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OPTIMIZATION OF THE THYRISTOR VALVES DESIGN FOR TCR STATIC VAR COMPENSATORS

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INTRODUCTION

The Static Var Compensators(SVCs) are equipments that have been more and more used in power systems. Therefore there is a strong desire to reduce their costs. From the manufacturer's point of view, these equipments should be purchased as optimized turnkey projects. On the other hand, the utilities companies claim that these optimized turnkey projects lead to non standard equipments, which increase their spare parts and maintenance costs, and that the total cost might be smaller if they buy the SVC piece by piece.

Considering these problems, we developed a digital program to optimize the design of thyristor valves for Thyristor Controlled Reactors(TCR) with Fixed Capacitor Banks(Figure 1). This program will be used on the future as a subroutine of a complete SVC optimization program. Of course, it does not provide biding prices but it can give relative costs of different design alternatives which is very useful for the utilities to make and judge their specifications.

The design of thyristors valves basically consists on the choice of the thyristor, the design of the snubber circuit, the design of the refrigeration system and choice of the overvoltage and overcurrent protections. For a specific power system and design criteria there are many possible designs with different costs. Therefore, it is important to have a tool capable to give the indication of the best one.

As an example of application, this work presents the results of the use of this program for the optimization of a TCR of 5 MVAr capacitive and 15 MVAr inductive to be connected on the 13.8 kV tertiary of a 30 MVAr existent transformer. This example was used to verify the influence of different design criteria on the cost of the SVC and its results will be used by the brazilian utilities companies to make future specifications.

DESCRIPTION OF THE PROGRAM

Based on the input data, the program implements the fluxogram of Figure 2. For all thyristors and heatsinks of the data bank, the program optimizes the snubber circuit in order to achieve the minimum cost and the ten cheapest ones are given as an output.

Input Data

The input data that must be provided to the program is divided into equipments data, power systems data, design safety factors and tests safety factors.

Table I–Thyristors data

SCR	Io(a)	P(W)	Rthjh(^{o}C/W)	Itsm(A)
1	650	1400	0.059	7000
2	901	1700	0.047	10000
3	1002	1700	0.047	13000
4	1450	1700	0.031	19000

Io–maximum mean value of the thyristor's current.
P–mean loss of the thyristor with Io.
Rthjh–thermal resistance between junction and heatsink.
Itsm–peak value of the surge current with 50ms of duration.

Table II–Thyristor prices(US$)

Vdrm(V)	600	800	1200	1400	1600	2000	2200
SCR							
1	—	380	430	483	560	761	899
2	—	—	571	623	694	943	1115
3	468	543	694	760	843	1146	1352
4	559	803	1289	1546	1778	2561	2945

Table III–Heatsinks data

Heatsink	Rthha(^{o}C/W)	T(s)	Cost(US$)
1	0.18	245	25.51
2	0.095	194	36.71
3	0.08	218	50.21
4	0.085	273	89.32
5	0.05	353	140.73
6	0.035	394	175.0
7	0.072	363	127.47
8	0.04	402	194.95
9	0.03	528	381.0

Rthha–heatsink thermal resistance.
T–heatsink thermal impedance time constant.

Equipments data. The equipments data used by the program are: the thyristors data and the heatsinks data. They are always available by the program in a data bank and were obtained from the thyristors manufactures data sheets. A total of 25 thyristors and 9 heatsinks were used in this work which leads to approximately 200 different possible designs.

Table I and Table II show some of the characteristics of the thyristors used by the program and Table III shows the characteristics of the heatsinks. Only air cooled heatsinks were considered due the lack of data on water cooled heatsinks.

Power systems data. The power system data used by the program are: the maximum continuous operating voltage at the SVC's bus, the overload cycle, the protections actuation time, the range of voltage control, the cost of the losses, the maximum ambient temperature, the thyristors redundancy factor, the overcurrent factors, the firing angle at zero MVAR, the reactance of the SVC transformer, the nominal values of voltage, frequency and reactive power and the controlled reactor inductance.

The maximum continuous operating voltage is the maximum steady–state voltage that can appear on the SVC bus and must be determined by previous load flow studies. The basic case value used was 1.1 p.u.

The overload cycle, shown on fig.3, is the worst overvoltage versus time that can appear at the SVC bus. This cycle must be determined also by previous overvoltage studies. Since the SVC should continue to operate after it, the thyristors junction temperature, in this case, should be limited to the maximum thyristors temperature. Table IV shows the overload cycle used by the basic cases. It was also considered that before this cycle the SVC was operating at its maximum continuous voltage. The last step of this cycle means that the SVC operates for some time also at its maximum continuous operating voltage. This is a very severe condition that will be discussed later.

Table IV– Overload cycle of the basic case.

Step	Overload(p.u.)	Duration(s)
1	2.0	0.05
2	1.5	0.05
3	1.2	10.00
4	1.1	100

The protection's actuation time is the time necessary for the backup protection system to detect and clear a fault. The default time used by the program is 500 ms.

The range of voltage control is the maximum voltage during the overload cycle that the SVC should operate without action of the overvoltage protection. The protection action considered in this case was the continuous firing of the valve. The value used on the basic case was 1.2 p.u.

There are some controversies among the utilities and manufactures on how to include the cost of the losses in the design of SVCs. In this program, the cost of the losses is determined according with the following equation:

$$CL = Mc\cdot(k_l\cdot L_{ind} + k_0\cdot L_0 + k_c\cdot L_c) \qquad (1)$$

where:

CL is the total cost of the losses.

Mc is the utilities losses cost which reflects its generating and marginal expansion costs. The basic case value was US$ 1500.00/kW.

k_l is the weight factor for the losses of the SVC operating at the inductive limit. The basic case value used was 0.1.

L_{ind} is the SVC's losses at the its inductive limit.

k_0 is the weight factor for the losses of the SVC operating at zero MVAr. The basic case value used was 0.8.

L_0 is the SVC's losses at zero MVAr

k_c is the weight factor for the losses of the SVC operating at its capacitive limit. The basic case value used was 0.1.

L_c is the SVC's losses at the its capacitive limit

The maximum ambient temperature is the maximum ambient air temperature expected at the SVC's location. The basic case value used was 40 degrees centigrade.

The thyristor's redundancy factor is the amount of extra thyristors used in the valve for reliability purposes. The default value used in the program is 10%.

The firing angle at zero MVAR is the firing angle of the thyristor valve which puts the SVC at zero MVAR. This value is used to calculate the cost of the losses. The value used in the basic case was 114 degrees.

The overcurrent factors take in account the overcurrents caused by short circuits on the ac system, short circuit on the SVC's reactor and misfiring of the thyristor valve. They are very important because they determine, with the overload cycle, the highest expected thyristor temperature. Two design criteria can be used in the program regarding these factors; limit the maximum thyristor's temperature at its maximum junction's temperature or limit the thyristors peak current at its maximum surge value. The former should be used if the SVC should continue to operate after the clearance of the fault. This is a desirable characteristic from the utilities point of view but, as will be shown, it has strong influence on the cost of the valve. The latter should be used if protection system disconnects the SVC after the fault. This is not desirable from the system's point of view but if we consider that these fault cases are worst cases with low probability of occurrence it may be accepted.

The reactance of the SVC's transformer is the value of transformer leakage reactance. The value used in the basic case was 1.02 Ω.

The nominal value of voltage, frequency, and reactive power are the RMS value of the nominal line system voltage, the nominal system frequency and the reactive power to be compensated in order to maintain the desired bus voltage between appropriated limits. The values used in the basic case were; 13.8 kV, 60 Hz and 5 MVAR ind/ 15 MVAR cap.

The controlled reactor inductance is the value of controlled reactor phase inductance which depends on the minimum firing angle, the capacitor bank, the harmonics filters, the nominal system characteristics (voltage,frequency and reactive power) and the transformer reactance. The quality factor(Q) and the mutual inductance of the reactor must also be provided because they are used to evaluate the thyristor's temperature during the system's short circuit close to the SVC and during the reactor's short circuit. The values used in the basic case were; 72.43 mH and 100.

Design's safety factors.These factors take in account the security margin that must exist between the overvoltage protection and the voltage rating of the thyristors and other statistical variations of the thyristor parameters. Regarding this work these factor's were not varied.

Test's safety factors. These are the safety factors specified by IEC (1) for the thyristor's valve tests. They are very much affected by the type of surge arrester used. Since the cases in this work did not use surge arresters these factors were also constants.

Optimization procedure

For a given thyristor family(SCR of table II) and heatsink the program checks if the overload and temperature criteria are fulfilled. After this, it optimizes for each value of thyristor voltage(Vdrm) the snubber circuit and determines the cost of the design. The snubber circuit is optimized, according with Mcmurray(2) and Lima(3), in order to give the smallest commutation overvoltage. After that, the program determines the number of series connected thyristors. Since the decrease of this overvoltage increases the snubber's losses the program finds a compromise design that minimizes the total cost.

DESIGN CRITERIA USED FOR THE DESIGN OF SVC'S THYRISTOR'S VALVES

The optimization program was based on a series of design criteria in order to calculate the thyristor's maximum operating junction temperature, the thyristor's peak current currents, the number of series connected thyristor and the snubber circuit.

Thermal design.

The thermal design consists on the selection of thyristors and heatsinks that do not allow the thyristor junction temperature to reach its established maximum limit.

The first case checked is the maximum continuous operation. In this case, the maximum junction temperature of the valve is limited to the thyristor's maximum junction temperature.

The second case checked is the SVC's reactor short circuit. In this case, it is assume a short circuit at half of the reactor with the minimum firing angle and the maximum continuous operating voltage. Two criterion can be used; limit the thyristor's junction temperature to its maximum limit or limit the short circuit's peak current to the thyristor's maximum surge current with that duration.

The third case checked is misfiring of the valve(Fig.4). In this case, it is assumed a zero degrees firing of the valve with the duration of the backup protection actuation time. The two criteria mentioned before can also be used.

The fourth case checked is the overload cycle. In this case, the thyristors operating junction temperature is limited to its maximum value.

The last case checked is the short circuit close to the SVC(Fig.5). There is some controversies about this case. The worst condition occurs for a short circuit at a specific point of the sine wave and cleared at another specific point. The quality factor(Q) of the reactor, the protection actuation time and the power factor of the short circuit affect very much the maximum temperature of the valve.

RESULTS OF THE OPTIMIZATION

As an example, a SVC of 5MVAR inductive and 15 MVAR capacitive connected at the tertiary winding of a 30 MVA, 132/69/13.8 kV transformer was selected. The basic case was the optimization of the project with the data described before.

With the thyristors data available, it was only possible to have solutions considering for the thermal design the criterion of limiting the fault's current peak to the thyristor's surge current. This means that for all the three types of faults considered the SVC must be disconnected from the system.

Table V shows the 5 minimum cost designs for this case. It is important to note that the differences between the cases are around 1%. This means that the cost function is smooth and optimization process converged to its minimum. Also, the minimum cost design did not use the highest voltage thyristor neither the extreme ranges of the components.

Table V–Basic case results

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
B1	1.0	2	5	27	1600
B2	1.02	2	5	20	2200
B3	1.03	2	6	27	1600
B4	1.04	2	6	20	2200
B5	1.05	2	8	27	1600

NSCT–number of series connected thyristors on the valve.
HtSk–heatsink used.

In order to have a better understanding of the cost function two sensitivity analysis cases were done. Tables VI and VII show the results for different losses cost and tables VIII and IX show the results for different nominal voltages of the valve keeping the reactive power of the SVC constant.

Changes of 33% on the losses cost affected the optimized cost on 8% and the design of the valve was not affected.

Table VI–Base case with lower losses cost.
US$1000.00/kW

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
1.1	0.92	2	5	27	1600
1.2	0.95	2	6	27	1600
1.3	0.96	2	5	30	1400
1.4	0.96	2	5	20	2200
1.5	0.97	2	8	27	1600

NSCT–number of series connected thyristors on the valve.
HtSk–heatsink used.

Table VII–Base case with higher losses cost.
US$2000.00/kW

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
2.1	1.08	2	5	27	1600
2.2	1.08	2	5	20	2200
2.3	1.10	2	5	20	2200
2.4	1.11	2	6	27	1600

NSCT–number of series connected thyristors on the valve.
HtSk–heatsink used.

Table VIII–Base case with higher voltage.
15.18 kV–87.64mH

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
3.1	1.05	2	7	29	1600
3.2	1.06	2	5	29	1600
3.3	1.07	2	7	24	2000
3.4	1.08	2	5	24	2000

NSCT–number of series connected thyristors on the valve.
HtSk–heatsink used.

The increase of 17% on the nominal voltage of the valve increased the valve cost on 5% and a 6% decrease caused a 5% decrease on its cost. On both cases the best designs were different from the best design of the basic case. This means that the valve's voltage really affects the total SVC's cost but, at least in our example, the valve's cost was not very sensitive to the SVC's nominal voltage.

Table IX–Base case with lower voltage.
13.0 kV–64.28mH

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
4.1	0.95	2	5	21	2000
4.2	0.97	2	5	26	1600
4.3	0.98	2	6	21	2000
4.4	0.98	2	5	19	2200
4.5	0.99	2	8	21	2000

NSCT–number of series connected thyristors on the valve.
HtSk–the heatsink used.

Table X–Base case with less overload.
Step's 4 duration = 10s

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
5.1	0.92	2	2	27	1600
5.2	0.95	2	4	27	1600
5.3	0.96	2	2	20	2200
5.4	0.96	2	2	30	1400
5.5	0.99	2	4	20	2200

NSCT–the number of series connected thyristors on the valve.
HtSk–the heatsink used.

Table XI–Base case with less overload.
10% decrease

Design	Cost(pu)	SCR	HtSk	NSCT	Vdrm(V)
6.1	0.91	2	2	27	1600
6.2	0.92	2	3	27	1600
6.3	0.95	2	2	30	1400
6.4	0.95	2	2	20	2200
6.5	0.95	2	4	27	1600

NSCT–number of series connected thyristors on the valve.
HtSk–the heatsink used.

As was mentioned before, the overcurrent factors have a strong influence on the valve's cost. Since the SVC must continue to operate after the overload cycle the highest expected junction temperature must be lower than the maximum junction temperature of the thyristor. Therefore, table X and table XI show the results of the optimization with a shorter last step overload and a 10 % reduced overload cycle.

The decrease of the last step from 100s to 10s was enough to reduce 8% the cost of the valve. Since this last step represents the operation of the SVC after the overload cycle with its maximum operating voltage this time can be chanced without much influence on the overall performance of the system.

The decrease of 10% on the overload cycle represented a 9% decrease on the cost of the valve. This means that, for this example, the overload cycle has a strong influence on the valve cost.

CONCLUSIONS

The optimization program developed for the design of SVC's thyristors valves is a powerful tool to analyze different designs, evaluate design criteria, judge and develop specifications.

The polemic question on how to purchase SVCs; turnkey or piece by piece, can now be more detailed analised by the utilities.

REFERENCES

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3) Lima, A.G.G. and Afonso, J. L., 1989, Proceedings of the 3rd European Conference on Power Electronics and Application.

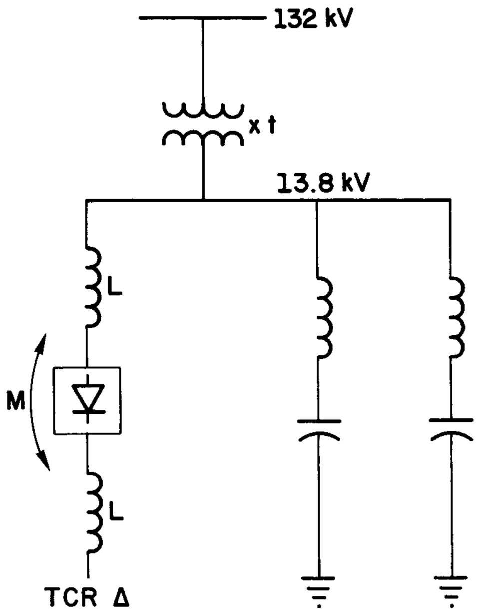

Figure 1 Static Var Compensator–TCR

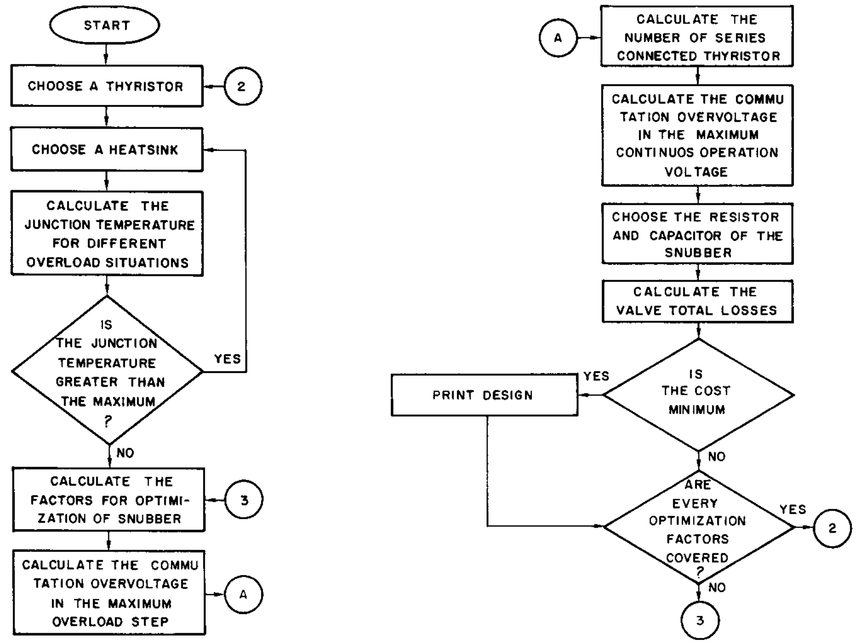

Figure 2 Program's fluxogram

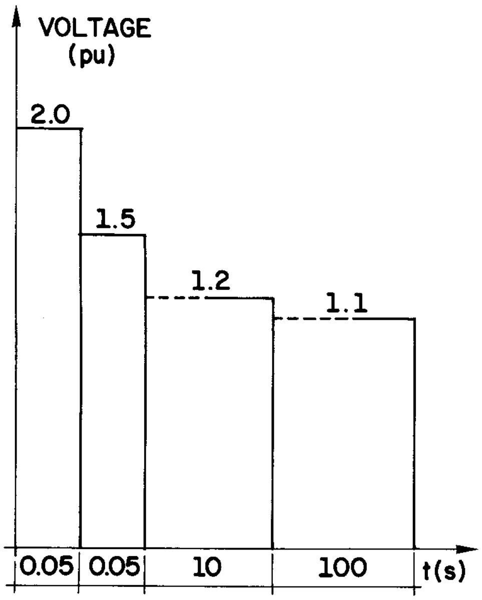

Figure 3 Overload cycle

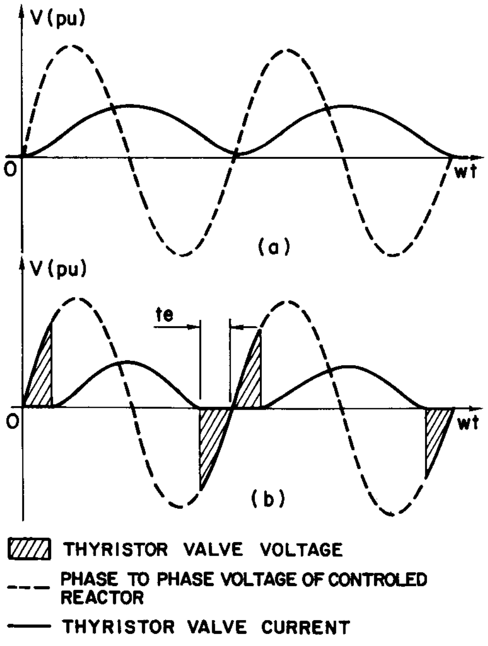

Figure 4 Misfiring

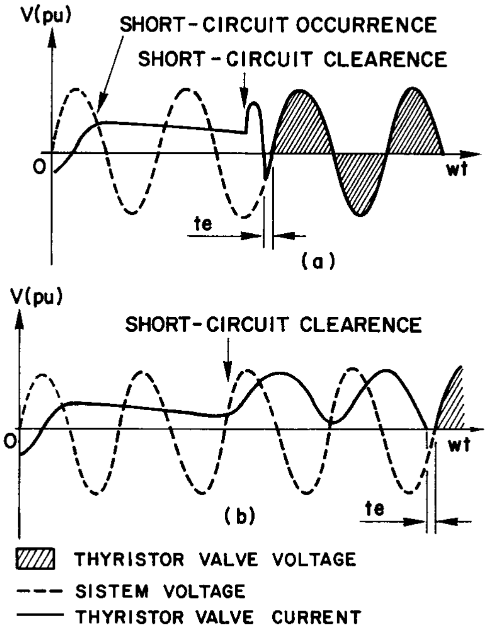

Figure 5 Ac system's short circuit