SCT dimensions optimization by harmony search algorithm

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Abstract— **in this paper, Controlled Shunt Compensator of Transformer type (CSCT) is introduced as a new shunt compensator and harmonic component of its current is presented. A filter block in tertiary winding of the CSCT is used to suppress these harmonics. It is demonstrated that operation of the filter block is influenced by the arrangement of the windings and their dimensions. Then two possible arrangements of the CSCT windings are considered and the best arrangement and CSCT winding dimensions will be determined using harmony search method.**

Keywords- **Harmony search algorithm, CSCT, harmonics filtering, windings dimensions.**

I. INTRODUCTION

Surplus reactive power in a transmission line over a permissible level will cause some problems such as: reduction of the capacity of transmission lines, extra voltage drop, and hazard for synchronous generators [1, 2]. Shunt reactors can be applied to mitigate such problems. So discreet units of conventional shunt reactors are therefore switched in and out in order of need for reactive power. If instead the reactance of the reactor can be controlled, the reactance could be adjusted to the load of the transmission line and thus providing continuous reactive power compensation.

The controlled shunt compensator of transformer type (CSCT) is one kind of the controlled reactors. The general scheme of this compensator is presented in Fig.1.this transformer consist of three windings .The network winding (NW) is connected to the network high voltage bus, and is the main winding of the compensator. The controlled winding (CW) is the second winding in which a thyristor valve (TV) in parallel with a voltage circuit breaker (VCB) are connected across the secondary. The third winding is the compensating winding (ComW) which is indicated as the tertiary winding in Fig.1.Two tuned harmonic filters are connected across this winding. It is important to note that the CSCT is a three phase compensator. Both the three phases NW and CW is of star-connected type, and the neutral is grounded. However the ComW can be of delta-connected type.

Now let's consider circumstance of operation of this structure. When the TV is open all the magnetic flux pass through the magnetic core, leading to a minimum reluctance and maximum capacitive current in NW. This eventually injects reactive power to the network. Further, when the TV is closed the flux is subjected to pass through the air gap including all of the windings. Hence the reluctance and inductive current of NW will be maximal. Since two modes leads to two different signs in reactive power, the compensator can practically operates both in capacitive and inductive modes.

Applying thyristors to control current of CSCT brings highest harmonics in the current. Hence, a tertiary winding has been predicted in the structure of this compensator which is connected to a filtering block, including several parallel branches that each branch is composed of an inductor and a capacitor in series, so that each branch is short circuited against its related harmonic and in this way the harmonic cannot pass through the main winding which is connected to the network.

Now, the basic question is that what is the best arrangement and dimensions of the windings to have the least harmonic injected to the network?

In [1] the CSCT as a new device to compensate reactive power in power systems has been introduced and the circumstance of operating the compensator has been interpreted. The useful applications of the device and its advantages have been remarked. Aforementioned paper has supposed that the configuration of the windings is known i.e. the control winding is the nearest winding to the core, the compensating winding is in the middle and the network winding is the outermost one. The paper has not proved that this arrangement of windings is optimal.

This work shows that operation of the filter block is influenced by the arrangement of the windings and their

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dimensions. and introduce an approach based on harmony search algorithm to demonstrate the best arrangement of the windings of the CSCT and determine the optimal dimensions of its windings.

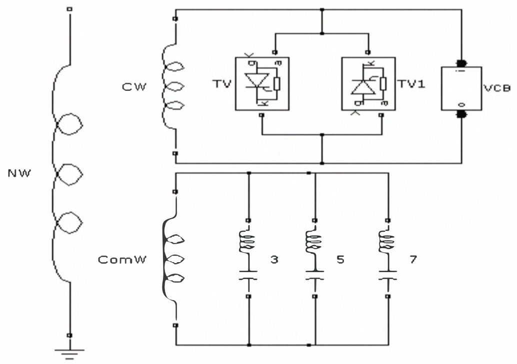

Figure 1. General sheme of CSCT :TV-thyristor valve, VCB:vacuum circuit breaker, 3, 5and 7: filter of third, fifth and seventh harmonics.

In Section II, harmonic component of the CSCT current is presented. In Section III two different configurations of windings is described and an investigation of them is complained. In Section IV harmony search algorithm as a new optimization method is presented. In section V, results of the optimization, optimal dimensions and the best arrangement of the windings are discussed. Some conclusions are given in section VI.

II. HARMONIC COMPONENT OF THE CSCT CURRENT

Applying the thyristors to control the current of the compensator brings highest harmonics in the current. Highest harmonics are formed during incomplete combustion angle of thyristors when current flows intermittently through thyristor block. With angles $0 < \omega t < \psi$ and $\pi - \psi < \omega t < \pi$ the current equals zero, and with angles $\psi < \omega t < \pi - \psi$,

$$i(t) = I_m(\sin\omega t - \sin\psi) \quad (1)$$

Where the firing angle ψ can change in the range of $0 < \omega t < \pi/2$. The effective current value trough the thyristor for half cycle of main frequency is:

$$I(\psi) = I_m.\sqrt{\int_{\psi}^{\pi-\psi}(\sin\omega t - \sin\psi)^2 d\omega t} \quad (2)$$

$$= I_m.\sqrt{\frac{1}{\pi}.[(\pi - 2\psi).(0.5 + \sin^2\psi) - 1.5\sin 2\psi]}$$

The ratio of the effective current value through the thyristor at arbitrary firing angle ψ to the effective value of the rated current $(I = I_m/\sqrt{2})$ equals to:

$$\frac{I(\psi)}{I} = \sqrt{[(1 - \frac{2\psi}{\pi}).(1 + 2\sin^2\psi) - \frac{3}{\pi}\sin 2\psi]} \quad (3)$$

The current through thyristor block decrease fast by increase in ignition angle. Thus the content of the highest harmonics strongly changes with change in ignition angle and can be calculated by formula

$$\frac{I_k}{I_1} = \frac{2}{k}.\frac{\frac{\sin(k-1).\psi}{k-1} + \frac{\sin(k+1).\psi}{k+1}}{\pi - 2\psi - \sin 2\psi} \quad (4)$$

Where I_k and I_1 are amplitudes of the k-th harmonic and the fundamental component.

III. ARANGEMENT OF THE WINDINGS

The main reason of arising the harmonic currents is the thyristor valve in the control winding. So, if we suppose this valve as the current source of harmonic, we should think of a remedy to prevent this current source from injecting the current to the network. To evaluate this subject and attain our purpose, we should have an electric equivalent circuit of CSCT. In Fig. 2, the single phase electric equivalent circuit of CSCT is depicted. This model has been extracted based on the duality between electric and magnetic circuits [3].

In the model illustrated in Fig. 2:

$L_{limb,A}$: the inductance of the main core A which the three windings of phase A are located on it
L_y: the inductance of yoke
R_y: resistant to model the losses of yoke
$L_{Shunt,A}$: the inductance of magnetic shunt which covers three windings of phase A
$L_{late,y}$: the inductance of lateral yokes
L_{1A}: the leakage inductance of the air gap between the outermost winding and the middle winding
L_{2A}: the leakage inductance of the air gap between the innermost winding and the middle winding
L_{3A}: the leakage inductance resulted from the mutual effect between the inductances L_{1A} and L_{2A}.

In Fig.2, for modeling each of windings, an ideal transformer has been used. Their secondary side windings have only one turn, and the number of turns of their primary side windings is equal to the number of turns in the related phase winding of CSCT. In this model, the transformer A is the outermost winding from the core; the ideal transformer B models the middle winding; and the transformer C is the nearest winding to the core.

About the CSCT, it is important to note that due to the insulation limitations, the optimal arrangement of windings is yield when the winding with the lowest voltage is the nearest winding to the core and farthest winding is the one with the highest voltage. On the other hand, the design of CSCT is in a way that always the winding connected to the network (network winding) is the farthest winding from the core. Now, we must determine the place of two other windings considering the design purposes of windings.

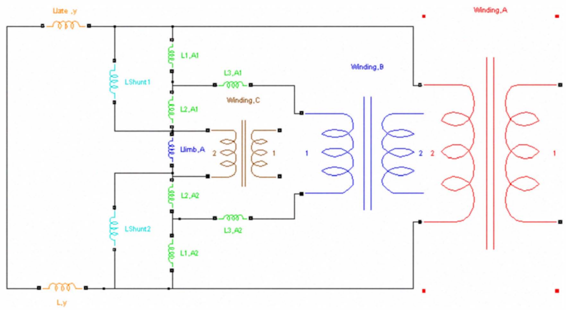

Figure 2. Figure 1Single phase model of CSCT

With these explanations, there are two possible arrangements for the windings of CSCT:
1) The control winding is between the two other windings.
2) The compensating winding is between the two other windings.
Now, we investigate these two arrangements to choose the optimal one among them.

A. Control winding is between the two other windings

In this condition, due to the switching operations in control winding, we consider the thyristor valve as a harmonic current source. On the other hand, the compensating winding is short circuited while the thyristor valve is closed. When the compensating winding is short circuited, the inductance and resistance of the core limb can be neglected. Therefore the equivalent circuit of Fig. 3 is obtained.
With an attention to the equivalent circuit of Fig.3, it can be understood that to reach to the desired purpose (no passing of current through the network winding), the windings should be designed so that the leakage inductance $L_{2,A}$ is zero. In the other words, the air gap between the two inner windings has very large magnetic reluctance in comparison to that of the other winding.

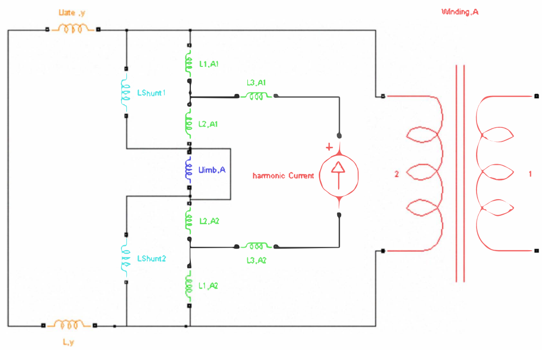

Figure 3. Figure 2The single phase model of CSCT from the viewpoint of thyristor valve (thyristors are on)

B. Compensating winding is between the two other windings

In this condition, we again consider the thyristor valve as a harmonic current source. Moreover, we know that in the switching time, the compensating block will be short circuited against the harmonics and makes the compensating winding short circuited. Hence, the equivalent circuit of CSCT will be as Fig. 4.

According to the resulted equivalent circuit, we can conclude that to reach to the desired goal (no passing of current through the network winding), the windings should be designed so that the leakage inductance $L_{3,A}$ is zero.

C. Determining the optimal arrangement and dimenssions of windings idea

Based on the discussions made in this sections, it can be concluded that to prevent the harmonic currents from entering to the network, proportional to the arrangement of windings, one of the leakage inductances $L_{2,A}$ and $L_{3,A}$ must be zero. Thus, depend on the ease of reaching to zero value of each of these inductances; the optimal arrangement of windings can be obtained.

D. Calculation of leakage inductances

Based on the short circuit tests and by using the magnetic energy method the leakage inductances $L_{2,\,A}$ and $L_{3,\,A}$ are yield according to (5) and (6) [3]:

$$L_{2,A} = \frac{\mu_0.\pi.N^2}{l}\left(\begin{array}{l}\left(d_{AC}.(a_{AC}+\frac{a_A+a_C}{3})+(\frac{a_A-a_C}{3}).(a_{AC}+\frac{a_A+a_C}{2})\right)+\\ \left(d_{BC}.(a_{BC}+\frac{a_B+a_C}{3})+(\frac{a_B-a_C}{3}).(a_{BC}+\frac{a_B+a_C}{2})\right)-\\ \left(d_{AB}.(a_{AB}+\frac{a_A+a_B}{3})+(\frac{a_A-a_B}{3}).(a_{BC}+\frac{a_A+a_B}{2})\right)\end{array}\right) \quad (5)$$

$$L_{3,A} = \frac{\mu_0.\pi.N^2}{l}\left(\begin{array}{l}\left(d_{AB}.(a_{AB}+\frac{a_A+a_B}{3})+(\frac{a_A-a_B}{3}).(a_{AC}+\frac{a_A+a_B}{2})\right)+\\ \left(d_{BC}.(a_{BC}+\frac{a_B+a_C}{3})+(\frac{a_B-a_C}{3}).(a_{BC}+\frac{a_B+a_C}{2})\right)-\\ \left(d_{AC}.(a_{AC}+\frac{a_A+a_C}{3})+(\frac{a_A-a_C}{3}).(a_{BC}+\frac{a_A+a_C}{2})\right)\end{array}\right) \quad (6)$$

In above equations:
N : number of winding turns
l : flux path
d_{AB}: the average diameter of windings A and B
d_{AC}: the average diameter of windings A and C
d_{BC}: the average diameter of windings B and C
a_{AB}: the radial distance between windings A and B
a_{AC}: the radial distance between windings A and C
a_{BC}: the radial distance between windings B and C
a_A: the width of winding A
a_B: the width of winding B
a_C: the width of winding C

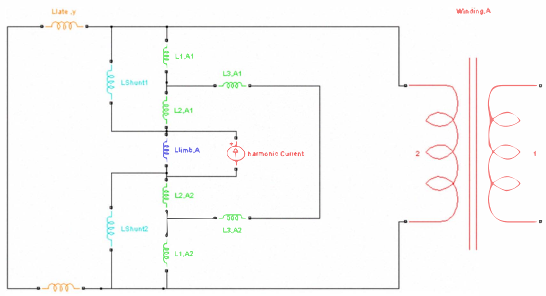

Figure 4. The single phase model of CSCT from the viewpoint of thyristor valve (thyristors are on)

As mentioned, to attain the optimal arrangement of CSCT windings, at least one of the leakage inductances $L_{2,A}$ and $L_{3,A}$ must be zero. It is clear about this subject that the dimensions included in the above equations must be determined so that the related inductance will be zero. Now, suppose:

x_1: the insulation distance between the core and the innermost winding (winding C)

x_2: the insulation distance between the middle winding (B) and the innermost winding

x_3: the insulation distance between the middle winding (B) and the outermost winding (A)

Therefore, we have:

$$d_{AC} = D_S + 2(x_1 + a_C + x_2) + a_B \quad (7)$$

$$d_{AB} = D_S + 2(x_1 + a_C + x_2 + a_B) + x_3 \quad (8)$$

$$d_{BC} = D_S + 2(x_1 + a_C) + x_2 \quad (9)$$

$$a_{AC} = x_2 + a_B + x_3 \quad (10)$$

$$a_{AB} = x_3 \quad (11)$$

$$a_{BC} = x_2 \quad (12)$$

D_S is the diameter of the core.

According to the equations (5) - (12), the decision variables are:

1) the diameter of core (it is known)
2) the insulation distance between the core and the innermost winding
3) the width of the innermost winding
4) the insulation distance between the middle winding and the innermost winding
5) the width of middle winding
6) the insulation distance between the middle winding and the outermost winding
7) the width of the outermost winding

Equations (5) and (6) are the relations with six unknown decision variables. Therefore, they cannot be solved (to determine the value of variables such that the inductance is zeros) using the conventional methods. But, by using one of the intelligent optimization methods such as Genetic Algorithm, Tabu Search, and Ant colony or other similar approaches can be employed. The proposed optimization method for solving this problem is Harmony Search method. This method is a new approach and has better performance compared to the other conventional methods. In the following sections, this method will be discussed and then it will be applied to each of two inductances, to reach the optimal arrangement and sizes of windings.

IV. HARMONY SEARCH ALGORITHM

Harmony search (HS) algorithm was recently developed in an analogy with music improvisation process where music players improvise the pitches of their instruments to obtain better harmony [6].The steps in the procedure of harmony search are as follows [6]:

Step1. Initialize the problem and algorithm parameters.
Step 2. Initialize the harmony memory.
Step 3. Improvise a new harmony.
Step 4. Update the harmony memory.
Step 5. Check the stopping criterion.

These steps are described in the next five subsections.

A. Initialize the problem and algorithm parameters

In Step 1, the optimization problem is specified as follows:

$$\begin{cases} Minimize & f(x) \\ Subject \quad to & x_i \in Xi = 1,2,...,N \end{cases} \quad (13)$$

Where f(x) is an objective function; x is the set of each decision variable xi; N is the number of decision variables, Xi is the set of the possible range of values for each decision variable, that is Lxi < Xi <Uxi and Lxi and Uxi are the lower and upper bounds for each decision variable. The HS algorithm parameters are also specified in this step. These are the harmony memory size (HMS), or the number of solution vectors in the harmony memory; harmony memory considering rate (HMCR); pitch adjusting rate (PAR); and the number of improvisations (NI), or stopping criterion.

The harmony memory (HM) is a memory location where all the solution vectors (sets of decision variables) are stored. This HM is similar to the genetic pool in the GA [6]. Here, HMCR and PAR are parameters that are used to improve the solution vector. Both are defined in Step 3.

B. Initialize the harmony memory

In Step 2, the HM matrix is filled with as many randomly generated solution vectors as the HMS.

$$HM = \begin{bmatrix} x_1^1 & x_2^1 & \cdots & x_{N-1}^1 & x_N^1 \\ x_1^2 & x_2^2 & \cdots & x_{N-1}^2 & x_N^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ x_1^{HMS-1} & x_2^{HMS-1} & \cdots & x_{N-1}^{HMS-1} & x_N^{HMS-1} \\ x_1^{HMS} & x_2^{HMS} & \cdots & x_{N-1}^{HMS} & x_N^{HMS} \end{bmatrix}$$

C. Improvise a new harmony

A new harmony vector, $x' = (x'_1, x'_2, ..., x'_N)$, is generated based on three rules: 1) memory consideration, 2) pitch adjustment and 3) random selection. Generating a new harmony is called 'improvisation' [6].
In the memory consideration, the value of the first decision variable (x'_1) for the new vector is chosen from any of the values in the specified HM range ($x'_1 - x'^{HMS}$). Values of the other decision variables ($x'_2, x'_3, ..., x'_N$) are chosen in the same manner. The HMCR, which varies between 0 and 1, is the rate of choosing one value from the historical values stored in the HM, while (1-HMCR) is the rate of randomly selecting one value from the possible range of values.

$$x'_i \leftarrow \begin{cases} x'_i \in \{x_i^1, x_i^2, ..., x_i^{HMS}\} & with probab\ ility \quad HMCR \\ x'_i \in X_i & with probab\ ility \quad (1 - HMCR) \end{cases} \quad (15)$$

For example, a HMCR of 0.85 indicates that the HS algorithm will choose the decision variable value from historically stored values in the HM with an 85% probability or from the entire possible range with a (100–85) % probability. Every component obtained by the memory consideration is examined to determine whether it should be pitch-adjusted. This operation uses the PAR parameter, which is the rate of pitch adjustment as follows:
Pitch adjusting decision for

$$x'_i \leftarrow \begin{cases} Yes & with probability \quad PAR \\ No & with probability \quad (1-PAR) \end{cases} \quad (16)$$

The value of (1-PAR) sets the rate of doing nothing. If the pitch adjustment decision for x'_i is YES, x'_i is replaced as follow:

$$x'_i \leftarrow x'_i \pm rand() * bw \quad (17)$$

where
bw is an arbitrary distance bandwidth
rand () is a random number between 0 and 1.
In Step 3, HM consideration, pitch adjustment or random selection is applied to each variable of the new harmony vector in turn.

D. Update harmony memory

If the new harmony vector, $x' = (x'_1, x'_2, ..., x'_N)$ is better than the worst harmony in the HM, judged in terms of the objective function value, the new harmony is included in the HM and the existing worst harmony is excluded from the HM.

E. Check stopping criterion

If the stopping criterion (maximum number of improvisations) is satisfied, computation is terminated. Otherwise, Steps 3 and 4 are repeated.

F. Parameter selection

The HMCR and PAR parameters introduced in Step 3 help the algorithm find globally and locally improved solutions, respectively [6]. PAR and bw in HS algorithm are very important parameters in fine-tuning of optimized solution vectors, and can be potentially useful in adjusting convergence rate of algorithm to optimal solution. So, fine adjustment of these parameters is of great interest. The traditional HS algorithm uses fixed value for both PAR and bw. In the HS method PAR and bw values adjusted in initialization step (Step 1) and cannot be changed during new generations. The main drawback of this method appears in the number of iterations the algorithm needs to find an optimal solution. Small PAR values with large bw values can cause to poor performance of the algorithm and considerable increase in iterations needed to find optimum solution. Although small bw values in final generations increase the fine-tuning of solution vectors, but in early generations bw must take a bigger value to enforce the algorithm to increase the diversity of solution vectors. Furthermore large PAR values with small bw values usually cause the improvement of best solutions in final generations which algorithm converged to optimal solution vector.
To improve the performance of the HS algorithm and eliminate the drawbacks lies with fixed values of PAR and bw, PAR and bw should be changed dynamically with generation number as shown in Fig. 4 and expressed as follow:

$$PAR(gn) = PAR_{min} + \frac{(PAR_{max} - PAR_{min})}{NI} \times gn \quad (18)$$

where:
PAR: pitch adjusting rate for each generation
PAR_{min}: minimum pitch adjusting rate
PAR_{max}: maximum pitch adjusting rate
NI: number of solution vector generations
gn: generation number

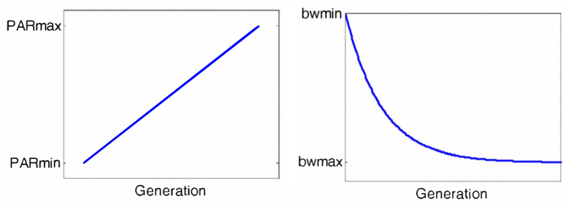

Figure 5. a) The curve of PAR versus harmony generation b) the curve of bw versus harmony generation

and:

$$bw(gn) = bw_{\max}.\exp(c.gn)$$

$$c = \frac{Ln(\frac{bw_{\min}}{bw_{\max}})}{NI} \quad (19)$$

where
bw(gn): bandwidth for each generation
bw_{min}: minimum bandwidth
bw_{max}: maximum bandwidth

V. OPTIMAL ARANGEMENT AND DIMENSSIONS OF WINDINGS

The harmony search method is applied for the optimization of inductances $L_{2,A}$ and $L_{3,A}$. The best results were obtained when the parameters of algorithm are selected as Table I.
The HS algorithm was implemented ten times and for 10000 iterations for each of inductances and the three best results is presented in Tables II and III.
As noted previously, in the first arrangement of windings, i.e. the situation that the control winding is between two other windings, for compensation of harmonics and prevention of them from entering to the network, the inductance $L_{2,A}$, in comparison with L_{3A}, must be very small, to neglect it. Whereas, according to the presented results in Table…, in the best condition, the ratio of these two inductances is 7.82, which is not very actable and we cannot neglect $L_{2,A}$ against $L_{3,A}$. In the other words, the configuration of windings is not any appropriate in this situation.
But, in the second configuration, i.e. the configuration that the compensating winding is between the others, for compensation of harmonics and prevention of them from entering to the network, the inductance $L_{3,A}$, in comparison with $L_{2,A}$, must be very small. From the TableIII, in the best solution, the ration of these two inductances is 541270, which is a very large number and we can neglect the inductance $L_{3,A}$. In other words, the arrangement of windings in this situation is excellent and it removes the harmonics from the viewpoint of the network.
Therefore, it can be said that the best configuration of windings is when that the network winding is the outermost winding and the control winding is the innermost one. As a consequence, the compensating winding will be the middle winding.
dimensions of CSCT windings. Also in this paper demonstrated that the optimum place to emplace ComW is between NW and CW.

TABLE I. THE PARAMETER OF THE HS ALGORITHM

Parameter	HMCR	PARmin	PARmax	bwmin	bwmax	HMS
Value	*0.8*	*0.3*	*0.7*	*0.3*	*0.7*	*5*

TABLE II. RESULTS FOR OPTIMIZATION OF THE LEAKAGE INDUCTANCE L2,A (all dimensions are in mm)

Solution	x1	x2	x3	a1	a2	a3	K12
1	*101.35*	*101.14*	*247.23*	*238.92*	*151.52*	*150.81*	*7.38*
2	*100.89*	*101.01*	*249.75*	*227.92*	*150.38*	*150.06*	*7.70*
3	*102.21*	*100.20*	*248.64*	*249.53*	*151.47*	*151.47*	*7.82*

TABLE III. RESULTS FOR OPTIMIZATION OF THE LEAKAGE INDUCTANCE L3,A (all dimensions are in mm)

Solution	x1	x2	x3	a1	a2	a3	K13
1	*133.02*	*201.52*	*109.91*	*160.44*	*195.22*	*244.07*	*84638*
2	*129.89*	*193.79*	*100.36*	*221.24*	*193.04*	*214.94*	*110240*
3	*154.45*	*220.45*	*101.60*	*213.32*	*215.84*	*199.01*	*541270*

VI. CONCLUSION

The CSCT as a new device to compensate reactive power in power systems was introduced in this paper. The general scheme of this device and its single phase model based on duality between electrical and magnetic circuits was presented. Using a thyristor block to control the current of CSCT leads to appearance of the harmonics in the current. Basic equations of highest harmonics in the current of the compensator are presented. Moreover adding a third winding with highest harmonic filter in less voltage and more current levels than NW is presented as a solution to suppress the harmonic. It is shown in this paper that the arrangement of the windings and their dimensions are high effective for obtaining efficient operation of ComW. An approach based on harmony search algorithm was represented and has been used to determine the optimal dimensions of CSCT windings. Also in this paper demonstrated that the optimum place to emplace ComW is between NW and CW.

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