Incorporating TCSC into the Voltage Stability Constrained OPF Formulation

Garng. M. Huang, *Senior Member, IEEE,* and Nirmal-Kumar C Nair, *Student Member, IEEE*

Abstract**--This paper investigates the effect of Thyristor Controlled Series Capacitor (TCSC) on the voltage stability constrained Optimal Power Flow (OPF) formulation where the objective function is to minimize power system load curtailment. Incorporating TCSC affects the topology and hence the power flow distribution. Some numerical cases are presented to discuss the effects of TCSC that is expected when it is incorporated into the load curtailment formulation. The test result reflects the impacts TCSC has in reducing load curtailment during a line congestion situation. The paper also discusses the applicability of the approach in security based reliability studies for systems having control components like TCSC.**

Index Terms**-- Load Curtailment, OPF, Voltage Stability, TCSC.**

I. INTRODUCTION

In the deregulated power systems, economic competition leads to an understatement as regards to maintaining security features of the overall system. One such security issue is the voltage stability of the system. Several voltage instability incidents have been reported, in the recent past, all over the globe. These are results of operating the system with very less voltage stability margin under normal conditions. Another offshoot of the deregulated operating environment is the existence of various transaction paths based on the location of the energy market players and their contract amount. Thus, congestion management has become one of an important operational issue. In a deregulated environment, congestion alleviation would mean load curtailment in certain situations. The authors have proposed an OPF based formulation, incorporating the voltage stability as an additional constraint, for evaluating the amount of load curtailment [1]. The voltage stability margin indicator used was discussed in the literature of an earlier reference [2]. The conventional OPF procedure has been well documented in many earlier works [3,4,5,6]. Further, the application of the voltage stability constrained OPF procedure in evaluating security based composite system reliability was dealt with in a subsequent work [7]. Thus, in the emerging deregulation market any control action has to incorporate security features to maintain an acceptable level of system reliability.

It is observed that when the OPF results into a load curtailment, some of the branches still have thermal capacity limits that are still under-utilized. Selective change of branch parameters can reduce the amount of load curtailment for a given loading scenario. Providing voltage support at weak voltage points can also help in reducing the load curtailments[8]. The above is the motivation for us in exploring the effects of Flexible AC Transmission System (FACTs) components into the voltage stability constrained OPF formulation.

Thyristor Controlled Series Capacitor (TCSC) has been used to enhance angle stability and to mitigate the sub-synchronous resonance [9,10,11]. However, the use of TCSC in redistributing power flow and its effect on load curtailment has also been demonstrated in previous works [8,12,13]. Static Var Compensator (SVC) used as reactive support at voltage weak points can also reduce potential load curtailment [8].

This paper first presents the method to include the steady state model for TCSC into the voltage stability constrained OPF formulation. The impacts realized, by incorporating TCSC, is then brought about by two case studies. For comparison purposes the results as obtained without TCSC following the voltage stability constrained algorithm [1,7] is also evaluated. Moreover, it also discusses the applicability of the above methodology in a security based composite reliability assessment.

II. THE MODEL OF TCSC FOR FLOW CONTROL

TCSC is a series compensation component. By controlling the firing of the thyristors, one can change its apparent reactance smoothly and rapidly. There are many papers on modeling the TCSC, both the steady state model representation [14,15] and the dynamic models [16,17].

The authors gratefully acknowledge the support from PSERC and Texas Advanced Technology Program of Texas.

Garng. M. Huang is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA(e-mail: huang@ee.tamu.edu).

Nirmal-Kumar C Nair is with the Dept. of Electrical Engineering, Texas A&M University, College Station, TX 77843 USA (e-mail: ncnair@ee.tamu.edu)

Since the voltage constrained OPF uses the steady state voltage stability margin index we choose to use a steady state model representation of the TCSC.

The steady state representation followed in this paper is shown in Fig.1 [18].

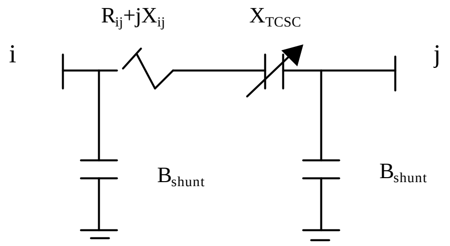

Fig.1. Steady State Model of TCSC

Where, i and j are the terminal buses of the transmission line; X_{ij} is the reactance of the line; R_{ij} is the resistance of the line.

In the model, we treat TCSC as a capacitor/inductor whose reactance can vary between –0.5 and 0.5 times the nominal reactance of the branch.

III. VOLTAGE STABILITY CONSTRAINED LOAD CURTAILMENT FORMULATION WITH TCSC

The formulation for incorporating the TCSC control, into the procedure proposed by the authors [1], is presented herewith. The details of the voltage stability index, L is described in published literatures [1,8]. When TCSC is installed in the system, its reactance is added as another control variable into the OPF algorithm.

To simplify the simulations we have kept the load power factor to be constant i.e. we assume that when a certain amount of real load has been shed at one bus, the corresponding reactive load will also be shed.

Objective: $min \sum_{i=1}^{n} load\_curtail_i$

S.T.:

$$P_{gi} - P_{li} - \sum_{j=1}^{n} |V_i||V_j|(G_{ij} \cos\delta_{ij} + B_{ij} \sin\delta_{ij}) = 0 \tag{1}$$

$$Q_{gi} - Q_{li} - \sum_{j=1}^{n} |V_i||V_j|(G_{ij} \sin\delta_{ij} - B_{ij} \cos\delta_{ij}) = 0 \tag{2}$$

$$P_{li} / P_{lireq} = Q_{li} / Q_{lireq} \tag{3}$$

$$0 \le P_{li} \le P_{lireq} \tag{4}$$

$$0 \le Q_{li} \le Q_{lireq} \tag{5}$$

$$|V_i|_{min} \le |V_i| \le |V_i|_{max} \tag{6}$$

$$P_{gi\,min} \le P_{gi} \le P_{gi\,max} \tag{7}$$

$$Q_{gi\,\min} \le Q_{gi} \le Q_{gi\,\max} \tag{8}$$

$$P_{ij}^2 + Q_{ij}^2 \le S_{ij\max}^2 \tag{9}$$

$$L_i \le L_{crit} \tag{10}$$

$$-0.5X_{mn} \le X_{TCSC} \le 0.5X_{mn} \tag{11}$$

Here,

$load\_curtail_i = P_{lireq} - P_{li}$

where,

P_{lireq}: real load demand at bus i

P_{li} : actual real load supply at bus i

n : total number of load flow buses in the system

P_{gi} : real power generation at bus i

Q_{gi} : reactive power generation at bus i

Q_{lireq}: reactive load demand at bus i

Q_{li}: actual reactive load supply at bus i

$|V_i|$: voltage magnitude at bus i

$|V_j|$: voltage magnitude at bus j

G_{ij}, B_{ij}: real/reactive part of the ijth element of the bus admittance matrix

d_{ij} : angle difference between the voltage phasor at bus i and bus j

$P_{gi\min}, P_{gi\max}$: minimum/maximum real power generation at generation bus i

$Q_{gi\min}, Q_{gi\max}$: minimum/maximum reactive power generation at generation bus i

$|V_i|_{min}, |V_i|_{max}$: minimum/maximum voltage magnitude at bus i

P_{ij}, Q_{ij} : real /reactive power flow through transmission line ij

$S_{ij\max}$: maximum apparent power flow allowable through the ijth line

L_i is the index L evaluated at the i th bus other than the generation buses

L_{crit} is the threshold value of the index acceptable for the system

X_{mn} is the reactance of the line where TCSC has been installed.

It can be observed in the OPF formulation that it includes the power balance equations (1,2) generation limits (7,8), line loading limits (9), voltage magnitude limits (6) and voltage stability constraint (10).

For the load curtailment policy, which we have adopted, i.e. constant power factor, an additional constraint (3) has been added. This works along with the allowable range of the possible load that can be supplied, which is represented by equalities (4) and (5). To incorporate the TCSC control into the OPF's description the constraint (11) has been introduced.

IV. THE EFFECT OF TCSC ON LOAD CURTAILMENT

A. Case I

Let us apply the OPF procedure to a three bus simple test system as shown in Fig. 2.

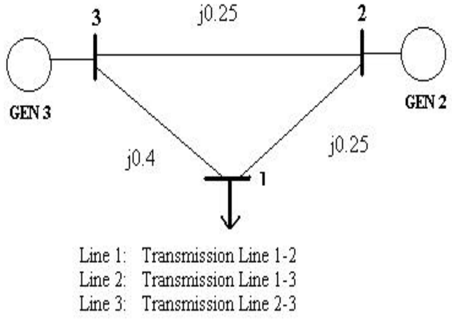

Fig.2. Three-bus Test System

In the above case we chose MVA limit of Line 1 as 0.5 p.u while the limit of Lines 2 and 3 was kept at 1.0 p.u. The load demand at Bus 3 was taken to be 1.4 + j 0.5 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u. The maximum and minimum acceptable voltage magnitude at the load bus 3 is taken to be 1.1 and 0.75 p.u. The TCSC impedance is supposed to be controllable by ± 50% of the line impedance where it is installed. The L_{crit} limit for the steady state voltage stability limit is changed from 0.1 to 0.3. The lesser this limit, the power system is operated at a larger voltage stability margin.

TABLE I
LOAD CURTAILMENT VALUES WITH & WITHOUT TCSC

Voltage Stability Margin Lcrit	Load Curtailment without TCSC (p.u)	Load Curtailment with TCSC (p.u)	% Improvement over desired load
0.10	0.8318	0.7356	6.87
0.15	0.5831	0.4366	10.46
0.20	0.4954	0.1621	23.81
0.25	0.4954	0.0955	28.56
0.30	0.4954	0.0955	28.56

Table I illustrates the improvement by using TCSC, primarily because of optimal usage of line flow redistribution because of changed line parameter. The TCSC has been introduced in the longest line i.e Line 2.

The algorithm results in a larger load curtailment with stricter voltage stability margin, that is with lower L_{crit} value. This is a direct effect of the index constraint hitting the limit before other constraint gets violated. However, as seen in the simulation for a system other constraints might get operative for larger index values. Incorporating TCSC definitely optimizes the line flow distribution in a way to reduce the curtailments as can be seen from the results.

A. Case II

We shall now apply the OPF to study the WSCC-9 bus test system as shown in Fig.3. The line parameters and the thermal limits are as shown in Table II.

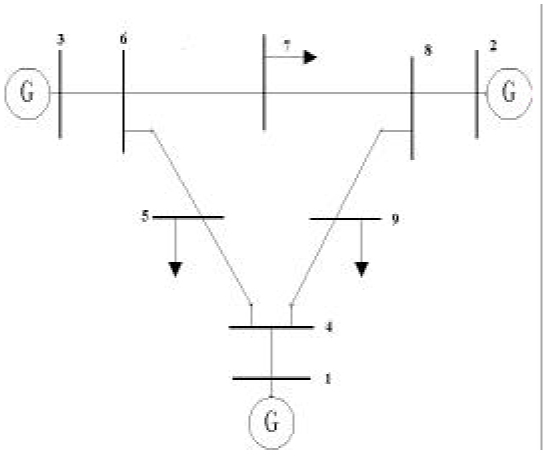

Fig.3. Wscc 9 Bus Test System

TABLE II
LINE PARAMETERS AND LOADING LIMITS

Line	Resistance (p.u)	Reactance (p.u)	Susceptance (p.u)	MVA Rating
1-4	0.0000	0.0576	0.0000	250
4-5	0.0170	0.0920	0.1580	250
5-6	0.0390	0.1700	0.3580	150
3-6	0.0000	0.0586	0.0000	300
6-7	0.0119	0.1008	0.2090	150
7-8	0.0085	0.0720	0.1490	250
8-2	0.0000	0.0625	0.0000	250
8-9	0.0320	0.1610	0.3060	250
9-4	0.0100	0.0850	0.1760	250

Three studies were carried out for the above test system. The details of the focus, the simulation set-up conditions and their details are discussed in the following sub-sections.

(1) Before evaluating the effect of TCSC incorporation into the system, let us first demonstrate the choice of the L_{crit} value for the test system. Load bus 5 was supposedly having a load demand of 90+ j 30 MVA, bus 7 a load demand of 100 + j 30 MVA and load bus 9 having demand of 149.67 + j 59.87 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u.

The system operates, with the following parameters of interest being observed and evaluated, as shown in Table III.

TABLE III
LINE FLOWS, VOLTAGES & MARGIN INDICES

Quantity	(p.u)	Quantity	(p.u)
P_{8-9}	0.8719	P_{9-8}	-0.8261
Q_{8-9}	0.1913	Q_{9-8}	-0.0677
S_{8-9}	0.8506	S_{9-8}	0.8288

Load Bus Number	Index Evaluated	Voltage Magnitude (p.u)	Voltage angle (deg)
5	0.1471	0.9727	-4.8816
7	0.1169	0.9873	-1.1337
9	0.1958	0.9458	-6.6039

It is observed that the load bus 9 has an index close to 0.2 under normal conditions. Now let us consider the loss of the line 4 - 9. Table IV gives the results for quantity of interest that are necessary to carry out our further discussion.

TABLE IV
LINE FLOWS, VOLTAGE AND MARGIN INDICES WHEN LINE 4-9 IS DOWN

Quantity	(p.u)	Quantity	(p.u)
P_{8-9}	1.7112	P_{9-8}	-1.4967
Q_{8-9}	1.6202	Q_{9-8}	-0.5409
S_{8-9}	2.3565	S_{9-8}	1.5914

Load Bus Number	Index Evaluated	Voltage Magnitude (p.u)	Voltage angle (deg)
5	0.1192	0.9752	-3.2530
7	0.1947	0.9283	-2.3801
9	=~1.0	0.6147	-24.6472

The results show that under this contingency situation the load bus 9 is very close to steady state voltage collapse situation. The voltage has dropped to a low 0.6147 p.u and the reactive flows and hence line flow has increased significantly which have traditionally been used for sensitivity based voltage collapse detection.

The above simulation brings out the fact that for a security based operating situation for the above test system the normal index at bus 9 has to be kept less than 0.2.

(2) Now let us apply the TCSC included Voltage Stability constrained OPF, to the WSCC 9 bus test system, to study its effect on load curtailment reduction. For the simulations we have used the following voltage magnitude constraints.

$$0.9 \le |V_i| \le 1.1 \quad \text{for } i = 1, 2, 3, 4, 6, 8$$

$$0.8 \le |V_i| \le 1.1 \quad \text{for } i = 5, 7, 9$$

Load bus 5 was supposedly having a load demand of 90+ j 30 MVA, bus 7 a load demand of 100 + j 35 MVA and load bus 9 having demand of 125 + j 50 MVA. All the generator buses are taken to be PV buses with scheduled voltage at 1.0 p.u. To demonstrate the effectiveness of TCSC, let us constrain the load bus 5 with a very strict voltage stability margin of L_{crit}=0.1 under normal conditions. The L_{crit} for load bus 7 and 9 is taken as 0.3. The result of running the voltage stability constrained OPF for various situations of TCSC placement and number of TCSC is given in Table V.

TABLE V
TCSC POSITION, CURTAILMENT, IMPEDANCE OF LINE WITH TCSC

TCSC Placement Position	Curtailment at Bus 5 with TCSC (p.u)	Impedance of line with TCSC (p.u / %)
No TCSC	0.3592	-
8-9	0.3100	0.153 (-50%)
5-6	0.2081	0.085 (-50%)
4-5	0.2382	0.046 (-50%)
5-6 & 4-5	0.0890	0.085&0.046 (-50%)

The strict voltage stability margin index of 0.1 causes load curtailment to be effected at load bus 5. However, the incorporation of TCSC causes lowering of the curtailment value. The impedance of the TCSC in all cases hits the maximum of –50% limit. Placing the TCSC on the longest line near the load bus5 i.e line 5-6 causes the most efficient reduction when only one TCSC is used. Incorporating two TCSC's in lines near bus 5 causes more reduction as the load becomes strongly supported by generators at Bus 1 and Bus 3.

(3) Another simulation was carried out to see the impacts of TCSC during contingency situation for different value of stability margin index. The details of the load are the same as presented in sub-section (2). However, the L_{crit} for the load buses 5 and 7 were taken to be 0.3. A contingency of line outage 4-9 was considered. This directly effects the load at bus 9. The results of the simulation without and with TCSC are given in Table VI & VII. It was observed that there is no curtailment when TCSC is placed in line 8-9 for this case.

TABLE VI
RESULTS WITHOUT TCSC FOR LINE 4-9 OUTAGE

L_{9crit}	Load curtailment at Bus 9 (p.u)	Voltage magnitude Bus 9 (p.u)
0.3	0.3796	0.9017
0.4	0.1754	0.8514
0.5	0.0255	0.8041

TABLE VII
RESULTS WITH TCSC IN LINE 8-9 FOR LINE 4-9 OUTAGE

L_{crit} at Bus 9	Voltage Magnitude at Bus 9 (p.u).	Impedance of Line 8-9 with TCSC (p.u)	Index at Bus 9
0.3	0.8803	0.0892	0.2999
0.4	0.8421	0.1267	0.3990
0.5	0.8296	0.1368	0.4310

The curtailment was effected when the simulation was carried out without TCSC as shown in Table VI. In each of the simulation the L_{crit} constraint caused the load curtailment However, as seen from Table VII by incorporating TCSC, the load curtailment has been avoided even for the strict case of a margin of 0.3. This brings out the fact that TCSC helps in improving the loadability of the system with regards to voltage stability. From a security viewpoint, TCSC helps in maintaining the safety margin for voltage stability margin without compromising on the load.

V. COMPOSITE POWER SYSTEM RELIABILITY ANALYSIS

The authors have demonstrated the applicability of the voltage stability constrained OPF algorithm in evaluating reliability measures like Expected Energy Not Served (EENS) [7]. The incorporation of TCSC into the algorithm, which has been demonstrated in this paper, would blend itself in a similar way for evaluating the reliability measures. Since TCSC can reduce load curtailment, the EENS would be reduced thus improving reliability indices in composite system studies.

VI. CONCLUSIONS

The paper discusses the approach to apply the constraint that can take care of incorporating TCSC into the voltage stability constrained OPF algorithm. It is seen that TCSC control improves line flow distribution. It is thus able to reduce load curtailment if any. We have seen from simulations that TCSC relaxes the OPF algorithm when it is constrained by the voltage stability margin indicator. Thus by effectively redistributing the reactive flows, the TCSC aids in relieving voltage stability constrained system operation to an extent. The applicability of the algorithm in evaluating system reliability measures in composite security based system reliability studies is discussed.

This paper is thus able to formulate an effective method to incorporate TCSC control into an OPF formulation that includes voltage stability. Numerical example illustrates the efficacy of the procedure. The method promises to be a useful tool in security based reliability evaluations of power system operations.

VII. REFERENCES

[1] G M Huang, N C Nair, "An OPF based algorithm to evaluate load curtailment incorporating Voltage Stability margin criterion", Conference Proceeding of NAPS 2001, TX, October 2001.

[2] P Kessel, H Glavitsch, "Estimating the voltage stability of a power system", IEEE Trans on Power Delivery, vol. PWRD-1, No.3, July 1986, pp. 346-354.

[3] H.W.Dommel, W.F. Tinney, "Optimal power flow solutions", IEEE PAS, vol. 87, Oct 1968, pp. 1866-1876.

[4] D.I Sun, B. Ashley, A Hughes, W.F. Tinney, "Optimal power flow by Newton Approach", IEEE Trans. Power System, vol. 103, 1984, pp. 2684-2880.

[5] O Alsac, B Stott, "Optimal power flow with steady state security", IEEE PAS, vol. 93, May 1974, pp. 745-751.

[6] O Alsac, J Bright, M Prais, B Stott, "Further developments in LP-based OPF", IEEE Trans. on Power Systems, vol. 5, no. 3, Aug 1990, pp. 697-711.

[7] G M Huang, N C Nair, "Voltage stability constrained load curtailment procedure to evaluate power system reliability measures", Proc. IEEE/PES Winter Meeting Jan 2002, NewYork.

[8] G Huang, P Yan "The impacts of TCSC and SVC on Power System Load Curtailments", Proc. IEEE/PES Summer Meeting, July 2001, Canada.

[9] L A. S. Pilotto, W. W. Ping, A. R. Carvalho, A. Wey, W. F. Long, F. L. Alvarado, A. Edris, "Determination of needed FACTS controllers that increase asset utilization of power systems," *IEEE Trans. Power Delivery*, vol. 12, no. 1, Jan. 1997, pp.364-371.

[10] L A. S. Pilotto, W. W. Ping, A. R. Carvalho, A. Wey, W. F. Long, F. L. Alvarado, C. L A. DeMarco, A. Edris, "Determination of needed FACTS controllers that increase asset utilization of power systems," *IEEE Power Engineering Review*, Vol.17, No.1, January 1997, pp.58 –59.

[11] E. V. Larsen, J. J. Sanchez-Gasca and J. H. Chow, "Concepts for design of FACTS controllers to damp power swings," *IEEE Trans. Power System*, vol. 10, no. 2, May 1995, pp.948-956 .

[12] G.M.Huang and S.C.Hsich," An optimal power delivery problem in deregulated open access environments," *Proceedings of the 1996 IEEE International Conference on Control Applications, 1996, pp.450-455.*

[13] G.M.Huang and S.C.Hsich, "Fast textured algorithms for optimal power delivery problems in deregulated environments," *IEEE Trans. Power Systems*, Vol.13 , No.2 , May 1998, pp.493 –500.

[14] S. G. Jalali, R. A. Hedin, M. Pereira, K. Sadek, "A stability model for the advanced series compensator," *IEEE Trans. Power Delivery*, vol. 11, no. 2, Apr. 1996, pp.1128-1137.

[15] C. R. Fuerte-Esquivel, E. Acha and H. Ambriz-Perez, " A thyristor controller series compensator model for the power flow solution of practical power networks," *IEEE Trans. Power Systems*, vol. 15, no. 1, Feb. 2000, pp.58-64.

[16] B. K. Perkins, M. R. Iravani, "Dynamic modeling of a TCSC with application to SSR Analysis," *IEEE Trans. Power System*, vol. 12, no. 4, Nov. 1997, pp.1619-1625.

[17] J. J. Paserba, N. W. Miller, E. V. Larsen, R J. Piwko, "A thyristor controlled series compensation model for power system stability

analysis," *IEEE Tran. Power Delivery*, vol. 10, no. 3, July 1995, pp.1471-1478.

[18] P Preedavichit, S. C. Srivastava, "Optimal reactive power dispatch considering FACTS devices," *Advances in Power System Control, Operation and Management, 1997. APSCOM-97. Fourth International Conference (Conf. Publ. No. 450)* , Vol.2 , 1997, pp.620 –625.

VIII. BIOGRAPHIES

Dr. Garng Huang received his B.S. and M.S. in E.E. from National Chiao Tung University, Hsinchu, Taiwan, R.O.C. in 1975, 1977 respectively. He received his doctorate degree in Systems Science and Mathematics from

Washington University, St. Louis in 1980. He had been teaching there since then until 1984. He joined Texas A&M University, Department of Electrical Engineering in 1984. He is currently a professor and the director of graduate studies there. He has been working on many funded research projects, such as Emergency Control of Large Interconnected Power System, HVDC Systems, Restoration of Large Scale Power Systems, On-line Detection of System Instabilities and On-line Stabilization of Large Power Systems, Fast Parallel/Distributed Textured Algorithms, Fast Parallel Textured Algorithms for Large Power Systems, Hierarchical Aggregation and Decomposition Algorithm for Data Network Routing Problem, etc. His current interest is the large scale systems theory, large scale parallel/distributed computing and control and their applications.

Dr. Huang is a senior Member of IEEE, and a Registered Professional Engineer of Texas. He has served as the Technical Committee Chairman of Energy System Control Committee and an associated editor in the IEEE Automatic Control Society; he has also been serving in a number of committees and subcommittees of IEEE PAS Society. Dr. Huang has published more than a hundred papers and reports in the areas of nonlinear, distributed control systems, parallel/distributed computing and their applications to power systems, data networks and flexible structures.

Nirmal-Kumar C Nair received his B.E in E.E. from M.S. University, Baroda, India in 1990. Thereafter, he received his M.E in E.E with specialization in High Voltage Engineering from Indian Institute of Science, Bangalore, India in 1998. He has around a decade of teaching and research experience in the field of electrical engineering. In 2000, he joined Texas A&M University to pursue his Ph.D under the guidance of Dr. Huang in the area of stability, security, reliability and energy market issues in power systems with focus on the deregulated environment. Mr. Nair is a student member of IEEE.