STATCOM Application in 400kv Iraqi Super Grid for Voltage Magnitude Improvement

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ABSTRACT

This paper presents a study of static synchronous compensator (STATCOM). One of the Flexible AC Transmission System (FACTS) devices, it can significantly improve power systems stability. Consisting of voltage sourced converters connected to an energy storage device on one side and to the power system on the other, it specifically can provide reactive support to buses.

This work presents a simple algorithm for identifying weak buses to determine the best location for STATCOM. Singularity of the power flow Jacobian matrix as an indicator of steady-state stability has used, the sign of the determinant of the load flow Jacobian was used to determine the system stability, by computing eigenvalues, eigenvectors , minimum singular value of load-flow Jacobian Matrix and sensitivity analysis between power flow and bus voltage changes.

Load flow analysis of the Iraqi grid 400 KV network has been carried out using Newton-Rephson Method with and without STATCOM. The result of Load flow analysis show improvement in bus voltage with the use of STATCOM in the system.

Keywords: Fact, Statcom, Load flow, Voltage Stability.

تطبيق STATCOM في شبكةالضغط الفائق العراقية Kv (400) لتحسين قيمة الفولتية

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الخلاصة:

في هذا البحث تم دراسة ثابت المعوض المتزامن .(STATCOM) واحد من أجهزة نظام نقل التيار المتردد المرنة ،حيث يمكن أن يحسن إلى حد كبير استقرار أنظمة الطاقة. يتكون من محولات مصادر الجهد متصلة إلى جهاز تخزين الطاقة على جانب واحد ونظام الطاقة من جهة أخرى، فإنه على وجه التحديد يمكن أن توفر دعم لل bus بالقدرة التفاعلية.

في هذا العمل تم الاعتماد على خوارزمية بسيطة لتحديد buses الضعيفة لتحديد أفضل موقع لSTATCOM، استخدمت singularity لمصفوفة جاكوبين لتدفق الطاقة كمؤشر على استقرارية النظام ،حيث تم اعتماد أشارة المحدد لمصفوفة جاكوبين لتدفق الحمل لتحديد استقرار النظام، من خلال حساب القيم الذاتية (eigenvalue) ، المتجهات الذاتية (eigenvectors) ، و minimum singular value لمصفوفة جاكوبين لسريان الحمل وتحليل الاستجابة بين تدفق الطاقة وتغيرات مجمع الجهد.

تم تحليل سريان الحمل للشبكة العراقية ٤٠٠ كف باستخدام طريقة نيوتن رافسن مع وبدون .STATCOM ونتائج التحليل أظهرت تحسنا في مجمع الجهد (bus voltage) بأستخدام STATCOM في النظام.

الكلمات الرئيسة : ,Fact , Statcom, سريان الحمل , استقرارية الفولتية.

List of symbols:

FACTS: Flexible Ac Transmissions System.

ISG: Iraqi Super Grid.

STATCOM: Static Synchronous Compensator.

ΔP , ΔQ active and reactive power mismatch

ΔV , $\Delta\delta$ voltage magnitude and voltage angle mismatch

∂P , ∂Q : Partial derivatives of the real and reactive power.

∂V , $\partial\delta$: Partial derivatives of the voltage magnitude and voltage angle .

Y admittance

$\Delta P_i^{(k)}$:mismatch active power at k_{ih} bus in i iteration

$\Delta Q_i^{(k)}$: mismatch reactive power at k_{ih} bus in i iteration

εspecified accuracy for active and reactive power mismatch

J Jacobin matrix

JR reduced Jacobin matrix

ξ, η right and left eigenvector of matrix JR

Λ diagonal eigenvalue of matrix JR

λ_{ih} the i_{th} eigenvalue.

$\xi_i$the i_{th} of column right eigenvector.

η_i the i_{th} of row left eigenvector

ΔQ_{mi} i_{th} modal reactive power variation

K_i Normalization factor.

P_{ki} Participation factor of the k_{th} bus in i_{th} mode .

P_k ,Q_k active and reactive power injection at bus k.

V_k voltage at bus k

V_j voltage at bus j.

Y_{kj} admittance between bus k and bus j.

P_{STAT} STATCOM active power.

Q_{STAT} STATCOM reactive power.

$E_{STAT}\angle\delta_{STAT}$ STATCOM voltage.

Y_{STAT} STATCOM admittance.

G_{STAT}, B_{STAT} conductance and suspectance of STATCOM.

1. INTRODUCTION

Voltage control and stability problems are not new in the electric power system industry but are now receiving special attentions. Voltage stability is the ability of a power system to maintain voltage irrespective of the increase in load admittance and load power resulting in control of power and voltage [1]. A system is said to enter a state of voltage instability when a disturbance causes a progressive and uncontrollable decline in voltage, which can occur because of the inability of the network to meet the increased demand for reactive power [2], which lead in the worst case, in the collapse of the power system. Appropriate voltage and reactive power control are one of the most important factors for stable power system. Where, the distribution system losses and various power quality problems are increasing due to reactive power [3].

There are several studies [2, 4, 5] focused on measures to predict system conditions with respect to voltage stability and optimal control actions to avoid collapse in the online paradigm. As most of these problems are highly nonlinear and computationally intensive, there is a need of research to help in reducing computation and using direct measurements for estimation of stability margin. Many analysis methods [6, 7] of voltage stability determination have been developed based on the load flow solution, optimal power flow, bifurcation technique, singularity of Jacobin etc. Different voltage stability indicators have also been established covering both static and dynamic aspects of the problem. Efforts also have been made to assess the voltage stability of large power systems in terms of network equivalents to obtain the global picture of voltage stability [2].

Now, more than ever, advanced technologies are paramount for the reliable and secure operation of power systems. Power electronic based equipment, such as FACTS controllers, are the most effective way for utilities to improve voltage stability of the system with their capability to respond rapidly the system events, increase power transfer limits, and improve the quality of power delivered, constitute one of the most-promising technical advancements to address the new operating challenges being presented today [8].The Static synchronous Compensator (STATCOM) is one of the most important FACTS devices, a regulating device used on alternating current electricity transmission networks and it is based on the principle that a voltage-source inverter generates a controllable AC voltage source behind a transformer leakage reactance so that the voltage difference across the reactance produces active and reactive power exchange between the STATCOM and the transmission network [9, 10].

This paper focuses on one such FACTS controller for voltage support as a reactive power (VAR) source, namely the static compensator (STATCOM). A systematic analytical methodology based on modal analysis of the modified load flow Jacobian matrix has been used as a static voltage stability index to determine the best location for STATCOM.

2. POWER FLOW SOLUTION

A power flow or load flow program computes the voltage magnitude and angle at each bus in a power system. Once they are calculated, real and reactive power flows for all equipment interconnecting the buses, as well as losses are also computed. There are two ways to represent the bus voltage equations to solve the load flow problem, the rectangular and polar coordinates of bus voltages. It is prefer to use polar coordinates to formulate the power flow equation. As the power flow method is implemented for voltage stability analysis, the Jacobian matrix of solved load flow equations, by Newton-Raphson method, can be used. The linearized steady-state system power voltage equation is expressed as [11]:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (1)$$

The Jacobin matrix can be written as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta |V| \end{bmatrix} \qquad (2)$$

The Jacobian matrix gives the linearized relationship between small changes in voltage angle $\Delta\delta_i^k$ and the voltage magnitude ΔV_i^k with the small changes in real and reactive power mismatch ΔP_i^k and ΔQ_i^k. Elements of the Jacobian matrix are partial derivatives of the real and reactive power, evaluated at $\Delta\delta_i^k$ and ΔV_i^k.and for more details in [9, 11].

The procedure for power flow solution by the Newton-Raphson method is as follows:

1. Read system and load data (including identified the slack bus, generator bus (PV) bus, and load bus PQ).

2. Form the nodal admittance matrix [Y].

3. Initialize δ, V

4. Calculate ΔP and ΔQ.

5. Calculate Jacobian matrix (2. through 1).

6. Solve for the voltage angle and magnitude.

7. Update the voltage magnitude and angles.

8. Check the stopping conditions. If met then terminate, else go to step 3.

$$\left|\Delta P_i^{(k)}\right| \leq \varepsilon$$
$$\left|\Delta Q_i^{(k)}\right| \leq \varepsilon$$

To express the relation between ΔQ and ΔV

For small change in real power ΔP=0 is assumed

So that equation (2) leads to be:

$$\Delta P = 0 = J_{11}\Delta\delta + J_{12}\Delta V$$

$$\Delta\delta = -J_{11}^{-1}J_{12}\Delta V \qquad (3)$$

And $\Delta Q = J_{21}\Delta\delta + J_{22}\Delta V$ (4)

Substituting Equation (3) in Equation (4):

$$\Delta Q = (J_{22} - J_{21}J_{11}^{-1}J_{12})\Delta V \qquad (5)$$

The expression in the brackets in (5) represents the reduced Jacobian matrix J_R of the system. It relates the bus voltage magnitude and reactive power injection.

The eigenvalues and eigenvectors of the reduced order Jacobin matrix J_R are used for the voltage stability characteristics analysis. Voltage instability can be detected by identifying modes of the eigenvalues matrix J_R. The magnitude of the eigenvalues provides a relative measure of proximity to instability. The eigenvectors on the other hand present information related to the mechanism of loss of voltage stability.

Let assume

$$J_R = J_{22} - J_{21}J_{11}^{-1}J_{12} = \xi.\Lambda.\eta \qquad (6)$$

Where:

ξ= right eigenvector matrix of J_R

η = left eigenvector matrix of J_R

Λ = diagonal eigenvalue matrix of J_R.

Equation (6) can be written as:

$$J_R^{-1} = \xi \Lambda^{-1} \eta \tag{7}$$

Using equation (1) and (2) the incremental changes in reactive power and voltage are related by:

$$\Delta V = J_R^{-1} \Delta Q = \xi \Lambda^{-1} \eta \, \Delta Q \tag{8}$$

Or

$$\Delta V = \sum_i \frac{\xi \eta}{\lambda_i} \Delta Q \tag{9}$$

Where λ_i is the i^{th} eigenvalue, $\xi_i$is the i^{th} of column right eigenvector and η_i is the i^{th} of row left eigenvector of matrix J_R.

λ_i ,ξ_i, and η_I define the i $_{th}$ mode of the system.

The i^{th} modal reactive power variation is:

$$\Delta Q_{mi} = K_i \xi_i \tag{10}$$

Where K_i is a normalization factor The appropriate definition and determination as to which node or load bus participates in the selected modes become very important. This necessitates a tool, called the participation factor, for identifying the weakest nodes or load buses that are making significant contribution to the selected mode and is suitable for STATCOM placement. If ξ and η represent the right and left hand eigenvectors, respectively, for the eigenvalue λi of the matrix *JR*, then the participation factor measuring the participation of the k_{th} bus in i_{th} mode is defined as [11,12]:

such that

$$K_i^2 \sum_j \xi_{ji}^2 = 1 \tag{11}$$

With ξ_{ji} the J^{th} element of ξ_i

The corresponding i^{th} modal voltage variation can therefore be written as:

$$\Delta V_{mi} = \frac{1}{\lambda_i} \Delta Q_{mi} \tag{12}$$

$$P_{ki} = \xi_{Ki} . \eta_{ki} \tag{13}$$

3. STATCOM – STATIC SYNCHRONOUS COMPENSATOR

The STASTCOM is one of the important shunt connected 'Flexible AC Transmission system' consisting of a power electronics device connected with a capacitor or reactance. A step down transformer, called coupling transformer, is needed to reduce the voltage level of the bus where the STATCOM is installed as shown in the **Figure (1)** [13].

It regulates the voltage at its terminals in power system, having as an ultimate goal the increase in transmittable power, and improvements of steady state transmission characteristics and of the overall stability of the system. Under light load conditions, the controller is used to minimize or completely diminish line over voltage; on the other hand, it can be also used to maintain certain voltage levels under heavy loading conditions [14].

Some papers discuss how to model STATCOM for load flow calculation. So, The bus at which the STATCOM is connected is represented as a PV bus , which may change to a PQ bus in the events of limits being violated depending on its primary application.. In such a case, the generated or absorbed reactive power would correspond to the violated limit, the STATCOM is represented as a voltage source for the full range of operation, enabling a more robust voltage support mechanism. In a load flow calculation, a STATCOM is typically treated as a shunt reactive power controller assuming that it can adjust its injected reactive power to control the voltage at the STATCOM terminal bus [11, 15]. This means that the STATCOM absorbs proper amount of reactive power . The power system to keep V_k constant for all power system loading within reasonable range, the ohmic loss of the STATCOM is accounted by considering the real part of Y_{stat}in power flow calculations. The net active/reactive power injection at bus k including the local load, before addition of the STATCOM, is known by P_k+jQ_k. The power flow equations of the system with STATCOM connected to Bus $_k$, can written as [16]:

$$P_k = P_{stat} + \sum_{j=1}^{N} |V_k| |V_j| |Y_{kj}| \cos(\delta_k - \delta_k - \theta_{kj}) \quad (14)$$

$$Q_k = Q_{stat} + \sum_{j=1}^{N} |V_k| |V_j| |Y_{kj}| \sin(\delta_k - \delta_k - \theta_{kj}) \quad (15)$$

$$P_{stat} = G_{stat} + |V_k|^2 - |V_k||E_{stat}||Y_{stat}| \cos(\delta_k - \delta_{stat} - \theta_{stat}) \quad (16)$$

$$Q_{stat} = B_{stat} + |V_k|^2 - |V_k||E_{stat}||Y_{stat}| \sin(\delta_k - \delta_{stat} - \theta_{stat}) \quad (17)$$

For more detail in [16].**Figure (2)** depicts a STATCOM and the traditional simple model used in this paper for load flow calculation. In this model reactive power load at bus i, jQi, is combined with STATCOM reactive power output[11, 15], and **Figure (3)** show the flow chart for Power Flow Solution by Newton-Raphson with STATCOM.

4. CASE STUDY

The Iraq super grid transmission line is large system having two voltage levels 400Kv and 132Kv; the network under consideration in this work is the 400Kv super grid (ISG).

This network contains twenty four bus bar connecting with fourteen transmission line. The generation unit in the system are distributed at the twelve buses for the grid. The single line diagram ISG for is shown in the **Figure (4).** The bus data with power demand, generation are given in the data information illustrated in **table (1)**. **Table (2)** presents the load flow output results by using Newton-Raphson method. The system has one swing bus and eleven P-V bus so the total number eigenvalue of the reduced Jacobin matrix (J_R) is expected to be (12), After employing eigenvalues at each load level, the buses are ranked in the order of the value of participation factor for these buses: the top ranked bus in the priority list has the greatest participation factor and refers as the weakest from others. The results of the eigenvalues and the participation factor are tabulated in the **tables (3).** Note from the table all the Eigenvalues are positive which means that the system voltage is stable. **Figure (5)** shows the participating factor for the minimum Eigenvalues of the system. It can be seen that the bus (19), (18) and (15) bus have the highest participation factor value to the critical mode. So, the most optimal bus to install STATCOM are buses 19, 18 and 15 respectively, 24-bus test system is used to assess the effectiveness of STATCOM model developed in this paper. The voltage profile of all buses without STATCOM is described in **Figure (6).** It can be seen that all the bus voltage are within the acceptable level (±5%), the lowest voltage compared to the other buses can be noticed in bus number 24. The voltage profile of all buses with statcom installation at bus 19 and 15 also shown in **Figure (6).**

5. CONCLUSION

STATCOM devices present an effective device in employing for voltage stability enhancement. The load flow studies are carried out with and without STATCOM and Newton-Raphson method is used in Load flow. Due to the high cost of FACTS controllers which improves voltage stability, FACTS Devices installed localization studies is important to prevent additional costs. In this paper modal analysis algorithm for optimal location of STATCOM was used. The modal analysis provided important information about the proximity of the system to voltage instability.
The results showed that the STATCOM can be used to improve an overall network voltage profile in practical power systems. Additionally, in general more reactive power was available in

the network with STATCOM installed than without. The STATCOM and the detailed simulation are performed using Matlab program.

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Table (1): bus data information for ISG

Bus No.	Bus Name	Voltage (P.U.)	Angle (degree)	Generation		Load	
				MW	MVAR	MW	MVAR
1.	MUSP	1.04	0.0	-	-	1.997795	1.166333
2.	MMDH	1.015	0.0	690.1	0	000	0
3.	BAJP	1.02	0.0	406.0	0	124.8622	92.2467
4.	BAJG	1.02	0.0	590.458	0	0	0
5.	KRK4	1.017	0.0	239.87	0	129.8567	10.4896
6.	MUSG	1.02	0.0	369.04	0	0	0
7.	HDTH	1.02	0.0	202.97	0	200.0540	50.612
8.	QDSG	1.01	0.0	735.305	0	0	0
9.	KAZG	1.0096	0.0	207.583	0	200.0419	100.6579
10.	HRTP	1.01	0.0	332.133	0	154.8291	72.1171

11.	NSRP	1.02	0.0	775.0	0	422.8665	100.3219
12.	DYL4	1.00	0.0	0	0	83.2415	21.1712
13.	BGW4	1.00	0.0	0	0	576.031	302.4481
14.	BGN4	1.00	0.0	0	0	412.8776	139.1261
15.	BGE4	1.00	0.0	0	0	849.0627	294.6579
16.	QIM4	1.00	0.0	0	0	109.8787	39.3182
17.	BGC4	1.00	0.0	0	0	49.9449	181.4688
18.	BGS4	1.00	0.0	0	0	0	0
19.	AMN4	1.015	0.0	184.518	0	126.5640	56.0014
20.	MSL4	1.00	0.0	0	0	649.2833	302.4481
21.	BAB4	1.00	0.0	0	0	307.9934	184.6695
22.	KDS4	1.00	0.0	0	0	213.0981	151.4458
23.	KUT4	1.00	0.0	0	0	259.7134	108.1756
24.	AMR4	1.00	0.0	0	0	311.0221	160.3709

Table (2): bus solution for ISG

Bus No.	Voltage (P.U.)	Angle (degree)	Generation		Load	
			MW	MVAR	MW	MVAR
1.	1.04	0	679.69	2422.66	1.997795	1.166333
2.	1.015	8.4837	690.1	58.06	000	0
3.	1.02	5.7762	406.0	-35.98	124.8622	92.2467
4.	1.02	5.8258	590.458	-65.46	0	0

5.	1.017	4.5233	239.87	-76.88	129.8567	10.4896
6.	1.02	0.2260	369.04	-2016.6	0	0
7.	1.02	1.9	202.97	-40.51	200.0540	50.612
8.	1.01	-0.8491	735.305	136.84	0	0
9.	1.0096	-3.4122	207.583	-4.77	200.0419	100.6579
10.	1.01	-4.0027	332.133	87.22	154.8291	72.1171
11.	1.02	-1.480	775.0	-48.14	422.8665	100.3219
12.	1.015	-1.3931	184.518	207.65	126.5640	56.0014
13.	1.0038	-0.8865	0	0	83.2415	21.1712
14.	1.0085	-1.1285	0	0	576.031	302.4481
15.	1.0086	-1.6927	0	0	412.8776	139.1261
16.	1.0163	0.4494	0	0	849.0627	294.6579
17.	1.0045	-0.8865	0	0	109.8787	39.3182
18.	1.0202	-0.8152	0	0	49.9449	181.4688
19.	1.0118	-0.9587	0	0	0	0
20.	1.0053	6.2414	0	0	649.2833	302.4481
21.	1.0334	-0.8086	0	0	307.9934	184.6695
22.	1.0274	-1.6149	0	0	213.0981	151.4458
23.	1.0018	-7.107	0	0	259.7134	108.1756
24.	0.9899	-8.048	0	0	311.0221	160.3709

Table (3): eigenvalue and participation factor magnitude for ISG

Bus number	Eigen value	Participation factor
13	2109.374	$1.583*10^{-12}$
14	906.961	$1.146*10^{-9}$
15	684.1398	$1.050*10^{-8}$
16	473.233	$8.6997*10^{-9}$
17	449.863	$8.687*10^{-21}$
18	119.394	$1.168*10^{-6}$
19	134.423	$3.523*10^{-6}$
20	130.824	$1.379*10^{-20}$
21	77.0474	$3.334*10^{-10}$
22	30.662	$1.971*10^{-10}$
23	224.595	$7.685*10^{-20}$
24	41.712	$2.552*10^{-19}$

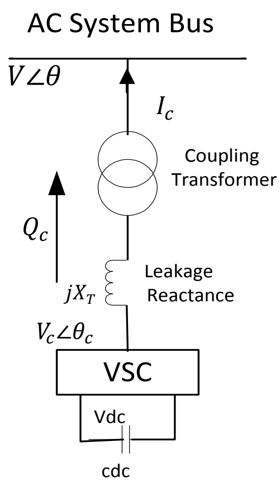

Figure. (1). STATCOM Configuration

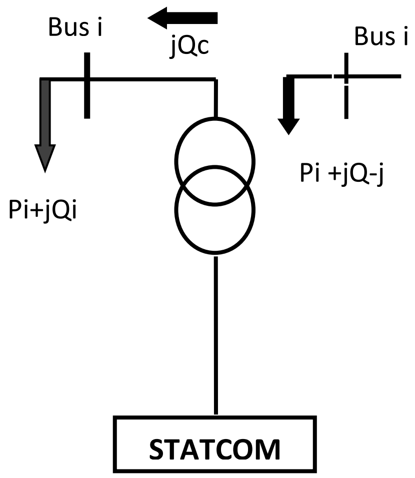

Figure (2): Model of STATCOM in load flow calculation

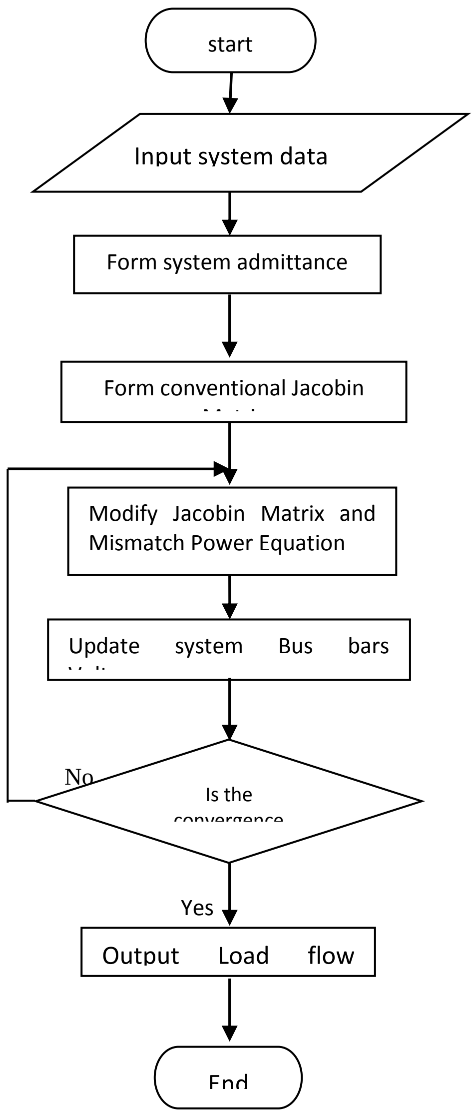

Figure (3): Power Flow Solution by Newton-Raphson with STATCOM

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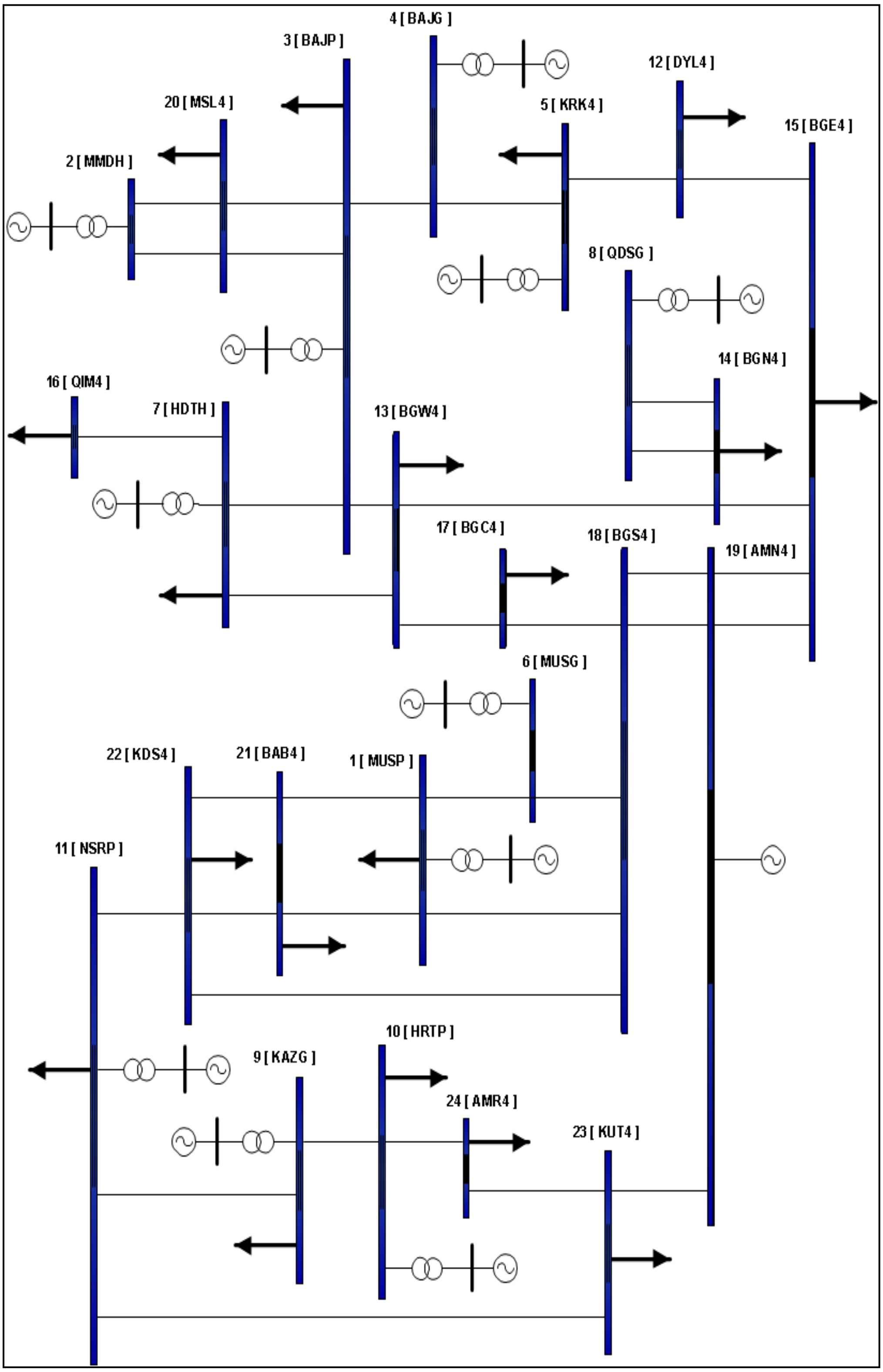

Figure (4): Configuration of the ISG

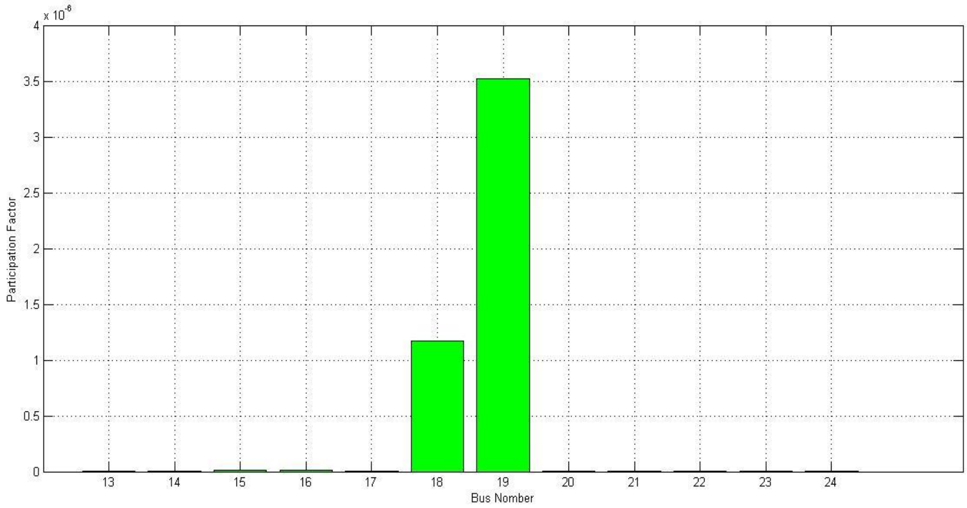

Figure (5): the participating factor profile for the minimum Eigenvalues of the ISG

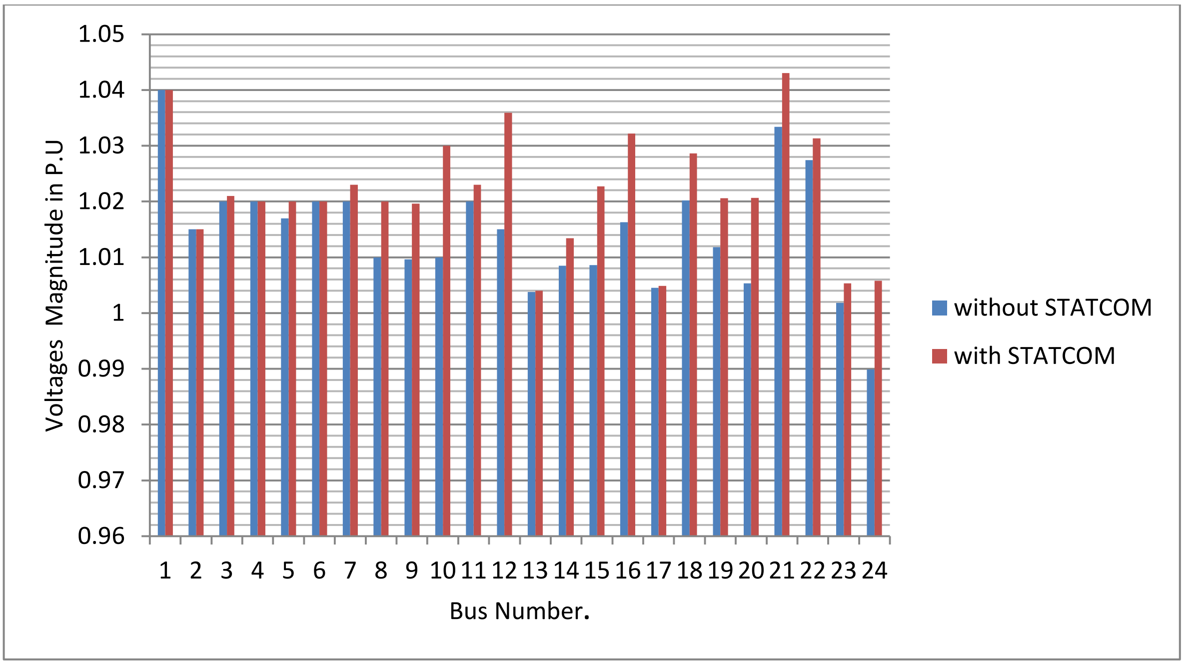

Figure (6): voltage of all buses with and without STATCOM.