ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 7, Issue 1, July 2017

Transient Stability Improvement of Multi-machine Power Systems Using Modern Energy Storage Systems

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Abstract— ***Transient stability is the ability of power system to maintain synchronism when subjected to a severe disturbance such as three phase fault on transmission line or large increase in load or loss of large load as a result of a separation in one of the transmission lines in the system. The energy storage systems represented by Static Var Compensator (SVC) and Solar Photo-voltaic Generator (PVG) are used to improve the transient stability of the power system. It regulates voltage at its terminal by controlling the amount of reactive power injected into or absorbed from power system.***

In this paper, the ability of energy storage systems to improve the transient stability has been studied. The multi-machine system was studied and IEEE 3-machine 9 bus system is taken as case study. The simulation is carried out using PSAT software. At the beginning the system has been simulated under three phase fault and then under sudden changes in load levels as a result of separation occurs in one of the transmission lines and without energy storage systems. Then energy storage system is installed in the system and its ability to enhance the transient stability has been investigated.

Keywords: **Multi-machine Power Systems, Transient Stability Improvement, Modern Energy Storage Systems and PSAT software.**

I. INTRODUCTION

Stability is the most significant feature needed in the modern power system. Stability problem in power system has been noticed during the recent years, because of the fast growth in electric and electronic loads. However, the developments and improvements in generation and distribution systems have not met yet this fast growing loads and the increasing in the number of important and sensitive devices in power system. Disturbances and short outages in generators or transmission lines always have negative effect on power system. In addition, a rapid variety in loads in the plant leads to voltage and frequency fluctuations. These disturbances and fluctuations that occur during the transient process cause stability and quality issues in power system [1].

Power system stability is subjected to changes in system or loads levels that may be sudden or gradual and severe or small changes. Stability is an important concept that determines the power system stable operation. In general, rotor angle stability is taken as index, but the concept of transient stability, which is the function of operating condition and disturbances deals with the ability of the system to remain intact after being subjected to abnormal deviations. A system is said to be synchronously stable (i.e., retain synchronism) for a given fault if the system variables settle down to some steady-state values with time, after the fault is removed [2].

Electric power system stability analysis has been recognized as an important and challenging problem for secure system operation. When large disturbances occur in interconnected power system, the security of these power systems has to be examined. Power system security depends on detailed stability studies of system to check and ensure security. In order to determine the stability status of the power system for each contingency of any disturbance occurs in power system, many stability studies are defined. Power system stability analysis may involve the calculation of Critical Clearing Time (CCT) for a given fault, which is defined as the maximum allowable value of the clearing time for which the system remains to be stable. The power system shall remain stable if the fault is cleared within this time. However, if the fault is cleared after the CCT, the power system is most likely to become unstable. Thus, CCT estimation is an important task in the transient stability analysis for a given contingency [3].

Over the past decades, the energy storage technologies have grown and provided some economic and environmental benefits for business and the society. The energy storage system , which is an electrical storage technology, is applied in many electrical and electronic power applications for improving and enhancing stability and the performance of modern power systems [1].

II. POWER SYSTEM STABILITY

Stability of a power system refers to the ability of a system to return back to its steady state when subjected to a disturbance. As mentioned before, power is generated by synchronous generators that operate in synchronism with the rest of the system. A generator is synchronized with a bus when both of them have same frequency, voltage and phase sequence so the power system stability can define as the ability of the power system to return to steady state without losing synchronism. Usually power system stability is categorized into **Steady State**, **Transient** and **Dynamic Stability** [4].

For a large disturbance, changes in angular differences may be so large as to cause the machines to fall out of step. This type of instability is known as transient stability and is a fast phenomenon usually occurring within 1sec for a generator close to the disturbance. Power systems are subjected to a wide range of disturbances, small and large. Small disturbances in the form of load changes occur continually; the system must be able to adjust to the changing conditions and operate satisfactorily. It must also be able to survive numerous disturbances of a severe nature, such as a short circuit on a transmission line or loss of a large generator. A large disturbance may lead to structural changes due to the isolation of the faulted elements. At an equilibrium set, a power system may be stable for a physical disturbance, and unstable for another. It is impractical and uneconomical to design power systems to be stable for every possible disturbance. The design contingencies are selected on the basis that they have a reasonably high probability of occurrence. Hence, large-disturbance stability always refers to a specified disturbance scenario.

The response of the power system to a disturbance may involve much of the equipment. For instance, a fault on a critical element followed by its isolation by protective relays will cause variations in power flows, network bus voltages, and machine rotor speeds; the voltage variations will actuate both generator and transmission network voltage regulators; the generator speed variations will actuate prime mover governors; and the voltage and frequency variations will affect the system loads to varying degrees depending on their individual characteristics [5].

III. EFFECT OF FAULT CLEARING ON TRANSIANT STABILITY

Transient stability is primarily concerned with the immediate effects of a transmission line disturbance on generator synchronism. Fig. (1) illustrates the typical behavior of a generator in response to a fault condition.

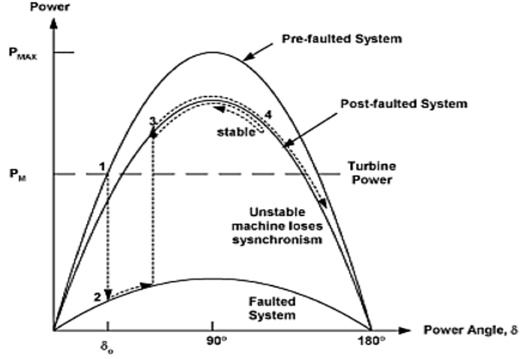

Fig. (1) Transient Stability Illustration.

Starting from the initial operating condition (point 1), a close-in transmission fault causes the generator electrical output power ***Pe*** to be drastically reduced. The resultant difference between electrical power and the mechanical turbine power causes the generator rotor to accelerate with respect to the system, increasing the power angle (point 2). When the fault is cleared, the electrical power is restored to a level corresponding to the appropriate point on the power angle curve (point 3). Clearing the fault necessarily removes one or more transmission elements from service and at least temporarily weakens the transmission system. After clearing the fault, the electrical power out of the generator becomes greater than the turbine power. This causes the unit to decelerate (point 4), reducing the momentum the rotor gained during the fault. If there is enough retarding torque after fault clearing to make up for the acceleration during the fault, the generator will be transiently stable on the first swing and will move back toward its operating point. If the retarding torque is insufficient, the power angle will continue to increase until synchronism with the power system is lost [6].

IV. SWING EQUATIONS [7]

The Swing Equations defining the dynamics of the synchronous generators connected to the power system. The trajectories of the swing equations are called swing curves, and by observing the swing curves for all the synchronous generators, we can determine the stability of the system. Consider a single synchronous generator with synchronous speed ωsm, electromagnetic torque Te, and mechanical torque Tm means mechanical torque. In steady-state,

$$T_m = T_e \qquad \dots (1)$$

When a disturbance occurs, the torque deviates from steady-state, causing an accelerating ($T_m > T_e$) or decelerating ($T_m < T_e$) torque:

$$T_a \text{ (accelerating torque)} = T_m - T_e \qquad \dots (2)$$

Assume J is the combined inertia of generator and prime mover, neglecting friction and damping torque we have:

$$J\,\theta_m'' = T_a = T_m - T_e \qquad \dots (3)$$

Where θ is the angular displacement of the rotor relative to the stator, the suffix m means generator. The rotor speed relative to synchronous speed is given by:

$$\theta_m = \omega_{s_m} t + \delta_m \qquad \dots (4)$$

From equation (4), we obtain the angular speed of the rotor:

$$\omega_m = \theta_m' = \omega_{s_m} + \delta_m' \qquad \dots (5)$$

Where

$$\theta_m'' = \delta_m'' \qquad \dots (6)$$

Substituting (6) into (3), we obtain:

$$J\,\delta_m'' = T_a = T_m - T_e \qquad \dots (7)$$

Multiply eq. (7) by ω_m :

$$\omega_m J\,\delta_m'' = \omega_m T_m - \omega_m T_e = P_m - P_e \qquad \dots (8)$$

J ω_m is called the constant of inertia, referenced by “M” and associated with W_k (kinetic energy):

$$W_k = 0.5\,J\omega_m^2 = 0.5M\omega_m \qquad \dots (9)$$

or $M = (2W_k/\omega_{sm})$ … (10)

For small changes ω_m, it is reasonable to assume that M is constant, so

$$M= (2W_k)/ (\omega_{sm}) \quad ... (11)$$

Then we obtain the standard from of the swing equation:

$$M\ \delta_m'' = P_m - P_e \quad .... (12)$$

V. MODERN ENERGY STORAGE

Modern energy storage originated at the grid scale in the mid-1920s in the form of pumped hydro storage in order to provide a means of shifting electricity from periods of low demand to periods of high demand. Energy storage has become a proven solution for a variety of commercial end uses, including demand response, peak demand reduction, power quality regulation, and emergency response. While there are several types of technologies that support facility-scale energy storage, batteries are the most mature and readily available for smaller applications. The advantages that batteries offer over competing technologies, such as generators, are response times on the order of milli-seconds and highly accurate load-following capability. It is estimated that once batteries achieve installed costs of $300 per kWh they will be able to displace generation used for peak power requirements. Energy storage can provide solutions for grid stability, power quality, demand management, and renewables integration. More over Higher levels of energy storage are required for grid flexibility and grid stability and to cope with the increasing use of intermittent renewable energy sources. New energy sources rely mainly on renewable resources. Consequently, an energy reserve is required and energy storage devices can be very useful for an efficient energy management. Energy storage technologies basically perform two functions:

- Storing the excess energy generated in the system, and
- Providing the stored energy for use whenever demanded by the system .Different Energy storage technologies—such as compressed air energy storage, various types of batteries, flywheels, superconducting capacitors, etc., provide for multiple applications: energy management, backup power, load leveling, frequency regulation, voltage support, and grid stabilization [8]. The Fig.(2) show provides forecasts for new energy storage capacity and revenue for each of the six major developing regions identified [9]. In the paper the modern energy storage systems model is used.

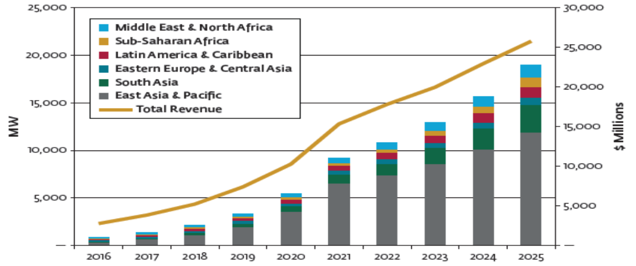

Fig. (2) Projected Annual Stationary Energy Storage Deployments, Power Capacity and Revenue by Region 2016–2025.

VI. STATIC VAR COMPENSATOR (SVC)

SVC is a shunt connected variable var generator whose output is adjusted to exchange capacitive or inductive current to system. SVC regulates voltage at required bus by controlling amount of reactive power injected into or absorbed from power system. Most widely used svc configuration is fixed capacitor- thyristor controlled reactor (FC-TCR). In this a fixed capacitor is connected in parallel with thyristor controlled reactor as shown in Fig.(3). The effective reactance of FC-TCR is varied by firing angle control of anti-parallel thyristors. The firing angle is controlled through a proportional integral (PI) controller in such a way that voltage of bus where svc is connected is maintained at reference value [10].

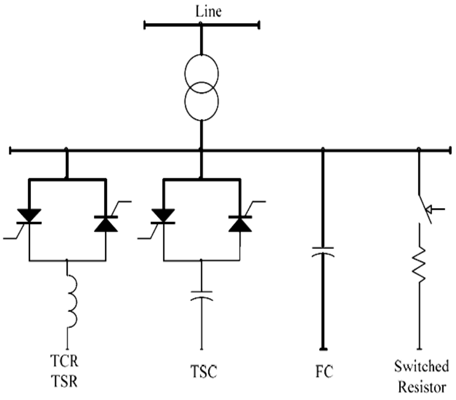

Fig. (3): Static VAR Compensator (SVC).

VII. PHOTOVOLTAIC CELLS

The PV system directly converts sun radiation into electricity. The fundamental of Photovoltaic system is ‘PV cell’. These cells are made up from semiconductor structures as in the computer technologies. This material absorbs sunrays and electrons are emitted from the atoms. This release activates a current. Photovoltaic (PV) is process between radiation absorbed and the electricity induced. Solar power is converted into the electric power by a common principle called photo electric effect. The solar cell array or panel consists of an appropriate number of solar cell modules that are connected in series or parallel based on the required current and voltage [11].

VIII. PHOTOVOLTAIC GENERATOR (PVG)

Photovoltaic generator (PVG) is based on semiconductor device and solid-state synchronous voltage source converter that is analogous to a synchronous machine except the rotating part. Voltage source converter in photovoltaic generator converts a DC input voltage into AC output voltage and supply active and reactive power to the system. It generates a balance set of sinusoidal voltage at fundamental frequency with rapidly controllable amplitude and phase angle. A block diagram of grid connected PV system is shown in Fig. (4) [12].

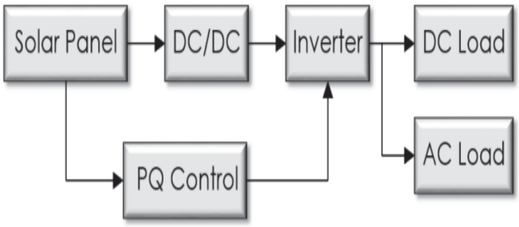

Fig (4). Block diagram of grid connected PV system.

IX. SIMULATION RESULTS

The complete system of IEEE three machines and nine buses system with all the required components has been modeled by using PSAT as shown in Fig.(5). All the system data are given in Appendix (I).

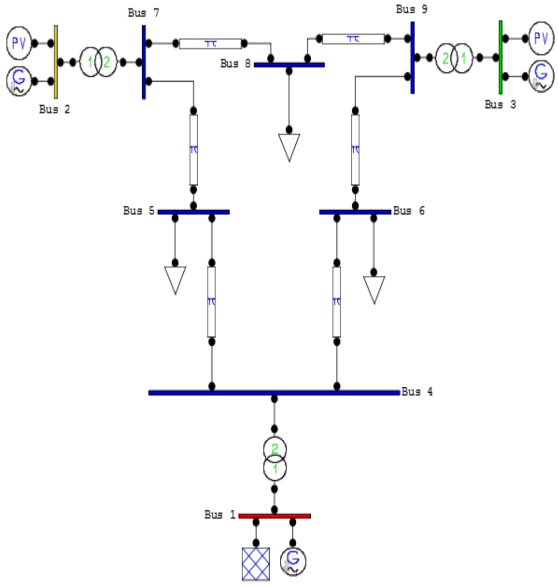

Fig. (5) Single line diagram of IEEE 3 machine 9 bus system.

The simulation is done with a three-phase fault occurred at 1 sec at many buses in the system. The fault is cleared at 1.1 sec, which means the fault clearing time is 0.1 sec. The simulation is done also with sudden changes in load levels as a result of separation occurred in the transmission line at 1 sec between (bus 5 and bus 7). The separation is cleared at 3 sec, which means the separation clearing time is 2 sec.

Firstly, the simulation results show the rotor angle and the rotor speed for multi-machine power system without using energy storage systems, as shown in the following resultant Figures (6-10).

Secondly, determine the weakest buses and more effective weak bus on transient stability analysis. As shown in Figures (11-13).

Thirdly, the system has been analyzed with the energy storage systems as (SVC and PVG) which are connected at the weakest buses, the simulation results are shown in the following Figures (14-25). The improvement in the transient stability has been investigated. All data for SVC and PVG are given in Appendix (I).

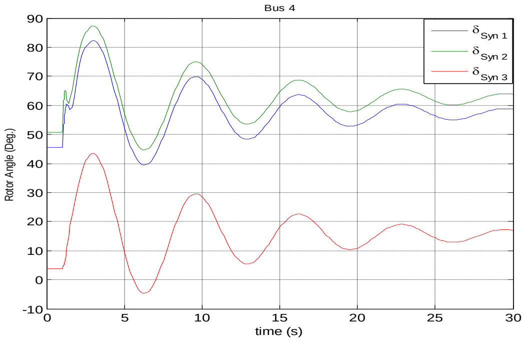

Fig. (6) The effect of fault on the relation of rotor angle with the time at bus#4 without using energy storage systems.

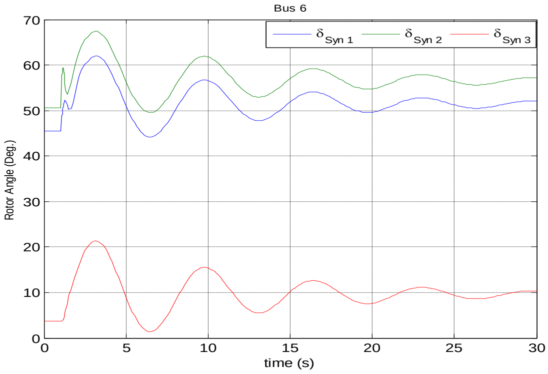

Fig. (7) The effect of fault on the relation of rotor angle with the time at bus#6 without using energy storage systems.

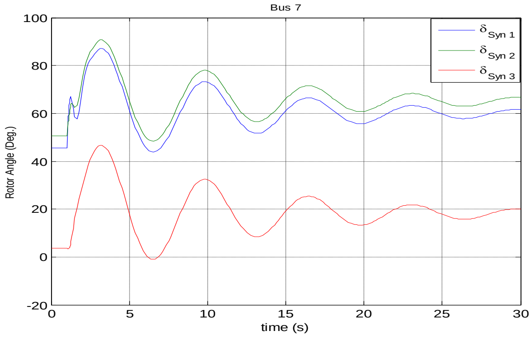

Fig. (8) The effect of fault on the relation of rotor angle with the time at bus#7 without using energy storage systems.

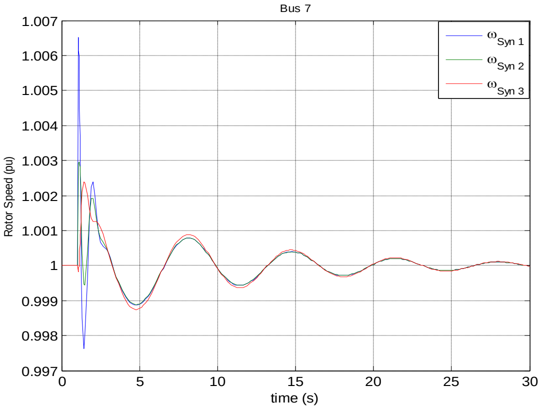

Fig. (9) The effect of fault on the relation of rotor speed with the time at bus#7 without using energy storage systems.

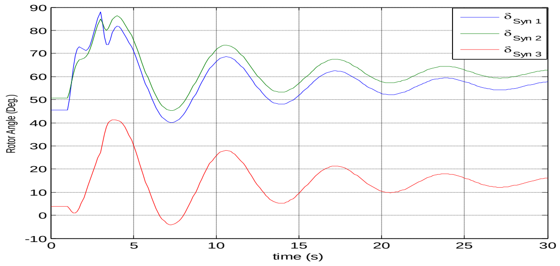

Fig. (10) The effect of the separation occurred in the transmission line between bus#5 and bus#7 on the relation of rotor angle with the time without using energy storage systems.

A. V-Q SENSITIVITY ANALYSIS METHOD

After solving the power flow problem, it is possible to compute and visualize the eigenvalues and the participation factors of the system. The eigenvalues can be computed for the state matrix of the dynamic system (small signal stability analysis), and for three different types of power flow Jacobian matrices (V-Q sensitivity analysis).

The state matrix **[A$_S$]** is simply obtained by eliminating the algebraic variables, and thus implicitly assuming that J_{LFV} is non-singular (i.e. absence of singularity induced bifurcations):

$$A_S = F_x - F_y G_y^{-1} G_x \qquad \text{…. (13)}$$

When all the eigenvalues are computed, it is also possible to obtain the participation factors that are evaluated in the following way. Let V and W be the right and the left eigenvector matrices respectively, such that $V = WA_SV$ and $W = V^{-1}$, then the participation factor p_{ij} of the i^{th} state variable to the j^{th} eigenvalue can be defined as: [13]

$$P_{ij} = (W_{ij} V_{ji}) / (W_j^t G_j) \qquad \text{…. (14)}$$

So in any power system, buses can be arranged from their weakest bus to the strongest bus using the V-Q sensitivity method where weak buses have higher participation factors with smallest eigenvalues. In this work, this V-Q sensitivity method has been applied to the IEEE 9-bus system to determination the weakest buses in the system. Figure (11) depict the weak buses for IEEE 9-buses system.

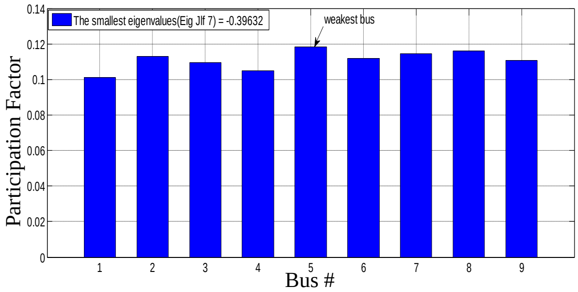

Fig. (11) Participation Factor for the smallest Eigen value (Eig JIf7) for IEEE 9-bus sample system.

After determination the weakest bus in the system, modern energy storage systems should be placed at the weakest bus (Bus#5) to improve transient stability when exposed to sudden disturbance due to a fault or sudden change in the load.

B. Selection more effective weakest buses #5or #8

Fig. (11) shows the weakest buses #5 and #8 respectively. To determine more effective weakest buses on transient stability state a new analysis must be do at two buses. Figures (12) and (13) show the compared simulation results between added SVC and PVG at bus#5 and bus#8 individually.

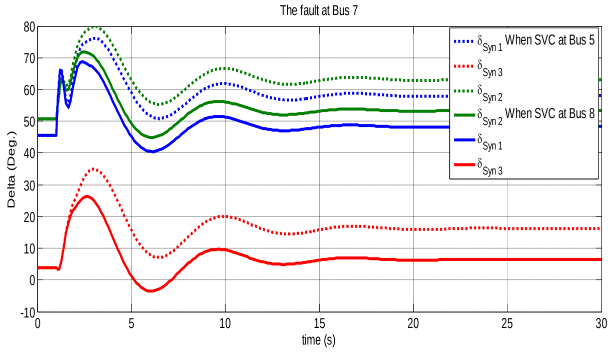

Fig. (12) The effect of fault on the relation of rotor angle with the time at bus#7 when SVC at (bus#5 and bus#8).

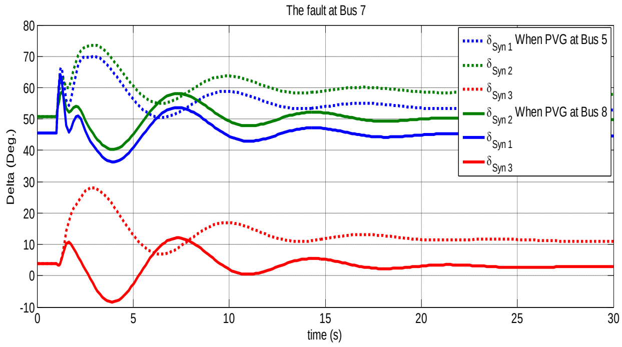

Fig. (13) The effect of fault on the relation of rotor angle with the time at bus#7 when PVG at (bus#5 and bus#8).

The above simulation results, Figures (12 and 13), show that bus#8 have more effective weak bus depend on machines swing curves because it is a second weakest bus and near to bus#5 (first weakest bus in the system). Result in, the energy storage systems will be add to bus#8 for improving transient stability of the given sample power system.

C. Adding SVC on bus#8

The following Figures (14-17) show the simulation results when added SVC.

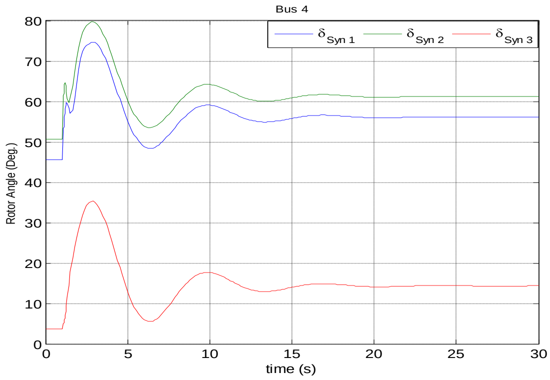

Fig. (14) The effect of fault on the relation of rotor angle with the time at bus#4 with SVC.

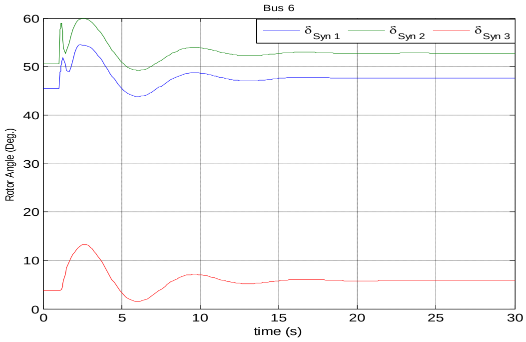

Fig. (15) The effect of fault on the relation of rotor angle with the time at bus#6 with SVC.

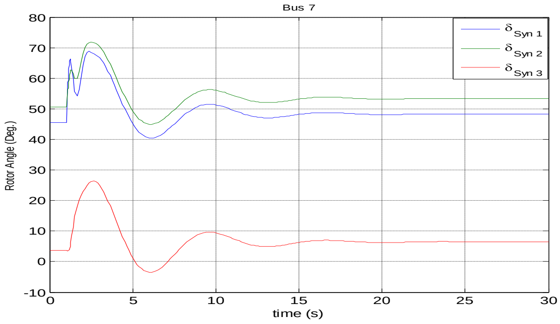

Fig. (16) The effect of fault on the relation of rotor angle with the time at bus#7 with SVC.

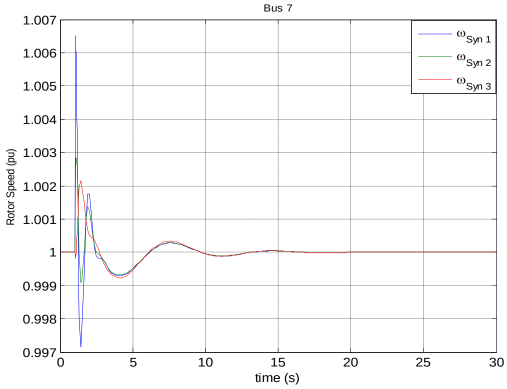

Fig. (17) The effect of fault on the relation of rotor speed with the time at bus#7 with SVC.

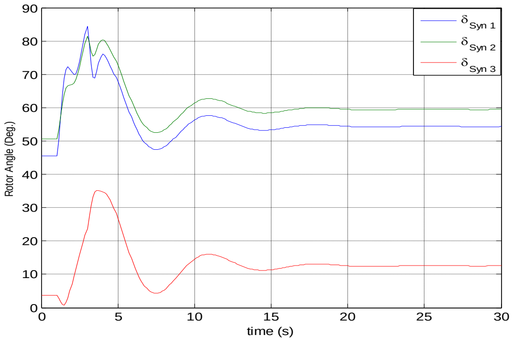

Fig. (18) The effect of the separation occurred in the transmission line between bus#5 and bus#7 on the relation of rotor angle with the time with SVC.

D. Adding PVG on bus#8

The following Figures (19-23) show the simulation results when added PVG.

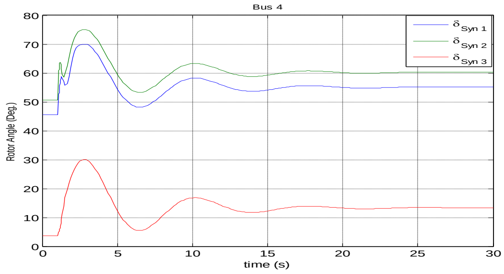

Fig. (19) The effect of fault on the relation of rotor angle with the time at bus#4 with PVG.

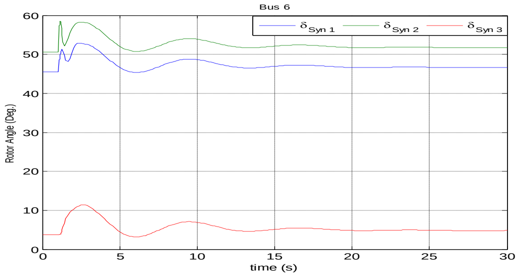

Fig. (20) The effect of fault on the relation of rotor angle with the time at bus#6 with PVG.

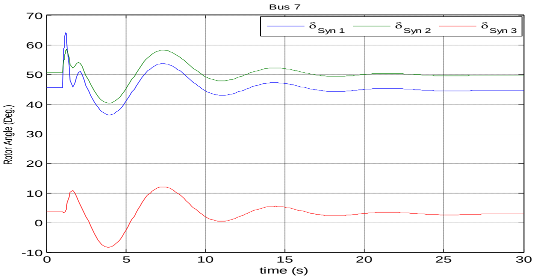

Fig. (21) The effect of fault on the relation of rotor angle with the time at bus#7 with PVG.

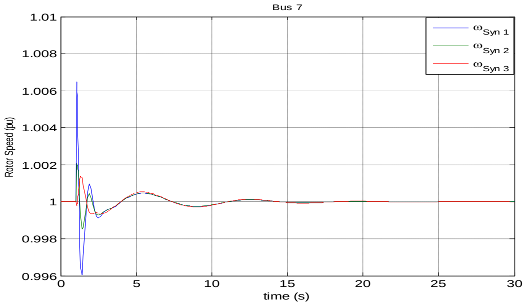

Fig. (22) The effect of fault on the relation of rotor speed with the time at bus#7 with PVG.

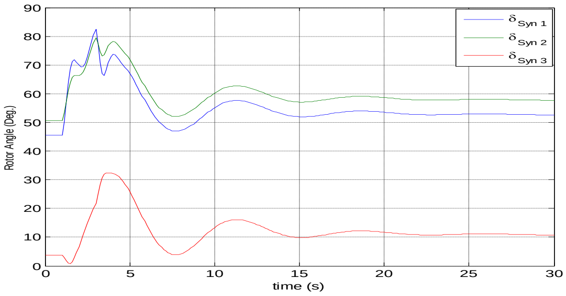

Fig. (23) The effect of the separation occurred in the transmission line between (bus#5 and bus#7) on the relation of rotor angle with the time with PVG.

E. Adding SVC and PVG on bus#8

The following Figures (24) and (25) show the compared simulation results between added SVC and PVG.

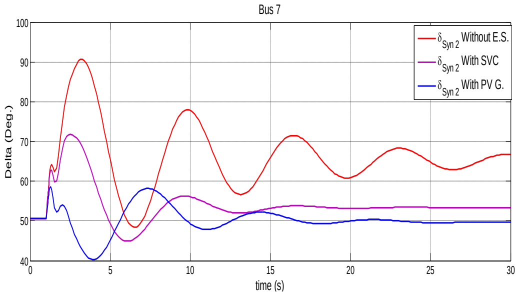

Fig.(24) Comparison between SVC and PVG for the rotor angle when the fault occurred at bus#7.

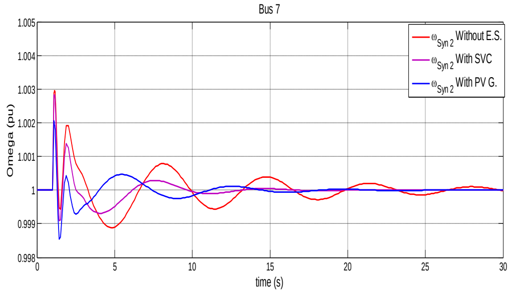

Fig. (25) Comparison between SVC and PVG for the rotor speed when the fault occurred at Bus#7.

X.CONCLUSION

In this paper, the effect of conversional and modern energy storage systems for improving transient stability of multi-machine power system under 3-phase fault and sudden changes in load levels as a result of separation occurs in one of the transmission lines is investigated. The system higher participation factors with smallest eigenvalues are determined to find the more effective weakest bus that chosen to add the energy storage system (SVC and PVG). The results show higher improvement in the transient stability when adding, on the selected bus, modern energy storage equipment that is characterized by the amount of capacity and the speed of performance and lack of harmonics.

APPENDIX (I)

The system data are given in the following Table (1) while The SVC and PVG data are given in the Table (2) and (3).

Table (1) The sample system data.

	Bus No.		
	1	2	3
Power Rating (MVA)	247.5	192	128
Machine Model	4	4	4
X_L (p.u)	0.0336	0.0521	0.0742
R_s (p.u)	0	0	0
X_d (p.u)	0.146	0.8958	1.3125
X'_d (p.u)	0.0608	0.1198	0.1813
T'_{d0} (s)	8.96	6	5.89
X_q (p.u)	0.0969	0.8645	1.2578
X'_q (p.u)	0.0969	0.1969	0.25
T'_{q0}(s)	0.31	0.535	0.6
H (s)	23.64	6.4	3.01
D	0	0	0

Table (2) SVC data

Power (MVA)	**100**
Voltage Rating (KV)	**230**
Frequency Rating(Hz)	**50**
Model Type	**1**
Regulator Gain Kr [p.u./p.u.]	**50**

Table (3): PVG data

Active Power (MW)	**0.05**
Voltage Reference (p.u.)	**1.045**
Invertor response times (T_p, T_q) [s, s]	**[1 30]**
Voltage (kv)	**5**
PI Controller Gains (ki)	**1**

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