformer and switches losses. The power lost in the transformer could be achieved using equation (25).

$$P_{LossT} = I^2{}_{dc} * R_T \tag{25}$$

4 Simulation procedure

In order to demonstrate validity of equations and proposed models, two discussed inverters are investigated through simulation, and also, simulation results are compared with theory and genetic algorithm results. Elementally, genetic algorithm is used to achieve the optimal capacitance in order to minimize capacitance loss and maximize transmitted power into the load (appendix 1). In order to maximize transmitted power into the load and minimize power loss in the capacitor, target function is chosen as subtraction of transmitted and lost power. Moreover, Voltage and current constraints are considered in optimization problem.

4.1 Parallel resonance inverter

Parameters of assumed system are represented in Table 1.

Induction heater system fed by current source inverter is simulated with MATLAB/SIMULINK. Values for consumed power in different parts of the system are obtained for different values of capacitance which are shown in Fig.2. In the same figure analytical results using equations (4) and (5) for both cases with and without considering the effect of frequency changes on the load impedance are illustrated.

The validity of optimal capacitance calculation method mentioned in the previous sections can be inferred from figure.8. For the two case studies introduced above genetic algorithm results are shown in Table 2.

Table 1

Parameters value of the system under investigation

parameter	value
C	$80-550\mu F$
K''	1.35×10^{-6}
K'	1.35×10^{-4}
K	7.14×10^{-4}
L_T	$9\mu H$
L	$50\mu H$
n	1
I_{dc}	$1160A$

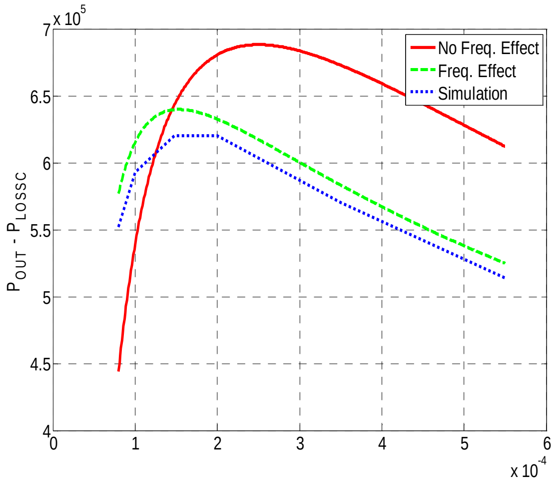

Fig.8

Variations of the subtraction between output and dissipated power in the capacitor for changes in capacitance with and without considering the effect of frequency on impedance based on theory and simulated results

Table 2
Results of Genetic algorithm

Case study	$C_{OPTIMUM}(\mu f)$	V_{Cmax}
1	180	2000 (V)
2	365	600 (V)

Table 3
Parameters value for the system under investigation

parameter	value
C	*1-300 μF*
K''	1.35×10^{-6}
K'	1.35×10^{-4}
K	7.14×10^{-4}
L	$50\mu H$
n	1
L_T	$9\mu H$
V_{DC}	*513 V*

In table 2 the results are shown for two cases of study. In the first one the constraint of the capacitor voltage is assumed to be 2000 (V). In this study the optimum capacitance is obtained equal to 180 μf . The result is exactly the same as in fig.8. However when the constraint is assumed to be 600(V) the optimum capacitance is obtained equal to 365 μf .

As shown in Fig.8 transmitted power into the load is maximized and lost power in the capacitance is minimized for a particular value of capacitance. Indeed, mentioned for series scheme, voltage and current constraints must be considered in the optimization

4.2 Series resonance inverter

Parameters for the studied system are shown in Table.3.

Analogous to parallel resonance inverter, the circuit for this system is simulated in the range of variations for capacitance, and consumed power is derived for each element.

Fig.3 illustrates variations of $P_{out} - P_{LOSS}$ vs. capacitance changing (micro Farad). It can be understood from figure.3 that the results for both results are in agreement which verifies the proposed model for the induction heating system based on voltage source inverter.

As it can be seen from Fog.9 in the case that the capacitor is in series with the load, capacitor losses are maximum for a specified capacitance and by decreasing the capacitance, transmitted power into the load increases and capacitor loss decreases. It is important to mention that increasing capacitance will change the resonance frequency and consequently the switching frequency should be changed. Therefore limiting factor for capacitance changing is the resonance frequency which must be in a particular range for each application. Decreasing the resonance frequency and therefore the switching frequency increases the current needed for heating in particular rate.

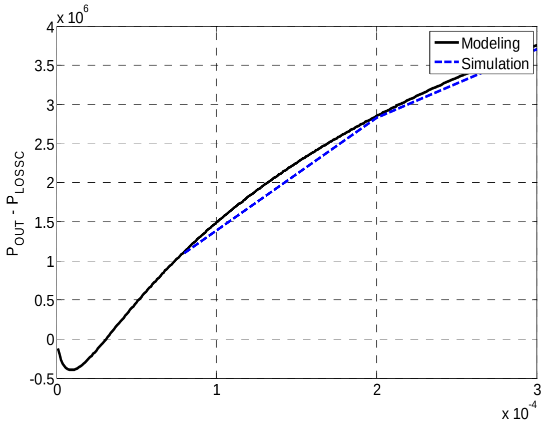

Fig.9
Variations of the subtraction between output and dissipated power in the capacitor for changes in capacitance with and without considering the effect of frequency on impedance based on theory and simulated results

5 Conclusion

The target in this paper is to determine power loss sources through representing an accurate model of induction heating systems based on voltage and current source inverters, and an appropriate design procedure based on minimization of losses is proposed. In the case the load and the capacitor are in series, increasing capacitance will result in increasing in the transmitted power into the load, and the capacitor loss is maximum for a particular value of the capacitance. In inductive heaters which current source inverter is used in their structure and load and capacitor are paralleled, the transmitted power into the load is maximum and lost power in the capacitor is minimum for a particular value of the capacitance.

6 Appendix

Utilized genetic algorithm
Use of genetic algorithm in order to optimize complex functions is of different types. The algorithm used in this paper has a procedure similar below:
Population construction
Parent Selection

Recombination (Offspring production)
Mutation
Substitution
The difference of this algorithm with others is in the substitution stage as below:
We will have finally one offspring (main or mutated) after mutation. In this stage this offspring will replace one member of population based on the procedure below:

- If the offspring is worse than the worst member of population it will be eliminated.
- If the offspring has better fitness than the worst member of population then:
  - If there is a member analogous to this offspring, it will be eliminated.
  - Otherwise the offspring will replace the worst member.

The procedure above will be repeated for particular times till finally the algorithm stops and the best fit member will be chosen as the result.
Here the criteria for loss fitness are the constraints defined in the problem.

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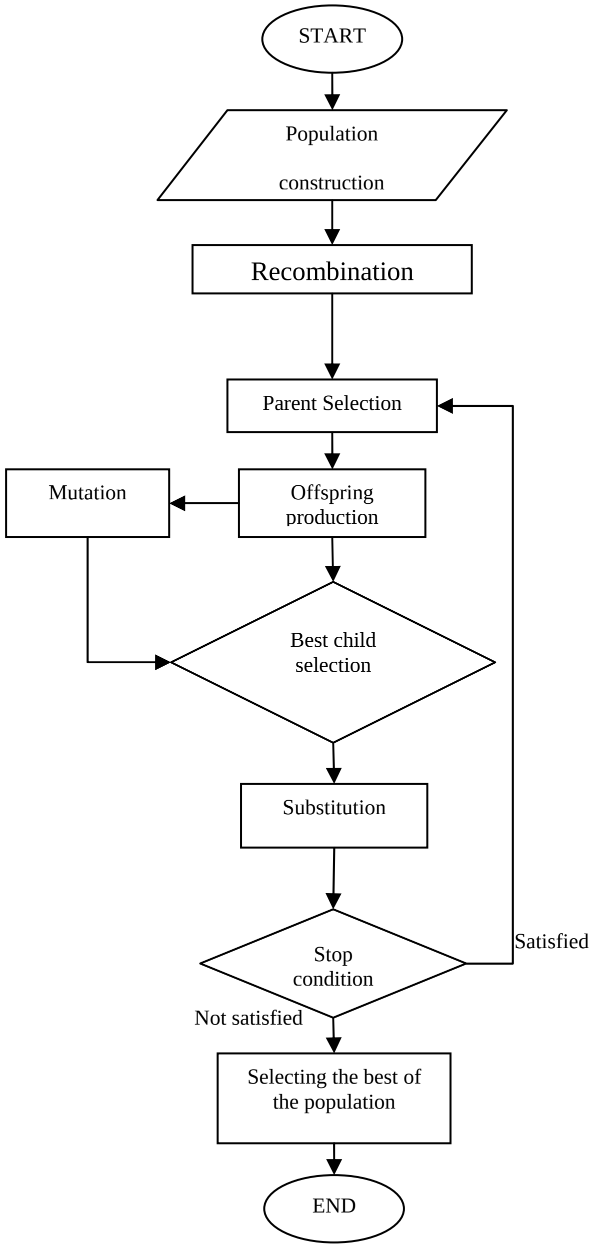

Fig.10
Algorithm procedure used to find optimal capacitance