

Optimal Placement and Sizing of Active Power Line Conditioners for Minimizing Power Quality Problems

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Abstract

In this paper, a problem of allocation and sizing of multiple active power-line conditioners (aplcs) in power systems is handled with novel formulation. The utilized objective function comprises two main factors such as reduction of total harmonic distortion and the total cost of active power-line conditioners (aplcs). The formulated problem is solved by optimization technique SHUFFLE FROG LEAP ALGORITHM (SHFLA) using MATLAB. To evaluate the competence of the proposed formulation, the IEEE 18-busdistorted distribution test system is employed and investigated with various number of aplcs placement. These cases are based on the discrete and limited size for aplcs, requiring the optimization method to solve the constrained and discrete nonlinear problems. The comparison of results in this paper showed that the proposed SHFLA is the most effective result among others in determining optimum location and size of APLC in distribution systems.

Keywords: active power-line conditioner (APLC), harmonics, shuffle frog leap algorithm (SHFLA), optimal allocation and sizing of APLCs (OASA) problem

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1. Introduction

The APLC is converter based compensation device and it is designed to improve the power quality of the entire distribution system by injecting corrective harmonic current at selective (sensitive) buses. APLC consists of set of shunt active filters. APLC's placement, sizing and compensation levels (e.g., orders, magnitudes and phases of injected current harmonics) are optimally placed to improve the power quality of the entire distribution system. The number of required APLC units depends on the distortion level, the nature of the distribution system and the type of nonlinear loads as well as the quality of electric power.

Although passive filters are widely employed due to their simplicity and economical cost, active power line conditioner is deemed the most efficient device for the reduction of harmonic level. The advantages of active power line conditioners are well established in literatures. Despite of the advantages, installation of active power line conditioners in a power distribution system is a very complicated problem. The harmonic standard, locations and sizes of APLCS, as well as the injection currents spectra of APLCs must be thoroughly considered. In addition, the sizes of the commercially available APLCs have discrete values. Despite a large number of benefits provided by APLCs, their huge installation and operation costs prevent electrical engineers from employing these profitable instruments without any restriction at all buses in power distribution systems.

Hence, in a large distribution system, it becomes necessary to locate suitable places for APLC installation to reduce these distortions and fixing their sizes is also essential. Owing to this fact, a variety of solution techniques have been utilized to solve the APLCs allocation and sizing problem. These techniques are mainly categorized into two groups:

- 1) Allocation of only one APLC and
- 2) Allocation of multiple APLCs.

The authors Grady & Samotyj (1992) and Chang & Grady (1994) have introduced the initial steps toward solving Optimal Allocation and Sizing of APLCs (OASA) problem.

Zhao, et al., (2001) have proposed chance constrained programming for optimal planning of harmonic filter in distribution systems. Chang, et al., (2001) have proposed a

combined differential evolution/multiple gradient summation approach for reducing harmonic distortion using APLCs. The goal of this approach is to minimize the total injection currents of APLCs, while satisfying standard constraints such as the individual harmonic voltage distortion, total harmonic voltage distortion (THD) limits, and the commercially available discrete sizes of the APLCs. Iman Ziari, et al., (2010) have presented a PSO algorithm for allocation and sizing of multiple Active Power Line Conditioners (APLCs) in power systems. They considered the objectives of minimizing the APLC rating as well as THD.

In these works, the cost of APLC is not considered. The realistic investment cost of an APLC is divided into two different parts, constant cost and the incremental cost. The constant cost, which is not related to the APLC rating called fixed installation cost, is constant and the incremental cost is proportional with the APLC rating. If APLC rating is the objective to be minimized, it indirectly results in ignoring the fixed installation cost. This assumption influences the results and leads the optimization method in use of a number of APLCs with higher investment cost.

Also, In all these works, the standard IEEE 18 bus distorted distribution system is taken for the case study and in this system, the non linear loads occurs at only at three to five buses. Hence the problem convergence is fast and the allocation of APLC units falls within these buses. Luis Sainz, et al., (2012) have explained the increase of nonlinear loads (NLLs) in supply networks that has led to an increase of harmonic content in supply currents. Thus in practical, the sizes of non linear loads are increasing greatly and cannot be restricted to limited number of buses. Hence in this work, it is considered about 11 buses are having non linear loads and the APLC placement may be in any of the 18 buses.

Iman Ziari, et al., (2012) have considered the problem with the objective of cost minimization of APLCs. The fixed cost of an APLC is taken as 90000\$ and the incremental cost of an APLC is taken as 720000\$ per 1 pu (Zhao 2001). Using these values, the realistic investment cost of APLC is calculated. The objective function is the investment cost of APLCs and the constraints are voltage THD and the individual voltage harmonic distortion which should be maintained less than 5% and 3%, respectively. Hence in this work, APLCs placement and sizing are evaluated for a distorted distribution system considering two main objectives such as reduction in THD as well as APLC cost under the presence of more number of non linear load buses.

2. Problem Formulation

The APLC is modeled as a set of current sources which inject different order of harmonics to the point of common coupling. To assume amplitude and phase angle for an APLC current, the phasor model is shown by:

$$I_{F,m}^h = I_{F,m}^{h,r} + jI_{F,m}^{h,i} \quad (1)$$

Where,

$I_{F,m}^h$ APLC current at bus m for harmonic order h ;

$I_{F,m}^{h,r}$ real part of APLC current at bus m for harmonic order h ;

$I_{F,m}^{h,i}$ imaginary part of APLC current at bus m for harmonic order h ;

The indices r and i represent the real and imaginary parts of the APLC current, respectively.

The objective is to minimize the total investment cost of APLCs and the total harmonic distortion that occur in the system. The constraints are individual harmonic distortion. THD is also introduced as one of the constraints. The investment cost of an APLC includes of the constant cost and the incremental cost. The constant cost, called fixed installation cost, is constant and is not related to the APLC rating, e.g. the required cost for securing and purchasing land. The incremental cost, e.g. the purchase cost, is proportional with the APLC rating. The objective function is formulated as follows:

$$OF = \beta_1 OF_{THD} + \beta_2 OF_{COST} \quad (2)$$

Where β_1 and β_2 are weight factors.

OF_{THD} can be formulated as follows:

$$OF_{THD} = \frac{\sum_{m=1}^M THD_m}{M} \quad (3)$$

$$THD_m = \frac{\sqrt{\sum_{h=2}^N |V_m^h|^2}}{|V_m^1|} \quad (4)$$

Where: M – Total number of buses

N - maximum considered harmonic order V_m^h - voltage at bus m for harmonic order h

THD_m - THD at bus m

OF_{COST} can be formulated as follows:

$$OF_{COST} = \sum_{m=1}^{NB} C_C + C_I S_{APLC_m} \quad (5)$$

Where: C_C -constant cost of APLCs

C_I - incremental cost of APLCs

S_{APLC_m} - rating of an APLC located at bus m which is proportional with its current.

NB - number of APLC buses

$$I_{F,m} = \sum_{h \in S_N} [(I_{F,m}^{h,r})^2 + (I_{F,m}^{h,i})^2]^{1/2} \in S_{size} \quad k \in S_{NB} \quad (6)$$

S_N - the set of harmonic orders.

S_{NB} - the set of bus installations of the APLCs.

$$S_{size} = \{I_b, 2I_b, \dots, \max I_b\} \quad (7)$$

I_b - the base unit size of the APLC.

$\max I_b$ - maximum size of the APLC. The constraints are given as follows

$$\frac{|V_i^h|}{|V_i^1|} \leq V_{max}^h \quad i = 1, \dots, M$$

$$h \in S_N \quad (8)$$

Where (8) is the individual harmonic voltage distortion for each bus within the limit, and V_{max}^h is usually 3%. Equation 7 denotes that the sizes of APLCs are discrete in nature.

V_i^h - the harmonic voltage at bus i for harmonic h .

V_i^1 - the fundamental frequency voltage at bus i .

Due to the occurrence of parallel resonance, the most serious voltage harmonic distortion may occur at those buses, where there is no nonlinear load but there is a capacitor installed. A bus where exists no nonlinear load but a high level of voltage harmonic distortion may not be the perfect candidate location to install APLCs to eliminate harmonics (Chang 2000). Also, the rating of APLC depends on the individual harmonic current injection into the bus by APLC. Hence, there is a possibility that, wrong current injections may lead to excessive rating of APLC as well as increase in THD levels. These are some of the reasons that make the problem with many local solutions and so, search space is wider.

3. Shuffle Frog Leap Algorithm (SHFLA)

The SFLA is a optimization method that the memetic evolution of a group of frogs when seeking for the location that has available of food. The algorithm consists of local search and global information exchange. The SFL algorithm involves a population of possible

solutions defined by a set of frogs (i.e. solutions) that is partitioned into subsets referred to as memeplexes. The different memeplexes are considered as different cultures of frogs, each performing a local search. Within each memeplex, the individual frogs hold ideas, that can be influenced by the ideas of other frogs, and evolve through a process of memetic evolution. After a number of memetic evolution steps, ideas are passed among memeplexes in a shuffling process. The local search and the shuffling processes continue until convergence criteria are satisfied. Frog's fitness can be simply defined as:

$$\text{fitness} = f(X) + C \quad (9)$$

Where $f(X)$ is the cost function to be optimized, and C is a constant chosen to ensure that the fitness value is positive. Afterwards, the frogs are sorted in a descending order according to their fitness. Then, the entire population is divided into m memeplexes, each containing n frogs, in such a way that the first frog goes to the first memeplex, the second frog goes to the second memeplex, the m th frog goes to the m th memeplex, and the $(m+1)$ th frog goes back to the first memeplex,

According to the original frog leaping rule, the position of the worst frog is updated as follows:

$$D = r \cdot (X_b - X_w) \quad (10)$$

$$X_w(\text{new}) = X_w + D, (|D| < D_{\max}) \quad (11)$$

Where: r is a random number between 0 and 1;

D_{\max} is the maximum allowed change of frog's position in one jump.

If this leaping produces a better solution, it replaces the worst frog. Otherwise, the calculations in Equation (10) and (11) are repeated but respect to the global best frog (i.e. X_g replaces X_b). If no improvement becomes possible in this case, the worst frog is deleted and a new frog is randomly generated to replace it. The calculations continue for a predefined number of memetic evolutionary steps within each memeplex, and then the whole population is mixed together in the shuffling process. The local evolution and global shuffling continue until convergence criteria are satisfied. Usually, the convergence criteria can be defined as follows:

1. The relative change in the fitness of the best frog within a number of consecutive shuffling iterations is less than a pre-specified tolerance;
2. The maximum user-specified number shuffling iterations is reached. The SFLA will stop when one of the above criteria is arrived first.

4. Methodology

The solution methods aim at determining optimal allocation and sizing of APLC. The problem solving involves load flow analysis, harmonic flow analysis and calculation of APLC cost for each feasible solution. Hence, Fundamental and Harmonic load flow analysis are integrated with the optimization technique, in order to obtain the fitness functions for the individual harmonic distortion and total harmonic distortion that occur in the distribution system. Load-Flow studies are performed to determine the steady-state operation of an electric power system.

4.1. Load Flow Analysis

A load-flow study calculates the voltage drop in each feeder, the voltage at each bus, and the power flow in all branch and feeder circuits. The conventional methods for load flow analysis include Single-Line Equivalent Method, Very Fast Decoupled Method, Ladder Technique, Power Summation Method and Backward and Forward Sweeping Method. An effective approach proposed by Alsaadi & Gholami (2009) for distribution power flow solutions is utilized in this work. The special topological characteristics of distribution networks have been fully utilized to make the direct solution. Two matrices namely the Bus-Injection to Branch-Current matrix (BIBC) and the Branch-Current to Bus Voltage matrix (BCBV) and a simple matrix multiplication are used to obtain power flow solutions.

For distribution networks, the equivalent current injection based model is more practical. For bus i , the complex load ' S_i ' is expressed by:

$$S_i = P_i + j Q_i \quad (12)$$

Where $i = 1, 2, 3, \dots, M$

And the corresponding equivalent current injection at the k^{th} iteration of solution is:

$$I_i^k = (P_i + j Q_i) / V_i^{k*} \quad (13)$$

Where V_i^k and I_i^k are the bus voltages and equivalent current injection of bus i at k^{th} iteration, respectively.

$$[B] = [BIBC]^* [I] \quad (14)$$

Where BIBC is a bus injection to branch current matrix and the BIBC matrix is a upper triangular matrix which contains 0's and 1's only.

The relation between branch currents and bus voltages can be obtained by using the following equation.

$$V(m2) = V(m1) - B^* Z \quad (15)$$

Where, $m1, m2$ are the sending and receiving ends.

4.1.1. Harmonic Load Flow Analysis

The conventional harmonic power flow method is used. The bus voltage for all harmonic orders is then calculated by multiplying the injecting currents and the impedance matrix is:

$$V_{BUS}^h = (1 / (Y_{BUS}^h)) \times I_{BUS}^h \quad (16)$$

Where V_{BUS}^h and I_{BUS}^h are the bus voltages and the injecting current vectors for h^{th} harmonic order, respectively. Y_{BUS}^h is the admittance matrix for h^{th} harmonic order and is determined for all the harmonics orders considered. The admittance matrix is formed using direct inspection method (Wadhwa 2010)

In this procedure, the current injecting to buses, I_{BUS}^h , is obtained using the following equation:

$$I_{BUS}^h = I_{APLC}^h - I_{NLD}^h \quad (17)$$

Where I_{NLD}^h and the I_{APLC}^h are injecting current vectors related to the nonlinear loads and APLCs, respectively.

The APLC currents are modified using Equations (19) and (20) to convert it as a discrete structure using integer optimizer.

$$I_{APLC_m} = I_{APLC_m} \times K_{C_m} \quad (18)$$

$$K_{C_m} = \frac{I_b \times \text{round}\left(\frac{I_{APLC_m}}{I_b}\right)}{I_{APLC_m}} \quad (19)$$

Here 'round' will convert the float variable to the nearest integer. K_{C_m} is a correction factor to correct the rating of the APLC located at bus m as integer multiples of Base Unit Rating (I_b) of APLCs. As mentioned, I_b is assumed to be 0.01 p.u.

4.2. Algorithmic Steps to Solve OASA Problem

The sequential steps are as follows:

Step 1: Create an initial population of P frogs generated randomly.

SFHLA Population = $[X_1, X_2, \dots, X_p]_{p \times n}$

Where, $P = m \times n$,

N = number of APLC=3

m = number of memplexes= 5 and

n = number of frogs in each memplex=20.

Step 2: For each individual population, calculate fitness function. Fitness function = THD + COST. THD and COST formula is given in the equation (4) & (5).

Sort the population increasingly and divide the frogs into m memplexes each holding n frogs such that $P = m \times n$. The division is done with the first frog going to the first memplex, second one going to the second memplex, the mth frog to the mth memplex and the m+1th frog back to the first memplex.

Step 3: Within each constructed memplex, the frogs are infected by other frogs' ideas; hence they experience a memetic evolution. Memetic evolution improves the quality of the meme of an individual and enhances the individual frog's performance towards a goal. Below are details of memetic evolutions for each memplex.

1. Set $m_1 = 0$ where m_1 counts the number of memplexes and will be compared with the total number of memplexes m. Set $y_1 = 0$ where y_1 counts the number of evolutionary steps and will be compared with the maximum number of steps (y_{max}), to be completed within each memplex.
2. Set $m_1 = m_1 + 1$
3. Set $y_1 = y_1 + 1$
4. For each memplex, the frogs with the best fitness and worst fitness are identified as X_w and X_b respectively. Also the frog with the global best fitness X_g is identified, and then the position of the worst frog X_w for the memplex is adjusted such as Equation (10) and (11). If the evolutions produce a better frog (solution), it re-replaces the older frog, otherwise X_b is replaced by X_g in (10) and the process is repeated. If no improvement becomes possible in this case a random frog is generated which replaces the old frog.

5. If $m_1 < m$, return to step 3-b.

If $y_1 < y_{max}$, return to step 3-c, otherwise go to step 2.

Step 4: Check the convergence. If the convergence criteria are satisfied stop, otherwise consider the new population as the initial population and return to the step 2. The best solution is that we get both THD (should be less than 5% within the standard limit) and cost are to be minimum.

5. Results and Discussion

In this case, the modified IEEE 18-bus system (Iman Ziari & Alireza Jalilian 2012) is used as a test system. The base voltage is 12.5kV and base power is 10MVA. In this system, 16 buses (Bus number 1 to 16) are assumed as candidate for installation of APLCs.

The bus and line data are provided in reference [7]. The nonlinear loads are modeled as identical harmonic current sources. In this system, eleven identical harmonic current sources are employed as nonlinear loads and located at buses 3,4,5,6,7,8,11,13,14,15,16. The harmonic contents of the employed harmonic current sources (the nonlinear loads) are shown in Figure 1. Eight harmonic orders such as 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th are considered.

Before the installation of APLC, the base case analysis is done. The fundamental voltage profile of the distribution system is determined using Equations from (12) to (20). The iterative algorithm repeats calculation of these equations until convergence occurs. The fundamental voltage profile of the system is shown in Figure 2.

The admittance matrix for each harmonics is calculated using the line data of the system. Then, harmonic voltages for the considered eight orders at each bus are calculated. Equations (16) and (17) are used. Thus, Voltage distortions for all harmonic orders as well as THD at all buses are calculated by using the admittance matrix for all harmonic orders and the harmonic contents of nonlinear loads. It should be noted that since no APLC is installed, APLCs current injection matrix in Equation (17) is considered as a zero matrix.

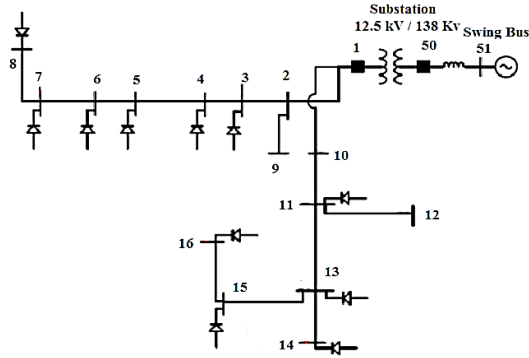


Figure 1. IEEE 18 Bus Test System Configuration

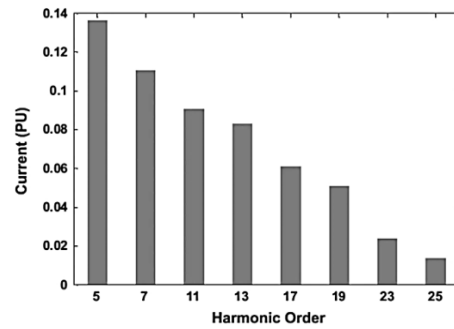


Figure 4. Harmonic Content of Used Non Linear Loads

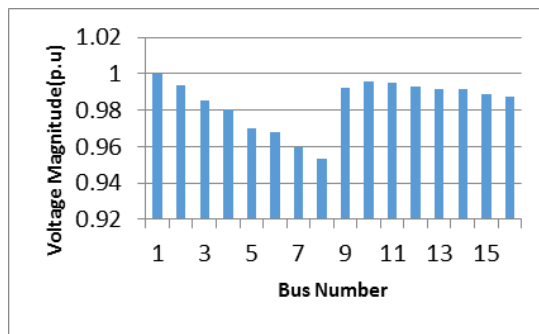


Figure 3. Voltage Magnitude in Distribution System

Table 1. Voltage conditions at different buses in no APLC state

Bus no	5	7	11	13	17	19	23	25
1	3.41	4.03	4.90	5.46	5.02	5.13	2.82	1.83
2	3.17	3.73	4.55	5.06	4.66	4.77	2.62	1.70
3	2.67	3.09	3.77	4.20	3.86	4.66	2.17	1.41
4	2.37	2.83	3.46	3.86	3.56	3.86	2.00	1.30
5	2.14	2.56	3.17	3.54	3.27	3.35	1.84	1.20
6	2.24	2.68	3.31	3.70	3.42	3.50	1.93	1.26
7	2.26	2.70	3.33	3.72	3.43	3.52	1.97	1.25
8	2.30	2.74	3.37	3.76	3.47	3.56	1.98	1.27
9	3.17	3.73	4.55	5.06	4.66	4.47	2.00	1.70
10	3.65	4.26	5.15	5.72	5.24	5.36	2.73	1.91
11	3.96	4.62	5.55	6.18	5.66	5.78	3.20	2.07
12	3.95	4.61	5.54	6.17	5.65	5.77	3.54	2.06
13	4.32	5.09	6.14	6.81	6.24	6.38	3.50	2.28
14	4.43	5.16	6.22	6.96	6.32	6.46	3.91	2.30
15	4.47	5.22	6.31	7.01	6.43	6.57	3.60	2.34
16	4.49	5.52	6.34	7.04	6.45	6.60	3.66	2.35

In this Table 1, it shows the voltage distortion for each harmonic order at each 16 bus. It means for each bus the harmonic distortion of 5, 7, 11, 13, 17, 19, 23, 25th are discussed. The minimum distortion for each individual voltage harmonics should be within the limit of 3%.

It gets violated in without APLC state. From Table 2, the average THD at all buses is 12.548% which represents an unallowable harmonic distortion level regarding to the IEEE standard (the standard limit is 5%).

Table 2. THD at different buses in no APLC state

Bus number	THD (%)
1	12.691
2	11.727
3	9.6681
4	8.8692
5	8.1307
6	8.5097
7	8.5614
8	8.6749
9	11.773
10	13.716
11	14.974
12	15.009
13	16.672
14	16.776
15	17.437
16	17.585
Average	12.548
Maximum	17.585

Table 3. APLC current rating without optimization

Bus Number	APLC Rating(p.u)
1	0
2	0
3	0.02
4	0.09
5	0.2
6	0.12
7	0.01
8	0.02
9	0
10	0
11	0.03
12	0
13	0.07
14	0.07
15	0.06
16	0.02
Total APLC Rating (p.u)	0.53
Average THD (%)	0

The maximum THD occurs at bus 16. It has high voltage THD level of 17.585%. If only the non linear load current spectrum is considered for placement of APLC, APLCs are to be installed in all the non linear load buses with the rating of 0.233p.u. Hence, 11 APLCs with rating about 0.24 pu (nearest discrete value) should be placed at each non linear load buses (Iman Ziari, 2012). This results in huge investment cost. If only base case analysis is considered without optimization method, the APLCs can be simply located at the nonlinear load buses with the same size of the corresponding nonlinear load and is assumed in Table 3.

To reduce the total investment cost as well as THD, an optimization procedure is required to find the optimal placement and rating of APLCs in these types of distribution networks.

To make the problem more realistic, the APLC current rating is assumed as integer multiples of 0.01 p.u. For this purpose, the APLC currents are modified using Equation (18) and (19). To place APLCs in a distorted system, different strategies are considered. Number of APLCs to be commissioned is fixed.

In this thesis, OASA problem can be solved by using Shuffle Frog Leap Algorithm.

Assumption: Number of APLC used =3

Table 4. Parameters obtained from SHFLA algorithm by installing APLC in 18 Bus distribution system

LOCATION	8,15,12
AVERAGE THD (%)	4.6
APLC RATING (p.u)	0.09
INVESTMENT COST (\$)	1.54800*10 ⁵

From this Table 4, the parameters are obtained after optimal placement of APLC in the 18 bus distribution system by Shuffle frog leap algorithm (SHFLA).Based on optimization procedure, the best optimal solution is to provide 3 APLC at buses 8,15,12 respectively to handle the more harmonic case. In that case, the average THD is 4.6%, the current injected

by APLC is 0.09p.u and the total investment cost is 1.54800×10^5 .

Table 5. Individual APLC rating

LOCATION	RATING(p.u)
8	0.02
15	0.03
12	0.04

6. Conclusion

In this work, the problem of the optimal placement and sizing of Active Power Line Conditioner in distribution system is examined. An optimization problem is formulated as a constrained nonlinear optimization problem. SHUFFLE FROG LEAP ALGORITHM (SHFLA) is used for allocation and sizing of Active Power Line Conditioner (APLC) in distribution systems. It is observed that the results obtained using SHFLA are more encouraging.

After placement of APLC with appropriate rating, there is a reduction of THD, total investment cost and the current injected by APLC. It is observed that, after optimal allocation of APLC in the distribution system, the APLC current rating is minimized and the cost gets reduced. The technical constraints such as THD and individual harmonic distortion at buses are satisfied.

It is observed that choosing proper APLC rating and placement has a significant impact on minimizing the cost and total harmonic distortion. In the system understudy, optimum solution by SHFLA algorithm which reduces the average THD from 12.548% to 4.6%. the current injected by APLC is 0.09 p.u and the total investment cost is 1.54800×10^5 .

Acknowledgements

The authors gratefully acknowledge the management of Thiagarajar College of engineering for the kind support to complete this work by providing some resources.

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