An Approach Based On Potential Energy Balance For Transient Stability Improvement in Modern Power Grid

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***Abstract*—Direct energy function based methods for power system stability analysis proves to be more important especially when dealing with distributed energy resource (DER) integrated power grid. In this paper, it is shown that in order to make a system more stable, either the kinetic energy absorbed during a disturbance should be reduced, or the potential energy absorbing capacity of the network should be increased. Further, a method based on this concept is proposed using reactive power (VAR) control, which increases potential energy absorbing capacity of the grid during transient conditions. The proposed method has been first proved mathematically, and the results for its application on the IEEE 9 bus system is presented.**

***Index Terms*—Direct Methods, Energy Function, Structure Preserved, Transient Stability Assessment, VAR Control.**

I. Introduction

Power networks are highly nonlinear systems that changes continually due to changes in loads, generators outputs, or operating parameters. Increased size of generation units with lower inertia constant, demand growth, heavy loads on existing transmission lines, equipment failure, and negative damping effect of controllers, such as fast exciters, are issues that have made power system susceptible to disturbances. Transient instability occurs because large disturbances create significant power imbalance between the input mechanical power, supplied to the generator via the turbine, and the electrical output power. Under such conditions, generators will swing away from their equilibrium points, and eventually lose synchronism. Although the stability of the system depends on its initial condition, the Transient Stability (TS) problem is the study of the post-disturbance system. The focus of this paper is on the transient stability of power systems.

Stability of a system is the continuance of correct operation of the system, following a disturbance. It depends on the initial operating condition, the nature of the physical disturbance, and the duration of the disturbance. The most straightforward approach for assessing the post-fault system stability has been through numerical integration of system equations, based on direct time simulation of transient dynamics following a contingency. Advances in computational hardware have made this methodology fast and accurate even for large scale systems [1], [2], [3], [4], [5], [6], [7]. An alternative approach for stability analysis using Lyapunov theory was proposed in 1966 by Gless, and El-Abiad and Nagappan. Lyapunov has defined a function by considering the concept of energy. This function represents a relationship between accumulated energy in a system and the dynamics of the system. According to his theory, a system is stable if the system's energy is continuously decreasing until an equilibrium state is reached. It should be noted that the time derivative of a Lyapunov function is negative if the total energy of a system continuously decreases [4], [5], [6], [8], [9], [10].

Different approaches toward analyzing and predicting power system transient dynamics have been discussed in the literature, and various methods have been suggested to improve the transient stability of power systems. References [11], [12] present a Wide Area Control (WAC) design based on a nonlinear optimal control algorithm using Reinforcement Learning (RL) and Neural Networks (NNs), to enhance the transient stability of Doubly Fed Induction Generators (DFIG) integrated power grid. In [13], using an energy function based intelligent optimal controller, an intelligent wide-area damping controller is proposed for a wind integrated power grid. In [14], large PV farms equipped with a fuzzy gain scheduling of proportional-integral-derivative controller is used for transient stabilization of a multi-machine power system. References [15], [16] uses fault identification and data mining to take necessary control actions to improve the system stability. Authors of [2], [3] present a novel wide area control method for transient stability improvement. In [17], a control strategy is introduced for voltage-source converters (VSCs) in high-voltage direct-current multi-terminal systems to improve power system transient stability. Ref. [18] presents transient stability enhancement of power system using Thyristor Switched Series Capacitor (TSSC) device. Article [19] presents a wide-area control approach to improve the transient stability of the power systems. In [20], DC resistive fault current limiter is used to improve TS. Reference [21] proposes the coordinated control of the optimized resistive type superconducting fault current limiter (SFCL) and SMES. In [22], Transient Power System Stabilizers (TPSS) is used for TS improvement. Ref. [23] uses phase-shifter for improving transient stability of the system.

In this paper, the potential energy absorbing capacity of the network is increased via VAR injection such that the transient stability margin of the system is improved. This paper is organized as follows: First, the energy function for single

machine and multi-machine power systems is obtained. Next, the concept of energy conversion and its relation with transient stability is discussed. Then, the proposed method is explained. At the end, results and conclusions are provided.

II. Transient Stability Assessment Using Energy Function

The main goal of using direct methods is to perform Transient Stability Assessment (TSA) without solving the dynamic equations numerically. In order to use direct methods, a scalar function that describes the energy of the system should be found. This function is usually called energy function, and it should meet the Lyapunov criteria. According to Lyapunov's theory, energy in a system converts from kinetic to potential form, when the system undergoes a disturbance. For a system to be stable, there should be a balance between energies, and the system should have the capacity to convert the kinetic energy into potential form. To better understand the concept of energy and leveraging it toward transient stability, the transient dynamics of the system should be elaborated.

A. Power System Dynamics

In power system transient stability analysis, the main equations are those describing the dynamic behavior of the synchronous generators and model the important torques related to the generators' rotors and their controllers. The rest of the system is modeled only to the extent that influences the torques of the generators [4], [5]. Dynamics of generators are mostly represented by the so-called "swing equation":

$$\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} + D_i\omega_i = P_{m_i} - P_{e_i} \tag{1}$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s, \quad i = 1, 2, \ldots, n \tag{2}$$

where δ_i is the generator angle with respect to synchronous frame, ω_s is the reference speed, ω_i is the speed of generator i, and D_i and H_i are the damping factor and inertia constant of the generator i, respectively.

This model is the simplest power system model used for stability studies, and it is limited to analysis of so-called "first swing" transients. Constant input mechanical power, neglecting asynchronous power, and modeling synchronous machines with a constant voltage source behind their transient reactance, are the main assumption for modeling the generator dynamics with equations 1 and 2. Loads are modeled by passive impedance obtained from pre-disturbance conditions, and are considered constant during the stability study.

B. Energy Function For a Single-Machine Infinite-Bus System

In order to achieve an energy function for a power system, integrating the swing equation is performed, because the time integration of power gives the energy. The details can be found in [4]. Integrating 1 leads to 3 for machine i,

$$\frac{1}{2}M\omega_i^2|_{\omega_{i1}}^{\omega_{i2}} = P_{m_i}\delta_i|_{\delta_{i1}}^{\delta_{i2}} + Eei_{transferred}|_{t_1}^{t_2} + E_{Loss_i}|_{x_{i1}}^{x_{i2}} \tag{3}$$

In 3, ω_{i1} and ω_{i2} are the rotor speed at the beginning an and end of the time frame of study, respectively. The rotor angles are shown with δ_{i1} and δ_{i2}. $Eei_{transferred}$ represents electrical power transferred from machine i, and E_{Loss_i} shows the lost energy in the system when the state of the system changes from x_{i1} to x_{i2}. This equation is valid for the system before, during, and after a disturbance. However, appropriate parameters should be considered for each state.

The left side of the (3) gives the Kinetic Energy (KE) change of machine i, while the terms on the right side are Potential energy stored in the Rotor (PR), electric energy injected to the grid (P_{Mag}), and the dissipated energy (P_{Loss}). So, each term of energy, for any state of the system, is defined as follows:

Kinetic Energy of machine i:

$$KE_i = \frac{1}{2}M_i\omega_i^2 \tag{4}$$

Potential Energy of the Rotor Position of machine i:

$$PR_i = P_{m_i}\delta_i \tag{5}$$

Magnetic Energy:

$$P_{Mag_i} = Eei_{transferred} \tag{6}$$

The last term on the right side of 3, P_{Loss}, is the lost energy in the resistors and dampers. So, the total potential energy is defined as

$$PE = PR + P_{Mag} + P_{Loss} \tag{7}$$

To have a better view towards the concept of the energy, consider a SMIB system, as shown in Fig.1. In this system, the synchronous machine is connected to an infinite bus through a line with an impedance of Z . Suppose that a three-phase symmetrical fault is applied on the line, and the fault is removed after about 0.3 seconds without any change in the network configuration, and the post-fault system remains stable. Fig.2 depicts the Potential Energy (PE) and Kinetic Energy (KE) before, during, and after the fault. During the fault, no electrical power is transferred to the system from the synchronous generator. Hence, the mechanical power supplied to the machine via turbine causes the rotor to speed up and gain some extra kinetic energy compared to steady state.

It can be seen that when the system is gaining extra energy during the fault, the potential energy is changing as well. After the fault, the energy conversion from kinetic form to potential form continues until the system reaches to its new stable equilibrium point, or losses synchronism in an unstable condition.

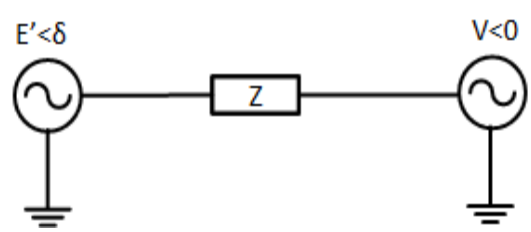

Fig. 1: A simple Single Machine Infinite Bus System.

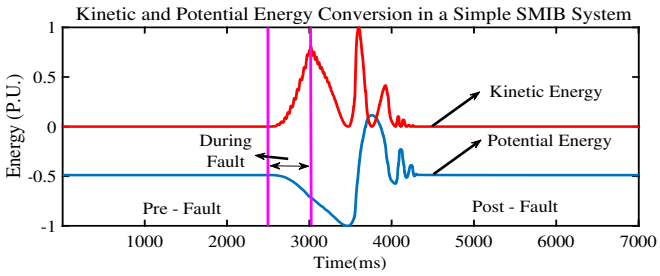

Fig. 2: Potential and Kinetic Energy Conversion for the noted SMIB system.

C. Energy Function For a Multi-Machine System

To use the energy concept for Transient Stability Assessment (TSA) in a multi-machine system with n generators, a generalized function should be found. Therefore, the summation of 3 for all the generators of the system is considered to find the energy balance equation of the entire system.

$$\sum_{i=1}^{n} \frac{1}{2} M\omega_i^2 |_{\omega_{i1}}^{\omega_{i2}} =$$

$$\sum_{i=1}^{n} P_{m_i} \delta_i |_{\delta_{i1}}^{\delta_{i2}} + \sum_{i=1}^{n} Eei_{transferred} |_{t_1}^{t_2} + \sum_{i=1}^{n} E_{Loss_i} |_{x_{i1}}^{x_{i2}} \quad (8)$$

The second term of the left side of (8), usually referred as Magnetic Energy (P_Mag), is basically the summation of the integration of load flow equation. Therefore, this term can be rephrased as:

$$\sum_{i=1}^{n} Pei_{transferred} |_{t_1}^{t_2} = \sum_{i=1}^{n} \sum_{j=1}^{n} |V_i| \, |V_j| \, |Y_{ij}| \, sin(\Theta_{ij} - \delta_i + \delta_j) |_{\delta_{i1}, \delta_{j1}}^{\delta_{i2}, \delta_{j2}} \quad (9)$$

where V_i, V_j, and $|Y_{ij}|$ are voltages of bus i and j, and transfer impedance between buses i and j, respectively. Θ_{ij} is the angle of Y_{ij}. Hence, each kind of energy, for the current state of the system is defined as
Total Kinetic Energy:

$$KE = \sum_{i=1}^{n} \frac{1}{2} M\omega_i^2 \quad (10)$$

Total energy related to rotors position:

$$PR = \sum_{i=1}^{n} P_{m_i} \delta_i \quad (11)$$

Total magnetic energy:

$$P\_Mag = \sum_{i=1}^{n} \sum_{j=1}^{n} |V_i| \, |V_j| \, |Y_{ij}| \, sin(\Theta_{ij} - \delta_i + \delta_j) \quad (12)$$

Based on (8), the kinetic energy change in generators between any two moments, during a fault for example, is equal to potential energy change in the same time frame.

$$\Delta KE = \Delta PE \quad (13)$$

Equation (7) holds true in multi-machine systems as well. In the critical case potential energy is equal to kinetic energy ($KE = PE$); in stable situations the ($KE < PE$); and instability occurs if ($KE > PE$), according to discussions in [4].

III. The Proposed Method

As mentioned earlier, the topology and the initial operating condition, (which makes changes in the potential energy absorbing capacity of the network) are some of the important parameters when considering the stability of a system. Hence, the proposed method is explained based on these parameters:

A. Network Topology

For an assumed configuration, there is a maximum amount of energy that the system can absorb. This maximum energy is called critical energy. Let this is represented as V_{cr}. When forces on the generators try to bring them to new equilibrium points, the system must be able to absorb the kinetic energy to avoid instability. This ability depends on the potential energy absorbing capability of the post-disturbance system, which in turn depends on the topology of the post-fault network. The transient kinetic energy can make a synchronous generator to depart from the initial equilibrium state if the network does not have the ability to absorb the extra energy gained by rotors during a contingency[8], [24], [25].

Potential energy varies along the post-disturbance trajectory [25]. If the fault is kept long enough for one machine (or more) to become critically unstable, the potential energy of the critical machine goes through a maximum before the system goes unstable (see Figs. 4, and5). In addition, this maximum value (of the potential energy along the post-disturbance trajectory) of a given machine is essentially independent of the duration of the disturbance. This value of potential energy represents the energy absorbing capacity of the network and is equal to V_{cr}.

B. Network Potential Energy Capacity

According to discussions in section II, if a system has a larger capacity to absorb the kinetic energy gained by generators during the fault, and can convert it to potential energy, that system is more stable against sudden changes. As it can be seen from (7), the potential energy change in the system consist of three terms: the first term is related to the potential energy stored in the rotor (PR), which depends on the angle of the generator, and is basically dictated by swing equation. The second term of PE is related to the electric power transferred

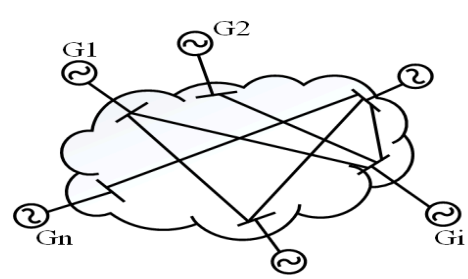

Fig. 3: A Multi-Machine System.

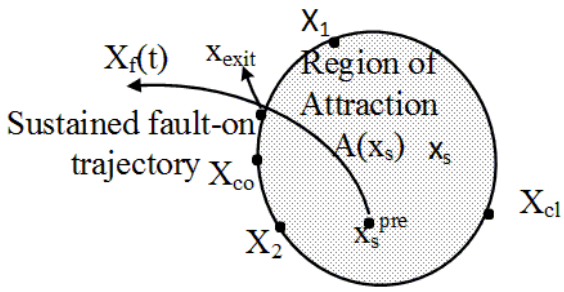

Fig. 4: The sustained fault-on trajectory moves towards the stability boundary and intersects it at the exit point.

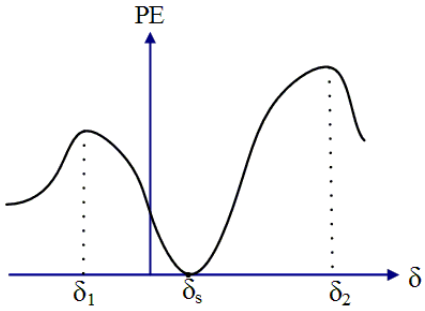

Fig. 5: The potential energy function is only a function of δ and reaches its local maximum at UEPs $\delta 1$ and $\delta 2$.

from machine i, and depends on the bus voltages and angles, which itself depends on the system topology. Finally, the last term of PE shows the dissipated energy which depends on the voltages and elements of impedance matrix. Therefore, the stability of the system depends on fault location, fault duration, and network topology. To understand on what happens in the network from an energy point of view, the system dynamics is analyzed in three stages as follows:

C. Before Fault and During Fault

At steady-state, the system is settled at its Stable Equilibrium point (SEP). This is the point that PE of the system is at its minimum. Also, it has been proven that the KE of a system is at the lowest amount [4]. During fault, the KE gained by the rotors makes the generator angles increase, which in turn makes the bus angles change. Since the rotor energy depends on the generator angles, the PE of the rotors increases. At the same time, the angle increase makes the Magnetic Energy decrease, as it depend on the cosine of the angles.

D. Post Fault

When the fault is removed, a sudden change happens in the amount of PE of the system, because of the immediate change that happens in the bus voltages and angles. Also, the direction of change in the kinetic energy changes. The amount of PE at the very moment of fault removal depends on the fault duration. Also, the angle increase in the generators continue, because the rotors still have positive speed although with negative acceleration. This cause PR to continue increasing. At the same time, the magnetic energy of network branches

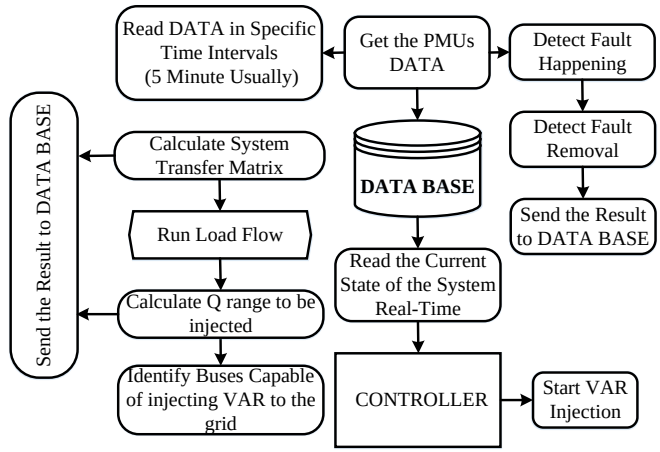

Fig. 6: Proposed Method Flow Chart

will decrease despite the voltage increase in the network. The reason is that as the angles are still increasing, the cosine term keep decreasing. The increase in PR and decrease in P_{Mag} continue until the speed deviation of the machines change its direction, which happens simultaneously with a change in the direction of magnetic energy. Therefore, it can be concluded that the magnetic energy reaches a minimum after the fault.

From now on, the stability of the system depends mostly on the energy conversion between PR and P_{Mag}. If the P_Mag goes lower than a certain limit, which means PR is crossing an upper limit, the system will lose synchronism. Crossing the noted limits means the difference between some of the angles of buses and machines are so high that they are out of synchronism. Hence, by controlling the amount of PE at this moment, the stability of the system can be controlled.

E. Increasing Potential Energy to Improve Transient Stability

From the aforementioned analysis, it can be concluded that the system branches should have the capacity to absorb the extra energy of rotors in order to keep the system stable. This capacity depends on the line impedance, voltages, and angles of the buses the line is connected (see (14)). Hence, each system has a maximum capacity of potential energy absorbing capacity, which depend on its SEP. The SEP itself depends on the configuration and initial condition of the post-fault network. Also, for a system to be able to reach to its maximum absorbing capacity, the deviation from the SEP should not be more than a certain amount that is determined by PE.

The lower limit of the PE depends on the cosine of the bus angles and voltage of the buses. The angles are dictated by swing equations. So, to extend the limits of P_{Mag} and make the system more stable, sudden voltage change can be considered. By increasing the voltages, P_{Mag} would increase according to (14). Consequently, the PE capacity of the network will increase, which helps the system be more stable. Using this method, the post-fault can absorb more portion of the kinetic energy injected into the grid during the fault, which in turn leads to a more stable post-fault network.

$$P_{Mag} = \sum_{i=1}^{n}\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}|\,cos(\delta_i - \delta_j) \tag{14}$$

The amount of VAR that can be injected to increase the PE, and bus voltages, is limited. Huge amount of VAR injection to the grid, can cause the generators to work in under-excitation mode, which can damage the generators. Also, it will increase the voltage of buses too much that will endanger devices. Finally, huge injection of reactive power increases the PE in a way that the system branches not only absorb the extra KE gained during the fault, but can cause more KE absorption from the rotors, because the higher voltage causes an increase in voltage dependant loads. This in turn causes a decrease in generator speed, which can make the system loose its synchronism. Therefore, it is necessary to reduce the injected VAR as time passes after fault removal. The equal amount of VAR that the system was generating before the fault, but under the faulted system voltages, is the maximum amount of VAR that can be injected to the grid without encountering the aforementioned problem, as presented in (15).

The minimum amount of VAR required to improve the transient stability can be obtained by considering that the VAR source should supply the reactive loss of the pre-fault network, so that no part of generators' capacity is used for supplying the reactive loss of the post-fult network. It can be calculated using (16). Different cases that were studied shows that the defined range is valid.

$$Q_{max} = \frac{V^2_{Faulted}}{Q_{BeforeFault}} \tag{15}$$

$$Q_{min} = \frac{V^2_{BeforeFault}}{Q_{BeforeFaultNetworkLoss}} \tag{16}$$

To inject the reactive power equal to Q, the required lead impedance can be found using (17).

$$Q = \frac{|V_i|^2}{|Z_c|} \tag{17}$$

If the Q is directly injected to bus i, the new voltage of bus i and other buses can be obtained using (18) and (19), respectively.

$$V_i^{new} = \frac{V_i Z_c}{Z_{ii} + Z_c} \tag{18}$$

$$V_j^{new} = V_j - Z_{ij} * \frac{V_i}{Z_{ii} + Z_c} \tag{19}$$

where Z_{ii} is the Thevenin impedance seen from buses i, and Z_{ij} is the transfer impedance between buses I and j.

If we separate the real and imaginary parts of voltages and impedance as shown in (20), and (21), new voltages after VAR injection can be calculated using (22) and (23).

$$V_k < \delta_k = V_k^R + iV_k^I \tag{20}$$

$$Z_{ij} = R_{ij} + iX_{ij} \tag{21}$$

$$V_i^{new} = \frac{(V_i^I - iV_i^R)((V_i^I)^2 + (V_i^R)^2)}{Q * R_{ii} + i(Q * X_{ii} - |V_i|^2)} \tag{22}$$

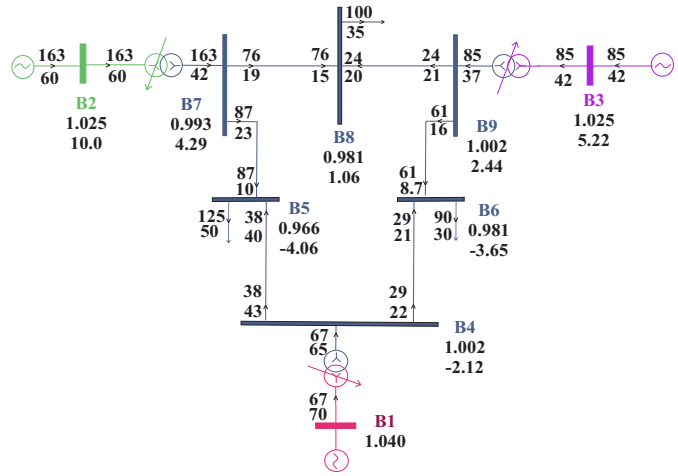

Fig. 7: IEEE 9Bus Load Flow

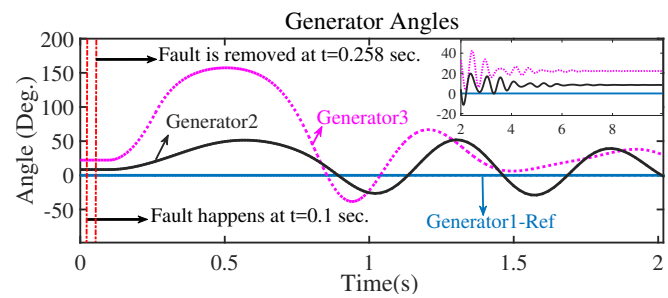

Fig. 8: Generator Angles

$$V_j^{new} = \frac{(QR_{ii}V_j^R - V_j^I(QX_{ii} - |V_i|^2) - QR_{ij}V_i^R + QX_{ij}V_i^I)}{Q * R_{ii} + i(Q * X_{ii} - |V_i|^2)}$$
$$+i\frac{(QR_{ii}V_j^I + QX_{ii}V_j^R - V_j^R|V_i|^2 - QX_{ij}V_i^R - QR_{ij}V_i^I)}{Q * R_{ii} + i(Q * X_{ii} - |V_i|^2)} \tag{23}$$

Substituting new voltages in (12) delivers the new PE. It should be noted that the new energy can be used for calculating the required Q for a specific amount of PE change. Fig. 6 shows the flow-chart of the proposed method. The proposed method is tested for different cases successfully using a power analysis software, PASHA [1].

IV. TESTS AND RESULTS

The proposed energy function based approach is tested using and IEEE 9 bus system (see Fig. 7). For this, a three phase symmetrical fault is applied on Bus7 at t=0.1 sec. Without voltage increase in the post-fault system, the critical clearing time, obtained by simulation, is 0.158 sec. Figs. 8 and 9 present generator angles and bus voltages respectively.

To implement the proposed method, in order to increase the post-fault voltages, a capacitor is used to increase the bus voltage. The capacitor is placed at Bus2. A three phase symmetrical fault is applies on Bus7 at t=0.1 sec. Time simulation shows if the capacitor is switched in at the moment of fault removal, system can be survived from loss of synchronism for a fault duration up to 0.273 sec., which means the critical clearing time has increased from 0.158 sec. to 0.173 sec. by

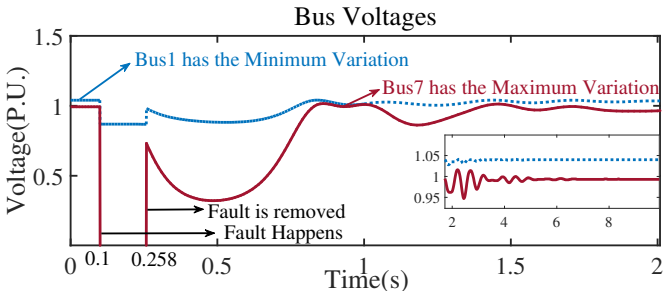

Fig. 9: Bus Voltages

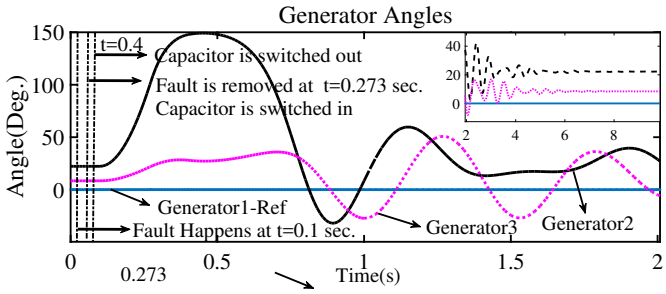

Fig. 10: Generator Angles - Capacitor Switched in at Fault Removal

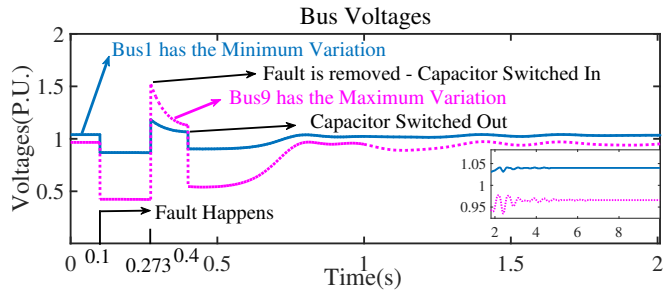

Fig. 11: Bus Voltages - Capacitor Switched in at Fault Removal

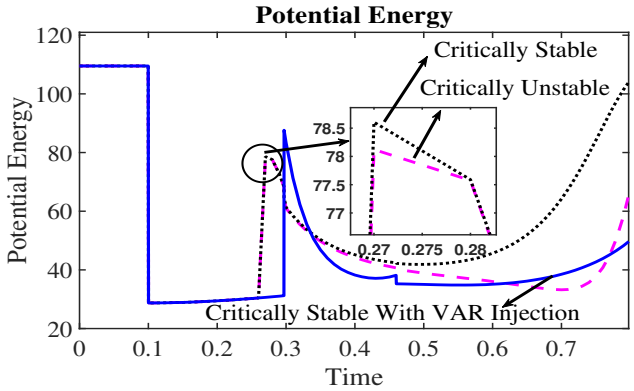

Fig. 12: Potential Energy

voltage increase. Figures 10 and 11 show the generator angles and bus voltages for this study. Figure 12 shows the potential energy in the system at the critically stable system, critically unstable system, and the critically stable system when the VAR is injected to bus 2 at the moment of fault removal.

Tables I-V present a comparison between critical clearing time, steady-state voltages and angles, and maximum and minimum of voltages and angles the voltages and angles of different buses, respectively.

TABLE I: Critical Clearing Time (mili-seconds)

Without Proposed Method	With Proposed Method
158	173

TABLE II: Steady State Voltages

		Post-Fault	
Pre-Fault		Without Proposed Method	With Proposed Method
Bus1	1.0400	1.0400	1.0400
Bus2	1.0250	1.0250	1.0250
Bus3	1.0250	1.0250	1.0250
Bus4	1.0020	1.0020	1.0020
Bus5	0.9660	0.9660	0.9660
Bus6	0.9810	0.9810	0.9810
Bus7	0.9930	0.9930	0.9930
Bus8	0.9810	0.9810	0.9810
Bus9	1.0020	1.0020	1.0020

TABLE III: Steady State Angles(Degree)

Without Proposed Method			With Proposed Method	
Busbars	Minimum	Maximum	Minimum	Maximum
Bus1	-178.7200	179.5600	-179.7500	176.5100
Bus2	-179.9200	179.4700	-179.3700	176.9300
Bus3	-179.7700	178.4100	-178.8000	179.6300
Bus4	-179.9700	178.4700	-179.5000	177.4700
Bus5	-179.7300	179.8500	-178.8100	178.3300
Bus6	-179.1200	179.9200	-177.9300	179.6100
Bus7	-178.1800	179.4700	-178.6500	178.2000
Bus8	-179.9500	178.3700	-178.9600	178.4700
Bus9	-179.3500	179.3900	-178.5800	179.7600
Generator2	-38.4200	157.3300	-31.9600	149.2000
Generator3	-28.9400	51.9800	-27.3400	50.7400

V. CONCLUSION

In this paper a new method for transient stability improvement is proposed. The method is based on the concept of energy function. In this method, the potential energy of the system is changed via injecting reactive power. The results for applying the proposed method on IEEE 9 bus system is presented. The results show an improvement in the transient stability of the system and an increase in critical clearing time.

TABLE IV: Post-Fault Voltage Extremum

Without Proposed Method			With Proposed Method	
Busbars	Minimum	Maximum	Minimum	Maximum
Bus1	0.8680	1.0410	0.8680	1.1820
Bus2	0.2990	1.0540	0.2990	1.0530
Bus3	0.7190	1.0340	0.7180	1.0500
Bus4	0.6660	1.0060	0.6650	1.2770
Bus5	0.4220	0.9770	0.4220	1.5200
Bus6	0.6080	0.9870	0.6060	1.1650
Bus7	0	1.0160	0	1.0170
Bus8	0.2240	0.9990	0.2230	0.9990
Bus9	0.5460	1.0140	0.5450	1.0410

TABLE V: Post-Fault Angles Extremum with respect to synchronous frame (Degree)

Without Proposed Method			With Proposed Method	
Busbars	Minimum	Maximum	Minimum	Maximum
Bus1	-178.7200	179.5600	-179.7500	176.5100
Bus2	-179.9200	179.4700	-179.3700	176.9300
Bus3	-179.7700	178.4100	-178.8000	179.6300
Bus4	-179.9700	178.4700	-179.5000	177.4700
Bus5	-179.7300	179.8500	-178.8100	178.3300
Bus6	-179.1200	179.9200	-177.9300	179.6100
Bus7	-178.1800	179.4700	-178.6500	178.2000
Bus8	-179.9500	178.3700	-178.9600	178.4700
Bus9	-179.3500	179.3900	-178.5800	179.7600
Generator2	-38.4200	157.3300	-31.9600	149.2000
Generator3	-28.9400	51.9800	-27.3400	50.7400

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