A NEW LOOK FOR SERIES COMPENSATION OF ELECTRICAL NETWORKS CONSIDERING VOLTAGE COLLAPSE

Sobhy M. Farrag
Faculty of Engineering
El-Menoufiya University, Egypt
sobhy@frcu.eun.eg

Abstract:- The paper presents a new look for allocating controlled variable series compensation in electrical transmission networks from the view points of voltage collapse, capacity of transmission, and transmission losses. For more realistic and accurate representation, the load is manipulated as a state variable and voltage dependent throughout the solution process. The solution algorithm searches for the optimal line to be compensated and ratings of series capacitive compensation in order to increase capacity of transmission, enhance voltage stability margin, define voltage collapse point, and finally identify the most sensitive and vulnerable nodes in the network.

Keywords: Load flow, Series compensation, Voltage collapse, FACTS, Optimization.

1. INTRODUCTION

Flexible AC transmission systems, "FACTS" is intended to provide new systems and methods of operation to help electric utilities get the most from their investments in transmission networks. Long transmission lines are characterized by high reactive losses when the system is heavily loaded. If the unbalance between reactive supply and load demand can not be corrected by a limited voltage decrease, voltage collapse takes place. Series compensation in such cases is a very economical and powerful means for alleviating these problems and increasing capacity of transmission. There are many factors controlling the site selection of series compensation [1] such as suitability for evaluating equipment performance at high stress conditions (e.g. high fault

Manuscript recceivied from Dr. S.M. Farrag at: 20/ 6/1998,
accepted at: 4 / 7/1998,
Engineering research bulletin, Vol. 21, No. 2, 1998,
Menoufiya University, Faculty of Engineering,
Shebin El-Kom, Egypt, ISSN. 1110-1180.

duty and steady state current), suitability for demonstrating control performance (SSR damping, power-swing damping, transient stability control and scheduling), accessibility for performing field tests on series compensation devices, benefits to the power system, availability of sites, and considerations for environmental impact.

There are many publications dealt with series compensation devices [1,2]. Others are concerned with series compensation process [3,4]. Many for voltage collapse problems. There have been significant debate [5] over whether the problem is static in nature and therefore be studied as a parametric load flow problem, or whether it is dynamic and must be studied as the trajectory of a set of differential equations. A majority of the work on the problem to date has been focused on it as a static problem [5-11]. Many publications handled its dynamic aspects [12-15]. This paper presents a novel look for allocating series capacitive compensation in electrical transmission networks. The novelty of the solution lies on the idea of introducing voltage collapse as a major factor for selecting the location and rating of series compensation in the transmission lines. The proposed solution algorithm can easily determine where to locate series capacitive compensation devices and their suitable sizes for increasing capacity of transmission as well as enhancing voltage stability margin. Furthermore, the solution algorithm identifies the most sensitive and vulnerable nodes in the network. Also, the paper clarifies the possibility of using the controlled variable series compensation devices as a bus voltage controlled tools.

2. LOAD MODEL AND MODIFIED POWER FLOW EQUATIONS

Load characteristics are known to have a significant effect on voltage stability. Classical load model such as constant P-Q , constant impedance, and constant current models are not appropriate for more accurate analysis to the voltage collapse phenomenon. In this paper the load model is expressed, as function of per unit bus voltages[16], as

$$P_{Di} = P_{Di0} V_i^a \tag{1}$$

$$Q_{Di} = Q_{Di0} V_i^b \tag{2}$$

where P_{Di0} , Q_{Di0} are the active and reactive powers of the ith bus at nominal voltage of 1.0 p.u. The exponential constants a and b reflect the load-voltage characteristics. They depend on the nature of loads. From some measures, constant a is found to be 0.37 for industrial loads and 1.55 for domestic loads. Constant b was 5 for industrial loads and 2.5 for domestic loads.
For n buses, total demand is written as

$$P_{Di} = \sum_{i=1}^{n} P_{Di0} V_i^a \tag{3}$$

$$Q_{Di} = \sum_{i=1}^{n} Q_{Di0} V_i^b \tag{4}$$

For a power factor distinguished by β_i, the relation between active and reactive powers at bus i is

$$Q_{Di0} = \beta_i \; P_{Di0} \tag{5}$$

Inserting generation and load participation factors γ_i and α_i respectively, we can write

$$P_{Gi0} = \gamma_i P_{D0} \tag{6}$$

$$P_{Di0} = \alpha_i P_{D0} \tag{7}$$

From equations (3) to (7) we can deduce

$$P_{Di} = \alpha_i V_i^a P_{D0} \tag{8}$$

$$Q_{Di} = \alpha_i \beta_i V_i^b P_{D0} \tag{9}$$

Thus, as shown in Figure 1, power flow equations at bus i are

$$P_i(V,\delta) - (\gamma_i - \alpha_i V_i^a) P_{D0} = 0 \tag{10}$$

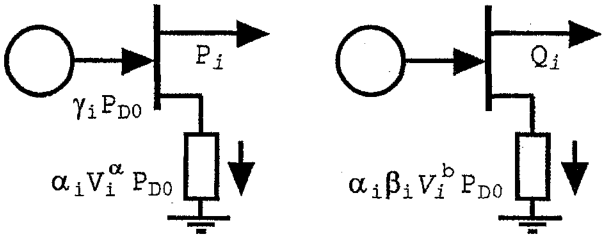
$$Q_i(V,\delta) + (\alpha_i \beta_i V_i^b) P_{D0} = 0 \tag{11}$$

where,

$$P_i(V,\delta) = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \cos(\delta_i - \delta_j - \theta_{ij}) \tag{12}$$

$$Q_i(V,\delta) = \sum_{j=1}^{n} \left|V_i V_j Y_{ij}\right| \sin(\delta_i - \delta_j - \theta_{ij}) \tag{13}$$

$Y_{ij} = \left|Y_{ij}\right| \angle \theta_{ij}$, and $V_i = \left|V_i\right| \angle \delta_i$



a. Active power b. Reactive power

Figure 1. Power flow model

3. VARIABLE SERIES COMPENSATION

The capacitive series compensation is one of the commonly used measures to overcome the technical problems associated with long distance HVAC transmission lines. There are several schemes for variable series compensators [15].

One of these schemes is shown in Figure 2. It consists of both conventional fixed capacitor (C_F) and thyristor-switched capacitor (TSC). The amount of series compensation can be adjusted continuously by switching in the appropriate number of the capacitors through the use of the thyristor bypass switch.

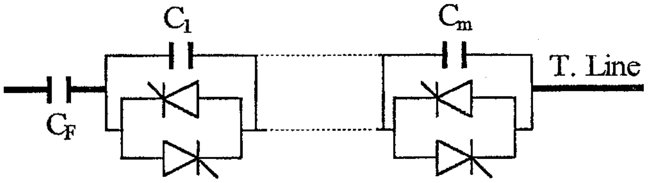


Figure 2. Thyristor-switched capacitor compensator

The effective reactance of the compensated line at any instant will be, (X_L-X_S) where X_L is the inductive reactance of the line and X_S is the capacitive reactance of the series compensator at this instant.

4. PHENOMENON OF VOLTAGE COLLAPSE AND SOLUTION PROCEDURE

Voltage collapse phenomenon is characterized by a slow variation in the system operating point, due to increase in loads, in such a way that voltage magnitudes gradually decrease until a sharp accelerated change occurs. Forcing the system artificially to do so step-by-step, the P-V curve can be traced and voltage collapse phenomenon can be conceptualized.

In order to solve considering voltage dependent load, a load bus voltage node is selected to be a parameter node which will be forced externally to decrease gradually in steps and the corresponding state variable load demand is calculated in each step from the power flow solution [16]. During solution process the parameter node will be excluded from the state vector, and instead of it, the unknown power demand is inserted as a last state variable. The N-R load flow solution is driven from equations (10) and (11) as

$$\begin{array}{|c|c|c|}\hline \partial P/\partial\delta & \partial P/\partial V & \partial P/\partial P_{D0} \\ \hline \partial Q/\partial\delta & \partial Q/\partial V & \partial Q/\partial P_{D0} \\ \hline \end{array} \cdot \begin{array}{|c|}\hline \Delta\delta \\ \hline \Delta V \\ \hline \Delta P_{D0} \\ \hline \end{array} = \begin{array}{|c|}\hline \Delta P \\ \hline \Delta Q \\ \hline \end{array} \qquad \ldots\ldots \quad (14)$$

The Jacobian matrix of equation (14) is the same as Jacobian of traditional N-R load flow, except, the column corresponds to the parameter node voltage magnitude is eliminated and a new column is inserted as last column related to dependent load demand.

The power mismatch vector, (right-hand-side of equation (14)), is the negative of the left-hand-side of equations (10) and (11). The solution algorithm can be stated as:

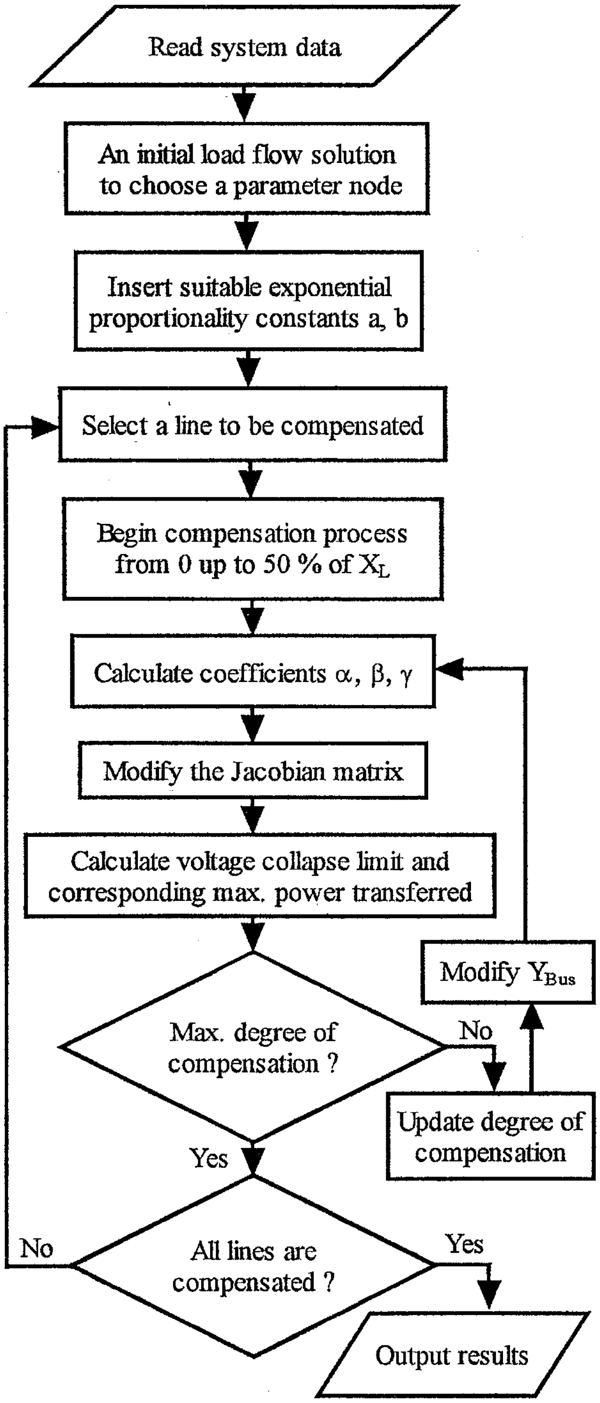


Figure 3. Flowchart of the proposed solution.

1. An initial load flow solution is executed to select a proper load bus voltage as a parameter node. The parameter node should be characterized either by the least voltage magnitude or, by a great bulk of load demand.
2. Modify the Jacobian matrix as given above to introduce the change in load demand ΔP_{D0} as a state variable.
3. Calculate elements of the modified Jacobian matrix.

4. Calculate the mismatch vector.
5. Solve equation (12) iteratively to find a new set of bus voltages. Update the corresponding demand as,

$$P_{D0} = P_{D0} + \Delta P_{D0} \tag{15}$$

6. Decrease the parameter node voltage magnitude by a small value ΔV and go to step 3. This is repeated until the voltage collapse point is reached.
7. Select a line to be compensated and its degree of compensation. Modify Bus admittance matrix accordingly, then return back to step 3. This process is repeated for all possible degrees of compensation, and all possible lines to be compensated.

The overall solution algorithm is depicted as shown in Figure 3.

The voltage stability margin is measured as the distance between nominal operating point and the point of voltage collapse. The most sensitive buses to voltage change are the weak or vulnerable buses. Hence, voltage changes between bus voltage magnitudes in the current solution and the previous solution indicate the weakness of these buses. The weakest bus is the bus of maximum voltage change.

5. VOLTAGE CONTROL VIA SERIES COMPENSATION

Figure 4 represents the voltage-load characteristic curves at different increasing degrees of capacitive series compensation in a transmission line. As the load increases, the operating point moves from position 1 towards position 1' and the voltage decreases from V_1 to $V_{1'}$. Increasing the degree of compensation will transfer the operating point from curve A to curve B with a voltage value of V_2 which is equal to V_1 and so on for curves C and D, and hence, thyristor-switched capacitors can be used to handle bus voltage deviation accompanied with the increase of load. The ability to accomplish this is a function of the size of switching steps.

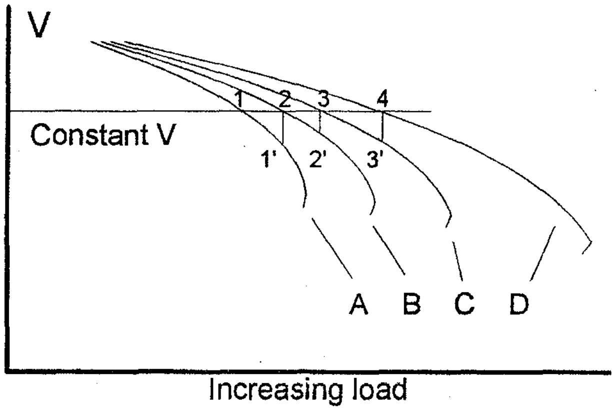


Figure 4. Voltage control via series compensation

6. ILLUSTRATIVE EXAMPLE

The simple five-bus test system shown in Figure 5 is used to illustrate the capability of the proposed solution. The line and bus data are given in Tables 1 and 2 respectively. All values in per unit on a 100-MVA base. The exponential constants a and b are taken as 1.3 and 3.3 respectively.

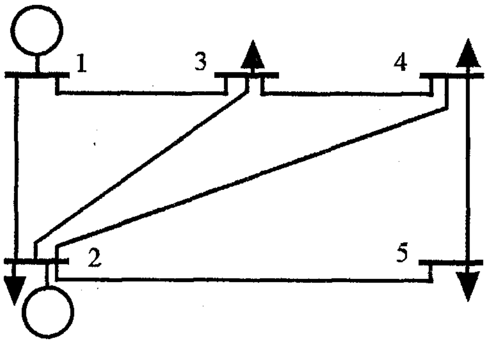


Figure 5. Five-bus example system.

Table 1. Line data (in p.u)

Line no.	Bus code p - q	Line impedance	1/2 Line charging
1	1 - 2	0.02+j 0.06	0.0+j 0.030
2	1 - 3	0.08+j 0.24	0.0+j 0.025
3	2 - 3	0.06+j 0.18	0.0+j 0.020
4	2 - 4	0.07+j 0.20	0.0+j 0.020
5	2 - 5	0.04+ j 0.12	0.0+j 0.015
6	3 - 4	0.01+j 0.03	0.0+j 0.010
7	4 - 5	0.09+j 0.26	0.0+j 0.026

Table 2. Initial bus data (in p.u)

Bus code	Bus voltage	Generation P_G	Generation Q_G	Demand P_D	Demand Q_D
1	1.06+j0				
2	1.0	0.4	0.3	0.20	0.10
3		0.0	0.0	0.45	0.15
4		0.0	0.0	0.40	0.05
5		0.0	0.0	0.60	0.10

A computer programming package is prepared for the solution algorithm and is tested via several electric networks of different sizes. The obtained results for the five-bus illustrative example are depicted as shown in Figures (6 - 12). Each figure represents the load-voltage characteristics for all possible degrees of compensation in a certain transmission line. The values of capacitive series compensation are taken as percentages of the inductive reactance of the line to be compensated. The maximum percentage value not exceeded than 50 % due to other safety and technical limitations.

In more compact form, optimal parameters concluded from Figures (6-12) are collected together as shown in Figure 13. It shows the effect of 50% capacitive series compensation within each transmission line of the network on: capacity of transmission, voltage stability margin, and system transmission losses. Different scaling factors are considered for capacity of transmission, voltage stability margin and system transmission to indicate their variations via different compensated lines in a relatively narrow range. Characteristic values for the original system, (without compensation), are the intersection points of the characteristic curves with axis Y.

Based on the performed studies, the following can be concluded:

- Although lines of small series inductive reactance have no meaning to be compensated, Figure 11, it is not necessary the line of maximum inductive reactance be the most proper line to be compensated for maximum revenue, Figure 12.
- The effectiveness of series-compensation device not only depends on its size or the inductive reactance of the line to be compensated, but basically on the position of the line in the network, Figures 7.
- It is possible to have a constant voltage level with the increase of load, Figure 4.
- The optimal line to be compensated was line no. 2 with a 50 % capacitive series compensation of the inductive reactance of the line, Figure 7.
- The capacity of transmission is increased by about 95.45 % before occurring voltage collapse.
- The voltage stability margin is enhanced by about 75 %.
- Unfortunately, the transmission losses are increased by about 7.2 %.
- The decision makers have to compromise between multifold mentioned objectives when deciding where to locate series compensation devices within an electrical network, Figure 13.

CONCLUSIONS

The author has proposed a new concept combining series compensation with static voltage stability problems. The load demand is modeled as a load-voltage dependent and considered as a state variable throughout the solution process. The proposed method searched for the optimal sizing of series compensation and its optimal location in the transmission lines in order to increase capacity of transmission, enhance voltage stability margin, and maintain a constant voltage level with the increase of load. Furthermore, the proposed method can easily identify the weakest and vulnerable nodes in the network.

It can from the performed studies be concluded that the proposed method could become a valuable tool for static voltage stability studies as well as for power system planning.

Acknowledgment:

The author has prepared this work during his stay in Brno, (Czech Republic) in a scientific mission at the Department of Electrical Power Engineering, Faculty of Electrical Engineering and Computer Science. He wishes to thank all the people in the department specially, Doc.Ing. Evzen Haluzik and Doc.Ing. Antonin Matousek for facilitating his work.

REFERENCES

[1] URBANEK, J.—PIWKO, R.J.—LARSEN, E.V.—DAMSKY, B.L.—FURUMASU, B.C.—MITTLEST- ADT, W.: Thyristor Controlled Series Compensation Prototype Installation at the Slatt 500 kV Substation, IEEE Trans. on (PWRD) 3 (1993), 1460-1469.
[2] KOSTEREV, D.N.—MITTELSTADT, W.A.—OHLER, R.R.—KOLODZIEJ, W.J.: An Application Study for Sizing and Rating Controlled and Conventional Series Compensation, IEEE Trans. on (PWRD) 2 (1996), 1105-1111.
[3] SAIED, M.M.: Optimal Long Line Series Comp-ensation, IEEE Trans. on (PWRD) 2 (1996), 248 -253.
[4] MILLER, J.E.: Reactive Power Control in Electric Systems, John Wiley & Sons Inc. (1982).
[5] CHIANG, H.D. —DOBSON, I.—THOMAS, R.J.— JAMES, S.T.—LAZHAR, F.A.: On Voltage Collapse in Electric Power Systems, IEEE Trans. on (PWRS) 2 (1990), 601-611.
[6] FARRAG, S.M.: Reactive Power Planning for Loss Reduction and Static Voltage Stability Enhancement, J. Electrical Engineering, 46 Bratislava, (1995), 94-99.
[7] FARRAG, S.M.: Rehabilitation of Loaded Power Systems for Loss Reduction and Security Enhancement, accepted for publication in Electric Machines and Power Systems, USA (1998).
[8] GUPTA, R.K.—ALAYWAN, Z.A.—STUART, R.B.—REECE, T.A.: Steady State Voltage Instability Operations Perspective, IEEE Trans. on (PWRS) 4 (1990), 1345-1351.
[9] CHOW, J.C.—FISCHL, R.—YAN, H.: On The Evaluation of Voltage Collapse Criteria, IEEE Trans. on (PWRS) 2 (1990), 612 -620.
[10] GUBINA, F.—STRMCNIK,B.: A Simple Approach to Voltage Stability Assessment in Radial Networks, IEEE Trans. on (PWRS) 3 (1997), 1121-1128.
[11] HONG, Y.H.—PAN, C.T.—LIN, W.W.: Fast Calculation of a Voltage Stability Index, IEEE Trans. on (PWRS) 4 (1997), 1555-1560.
[12] ABDEL-ATY E.: Series Compensation Schemes Reducing The Potential of Subsynchronous Resonance, IEEE Trans. on (PWRS) 1 (1990), 219-226.
[13] LEE, B.H.—LEE, K.Y.: Dynamic and Static Voltage Stability Enhancement of Power Systems, IEEE Trans. on (PWRS) 2 (1990), 612-620.

[14] DEUSE, J.—STUBBE, M.: Dynamic Simulation of Voltage Collapses, IEEE Trans. on (PWRS) 3 (1993), 894-904.

[15] CHOI, S.S.—SHRESTHA, G.—JIANG, F.: Transmission System Stability Enhancement Via Variable Series Compensation, Electric Machines and Power Systems 24, USA, (1996), 569-582.

[16] ARYA, L.D.—VERMA, H.K.: A Method for Tracing P-V Voltage Stability Analysis with Voltage Dependent Loads, Electric Machines and Power Systems 24, USA, (1996), 583-596.

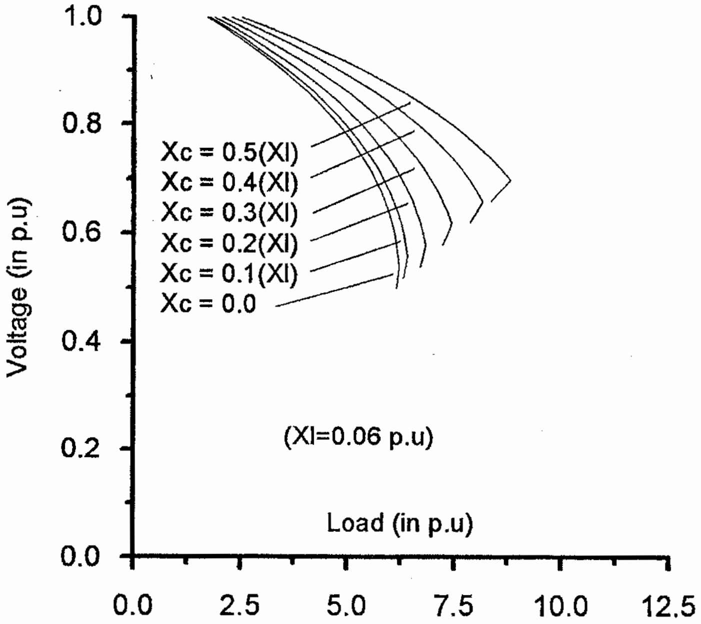


Figure 6. Compensation in line no. 1.

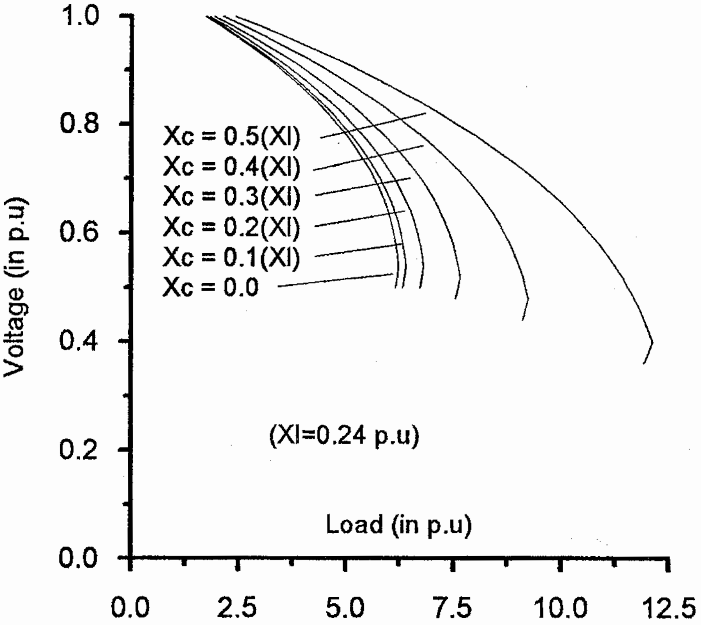


Figure 7. Compensation in line no. 2

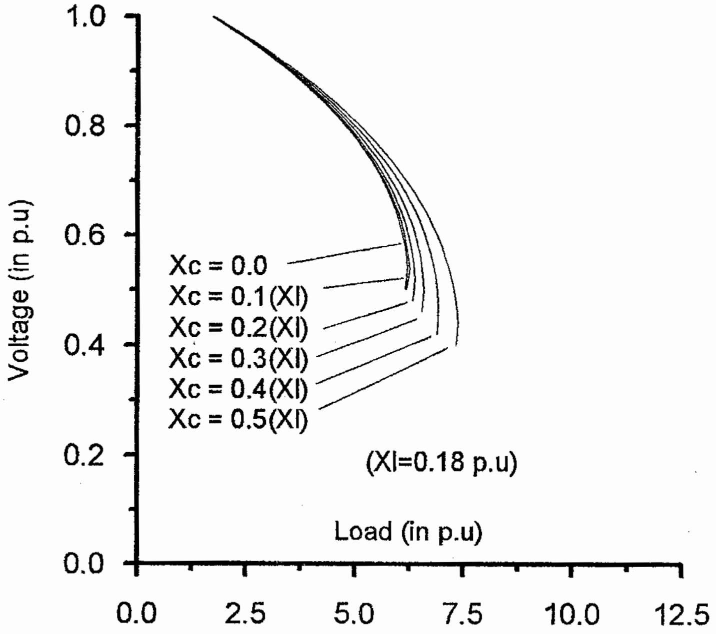


Figure 8. Compensation in line no. 3.

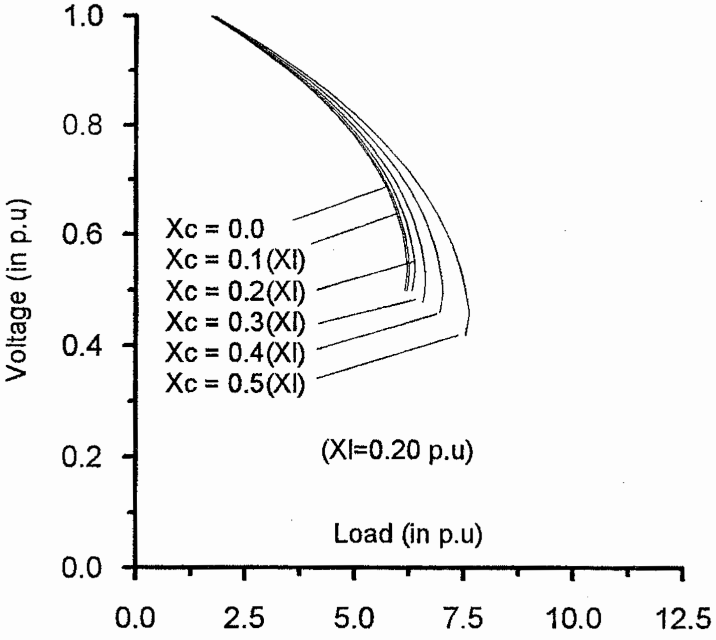


Figure 9. Compensation in line no. 4.

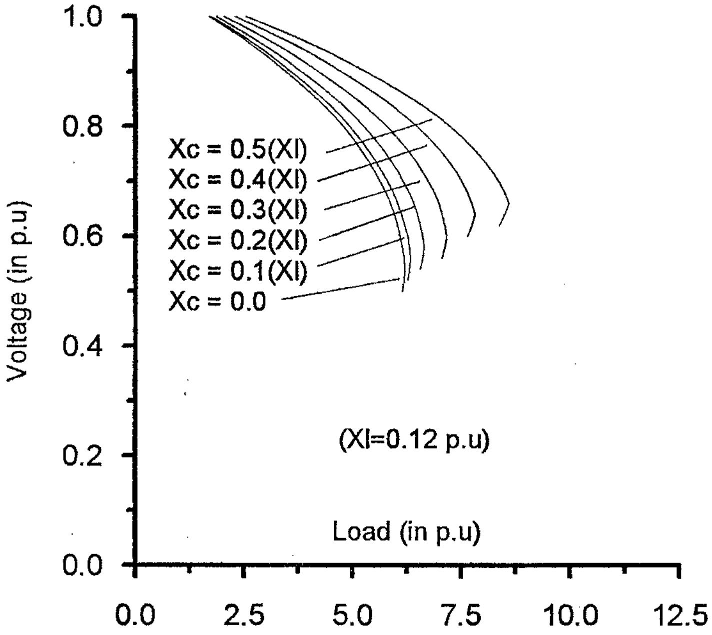


Figure 10. Compensation in line no. 5.

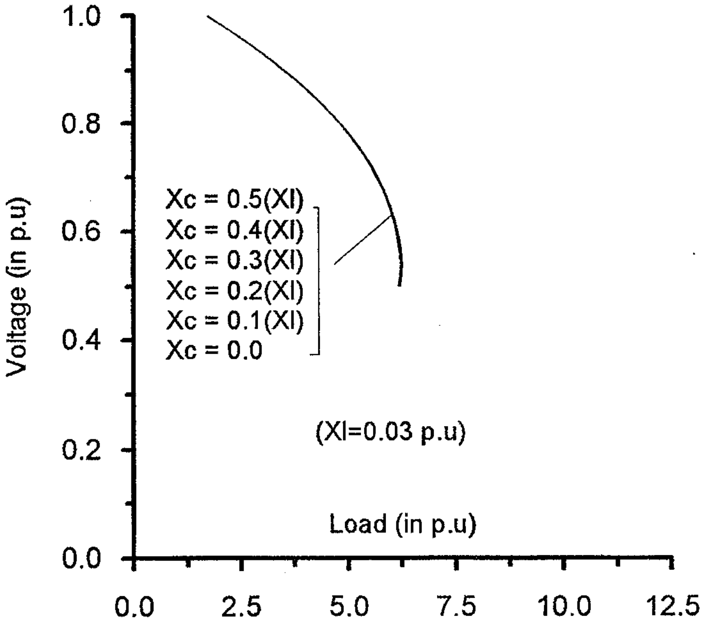


Figure 11. Compensation in line no. 6.

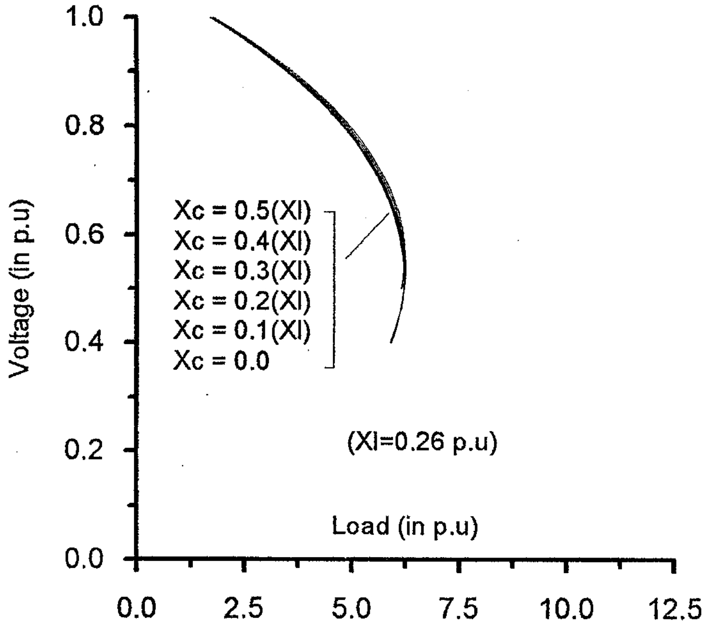


Figure 12. Compensation in line no. 7.

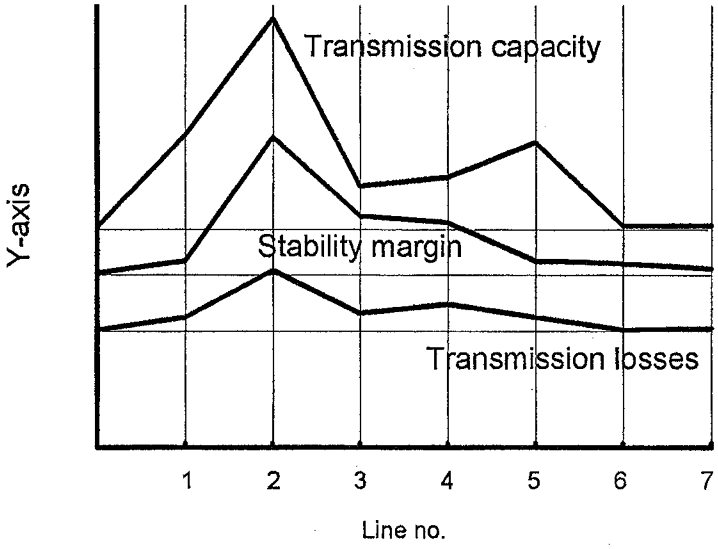


Figure 13. System characteristics at 50% series compensation (with different scaling factors)

نظرة جديدة لتعويض التوالى فى الشبكات الكهربية
آخذا فى الإعتبار إنهيار الجهد

د. صبحى محمد فراج
كلية الهندسة – جامعة المنوفية – شبين الكوم

ملخص البحث:

خطوط نقل الطاقة الكهربية ذات الضغط العالى المتردد كثيرا ما تعانى من إرتفاع مفاقيد القدرة الغير فعالة خاصة فى حالات التحميل الزائد ، وقد يؤدى ذلك إلى حدوث عدم اتزان بين مصادر القدرة الغير فعالة ومتطلبات الأحمال بدرجة لا يمكن تعويضها بإنخفاض قليل فى الجهد مما يؤدى إلى استمرار إنخفاض الجهد تدريجيا إلىدرجة معينة بعدها يكون الإنخفاض حاد وسريع مسببا إنهيار الشبكة الكهربية وحدوث حالات إظلام كامل. وقد تكررت هذه الظاهرة فى كثير من بلدان العالم مثل نيويورك – طوكيو – فرنسا – السويد – إسرائيل – ٠٠٠٠ . وقد دفع هذا الباحثين والمتخصصين فى الآونة الآخيرة إلى دراسة هذه الظاهرة ومعرفة أسبابها لمحاولة تفاديها أو التقليل من احتمالات حدوثها .

وتعد هذه الدراسة خطوه على الطريق ، حيث يقدم البحث رؤية جديدة وشامله يجب مراعاتها والأخذ بها عند استخدام معوضات التوالى فى تدعيم شبكات القوى الكهربية وتحسين خواص التشغيل بها. وتهدف الدراسة إلى إيجاد أفضل أماكن وقيم لمعوضات التوالىاللازم إدخالها فى خطوط النقل للشبكة الكهربية بغرض :

١. زيادة سعة النقل فى خطوط الضغط العالى المتردد إلى أقصى قيمة ممكنه.
٢. توفير عامل أمان كافى لجهد الإتزان يضمن عدم حدوث الإنهيار المفاجئ فى الجهد وتكرار حالات الإظلام فى الشبكة الكهربيه.
٣. دراسة تأثير تلك المعوضات على مفاقيد النقل الكهربيه.
٤. إمكانية استخدام معوضات التوالى للتحكم فى الجهد عند زيادة الأحمال.

وقد قام الباحث بعمل حزمة برامج متكاملة وعامة لطريقة الحل المقترحه يمكن تطبيقها على كافة أنواع نظم القوى الكهربية ذات الأحجام المختلفة ، وتمت تجربتها بنجاح.

هذا وقد أوضحت الدراسة التطبيقية على مثال عددى مدى كفاءة الطريقة المقترحة وأهميتها لدى مخططى ومسئولى التشغيل لشبكات القوى الكهربيه.