Use of PQV Surface as a Tool for Comparing the Effects of FACTS Devices on Static Voltage Stability

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***Abstract*— PV or QV curves are commonly used to determine static voltage stability margin of a power system. Using PV or QV curves has its own advantages, disadvantages and limitations. In this paper, a novel method based on a surface in active power, reactive power and voltage (PQV) space is proposed; and PQV surface has been used for a comprehensive comparison of series and shunt FACTS devices for enhancing static voltage stability. Using this method can show a perfect image of the effects of FACTS devices on voltage stability. By using Power System Analysis Toolbox (PSAT), on the 6-bus test system and the IEEE 14-bus test system, the optimal locations of these controllers are determined. Some of the results obtained by the proposed method are compared with the results obtained by the computation of maximum loading point method. The results of the proposed method are more reasonable.**

***Index terms* – Voltage stability index, Voltage stability margin, Static analysis, FACTS devices**

I. Introduction

Fully utilizing transmission lines are becoming important for several reasons including environmental concern, economical concern, construction cost of new lines and deregulation policies [1]. It can be the main cause of voltage instability or collapse. Therefore, a sufficient knowledge of the voltage stability margin is important for safely operation of the system. There are three effect factors on voltage stability: power system configuration, generation pattern and load pattern [2]. By using reactive power sources i.e. Flexible AC transmission system (FACTS) power system configuration can be modified. Series and shunt FACTS can be utilized for this purpose. Each of FACTS devices has its own advantages and limitations [3].

In the last two decades, a lot of studies have been allocated to voltage stability. The performed studies from 1985-1998 are collected in [4].There are two different methods for analyzing the voltage stability problem of a power system. They include static and dynamic methods [5]. Static approach have used for steady-state condition. There are various methods for the analysis of static voltage stability; however all of these methods are based on power flow. Power flow based methods include the continuation power flow methods, optimization methods, singular decomposition methods, etc [5].Some of these methods has been used for analyzing the effects of FACTS devices on static voltage stability [1], [3], [5]-[12]. Continuation power flow method has been proposed in [13]. Results of this method show that shunt reactive power compensation control is very useful but series and series-shunt reactive power compensation controls are not effective [3],[5]-[8].

In [9], [10] using singular value decomposition analysis showed the similar results about series and shunt FACTS; however the results of series-shunt FACTS installation were shown to be converse. In [12], using modal analysis, it was observed those better enhancements were obtained with series compensation using TSSC in comparison to the shunt compensation by SVC.

Usually PV or QV curves are used for analyzing voltage stability [14], [15]. Use of PV or QV has its own advantages and disadvantages and every one give some information about voltage stability. Also different Indices have been proposed in various papers. Some of these Indices can be seen in [16]-[20]. In this article, a novel method is suggested for considering voltage stability and studying the effect of FACTS devices on voltage stability.

In analyzing voltage stability, knee point in PV curve or QV curve is used for finding collapsing point of voltage[14], [15].

A.PV curve

When studying voltage stability, the relationship between transitional power (*P*) and voltage bus is considered [15]. Voltage stability analysis process depends on transitional power from one point to another point of the system and the amount of its effect on the voltage system.

A common method of analyzing voltage stability is an analysis according to PV curve. A typical PV curve is shown in Fig.1. Here, voltage bus is a function of the total load power. When the load increases, in the knee point of PV curve, power flow will not be converged and the system will be instable. This point is called critical point.

There fore, PV curve can be used for determining the limit of voltage stability of the system. In general, if operating point of the system is located before critical point of the system, the system will be stable.

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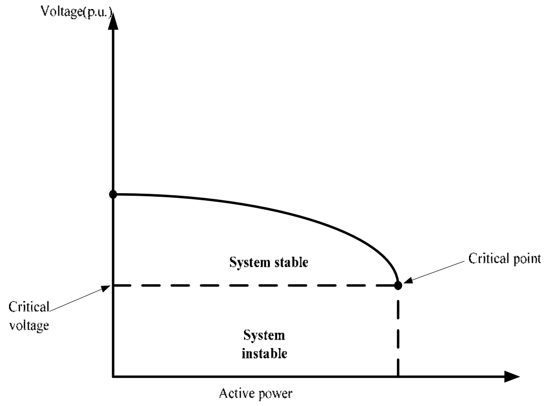

Fig.1. Typical power-voltage (PV) curve

B.QV curve

Voltage stability depends on how the deviations in Q and P affect the voltages at the load buses. The effect of reactive power characteristics of the devices at loads (or compensating devices) is more apparent in a QV relationship [15].

Fig.2. shows a typical QV curve. This curve shows the limit of voltage stability in the places where derivative dQ/dV is zero. This point also determines the minimum reactive power required for consistent performance. So, if the operating point of the system is on the right side of the QV curve, the system will be stable, and if the operating point is on the left side of the curve, the system will be instable [15].

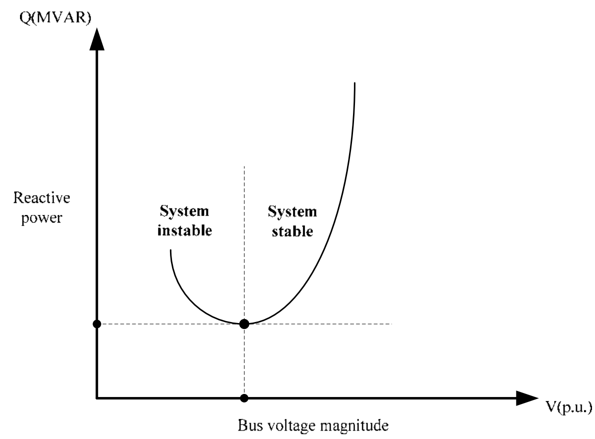

Fig. 2.Typical reactive power-voltage (QV) curve

In this article, by using PQV surface, the effects of series and shunt FATCS devises on static voltage stability have been compared. Information of both of PV curve and QV curve in PQV surface can be seen.

The rest of this paper is organized as follows: in section II, the classification of voltage stability analysis methods are introduced. In section III the problem of the common analysis methods are considered. The proposed methodology has been developed and explained in Section IV. The results obtained for the test systems is given and discussed in Section V. Finally, Section VI contains the conclusion.

II. Voltage stability study methods

According to utilized PV or QV curves for analyzing voltage stability, voltage stability study methods can be divided into two groups [14]:

i) Methods which evaluated real power limit (or PV analyses)

ii) Methods which evaluated reactive power limit (or QV analyses)

Methods such as CPF, CMLP and RPF belong to the first group and methods like modal analysis and singular value decomposition analysis belong to the second group.

III. Definition of the problem

Used indices for determining voltage stability margin in the two categories of proposed methods of voltage stability analysis in section II are completely different. Analysis methods of the first group are preformed on PV curve and methods of the second group are conducted on QV curve. Consequently, the voltage stability margin calculated for a determined system in these two categories can be completely different (see Fig.3).

Results of each analysis method will depend on:

(a) System conditions

Numbers of nodes, number of generators and compensating elements of reactive power on the obtained voltage stability margin have significant roles in each method. For example, PV analyses in a small system with lots of generators show a good voltage stability margin, but QV analysis may show lower voltage stability margin. The effect of installing compensating element of reactive power on voltage stability can also be different according to the used method.

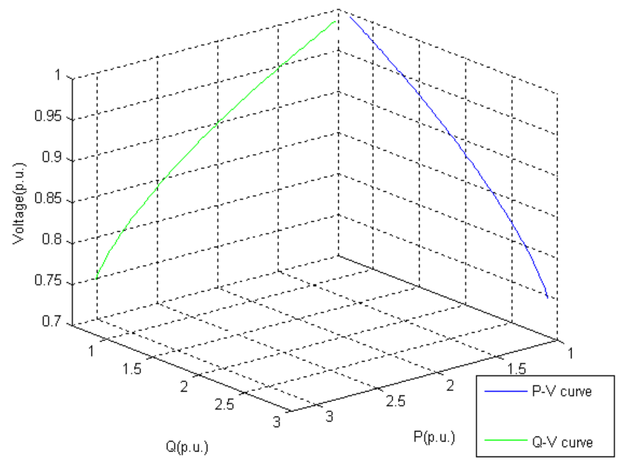

Fig. 3.Typical power-voltage (PV) curve and reactive power-voltage (QV) curve

(b) Modeling and simulating conditions

In the methods such as OPF, CPF, CMLP and RPF, active power and reactive power of loads are changed simultaneously so that load power factors remain constant.

In QV analysis, it is assumed that real power changes in an operating point are minor and negligible. Therefore, voltage changes depend on reactive power changes, and consequently only reactive power of loads has been used for analyzing voltage stability.

IV. PROPOSED METHODOLOGY

Voltage stability of a power system depends on simultaneous changes of P and Q; Therefore in this paper, using a surface in PQV space is proposed for analyzing voltage stability. This surface shows magnitude of voltage bus according to active power and reactive power of the load. This surface is plotted by using a modified algorithm of computation of the maximum loading point method.

A. Computation of the Maximum Loading Point (CMLP)

In this method, maximum loading point can be calculated by repeating the computation of load flow. Computation of load flow is repeated until power flow is converged. In [22], an algorithm for this purpose is proposed. This algorithm is shown in Fig.4.

B. Modifying the method

In computation of the maximum loading point, time simulation is used in each step and special conditions are provided so that performing controlling reactive power such as tap changer, compensating reactive power and etc become very easy. In addition, number of commands in each iteration will also decreases. The modified algorithm of the method is shown in Fig. 5.

C. Computation of the Maximum Loading Point in Two Dimensions (CMLPTD)

Calculating the maximum loading point in active power, reactive power and voltage (PQV) space are performed in two steps. In the first step, read load power will be held constant and load reactive power will increases until power flow converges. Then in the second step, load read power increases and again load reactive power increases until power flow converges. The operating point of the system will be calculated with time simulation in each step. The proposed calculating algorithm in this article is shown in Fig.6.

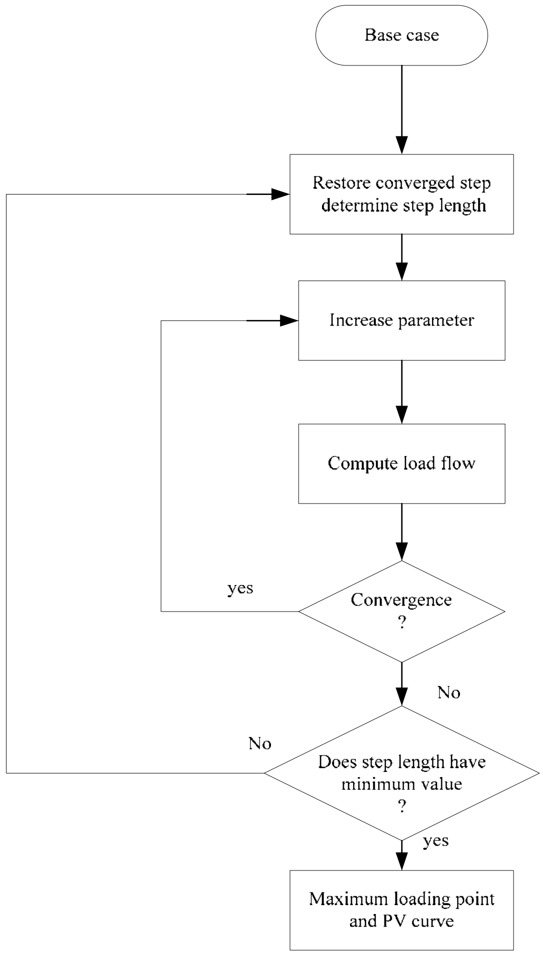

Fig. 4. Algorithm of the maximum loading point computation

D. Performance Index

Here, the points located on the lower edge of the surface show the maximum loading points of the system in different states of loading system. The closest point of the lower edge of the surface of the base operating point is minimum voltage stability margin (MVSM). The minimum voltage stability margin represents the amount of the load that matches the system to its stability threshold. Here, index of voltage stability is defined by the difference between complex power of load in base operation point and complex power of load in the closest point of the lower edge of the surface of the base operating point. This index is called MVSM and is defined as follows:

$$MVSM = \frac{S_{critical} - S_{base}}{S_{base}} \tag{1}$$

where

$S_{critical}$: Complex power in the closest point of the lower edge of the surface of the base operating point;

S_{base} : Complex power in base operation point.

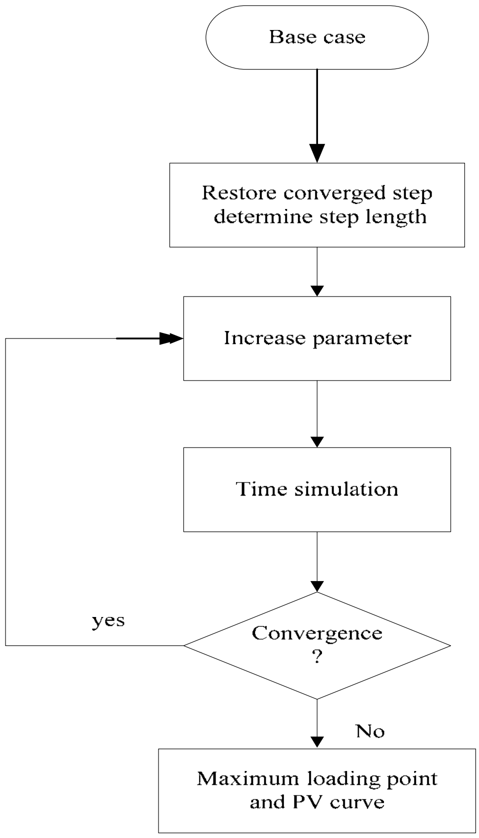

Fig. 5. Modified algorithm of the maximum loading point computation

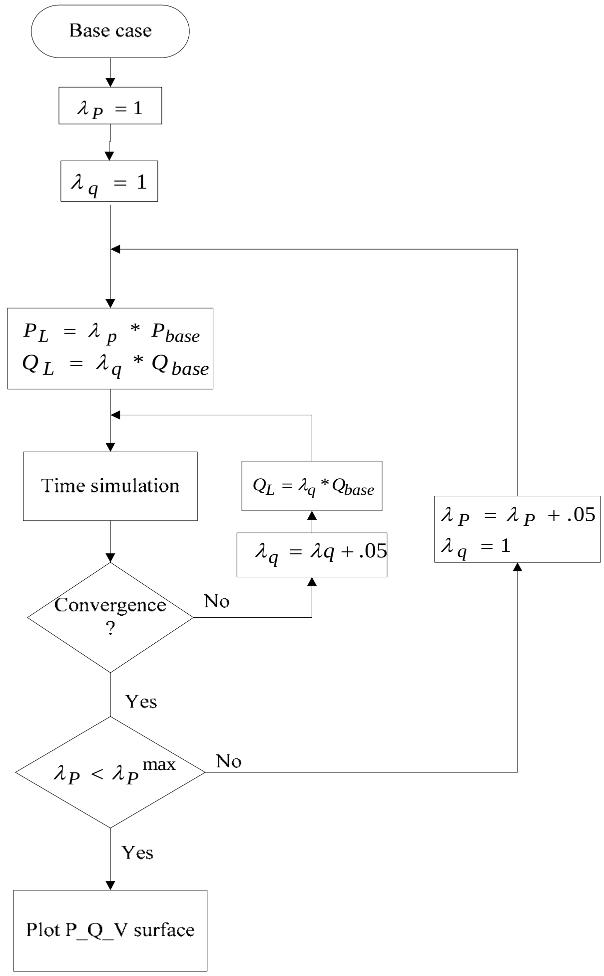

Fig. 6. Algorithm of maximum loading point computation in two dimensions

V. SIMULATION RESULTS

In this section the proposed method of assessing voltage stability margin is tested on the 6-bus system and the IEEE 14-bus system. The 6-bus system is shown in Fig.7.

First, the two-dimensional maximum loading point is computed for both of these systems. PV curves of the 6-bus system load buses are shown in Fig.8. PQV surface of bus number 4, 5 and 6 are shown in Figs. 9, 10 and 11. MVSM of the 6-bus test system and the IEEE 14-bus test system is shown in table I and III (PQV surface of buses of the IEEE 14-bus test system is shown in appendix)

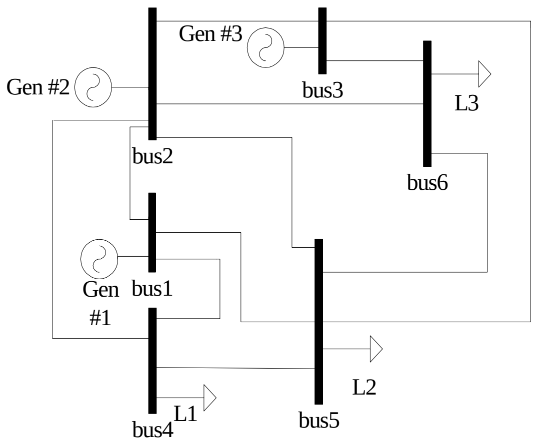

Fig.7. The 6-bus test system

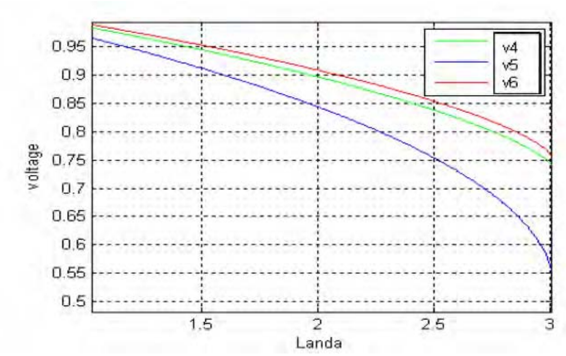

Fig. 8. PV curves for the 6-bus test system without FACTS

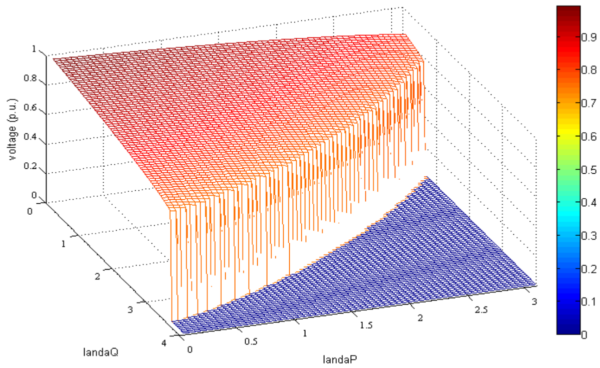

Fig. 9. PQV surface for bus number 4 of 6-bus test system without FACTS

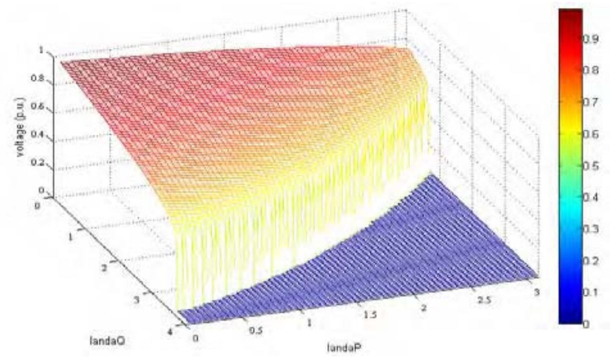

Fig. 10. PQV surface for bus number 5 of 6-bus test system without FACTS

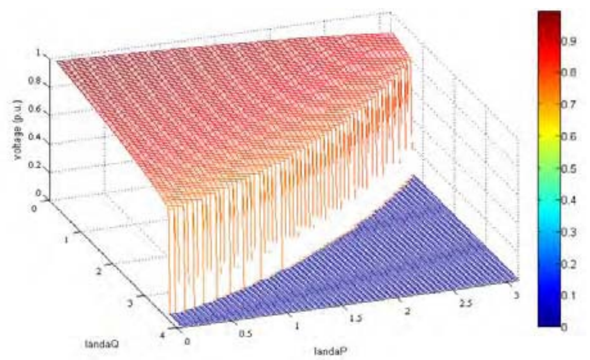

Fig. 11. PQV surface for bus number 6 of 6-bus test system without FACTS

Table I shows calculated MVSM for the buses and evaluated λ by CMLP method. λ is the same for all buses and critical bus can not be determined by using them. In CMLP method for this condition, critical bus is determined according to the PV curve slope. But by using MVSM, it can be observed that two buses 4 and 6 have the least amount of MVSM, hence instability possibility is in its highest level in these two buses and voltage stability limit is $MVSM = 1.5436$.

TABLE I
MVSM AND LANDA FOR 6-BUS TEST SYSTEM WITHOUT FACTS

PV bus number	4	5	6
$MVSM$	1.5436	1.6164	1.5436
λ	3.00219	3.00219	3.00219

Table II shows calculated MVSM for buses of IEEE 14-bus test system. Here also by using MVSM, it can be seen that bus 4 has the minimum of voltage stability limit and is clearly the weakest bus.

By installing a STATCOM in bus 6 in the 6-bus test system and also in bus 4 in the IEEE 14-bus test system, voltage stability was improved 14.62 percent and 12.33 percent respectively (see tables III and VI). Installing a SSSC in line 4-5 of 6-bus system showed that this device may not be effective (see Table II).The results of installing a SSSC in IEEE 14-bus system is observed in table VI Similarly, these results also show that installing a SSSC in this system is not effective.

In table V the result of this method is compared with the results of CMPL method and it was observed that CMLPTD results have lower sensitivity duo to system condition changes and show the effects of STATCOM in a more reasonable manner.This table show that shunt reactive compensation is useful for enhancing static voltage stability; but series reactive compensation is not effective.

TABLE II
MVSM FOR 6-BUS TEST SYSTEM WITH FACTS

PV bus number	**4**	**5**	**6**
$MVSM$ **for system with a STATCOM**	1.7693	1.8460	1.7693
$MVSM$ **for system with a SSSC in line 4-5**	1.5817	1.6549	1.5817

TABLE III
MVSM FOR IEEE 14-BUS TEST SYSTEM WITHOUT FACTS

PV bus number	**4**	**5**	**9**	**10**	**11**	**12**	**13**	**14**
MVSM	0.2620	1.1487	2.4609	2.3553	2.5219	1.5467	2.6234	2.1023

TABLE VI
MVSM FOR IEEE 14-BUS TEST SYSTEM WHIT FACTS

PV bus number	**4**	**5**	**9**	**10**	**11**	**12**	**13**	**14**
MVSM **for system whit a STATCOM**	0.2943	1.2630	3.3908	3.4435	3.3593	1.6927	3.0083	2.2894
MVSM **for system whit a SSSC**	0.27676	1.201275	3.242179	3.106759	3.314813	1.613948	2.873628	2.188473

TABLE V
COMPARING THE VOLTAGE STABILITY MARGIN WITH VARIIOUS FACTS CONTROLLER

SYSTEM	6-BUS TEST SYSTEM			IEEE 14-BUS TEST SYSTEM		
	WITHOUT FACTS	WITH A STATCOM IN BUS NUMBER OF 6	WITH A SSSC IN LINE 4-5	WITHOUT FACTS	WITH A STATCOM IN BUS NUMBER OF 4	WITH A SSSC IN LINE …….
MINIMUM OF MVSM	1.5436	1.7693	1.5817	0.2620	0.2943	0.27676
PRESENT OF INCREASE OF THE MAXIMUM VOLTAGE STABILITY	—	14.62	2.46	—	12.33	5.63

VI. CONCLUSION

Common voltage stability analysis methods only focused on PV curves or QV curves, so the effects of changes in both active and reactive powers on voltage stability can not be observed simultaneously. In addition, because of heavy dependence of these methods to system conditions and the type of simulation, the possibility of error is high in these methods. In this article, voltage stability calculating method in two dimensions was proposed for studying voltage stability. Two dimensional voltage stability margin calculating method possesses some advantages in comparison with common methods:

1) Simultaneous observation of the effects of reactive and active power changes on voltage stability.

2) Independence of analysis results related to system conditions, modality and simulation.

3) The introduced index of this method is defined in a way that any changes in loads are covered.

The results of preformed simulation on the 6-bus test system and also on the IEEE 14-bus test system showed more logical results in comparison with common voltage stability analysis methods. The results were also more reasonable related to the effect of installing SATCOM on voltage stability. The results of simulation showed that shunt FATCS devices have a very useful effect on voltage stability, but the effects of series FACTS devices are not sufficient.

APPENDIX

PQV surface of buses of the IEEE 14-bus test system is shown in Figs.12-22. Figs. 12-19 show PQV surface of bus number 4, 5, 9, 10, 11, 12, 13 and 14 without FACTS devices; and Figs. 20 and 21 show PQV surface of bus number 4 of the IEEE 14-bus test system with STATCOM and SSSC.

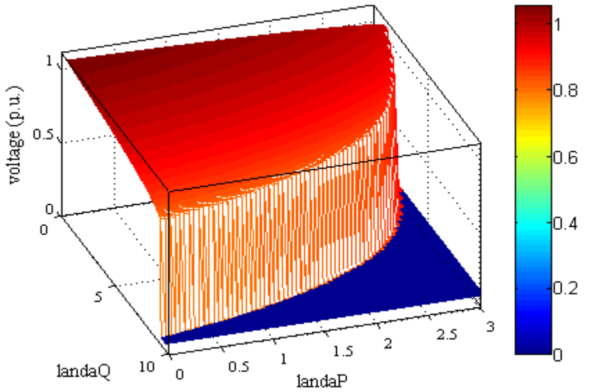

Fig. 12. PQV surface for bus number 4 of IEEE 14-bus test system without FACTS

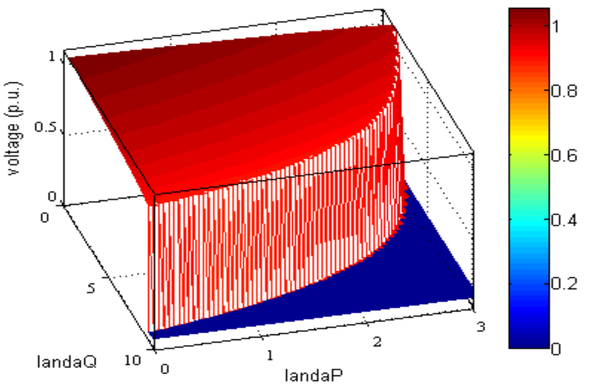

Fig. 13. PQV surface for bus number 5 of IEEE 14-bus test system without FACTS

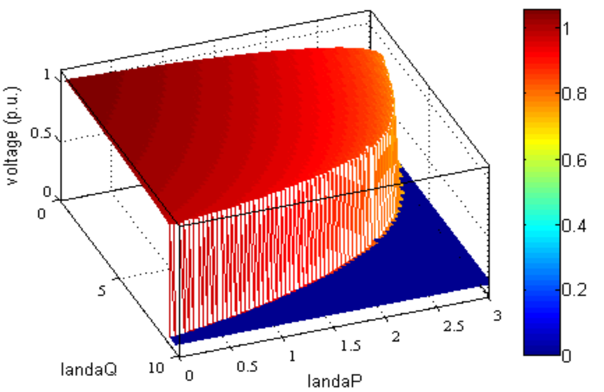

Fig. 14. PQV surface for bus number 9 of IEEE 14-bus test system without FACTS

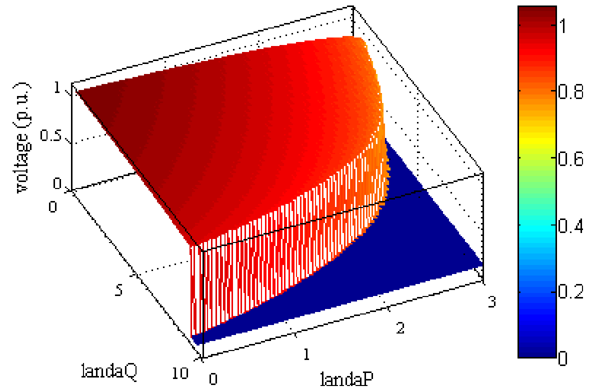

Fig. 15. PQV surface for bus number 10 of IEEE 14-bus test system without FACTS

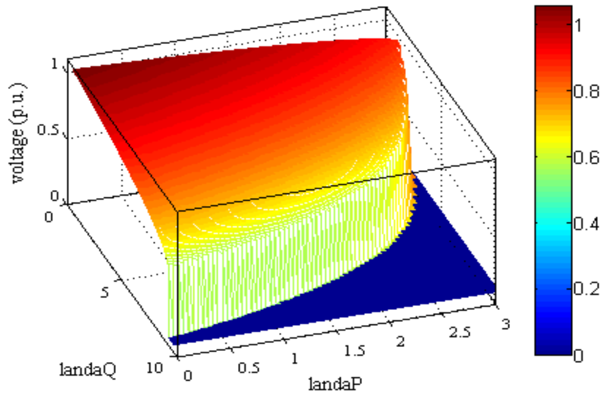

Fig. 16. PQV surface for bus number 11 of IEEE 14-bus test system without FACTS

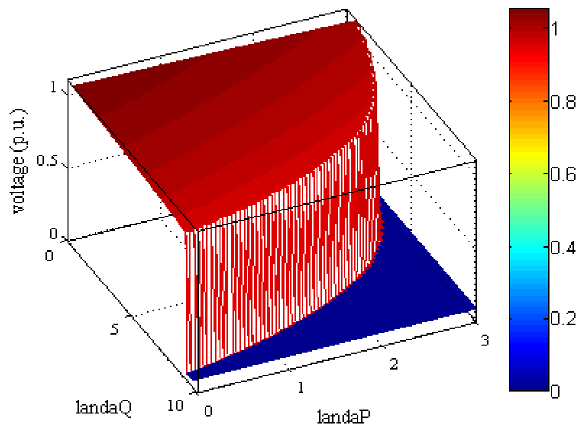

Fig. 17. PQV surface for bus number 12 of IEEE 14-bus test system without FACTS

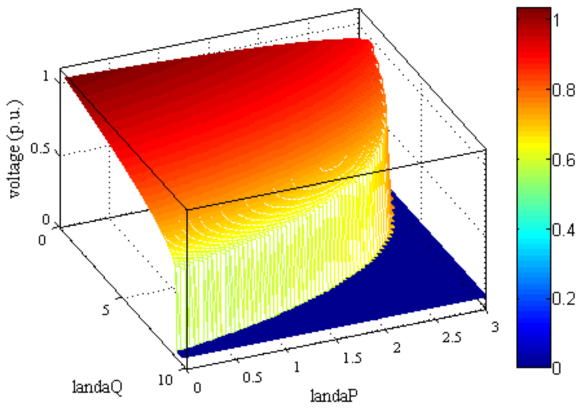

Fig. 18. PQV surface for bus number 13 of IEEE 14-bus test system without FACTS

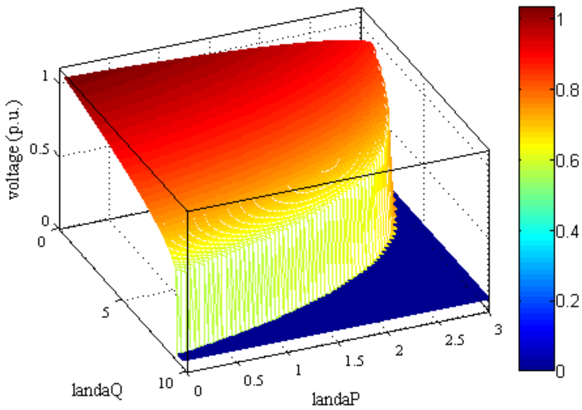

Fig. 19. PQV surface for bus number 14 of IEEE 14-bus test system without FACTS

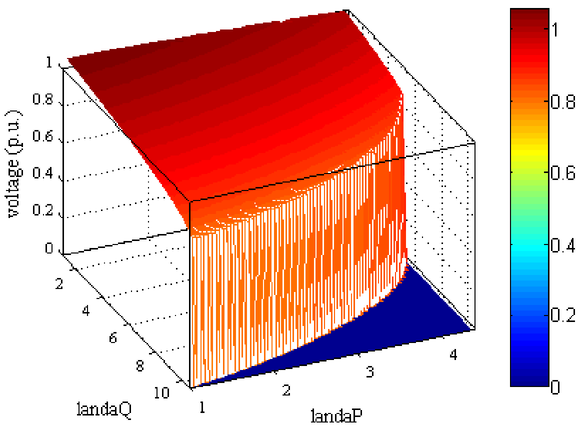

Fig. 20. PQV surface for bus number 4 of IEEE 14-bus test system with STATCOM

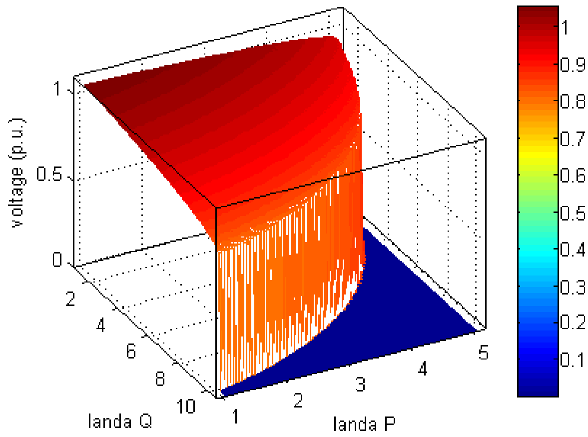

Fig. 21. PQV surface for bus number 4 of IEEE 14-bus test system without SSSC

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