

Enhancing Stability Performance of Renewable Energy Generators by Utilizing Virtual Inertia

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Abstract—This paper presents a method of improving the transient stability of power systems with high penetration of distributed generation. Most distributed generators are characterized by having small or even no intrinsic rotational inertia. When small inertia sources such as micro-turbine or non-inertial sources such as PV system are integrated to the power system, the overall rotating inertia will decrease significantly. This decrease in rotating inertia may cause loss of synchronism under some fault conditions and may lead to system instability. One of the solutions to overcome this problem is to use energy storage elements to provide virtual inertia. This paper presents a new method to include the energy storage devices as virtual inertia in the transient stability studies and utilizes the energy storage devices to enhance stability in systems with embedded distributed generation, as well as to determine the size of storage energy elements to maintain system stability.

Index Terms—kinetic energy, transient stability, storage elements, virtual inertia.

I. INTRODUCTION

In recent years, renewable energy resources or Distributed Generators (DGs) have become a significant part of the generation portfolio in many electric systems. These DGs are usually located at or near load points, and operate in stand-alone or in grid-connected modes [1]. However, the significant majority of DGs currently in operation are grid-connected [2]. Also, many of these DGs are connected via power electronic converters which hide the intrinsic rotational inertia [3].

Integrating renewable energy generators or DGs in power systems can introduce many stability problems. One of the most pronounced problems is the lack of rotational kinetic energy which is required with combination with control algorithms in maintaining voltage and frequency stability of power systems [4]. Power system networks are usually operated at or near their stability limits, and when the penetration level of DGs in power system grids increases, these systems will become more vulnerable to stability problems.

In contrast to large synchronous generators, renewable energy generators have relatively light or low-inertia turbines such as wind energy generators, or do not have rotating kinetic energy at all such as PV systems. During large disturbances, kinetic energy stored in turbine-generator systems plays a major role in maintaining system stability by momentarily absorbing or injecting energy from or to the grid; this capability is practically absent in renewable energy generators.

Majumder et al. [5] proposed a new method to utilize the distribution static compensator (DSTATCOM) to improve system stability. They used droop control through a parallel connected converter to produce the required real and reactive power by controlling voltage magnitude and angle. A large capacitor bank was used to provide a short-term power. The size of the capacitor has to be chosen carefully so as not to introduce low frequency oscillations. In [6], trajectory sensitivity approach was used to identify the most vulnerable machines for integration of DGs.

The phenomenon of absorbing or supplying energy during disturbances is described by the well-known swing equation. In this work, we develop results from the swing equation to determine the amount of required power from the energy storage devices during the transient period to assist low- or non-inertial DGs in maintaining transient stability. We also validate this approach by the use of appropriate example with a small system used in the literature.

The aim of the presented work is to use energy storage devices to compensate for the lack of rotating inertia due to the integration of large amounts of renewable energy resources. This paper addresses modeling of energy storage devices as virtual inertia in transient stability studies and estimating the sizes of these devices to maintain system stability.

This paper is organized as follows: section II explains the concept of virtual inertia, section III describes modeling of energy storage devices in power system transient stability analysis, section IV determines the required size of energy storage devices to maintain system stability, section V illustrates the solution algorithm for transient stability studies, section VI presents case studies, section VII discusses the results and section VIII gives some concluding remarks.

II. VIRTUAL INERTIA CONCEPT

Transient disturbances such as short circuit and large sudden change in system loading may change system's operating state and lead to system instability. Following a disturbance, if a power system returns to the original operating point or attains another stable equilibrium point without losing synchronism, the system is said to be stable [7]. There are many factors that have an effect on system stability such as total rotating kinetic energy, power reserve, control schemes, etc.

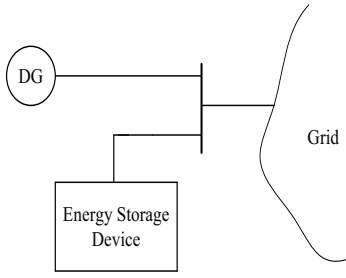


Fig. 1. A DG with Energy Storage Device Connected to a Grid

If the level of penetration of DGs in power system increased significantly, system stability may become more vulnerable. During disturbances, machines' rotors accelerate and decelerate according to the swing equation. If the total rotating inertia is small which may be caused by introducing DGs, the difference between acceleration and deceleration power during the disturbances may become significant and the system may lose its synchronism. Therefore, systems with low rotating inertia, a damping power need to be introduced during the disturbances. By using a proper control of storage energy devices at the distributed generators to provide short-term power, the lack of the kinetic energy of these generators can be compensated. This compensation of kinetic energy by the storage energy devices is known as virtual inertia. The DG will exhibit some of the inertial characteristics of the synchronous generators during the disturbances. These energy storage devices are connected in parallel with DGs to the grid by means of suitable power conversion devices as shown in Fig. 1. This concept has been investigated by a number of researchers and named "virtual inertia" and in some cases "virtual synchronous generator". This paper addresses the effect of the virtual inertia from energy storage devices on the transient stability as well as estimating the required size to maintain system stability.

III. MODELING OF ENERGY STORAGE IN TRANSIENT STABILITY STUDIES

The equation of motion of a machine connected to an infinite bus and ignoring the damping coefficient is given by the so-called swing equation:

$$\frac{2H}{\omega_s} \dot{\omega} = P_m - P_e = P_a \quad p.u. \quad (1)$$

where H is the inertia constant, ω_s is the system rated frequency, P_m is the mechanical power, P_e is the electrical power, P_a is the accelerating power and ω is the angular velocity of the rotating magnetic field.

By neglecting the stator winding resistance, the electric power P_e delivered by a rotational machine can be given as

$$P_e = \frac{|E_a||V_t|}{X_s} \sin \delta \quad (2)$$

where E_a is machine internal voltage, V_t is the terminal voltage, X_s is the synchronous reactance and δ is the torque angle.

The mechanical power for the first swing of transient stability study can be considered constant. In the case of a sudden disturbance occurs, the machine accelerates and decelerates according to the disturbance type, size and location. If a large load is suddenly connected to the grid, the generator will inject its stored kinetic energy to the network and starts to decelerate. On the other hand, if a large load is disconnected from the network, the transferred power from the generator will decrease and the generator starts to accelerate. Therefore, in order to maintain machines' stability and prevent them from fast deceleration and acceleration, generators' kinetic energy have to be increased. Also, by decreasing the transfer reactance, a significant amount of power can be transferred to the network during the disturbances and generators can be prevented from acceleration.

In addition to smoothing the variations in the output power and supporting the DGs during peak demand, storage energy devices may also be utilized to improve system stability. In the steady state operation mode, these devices do not require a particularly fast control scheme. However, if the control scheme is modified and if these devices controlled properly to produce or absorb power as the accelerating power goes through, the problem of lack of inertia of DGs can be solved. There is a significant research conducted in this area, yet there are not many available methods to determine the size of these devices and to model such devices in transient stability studies. Some studies assume some arbitrary sizes for the energy storage devices based on simulation analysis.

From (2), it is clear that the transfer of real power varies with the sine of the torque angle. During disturbances, to reduce this fluctuation, power must be supplied or absorbed by suitable storage devices. For a short term, the power supplied or absorbed by these devices is considered to be constant. To model these devices in transient stability studies, a constant amount of power is added to or subtracted from the machine output power during the deceleration or acceleration, respectively. Therefore, the swing equation of a machine with introducing virtual inertia will be as shown in (3).

$$\frac{2H}{\omega_s} \dot{\omega} = P_m - P_e \pm P_s = P_a \pm P_s \quad p.u. \quad (3)$$

where P_s is the power supplied or absorbed by the storage device.

The power is supplied to or absorbed from a machine according to the decelerating or the accelerating power, respectively. If the machine accelerates, a specific amount of power should be absorbed from the machine and if the machine decelerates a specific amount of power should be supplied to the system to decrease the stress on the machine.

IV. SIZING OF ENERGY STORAGE TO MAINTAIN SYSTEM STABILITY

During disturbances, if the accelerating and decelerating energy of machines' rotor are not equal, the machine may lose its synchronism. If this difference can be balanced somehow, the machine can maintain its stability. In low- or non-inertial

sources, it is useful to use the energy storage devices to compensate for the lack of inertia. Including of these devices to improve transient stability is presented in the previous section. This section estimates the energy storage devices' sizes.

Due to the dynamic nature of rotating machines and the uncertainty of the size and location of faults, the exact required size of the storage energy devices to maintain machine's stability can not be determined. However, some assumptions can be applied to estimate the size of these devices. Such assumptions may make the calculated size over or under estimated. With the assumption that the input mechanical power is constant for transient study, ignoring damping coefficient and linearization around the operating point; the size of the energy storage devices can be estimated.

If equation (1) is linearized with $\Delta P_m = 0$, we get the following result,

$$\frac{2H}{\omega_s} \frac{d^2 \Delta \delta}{dt^2} = -K \Delta \delta \quad (4)$$

where K is synchronizing power coefficient.

$$K = \frac{dP_e}{d\delta} = \frac{|E_a||V_t|}{X_s} \cos \delta_0 \quad (5)$$

From (1) and (4), to keep the machine running in a balanced condition, P_a has to be close to zero. Therefore, if this power is provided or absorbed by an energy storage device during the disturbances, the machine will maintain its stability.

Therefore, the storage energy device should provide power equal to the right hand side of equation (4).

$$P_E = \frac{|E_a||V_t|}{X_s} \cos \delta_0 \Delta \delta \quad (6)$$

where P_E is the required power to maintain system stability.

This power is the synchronizing power coefficient times the change in the power angle. Since the change in the power angle is function of time, the required power is also function of time. However, after injecting or absorbing some energy to or from the power system bus at which the machine is connected the machine may return to its synchronism state.

For instance, if the storage energy device is assumed not to be connected to the grid until the speed deviation reaches 1% of the rated speed to prevent the storage device from fluctuating between on and off. And, if the operating power angle is assumed to be 30° , which is the most common operating power angle of most machines. Therefore, the angle margin for the machine to enter to the unstable region is around 60° ($90^\circ - 30^\circ$). To make sure the machine will not enter the unstable region, the power angle deviation for this specific case is allowed to be 0.60° which is 1% of the angle margin.

Therefore,

$$P_E = \frac{|E_a||V_t|}{X_s} \cos \delta_0 \Delta \delta = \frac{|E_a||V_t|}{X_s} \cos (30^\circ) \times \left(0.60 \frac{\pi}{180}\right) \quad (7)$$

$$P_E = 0.00907 \frac{|E_a||V_t|}{X_s} \quad (8)$$

Since $|E_a|$ and $|V_t|$ are close to 1.0 p.u., the required energy storage size can be approximated as follows:

$$P_E \approx \frac{0.00907}{X_s} \quad (9)$$

Where, X_s and P_E are in p.u. values

However, this result is just an approximation with the assumptions that mentioned earlier. Therefore, this result is less conservative and hence for more conservative result, the energy storage size should be slightly larger than this value. Also, from using this estimation in the simulation, the exact required size can be estimated from the simulation results.

In this study, the energy storage devices are utilized to enhance transient stability of systems with high level of DGs penetration. Having said that, the protective devices are assumed not to operate during this transient period. Also, the control scheme is assumed to be very fast, which is the case for most of power electronic equipments, to connect these devices during the transient time horizon. However, to prevent the energy storage devices from fluctuating between charging and discharging and to operate in the fast control mode in transient conditions only, some speed deviation may be allowed.

Practically, charging or discharging of energy storage devices cannot be instantaneously. Including of the dynamics of the storage devices may change the shape of the results and the size may need to be increased to account for such dynamics. Therefore, for exact simulation results, a complete dynamic model of such devices should be included in the transient stability analysis. However, storage dynamics is out of the scope of this work since this paper is focusing on introducing the concept of the use of the energy storage devices as virtual inertia, including of these devices in the transient stability analysis and estimating the energy storages' sizes.

V. TRANSIENT STABILITY CALCULATIONS

For the first swing in the transient stability analysis, a simplified model can be utilized without compromising the results. This simplified model is characterized as follows [7]:

- 1) Mechanical power input is constant.
- 2) Damping or asynchronous power is negligible.
- 3) Constant-voltage-behind-transient-reactance model for the synchronous machines is valid.
- 4) The mechanical rotor angle of a machine coincides with the angle of the voltage.
- 5) Loads are represented by passive impedances.

The stability calculation procedures for multi-machine systems is well documented in the literature and only the flowchart is provided in this work for illustration and is shown in Fig. 2.

The only modification for conventional power system transient stability analysis algorithm, is injecting or absorbing some power by the energy storage devices to balance the acceleration and the deceleration dynamics. After calculating the final estimate of the power angle and speed deviation,

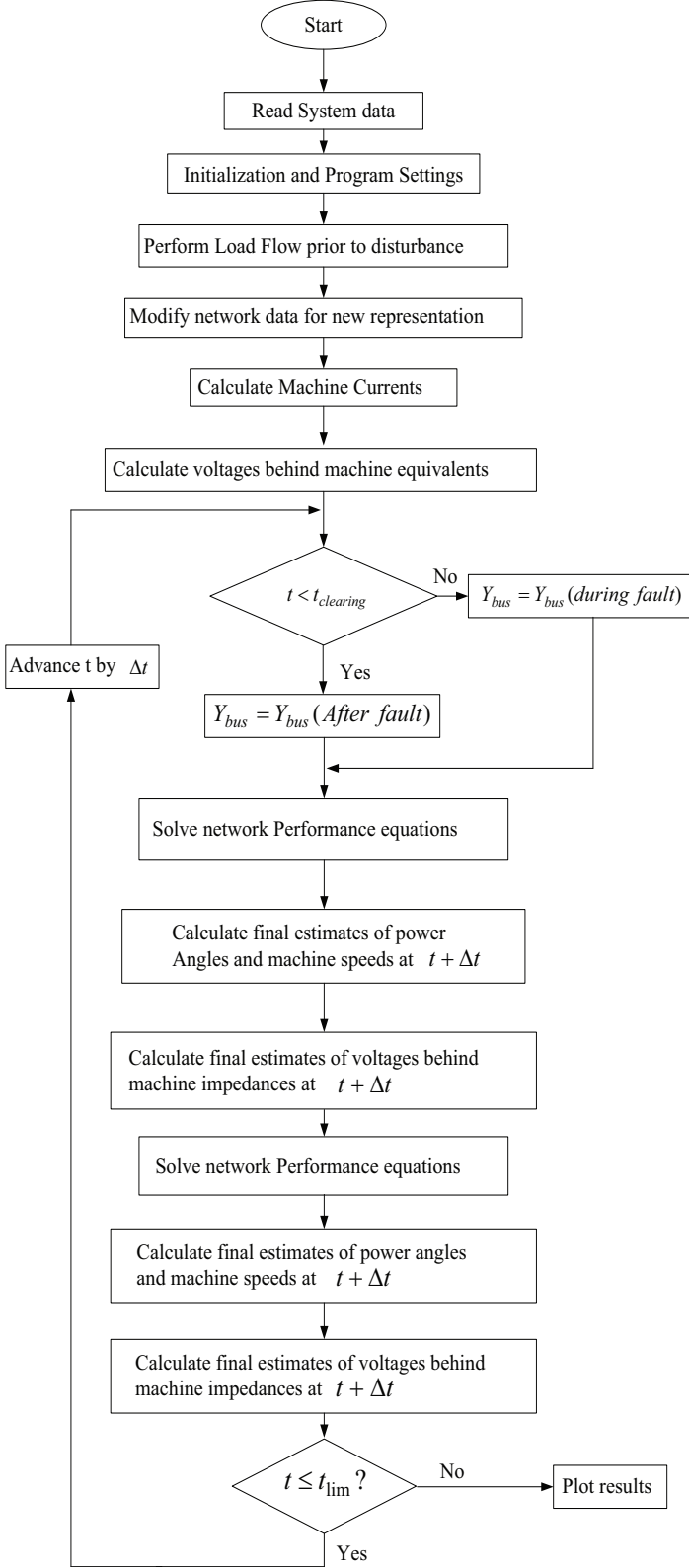


Fig. 2. Transient Stability Calculation Flowchart

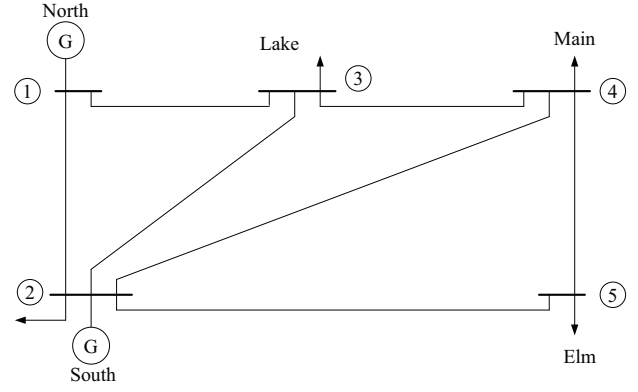


Fig. 3. Five Bus Test System Configuration

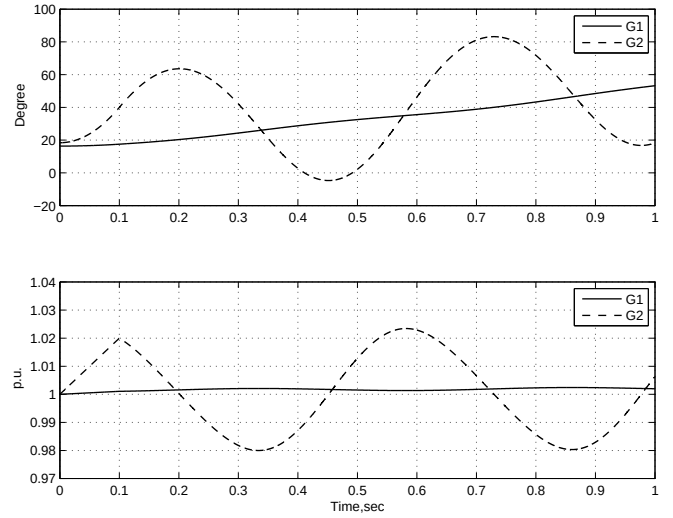


Fig. 4. Torque Angles and Speed Deviations due to a Three Phase Fault at Bus 3 for the Original System

the difference in accelerating and decelerating power can be balanced.

It should be noticed that, in this research, the time to provide or absorb power is assumed to be too small in comparison to the oscillation time and can be neglected.

VI. CASE STUDIES

A. Effect of Machine Inertia

The effect of small inertia of DGs is carried out using a small five bus system. The system is taken from [8] and is shown in Fig. 3. System data are given in the appendix. MATLAB was used to investigate the effect of generators' inertia and the results are shown in Fig. 4 and Fig. 5. Fig. 4 shows the angular and speed deviations due to three phase fault at bus 3 for 100 ms and inertia constant of generator 2 is 1 second. Fig. 5 shows the angular and speed deviations due to fault at bus 3 for 100 ms and changing the inertia constant of generator 2 to 0.3 second.

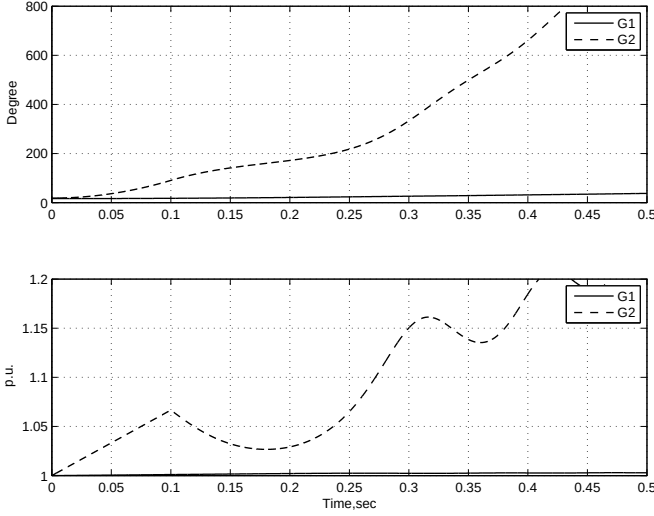


Fig. 5. Torque Angles and Speed Deviations due to a Three Phase Fault at Bus 3 after Changing the Inertia Constant of Generator 2 to 0.3 s

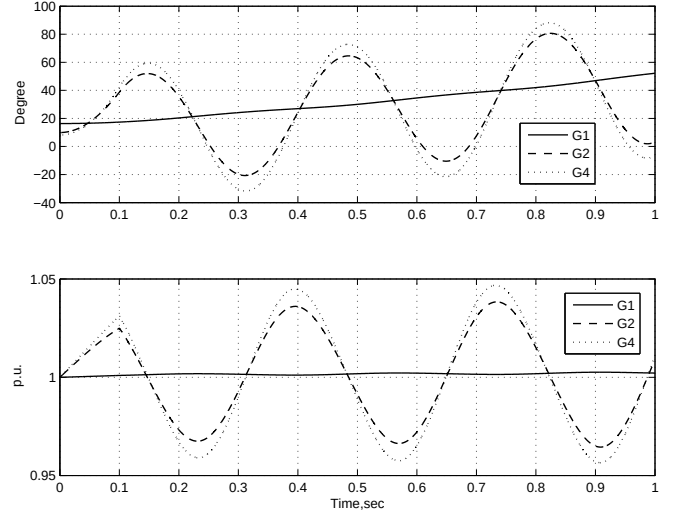


Fig. 7. Torque Angles and Speed Deviations due to a Three Phase Fault at Bus 3 for the Modified System after utilizing the energy storage devices as virtual inertia

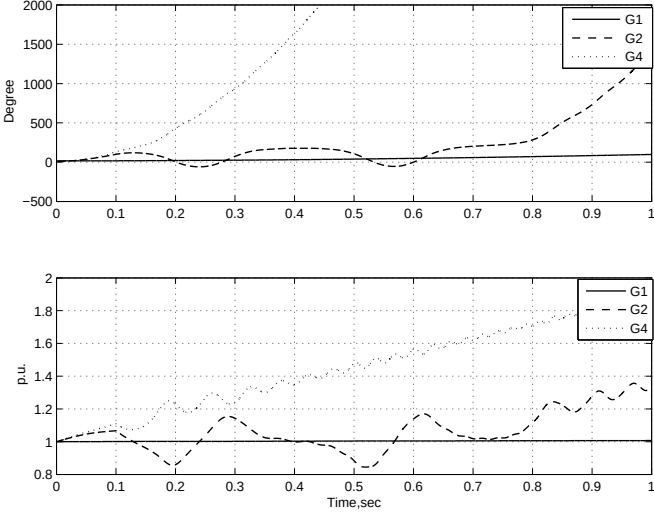


Fig. 6. Torque Angles and Speed Deviations due to a Three Phase Fault at Bus 3 for the Modified System and without Energy Storage Devices

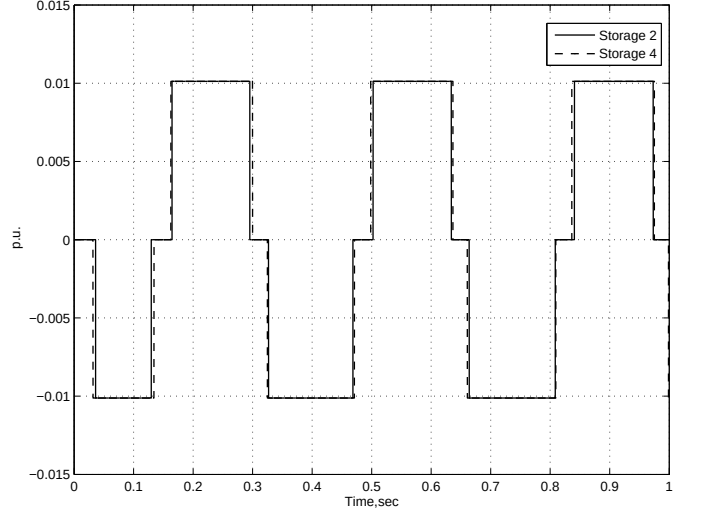


Fig. 8. Storage Energy Devices Power Profile During the Disturbance (Three Phase Fault at Bus 3)

B. Effect of Virtual Inertia

In this case study, to decrease the total rotating inertia and to consider the effect of the virtual inertia, the inertia of the generator 2 was divided by 10 and its power capacity was divided by 2. Also, a new generating unit is added at bus 4 and has the same parameters as generator 2 after the modification. The storage energy devices are connected to the grid when the speed deviation reaches 1%. Also, the time delay for these devices is considered to be 10 ms from the moment of receiving a signal to connect.

The energy device size is estimated according to equation (6) with the same assumptions of equations (7), (8) and (9). However, as mentioned earlier, such assumptions may under estimate the value of the required power. After using the estimated value from equation (6) which is 0.00847 p.u. in the

simulation, the system seemed to be near the critical stability operating point. After changing this value to 0.0095 p.u., the system became stable. The simulation results with including the energy storage device as virtual inertia for a fault at bus 3 for 100 ms, and no change in the network configuration after the fault was cleared are shown in Fig. 6 and Fig. 7.

VII. SIMULATION RESULTS AND DISCUSSION

From Fig. 4 and Fig. 5, a decrease in a machine's rotating inertia can make the system unstable. The system first simulated without any change in system parameters for a fault at bus 3 for 100 ms and the system is stable under this fault condition. By gradually decreasing the inertia constant for generator 2, the system started to be unstable when the inertia constant of generator 2 reached 30% of the original value. This case study

proves that, if the total rotational inertia of a power system is reduced significantly, the system may lose its synchronism. Therefore, as the penetration level of the distributed generators increases in power system networks, the networks will be vulnerable for transient stability.

From case study B, when a three phase fault is applied at bus 3 for 100 ms, the system is unstable due to the small inertia of assumed DGs. However, when the virtual inertia is utilized, the system recovered and returned to its stable state. Fig. 8 shows the required power from the energy storage devices to maintain system stability. Therefore, we can conclude that, injecting or absorbing a small amount of power to or from a bus at which a DG is connected, can make a big difference in the transient stability of the power system.

VIII. CONCLUSION

When distributed generators are introduced in power system networks, they provided controllability and flexibility for power system operation. However, as the penetration level of the distributed generators increases in power system networks, the total rotational inertia decreases significantly and may cause the system to operate at stability limit borders or lose its stability under some fault conditions.

In this work, the simulation results showed that the DGs forced the system to be unstable under some short circuit conditions. To increase system stability margin, a short term power is supplied to or absorbed from the system at the time of disturbances by utilizing energy storage devices as virtual inertia. The utilization of the energy storage devices as virtual inertia can maintain system stability and increase system strength during transient stability.

Modeling of these devices in power system stability studies is presented and used to investigate their effect on power system stability. Also, a method to estimate the required capacity of these devices to maintain system stability is introduced.

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APPENDIX

System data for the base case and after modification are shown as follows:

TABLE I
LINE DATA

From	To	R (p.u.)	X (p.u.)	$B/2$ (p.u.)
1	2	0.02	0.06	0.030
1	3	0.08	0.24	0.025
2	3	0.06	0.18	0.020
2	4	0.06	0.18	0.020
2	5	0.04	0.12	0.015
3	4	0.01	0.03	0.010
4	5	0.08	0.24	0.025

TABLE II
GENERATION DATA FOR THE ORIGINAL SYSTEM

Gen. No.	Voltage (p.u.)	Real Power MW	Reactive Power MVar	R (p.u.)	X_s (p.u.)	H s
1	1.06	Inf. Bus	Inf. Bus	0.0	0.25	50
2	1.00	40	30	0.0	1.5	1

TABLE III
GENERATION DATA FOR THE MODIFIED SYSTEM

Gen. No.	Voltage (p.u.)	Real Power MW	Reactive Power MVar	R (p.u.)	X_s (p.u.)	H s
1	1.06	Inf. Bus	Inf. Bus	0.0	0.25	50
2	1.00	20	15	0.0	1.5	0.1
4	1.00	20	15	0.0	1.5	0.1

TABLE IV
LOAD DATA

Bus No.	Real Power (MW)	Reactive Power (MVar)
1	0	0
2	20	10
3	45	15
4	40	5
5	60	10

BIOGRAPHIES

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