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Reactive Power Control using STATCOM for Power System Voltage Improvement

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ABSTRACT

Stability of power system is the ability of the system, with a certain initial operation conditions, to restore the operating balance conditions after exposure to disturbance such as faults or sudden load changes. More attention is required to address voltage instability problems to keep voltage profile under control during abnormal conditions. This paper proposes a Static Synchronous Compensator (STATCOM) using (MATLAB / Simulink Program) The STATCOM includes proportional-integral (PI) control model is used to control the voltage during abnormal conditions by absorbing or injecting reactive power into the power system. Simple and reliable PI controller has been used and designed to be stable under various operating conditions. Three phase Two level PWM strategy technic used in STATCOM controller to decrease the harmonics injected after adding STATCOM to the power system (THD = 2.21%). The simulation study has been done by using 9 buses IEEE system after making a disturbance such as sudden load change. Then the voltage profile during this interval is being studied with and without using STATCOM. The simulation results show that adding STATCOM to this system led to improve the voltage profile during disturbance interval and made the system more stable and reliable by preventing the disturbance effects from reaching the generation side (Vbus 5 = 0.8980 pu, during disturbance before adding STATCOM, Vbus 5 = 1.0003 pu, during disturbance after adding STATCOM*). The fast response of the STATCOM controller gives the ability of injecting or absorbing reactive power during disturbances and keeping the system voltages within the IEEE standards limits (0.95 pu <V< 1.05 pu).*

Keywords:

FACTS, STATCOM, Power System Stability, Reactive Power Compensation.

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1. INTRODUCTION

Power system is a complex grid which consists of generators, transformers, transmission lines and different loads. Increased in power demand led to increase the load on the transmission lines and this will cause the power system to run at its thermal limits [1]. Increased in voltage stability and control in some power systems of operating and planning have become a limiting factor. Adding a new transmission line is very complex and depends on too many factors so the new researches focused on inserting new devices to the transmission lines to increase the capability of the transmitted power and make the transmission line more flexible instead of installing a new transmission line. Flexible Alternating Current Transmission System (FACTS) is a power system supported with new devices to make the system more flexible by controlling all variables of the system such as voltage, current, impedance and phase angle [2].

STATCOM is one of the FACTS devices and is connected in parallel with the power system via leakage reactance. The ability of fast response in absorbing or injecting reactive power into the system during disturbances made the STATCOM is the most suitable device to control the reactive power in power system. The working principle of the STATCOM is that the voltage source inverter produces controlled AC voltage in primary side of transformer-leakage reactance. The potential difference between two sides of the reactor, work to exchange active and reactive power between the STATCOM and the power system. Several, STATCOM dynamic experiments, were implemented to arrive at an appropriate design in enhancing voltage to improve the voltage profile of power system [3].

2. STATCOM

2.1. Principle of Operations

The principle of operation of the STATCOM is generating a three-phase voltage close to the sinusoidal waveform. The AC voltage generated in STATCIM depends on the DC side regulated by DC capacitor or energy source which controlled by a suitable control strategy to maintain a fast response and decrease the injected harmonics into the power system. Inserted FACTS devices into power system lead to inject harmonics in that system and to decrease the injected harmonics many control strategies have been studied and implemented to keep these harmonics within the permission limits [4]. Figure 1 shows some of those strategies to reduce the total harmonic distortion after adding FACTS devices [5].

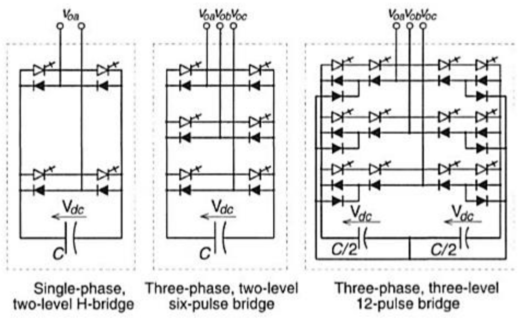

Fig. 1 Voltage Source Converter modeling for Reactive power compensation [6]

2.2. Modes of Operation

There are three modes of operation in STATCOM:

Mode (I): if ($V_1 < V_2$) the STATCOM works as a capacitor.

Mode (II): if ($V_1 > V_2$) the STATCOM works as an inductor.

Mode (III): if ($V_1 = V_2$) the STATCOM is floating in this mode because no reactive power exchanged between the two nodes. Figure 2 explain the modes of operation of STATCOM [7].

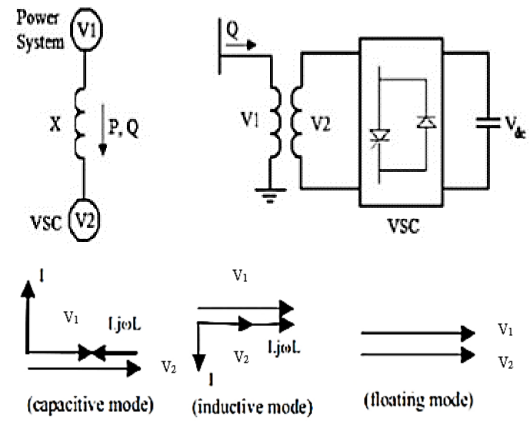

Fig.2 STATCOM Modes of operation

Where:
P: Active Power.
Q: Reactive Power.
V_1: System Voltage.
V_2: Voltage Source Converter (VSC) Output Voltage.
X: Reactance of the Coupling Transformer.
δ: Phase Shift between the Voltage V_1 and V_2.

The output active/reactive power transferred between the system and the VSC can be expressed by equation 1 and 2 respectively [8].

$$P = \frac{V_1 V_2}{X} \sin\delta \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$Q = \frac{V_1 V_2}{X} \cos\delta - \frac{V_1^2}{X} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

3. STATCOM MODEL

3.1. System Configuration

The equivalent circuit of adding STATCOM to AC power system is shown in figure 3. where:

v_a , v_b and v_c represent the three phase voltages at system side.

e_a , e_b and e_c represent the three phase output voltages at Inverter side.

i_a , i_b and i_c are the three phase Inverter output currents.

L is the transformer leakage inductance.

R is the series resistance with the voltage source converter (VSC) and it is representing the summation of the inverter losses and the transformer winding resistance losses.

Rs is the parallel resistance with the capacitor and it is representing the summation of the power losses in the capacitor and the switching losses of the inverter [9].

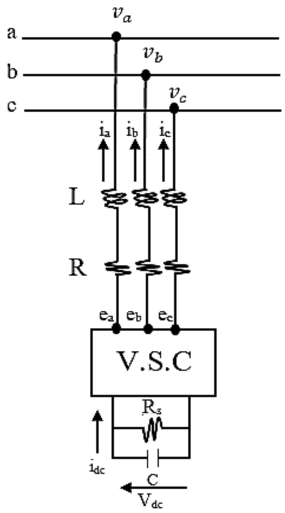

Fig.3 The equivalent circuit of adding STATCOM to AC power system

3.2. Dynamic Equations of the STATCOM

From figure 3 and by taking KVL equation it can be obtained.

$$v_a - e_a = R^* i_a + L^* \frac{di_a}{dt} \quad (1)$$

$$v_b - e_b = R^* i_b + L^* \frac{di_b}{dt} \quad (2)$$

$$v_c - e_c = R^* i_c + L^* \frac{di_c}{dt} \quad (3)$$

The equations above can be written in matrix form as follows:

$$p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & 0 & 0 \\ 0 & \frac{-R}{L} & 0 \\ 0 & 0 & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v_a - e_a \\ v_b - e_b \\ v_c - e_c \end{bmatrix} \quad (4)$$

Where $p = \frac{d}{dt}\ operator$

Converting equation 4 from abc axis to dq axis using park transformation (equation 5).

$$[c] = \frac{2}{3} \begin{bmatrix} \cos\phi & \cos\left(\phi - \frac{2\pi}{3}\right) & \cos\left(\phi + \frac{2\pi}{3}\right) \\ -\sin\phi & -\sin\left(\phi - \frac{2\pi}{3}\right) & -\sin\left(\phi + \frac{2\pi}{3}\right) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \quad (5)$$

Where the angle ϕ is the angle between (d-axis) and the phase a-axis of the abc coordinate.

After using the equation 5, it can be converting abc-axis to dq-axis. The relation between two axes is define as follow [10]:

$$[c]^{-1} = \frac{3}{2}[c]^T \ , \qquad \begin{bmatrix} i_d \\ i_q \\ 0 \end{bmatrix} = [c] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix},$$

$$\begin{bmatrix} e_d \\ e_q \\ 0 \end{bmatrix} = [c] \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix}, \begin{bmatrix} |v| \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix}$$

Converting equ. 4 from abc-axes to dq axes by park transformation equation (equ. 5).

$$p \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \frac{-R}{L} & w \\ -w & \frac{-R}{L} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{w}{L} \begin{bmatrix} V_d - e_d \\ V_q - e_q \end{bmatrix} \quad (6)$$

Where $w = \frac{d\phi}{dt}$

Inverter DC side equation can be written as:

$$pV_{dc} = \frac{1}{C}(i_s - i_{dc})$$

$$= \frac{1}{R_s \cdot C}(V_s - V_{\text{dc}}) - \frac{1}{C} i_{dc} \quad (7)$$

Instantaneous power on the AC side of the inverter is calculated by:

$$P_{ac} = e_a i_a + e_b i_b + e_c i_c \quad (8)$$

The relationship between the direct abc - axes and dq - axes is shown in figure 4. From this figure and after transforming the abc frame to dq frame can be obtained:

$$P_{ac} = \frac{3}{2}\left(e_d i_d + e_q i_q\right) \quad (9)$$

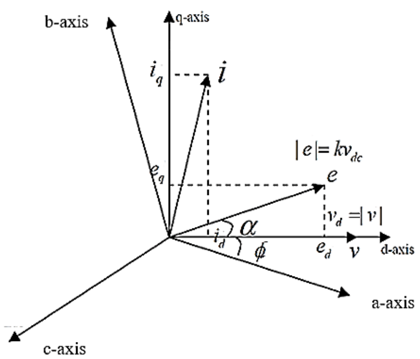

Fig. 4 Vector diagram of phase and dq voltages

Active power on the DC side of the inverter is calculated by:

$$P_{dc}=V_{dc}i_{dc} \quad (10)$$

Assume instantaneous power exchange between AC and DC side of the inverter is equal after neglecting the losses inside the inverter, equation 11 must hold:

$$P_{ac} = P_{dc}$$

$$V_{dc}i_{dc} = \frac{3}{2}\left(e_d i_d + e_q i_q\right) \quad (11)$$

So,

$$i_{dc} = \frac{3}{2}\left(\frac{e_d i_d + e_q i_q}{V_{dc}}\right) \quad (12)$$

Assuming d-axis coincides with the voltage vector, that is means, $V_d = |v|$, and V_q becomes zero. Neglecting the voltage harmonics produced by the inverter, one can write the pair of equation for e_d and e_q.

When the STATCOM inverter operates in SPWM mode, then the inverter output voltage of must satisfy the following equations

$$e_d = KV_{dc}\,\mathrm{M}\cos\alpha$$
$$e_q = KV_{dc}\,\mathrm{M}\sin\alpha \quad (13)$$

M and α in equation (13) represent the modulation index and the firing angle of the sinusoidal reference wave referring to the system voltage vector, while K is a factor which relates the DC side Voltage to the peak of the phase to neutral voltage at AC side of the inverter and depends on number of pulses used in converter.

Combining equ. 7 with equ. 6 and substituting them by equ. 12 and equ. 13, a dynamic model of the STATCOM can set up as:

$$p\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} = [A]\begin{bmatrix} i_d \\ i_q \\ V_{dc} \end{bmatrix} + \begin{bmatrix} \frac{V_{dc}}{2L}\mathrm{M}\cos\alpha \\ \frac{V_{dc}}{2L}\mathrm{M}\sin\alpha \\ -\frac{3i_d}{4C}\mathrm{M}\cos\alpha - \frac{3i_q}{4C}\mathrm{M}\sin\alpha \end{bmatrix} + \begin{bmatrix} -\frac{|v|}{L} \\ 0 \\ \frac{V_S}{R_S C} \end{bmatrix} \quad (14)$$

Where

$$[A] = \begin{bmatrix} -\frac{R}{L} & \omega_0 & 0 \\ -\omega_o & -\frac{R}{L} & 0 \\ 0 & 0 & -\frac{1}{R_s C} \end{bmatrix}$$

Converting equ. 14 to a linear system form as shown in equation 15 [10].

$$p\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta V_{dc} \end{bmatrix} = [A_o]\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta V_{dc} \end{bmatrix} + [B_o]\begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix} \quad (15)$$

Where

$$\begin{bmatrix} \Delta i_d \\ \Delta i_q \\ \Delta V_{dc} \end{bmatrix} = \begin{bmatrix} i_d - i_{do} \\ i_q - i_{qo} \\ V_{dc} - V_{dco} \end{bmatrix}, \quad \begin{bmatrix} \Delta M \\ \Delta\alpha \end{bmatrix} = \begin{bmatrix} M - M_0 \\ \alpha - \alpha_0 \end{bmatrix}$$

And

$$[A_0] = \begin{bmatrix} -\frac{R}{L} & \omega_0 & \frac{M_0\cos\alpha_0}{2L} \\ -\omega_0 & -\frac{R}{L} & \frac{M_0\sin\alpha_0}{2L} \\ -\frac{3M_0\cos\alpha_0}{4C} & -\frac{3M_0\sin\alpha_0}{4C} & -\frac{1}{R_s C} \end{bmatrix}$$

$$[B_0] = \begin{bmatrix} \frac{V_{dc0}\cos\alpha_0}{2L} & -\frac{V_{dc0}M_0\sin\alpha_0}{2L} \\ \frac{V_{dc0}\sin\alpha_0}{2L} & \frac{V_{dc0}M_0\cos\alpha_0}{2L} \\ -\frac{3(i_{d0}\cos\alpha_0 + i_{q0}\sin\alpha_0)}{4C} & \frac{3M_0(i_{d0}\sin\alpha_0 - i_{q0}\cos\alpha_0}{4C} \end{bmatrix}$$

Where $[\Delta i_d\ \Delta i_q\ \Delta V_{dc}]^T$ are state space variables vectors, and $[\Delta M\ \Delta\alpha]^T$ are the control variables.

The conventional control strategy can be specific, based on the equation (15) and the block diagram of STATCOM controller is shown in figure 5. The phase locked loop (PLL) coincides with the three-phase positive sequence component of the initial component of the phase voltage. [10].

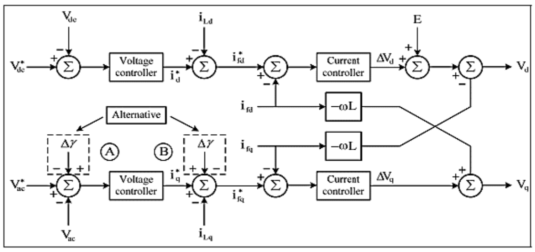

Fig. 5 STATCOM Controller

4. RESULTS AND DISCUSSION

Sudden load change and repeated faults in the network led to instability in the power system, as well as decreasing the voltage at system buses. MATLAB / Simulink program used to simulate the system then find out the weak bus in the system and modify it using STATCOM to enhance the voltage profile and improve the system stability. In this work a sudden load change introduced to IEEE 9-buses system near Bus 5. The system studied under two cases, without and with STATCOM.

Case A: IEEE 9-busbars system without STATCOM.
Case B: IEEE 9-busbars system with STATCOM.

Case A: IEEE 9-Busbars System without STATCOM.

sudden load change added to the system near bus 5 as shown in Figure 6. The voltage at system buses during the interval of disturbance is shown in table 1 and figure 7. Adding this disturbance to the system led to decrease the voltage at system buses especially bus 5, it is clear from the results that bus 5 is the weakest bus in the system, with a voltage of 0.8980 p.u, this value of the bus voltage is not accepted depends upon IEEE standard limits (0.95 <V <1.05) p.u.

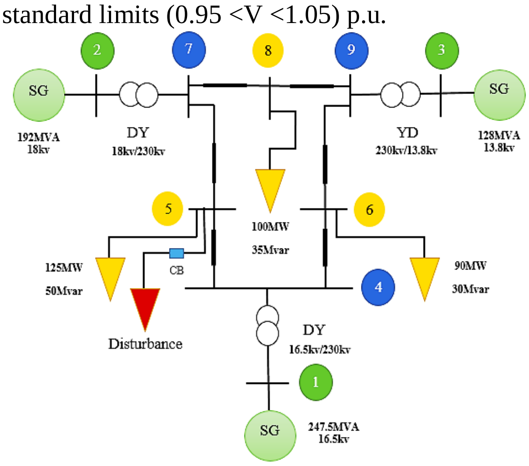

Fig.6 Simulink model of IEEE 9-bus system

Table 1: Load flow results of IEEE 9-bus system without STATCOM

Bus	Voltage (p.u)	PLOAD (MW)	QLOAD (MVAR)
Bus 4	0.9736	0	0
Bus 5	0.8980	125	50
Bus 6	0.9581	90	30
Bus 7	0.9556	0	0
Bus 8	0.9513	100	35
Bus 9	0.9747	0	0

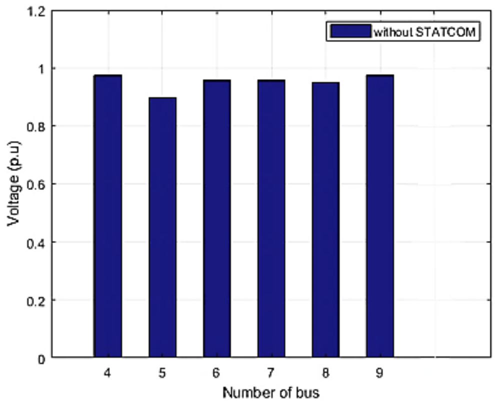

Fig.7 System buses voltages (p.u) during disturbance interval without STATCOM

Case B: IEEE 9-Bus System with STATCOM.

In this case, STATCOM added to the standard power system after adding sudden load change near bus 5 as shown in figure. 8, where the results of the system buses voltages are shown in table 2 and figure 9. Adding STATCOM to the system enhanced the system voltage profile during the interval of disturbance. The fast response of STATCOM with suitable control strategy made the system more stable during abnormal conditions.

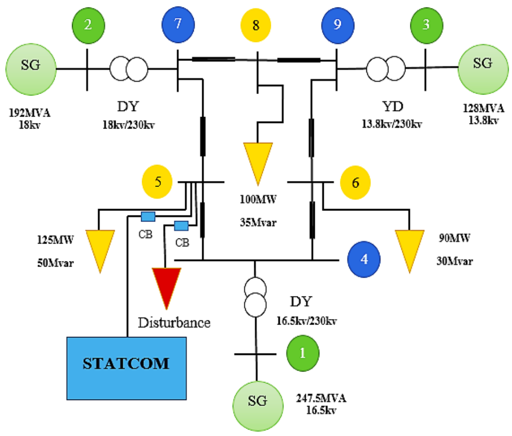

Fig. 8 Simulink model of IEEE 9-bus System with STATCOM

Table 2: Load flow of IEEE 9-bus System with STATCOM

Bus	Voltage (p.u)	PLOAD (MW)	QLOAD (MVAR)
Bus 4	1.0248	0	0
Bus 5	1.0003	125	50
Bus 6	1.0100	90	30
Bus 7	1.0171	0	0
Bus 8	1.0082	100	35

Bus 9	1.0269	0	0

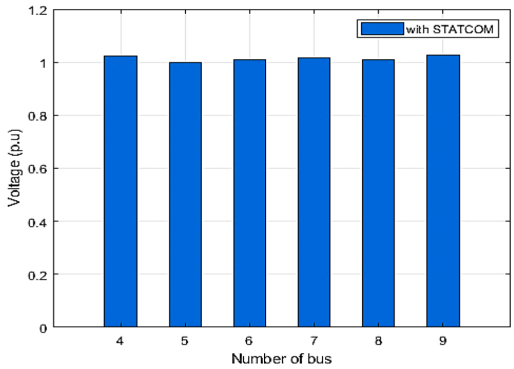

Fig.9 Buses Voltages (p.u) of power system with STATCOM during disturbance interval

It is easier to see the difference between the two cases by combination the results of the two cases in one figure such as shown in figure 10.

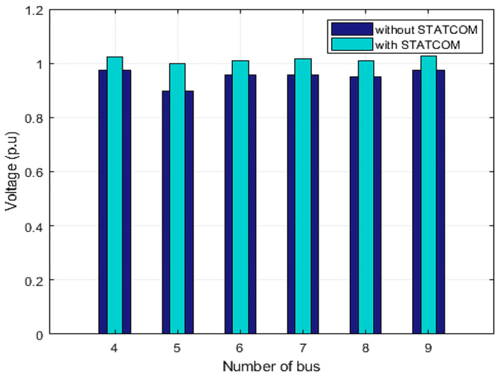

Fig.10 System buses Voltages (p.u) during the interval of disturbance without and with STATCOM

The STATCOM active and reactive power during the disturbance is shown in Fig. 11. The STATCOM added to the system at t = 2Sec where the sudden load change added during the interval (5-9) Sec. The fast response of the STATCOM to inject instantaneous reactive power into the system during the disturbance led to compensate the voltage drop at system buses instantaneously and enhanced the voltage profile of the power system. The STATCOM DC-side is supported with capacitor so no active power exchange between the system and STATCOM.

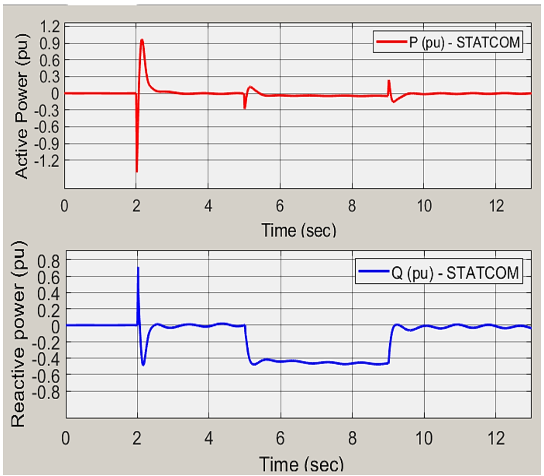

Fig. 11 STATCOM Active and Reactive power

The modulation index during the disturbance period is shown in Figure 12. The modulation index increased from (0.71) to (0.73) during the period (5-9) seconds, which represents the period of adding disturbance. The static synchronous compensator senses the drop in voltage at the point of common connection (pcc) and gives a signal to the STATCOM controller, which increase the modulation index and inject reactive power into the system to compensate the drop of the voltage.

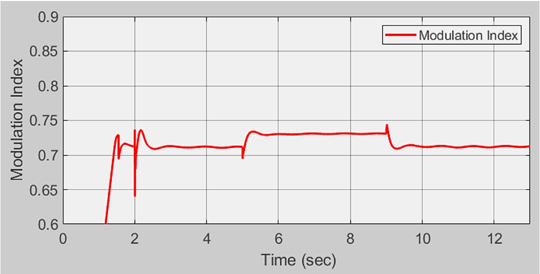

Fig. 12 Modulation index

5. CONCLUSION

In this article STATCOM has been proposed to improve the voltage profile of power system. The main feature of the STATCOM is the compensation of reactive power, so it can simultaneously compensate for the sag and its amplification by injecting or absorbing the reactive current through the transformer connected between the system and the STATCOM. The simulation is performed using (MATLAB / Simulink). Reactive power is inversely proportional to the magnitude of bus voltage. Increase in load reactive power on a bus stresses the particular bus and increase the voltage drop at bus, if this drop continues the particular bus will collapse. Adding sudden load to the system led to decrease the voltage at all system buses especially bus 5 (0.8980 p. u). this value of voltage is not accepted depends on IEEE standards limits (0.95 - 1.05) pu. Adding STATCOM to that system under same conditions led to enhance the voltage stability of the system where the voltage at bus 5 became 1.0003 pu. The fast response of STATCOM controller and capability of instantaneous reactive power compensation make the power system more stable and reliable during abnormal conditions. Harmonics injected into the power system has been decreased using PWM technque in STATCOM controller (THD = 2.21%). Converter losses has been neglected in this work by assuming that the switch device is an ideal switch.

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التحكم في القدرة المتفاعلة باستخدام المعوض المتزامن الساكن لتحسين فولتية نظام القدرة

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جامعة الموصل - كلية الهندسة - قسم الهندسة الكهربائية

الملخص

تعرف استقرارية نظام القدرة الكهربائية على انها قابلية النظام، تحت ضروف تشغيل معينة، على استعادة التوازن بعد تعرضه الى اضطراب معين مثل الاعطال او التغييرات المفاجئة في الحمل. اصبح من الضروري زيادة الاهتمام بمعالجة مشاكل عدم استقرار الفولتية في انظمة القدرة الكهربائية للحفاظ على ملف تعريف الجهد اثناء الضروف غير الطبيعية. تم في هذا البحث تصميم معوض متزامن ساكن باستخدام برنامج MATLAB/Simulink *حيث تضمن المعوض المتزامن الساكن دوائر السيطرة* (PI Controller) *للتحكم بفولتية النظام خلال فترة الاضطراب عن طريق حقن او امتصاص قدرة متفاعلة من نظام القدرة. استخدم المتحكم التناسبي التكاملي* (PI controller) *في هذا البحث لبساطته والموثوقية العالية التي يتمتع بها، كما صممت وحدة التحكم تلك لتكون مستقرة في ظل ظروف التشغيل المختلفة. استخدم مغير ذي مستويين مع طريقة تضمين عرض النبضة لتقليل قيم التوافقيات المحقونة بعد اضافة المعوض المتزامن الساكن الى نظام القدرة* (THD=2.21%)*. تم تنفيذ المحاكاة من خلال دراسة نظام قدرة قياسي* IEEE 9 Bus System *بعد ادخال اضطراب فجائي في الحمل الى المنظومة عند العمومي رقم 5 ثم دراسة تأثير الاضطراب على فولتيات عموميات المنظومة قبل وبعد اضافة المعوض المتزامن الساكن. اظهرت نتائج المحاكاة ان اضافة المعوض المتزامن الساكن الى نظام القدرة ادى الى تحسين ملف الفولتية في ذلك النظام خلال فترة دخول الاضطراب مما زاد من استقرارية وموثوقية نظام القدرة، وذلك من خلال منع تأثيرات الاضطراب من الوصول الى المولدات التزامنية، حيث اصبحت قيمة الفولتية عبر العمومي رقم 5 مساوية الى* (1.0003 pu) *اثناء وجود الاضطراب والمعوض المتزامن الساكن بينما كانت تلك القيمة مساوية الى* (0.8980 pu) *بوجود الاضطراب وغياب المعوض المتزامن الساكن. ان سرعة الاستجابة للمتحكم الخاص بالمعوض المتزامن الساكن وقابليته على حقن او امتصاص القدرة المتفاعلة انيا ادى الى الحفاظ على قيم الفولتيات عبر عموميات النظام، خلال فترة حدوث الاضطراب المفاجئ، ضمن الحدود المسموح بها حسب معيار* IEEE *(0.95 pu) <V<(1.05 pu).*

الكلمات الدالة :

انظمة نقل التيار المتناوب المرنة، المعوض المتزامن الساكن، استقرارية نظام القدرة، تعويض القدرة المتفاعلة.