IMPACT OF THE TRANSIENT STABILITY CONSTRAINT ON UNIT COMMITMENT WITH RENEWABLE ENERGY SOURCES

By

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A thesis presented to Ryerson University

in partial fulfillment of the requirements for the degree of

MASTER OF APPLIED SCIENCE

In

The Program of

Electrical and Computer Engineering

Toronto, Ontario, Canada, 2017

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ABSTRACT

Impact of the Transient Stability Constraint on Unit Commitment with Renewable Energy Sources

A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF APPLIED SCIENCE in the year 2017 at Ryerson University

by SHRIRAM SHUKLA

in the Program of Electrical and Computer Engineering.

The inertial energy of generators in a power system plays an essential role in maintaining the transient stability in response to the strike of short-circuit faults. Integration of large quantities of renewable energy resources, such as wind and solar energy, and the reduction in the number of conventional generators can lead to the reduction of the overall system inertia of the power system and may result in their vulnerability to faults.

To enable a higher integration of renewable energy and to ensure a reliable operation of the power system, it is imperative that the impact of transient stability criteria be incorporated into Unit Commitment algorithms.

This thesis proposes to incorporate an inertia based transient stability constraint in a unit commitment formulation. Algorithm to estimate parameters for the proposed transient stability constraint is developed and presented. A transient stability constrained unit commitment (TSUC) is formulated as a mixed integer linear programming (MILP) model. The effectiveness of proposed method is successfully tested on a 9-bus power system and results are discussed.

ACKNOWLEDGEMENTS

First and foremost I would like to express my deepest gratitude toward my supervisor, Professor: Dr. Bala Venkatesh, for his continuous guidance, encouragement and support throughout my Masters study and providing me with an inspiring research environment. I admire his intuitions and encyclopedic knowledge.

The financial support from NSERC grant, Canada awarded to Professor Bala Venkatesh is gratefully acknowledged.

I would like to extend my very special thanks to all my professors and colleagues at Ryerson University for guiding me along the way and for their tireless and patient teachings.

In addition, I express my special thanks to Dr. Peng Yu, Dr. Omid Alizadeh and Mr. Birendra N. Singh who have supported me a lot throughout the whole phase of graduate studies for research activities.

I thank Dr. Mohamed Awadallah and Dr. Bhanu Opathella for their valuable feedbacks. I thank them, other mentors and friends for encouraging me to apply higher standard of knowledge for better performance. I thank my other colleagues for being good colleagues and resources.

Finally, I would like to thank my parents for encouraging me to pursue graduate study. Most of all, I would like to thank my wife and my daughter. I thank my wife for being a better-half to get a success in graduate studies. Without her support and compromises, I would have never succeeded.

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LIST OF SYMBOLS:

TSUC	Stability Constrained Unit Commitment
MILP	Mixed Integer Liner Programming
IEEE	Institute of Electrical and Electronics Engineers
MATLAB®	Computer Program for Calculation, Optimization and Implementation

Abbreviation "i" for generator unit number "i"

Abbreviation "k" for time slot number "k"

Abbreviation "Δ" for deviation from mean value

Abbreviation "G" for generator

Abbreviation "M" for motor

Abbreviation "L" for line

Abbreviation "T" for Total System

Abbreviation "0" for Mean Value

Abbreviation "max" for Maximum Value

δ	Relative Angle
X	Reactance
E	Voltage
V	Potential Energy
P	Electrical Active Power

SEP	Stable Equilibrium Point
UEP	Unstable Equilibrium Point
$\Delta\delta$	Synchronizing torque component
T_s	Synchronizing torque coefficient
$\Delta\omega$	Damping torque component
T_d	Damping torque coefficient
T_e	Electrical Torque
T_m	Mechanical Torque
P_e	Electrical Power
SMIB	Single Machine Infinite Bus
I	Moment of Inertia
S_m	MVA rating of generator
M_i	Inertia Constant of machine "i", $I\omega_m$
H	Inertial Energy Constant MW.s/MVA
ω_i	Rotational Speed of machine i
T_a	(de)accelerating Torque
T_s	Synchronizing Torque
T_d	Damping Torque
P_e	Electrical power in p.u
P_m	Mechanical power in p.u
Q	Reactive Power
r	Radius of Rotor of Conventional Generator Unit

ω_m	Roration Speed of Rotor
KE	Kinetic Energy
CDM	Conservation and Demand Management
IESO	Independent Electricity System Operator

Abberaviations and Symbols for UC Formulation:

Definition of Convention:

$\overline{x}$, $\underline{x}$ Upper and Lower bars indicate upper and lower limits of the generic variable ‘x’

Definition of Variables:

t, n, m	Indices for time, generator and segment of a generator
l	Index for line number
i	Index for bus number
NH	Number of hours for the system
NG	Number of generators in the system
NM	Number of segments in a generator in the system
NT	Number of lines in the system
NB	Number of total buses in the system
U	Matrix of binary integers representing unit status
PG	Matrix of real power output of generators
PM	Matrix of real power output of segments
R	Matrix of Online spinning reserves

SU	Matrix of binary integers representing startup of units.
PL	Matrix of MW line flows
HG	Vector of Inertial energy supplied by committed conventional generators
PD	Vectors of real power load at buses
R10	Vectors of 10-minute ramp rates
R60	Vectors of 60-minute ramp rates
UT	Vectors of minimum up time of units
DT	Vectors of minimum down time of units
IC	Vector of initial conditions of units
G10	Set of indices of quick start (10 min) Units
P10	Vector of capacities of quick start units
SR	Vector of hourly required spinning reserve capacity for the system
α	Fraction of total hourly spinning reserve (SR_t) to be scheduled in the system
a, b, r, d	Vectors of constants of fixed unit costs ($), variable costs ($/MWh), reserve costs ($/MWh) and startup costs ($/start)

Chapter 1: INTRODUCTION

Electric utilities are required to reduce greenhouse gas substances. To achieve this target, an increasing amount of renewable energy systems are being integrated into power grids. According to US climate change action report, electricity sector is contributing about 30% in the greenhouse gas emissions. Recent advances in renewable energy systems can enable them to replace the existing conventional generation plants. Excluding Hydro-electric generation, capacity of total renewable energy sources in the province of Ontario 4,698 MW and is about 13% of the total system capacity. In addition, Ontario is aggressively procuring renewable generators according to its Green Energy Act [1]. To meet the constantly varying electricity demand, the generator units are dispatched and these interconnected generation and transmission systems are operating with specific reserve operating margin. The electricity usage is not constant and it follows an uneven, unpredictable trend. In addition, there are tripping mechanisms in the event of fault occurrence in the interconnected electrical power system. By adding more renewable energy resources in the electric grid, the participation of conventional generators is reduced. The renewables are typically inertia-less and their higher commitment in the power system poses challenges for the transient stability of the interconnected power system.

1.1 Transient Stability Problem

Faults in interconnected systems are undesirable and unpredictable events which disturb the balanced of power. The tripping mechanism is designed for fault isolation to avoid the fault feeding electrically by the healthy system and to maintain the interconnected power grid system to operate within limits. After isolating the faulty equipment, the remaining interconnected power system oscillates and transitions to a new operating state (equilibrium point). Inertia of rotating machines plays a vital role in keeping the power system stable. The transient stability of the system is accounted for an important role to maintain synchronism of the power system equipment and to maintain balance after fault event. The response of transient stability is depending on the type, location and severity of fault and connected equipment's inertial energy. The ability of the interconnected power system to remain stable depends upon the inertial energy present in the connected rotating machines [2]. However, renewable energy resources such as solar and wind energy systems interface with the power system using a power conversion unit and do not possess inertial energy. Hence, a larger dispatch of renewable energy to meet demand leads to a lesser total inertial energy available in the power system that come from the remaining dispatched conventional generators. The reduced amount of total inertial energy might not be sufficient to enable the power system to maintain stability after a large fault. Hence, it is imperative that while dispatching generators, conventional or renewable, the total available inertial energy is required to maintain at a mandatory level to ensure that the power system remains stable on the face of severe faults. By this thesis, the transient stability requirement is incorporated in unit commitment in the form of constraining inertial energy.

1.2 Unit Commitment

The day-ahead Unit Commitment (UC) challenge entails determining the optimal generation schedule for all participating generators in a power system to supply electricity to all connected loads. This objective is constrained by limits on equipment such as generators, transformers, transmission lines, etc. and network power flow limits. The challenge is coined as 24 hourly optimization problems. As the electricity demand in the system varies through the day, generators ramp up and down and in some cases are started and shutdown. The limits on ramp rates and start up and shut down form intertemporal constraints and interlink hourly optimization problems.

1.3 Research Work with Transient Stability, Unit Commitment and Renewables

Transient stability and unit commitment of power system have been widely discussed in the literature. The recent research related with power system and unit commitment is summarized here for the literature survey. Transient stability constraint within unit commitment is discussed in research work of reference [3]. This research work has considered fault events and transient stability constraint of unit commitment and cost implications. But this research work has not consolidated the effects of increasing dispatch participation of renewable energy sources in unit commitment. The effect of increased participation of renewable energy sources on transient stability is not considered in this research work.

The inertia consideration and renewable participation for unit commitment and economic dispatch is discussed in research work of reference [4]. But this research work has envisaged neither fault event nor transient stability. Instead the research work is featured with the Rate of Change of Frequency (ROCOF) and inertial constraint. The reliability of transmission system on the face of faults is not considered for this research work [4]. The research work performed by reference [5] has considered inertia and governor ramp rate for economic dispatch for primary response adequacy. Primary response considers for fault event and economic dispatch has considered lower operating cost. This research work has not considered the unit commitment which makes the forecast and scheduling of generators for the 24-hour scheduling horizon.

The research work performed so far for unit commitment and power system stability have considered ROCOF, transient stability, inertial energy, fault events and renewable participation for economic load dispatch, unit commitment and cost implications. No research work has been performed with the coordinated approach with renewable generator participation and inertial energy as a constraint of unit commitment for transient stability in view of fault event. The fault events are coordinated to find constraining inertial energy value in the system. The unit commitment decisions are compared and verified on the account of added constraint.

1.4 Motivation for the Thesis: Transient Stability Problem with Renewables

The motivation for this work is to examine the effects of renewables on transient stability, inertia of the system and unit commitment decisions. To purpose is to propose a transient stability constrained unit commitment (TSUC) algorithm considering minimum inertial energy requirement for transmission systems with renewables. The proposed TSUC should dispatch not only power to supply hourly demand, but also have sufficient inertial energy to maintain the power system stable after fault events. The research work performed with coordinated approach for transient stability constraint by inertial energy constraint, fault events and unit commitment with renewables is entirely exceptional for healthy operation of power system planning for 24-hour scheduling horizon. The Motivation is to find the constraining inertial energy value by simulation and verify unit commitment decision difference due to minimum inertial energy constraint.

This thesis uses PSS-E® to find constraining inertial energy and MATLAB® code is used to verify unit commitment decision difference.

1.5 Thesis Objectives

The objective of this thesis is to find the constraining inertial energy for the power system with renewables to maintain transient stability. The effect of constraining inertial energy value as a constraint of unit commitment is also to be verified by implementing the mathematical formulation. The renewables with higher priority for participation in the power system to supply electricity are committed to replace the existing conventional generators. These renewables are inertia-less generators and pose transient stability problems by reducing commitment of conventional generators which can contribute for transient stability and inertial energy. The purpose of this research is to propose a transient stability constrained unit commitment (TSUC) algorithm considering minimum inertial energy requirement for transient stability as a constraint for power system with renewable generators.

This thesis is organized in chapters in following manner.

Chapter 2 provides a theoretical foundation for this work. It introduces consequences of fault events on the balanced interconnected system, basic definitions and factors affecting system's kinetic energy and inertial energy for transient stability. Chapter 3 is discussing about a practical approach to find the constraining value of inertial energy to satisfy transient stability requirements of the power system in the event of fault. The proposed method to find constraining inertial energy is performed on the 9-Bus, 3-Generator system to verify transient stability. The technical data set for 9-Bus system are listed in chapter 3. Minimum inertial energy as a constraint of unit commitment and its formulation is presented in the chapter 4. The offer price bid data and 24-hour demand forecast of the 9-Bus system are noted in chapter 4.

The results of constraining inertial energy value and unit commitment decisions for 9-Bus system is recorded and discussed in chapter 5. The summary of unit commitment decision difference and cost impact due to inertial energy constraint is noted in chapter 5. The results are listed to demonstrate the effects on unit commitment decisions due to inertial energy constraint for transient stability.

In Chapter 6, conclusions from the study cases and test results are listed. The research contributions have been justified and conclusion has been reported in the chapter 6. The future research recommendations have also been noted herewith in the chapter 6. Finally, in the appendices, equations for small signals stability, supporting results for transient stability by optimization tools are reported.

1.6 Conclusion

The transient stability constrained unit commitment research studies have been performed considering ROCOF, transient stability, inertial energy, fault events and renewable participation. No research work has been performed with the coordinated approach with renewable generator participation and inertial energy as a constraint of unit commitment for transient stability in view of fault event. In this thesis, the fault events are coordinated to find constraining inertial energy value in the system and the unit commitment decisions are compared and verified for the added constraint.

Chapter 2: THEORY AND FORMULATION

This chapter introduces basic theoretical foundation for this research work, formulation and test procedure. In this chapter, we choose to use the definitions and consequences of fault occurring and transient stability as given in [6] and [7]. The basic theory and affecting factors of power system stability, inertial energy, transient stability, renewable sources and power balance have been provided in this chapter. The details of unit commitment algorithm, constraints, decision and affecting factors are also provided in chapter 4. Data set details used for the formulation and practical approach are also discussed. The practical approach to find the constraining inertial energy value is determined and mathematical formulation of unit commitment and constraints are also defined.

2.1 Types of Faults in Electrical Power System

Different types of faults in the interconnected electrical power system can be categorized according to types of their nature and severity as follows [2].

A. Short-circuit Faults

    a) L-G fault: Line to Ground short-circuit

    b) L-L fault: Line to Line short-circuit

    c) 3-L-G fault: Three Line to Line and Ground short-circuit

B. Open-circuit Faults

    a) Single-phase open circuit

    b) Two-phase open circuit

   c) Three-phase open circuit

C. Simultaneous Faults

   Combination of above two kinds of faults

D. Winding Faults: within generator and transformer

   a) Winding to earth short-circuit

   b) Winding to winding short-circuit

   c) Open-circuit winding

   d) Inter-turn winding short-circuit

The effects of these faults on transmission system, connected generators and loads depends on types of faults, location of fault, severity of fault, duration of fault, fault level and stability of the zone of protection. The effects of these faults can be reduced by proper coordination of relays and circuit breakers for fault clearing.

The faults are supposed to be cleared within specified time for the stability of the system and to save the system from further damage [8]. Once fault is initialized and during its clearing process, the response of inertial energy comes into effect in the form of transient stability [9].

2.2 Consequences of Faults on Balanced Electrical Power System

The faults in the electrical systems results in abnormally high currents (sometimes in terms of thousands of ampere) causing excess amount of power consumption and heat generation momentarily. The high amount of power consumption and heat dissipation due to fault event for extended time (sometime in terms of several seconds) can cause not only unbalance in grid frequency and bus voltage, but also can cause equipment damage. Hence, the faults are supposed to be isolated from the healthy operating power system within specified time [8]. Unbalance in real and reactive power demand-supply causes frequency and bus voltage deviations from nominal values respectively. Major unbalance in the frequency and bus voltage causes sequential tripping in power system considering severity of fault and contingency ranking [9]. The faults in the electrically balanced system cause transient unbalance due to mismatch between input mechanical power and connected electrical power output. The faults cause momentary shortfall of electrical power supply as high amount of current is fed to fault and turbine's mechanical controllers are not able to match with the speed of response.

Transient instability causes generators' rotor angles to be shifted from their positions magnetically due to turbine’s mechanical controllers’ comparatively slow response. The response of unbalancing of mechanical input and electrical output power of the system results in either accelerating or de-accelerating of generator's rotor [6].

2.3 Power System Transient Stability Concepts

Power system stability can be defined as a property of a power system that enables the state of operating equilibrium under normal operating conditions and to regain an acceptable state of equilibrium after being subjected to a disturbance [2]. Stability of power system is depending on the system configuration and operating mode. The necessary condition for system's stable operation is that all synchronous machines operate in synchronism. This aspect is influenced by the dynamics of the generator rotor angles and power-angle relationship.

In the stability assessment, the disturbance may be small in the form of switching load conditions, or large disturbances such as, short-circuit on a transmission line, loss of large load or generator, loss of tie-line between two subsystems. The system response to a disturbance depends on the connected equipment, type and location of fault. To simplify and focus on factors influencing the framework for transient stability, a brief description of power system instability and associated concepts is provided. Analysis of small signal stability is used to justify transient stability requirements in the event of faults within interconnected power transmission system.

2.3.1 Rotor Angle Stability

Rotor angle stability is the ability of interconnected synchronous machines of a power system to remain in synchronism [2]. The stability problem involves the study of the electromechanical oscillations inherent in power systems. A fundamental factor in this problem is to track the variation in the outputs of synchronous machines with respect to their rotors' oscillations.

When two or more synchronous machines are interconnected by transmission line(s), their stator voltages must be same and have the same frequency of rotor mechanical speed. Consider the system shown in Fig. 1. It consists of two synchronous machines connected by a transmission line having an inductive reactance x_L but negligible resistance and capacitance. Assume that machine 1 represents a generator feeding power to a synchronous motor represented by machine 2.

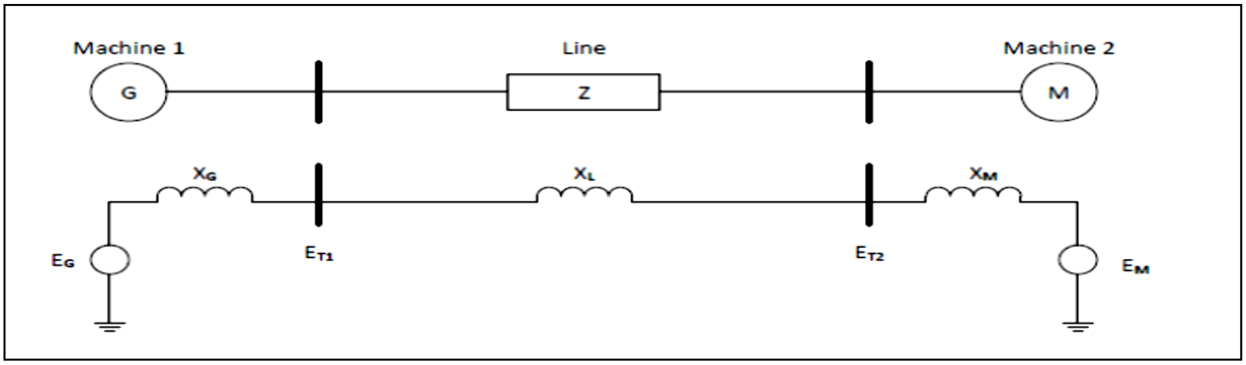

Figure 1: Single line diagram and equivalent circuit of a two-machine system [2]

The power transfer from the generator to the motor is a function of the angular separation δ between the rotors of the two machines. This angular separation is due to three components: generator internal angle δ_G, angular difference between the terminal voltages of the generator and motor, and the internal angle of the rotor of motor. A power-angle characteristics diagram identifying the relationships between voltage and angle is shown in Fig.2. The power transferred from the generator with reactance of x_G to the motor with reactance of x_M through a transmission line with reactance of x_L is given by equation 2.1.

$$P = \frac{E_G E_M}{X_T} \sin\delta \qquad (2.1)$$

where, $X_T = X_G + X_L + X_M$

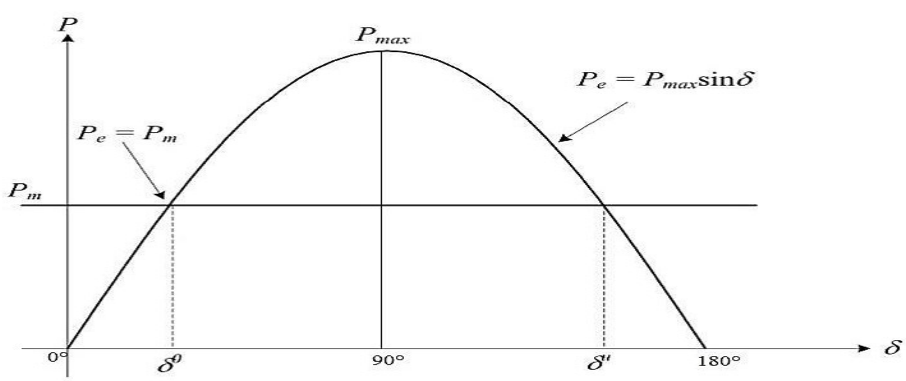

Figure 2: Power-angle characteristic of a two-machine system [2]

From Fig.2, there are two points of interest: stable equilibrium point δ^0 (SEP), and the unstable equilibrium point δ^u (UEP). In the steady-state status, the system rests on the SEP where the mechanical power is equal to the electrical power. However, if the system swings to the UEP, where the mechanical power is equal to the electrical power graphically, the synchronous machine loses synchronism (instability). Note that the system is assumed to be lossless.

Stability is a condition of equilibrium between opposing forces. In steady-state, there is equilibrium between the input mechanical torque/power and the output electrical torque/power of each machine, and the speed remains constant. However, if the system is experiencing perturbation, this equilibrium is disturbed resulting in acceleration or deceleration of the rotors of the machines according to the laws of motion of a rotating body [10].

Loss of synchronism may occur between one machine and the rest of the system or between groups of machines. In this case, synchronism may be maintained within each group after its separation from the others. The change in electrical torque of a synchronous machine following a perturbation can be resolved into two components:

$$\Delta T_e = T_s\Delta\delta + T_d\Delta\omega \tag{2.2}$$

where,

$T_s\Delta\delta$ is the component of torque change in phase with the rotor angle perturbation

$\Delta\delta$ is referred as synchronizing torque component

T_s is the synchronizing torque coefficient

$T_d\Delta\omega$ is the component of torque change in phase with the speed deviation

$\Delta\omega$ is referred as the damping torque component

T_d is the damping torque coefficient

The change of electrical torque required to maintain the balance of mechanical and electrical torque ($T_m - T_e$) is the quadratic sum of T_s and T_d which determine transient stability of the system [2]. Fig. 3 illustrates the responses of rotor angle with respect to values of synchronizing and damping torques.

For Negative T_s and Negative T_d case, the situation is described as "First Swing Instability" or "Out-of-Step Instability", in which the rotor angle deviation is such large that it is not oscillating at nominal value and the synchronous generator and/or equipment is tripped instantaneously [2]. Fig. 3 illustrates the difference of different types of transient stability responses for interconnected system.

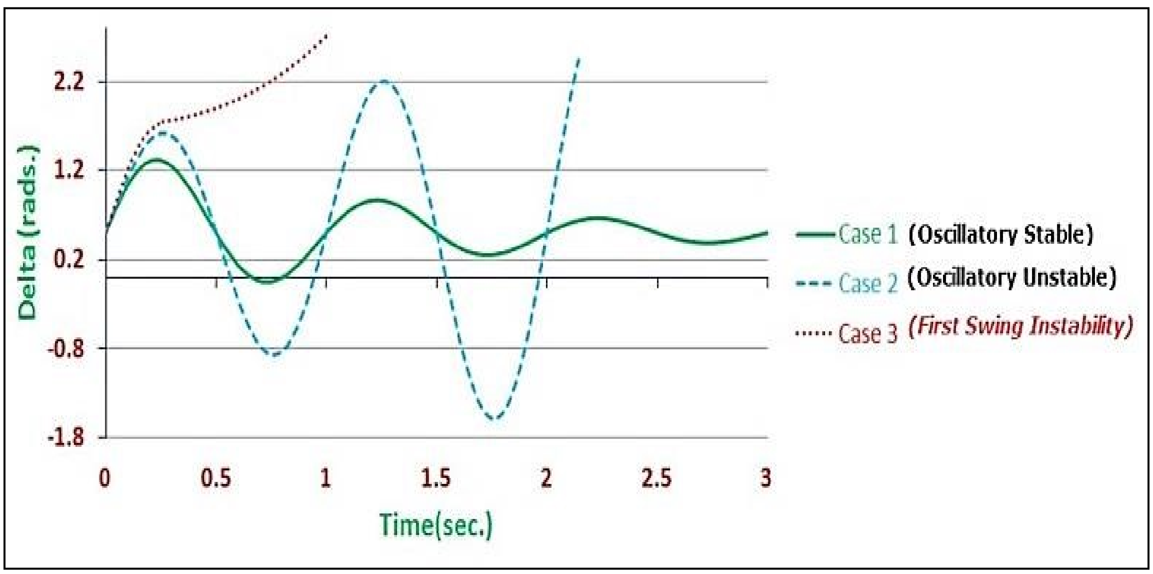

Figure 3: Rotor angle response to transient stability and instability [2]

Nowadays, a practical power system may experience small-signal instability due to insufficient damping of oscillations [2]. The types of oscillations due to instability are:

1. Local modes or machine-system modes: these are associated with the swinging of units at a generating station with respect to the rest of the power system

2. Inter-area modes: these are associated with the swinging of many machines in one part of the system against machines in other parts
3. Control modes: these are associated with generating units and other controls
4. Torsional modes: these are associated with the turbine-governor shaft system and rotational components

2.4 Faults, Transient Stability and Inertial Energy

The transmission systems face fault events due to equipment failure that threaten the healthy operation of the entire power system. After isolating the faulty equipment, the remaining interconnected power system oscillates and transitions to a new operating state (equilibrium point). Inertia of rotating machines plays a vital role in keeping the power system stable. In the event of fault, the excess amount of electrical energy is supplied to the fault causing unbalance between input generator source mechanical power and generated electrical power. The momentary unbalance of mechanical and electrical torques from equilibrium due to fault event is taken care by transient stability. The transient stability is supplied by the inertial energy present in the system which is supplied by rotating mass energy of the generators' rotors and turbines. The renewable energy sources do not have heavy mass rotating equipment to supply inertial energy. Hence, the first response for the fault event in the interconnected power system is the inertial energy supplied by conventional generators in the form of transient stability.

The ability of the interconnected power system to remain stable depends on the inertial energy present in the connected rotating machines [4]. Renewable energy resources such as solar and wind energy sources interface with the power system using a power conversion unit and do not possess inertial energy. Hence, a larger integration of renewable energy resources to meet the demand leads to a lower amount of inertial energy supplied by conventional generators to maintain transient stability. The reduced amount of inertial energy might not be sufficient to enable the power system to maintain stability after a large disturbance event. From above discussion, it is imperative that while dispatching generators, conventional or renewable, the total available inertial energy must be present to ensure that the power system remains stable when severe faults strike the system [9].

The recent developments in the technology of renewable energy resources have projected the renewable energy as a prime source of electricity generation to meet electricity demand. The renewable energy sources are merely able to supply sufficient amount of inertial energy to meet the reliability standards of transient stability in the event of fault. The synthetic inertial energy supplied by conventional energy sources is not considered as reliable source of inertial energy [8, 9]. The conventional heavy rotating mass generator units are supposed be dispatched in the optimal power flow to supply sufficient inertial energy.

Lack of sufficient synchronizing torque results in aperiodic drift in rotor angle while lack of sufficient damping torque results in oscillatory instability. Above phenomena is referred as small signal stability which is the ability of the power system to maintain synchronism under disturbances [2]. The change of electrical torque required to maintain the balance of mechanical and electrical torque $(\mathrm{T_m} - \mathrm{T_e})$ is the quadratic sum of $\mathrm{T_s}$ and $\mathrm{T_d}$ which determine transient stability of the system [2].

The standard equations coordinating moment of inertia (I), MVA capacity of generator $(\mathrm{S_m})$ and accelerating torque $\mathrm{T_a}$ are as following relations according to reference [2],

$$J = \frac{2HS_m}{\omega_m^2} \tag{2.3}$$

$$S_m = \frac{1}{2}\frac{I\omega_m\omega_m}{H} \tag{2.4}$$

$$(T_m - T_e) = T_a = J\frac{d^2\delta_m}{dt^2} \tag{2.5}$$

From above equations (2.3), (2.4) and (2.5), the (de)accelerating torque due to fault event is also the function of "H" energy and rotor angle deviation with respect to time as per following equation (2.6).

$$T_a = \frac{2HS_m}{\omega_m^2}\frac{d^2\delta_m}{dt^2} \tag{2.6}$$

From above equation (2.6) and discussion of synchronizing and damping torques, the value of electrical torque supposed to increase or decrease to match with mechanical torque is factorized in two parts in terms of synchronizing torque, T_s and damping torque,T_d. These torques are functions of "H" energy, the inertial energy constant of the system. Hence, ultimately the transient stability is directly dependent on the rotor angle deviation and the total "H" energy supplied by the rotating generator's rotor and turbine together [2].

2.5 Kinetic Energy, Inertial Energy and Affecting Factors

The inertial energy is defined as the kinetic energy stored in the rotating mass of the equipment which is called "H" energy. The concept of "H" energy supports Newton's law of motion for inertia. Here "H" energy can be represented as follows,

$$\text{"H" energy} = \frac{\text{Kinetic Energy stored in rotor of generator at Synchronous Speed}}{\text{machine rating, MVA}} \tag{2.7}$$

To meet the system demand, MVA rating of the generators are kept same, and conventional generator unit commitment is replaced by renewable generator unit of same MVA capacity. From above equation, as MVA rating is same, to change kinetic energy, "H" energy is changed by coordinating number of design parameters. The calculation of "H" energy value and affecting factors are represented by following equation (2.8),

$$\text{"H"energy} = \frac{2.31 \text{ X } 10^{-10} * M * r^2 * \omega_m^2}{\text{MVA rating}}[2] \tag{2.8}$$

For above equation (2.8), MVA rating and rotational speed, ω_m are constant parameters. For simulation and calculation, mass and radius of generator unit's rotor are replaced to get the same MVA rating from design parameters of different generator unit's commitment for dispatch. Each time the generator unit is replaced by another generator unit with lesser or higher value of "H" energy, transient stability analysis is to be performed to verify that the rotor angle deviation is within permissible limits. Every time the generator is replaced, small signal stability parameters are calculated to verify small signal stability of the system to avoid false tripping events. The equations for small signal stability are attached in appendix.

The replaced generator unit's inertial energy is calculated from following equations (2.9) and (2.10) using reference [2].

$$\text{Kinetic Energy (KE)} = (1/2) * (J * \omega_m^2) \tag{2.9}$$

$$\text{Moment of Inertia (I)} = (1/2) * (M * r^2) \tag{2.10}$$

From equations (2.9 and 2.10), the variables for selection of generator unit for replacement with different inertial energy are, weight of generator rotor, radius of generator rotor, material of generator rotor and generator to turbine inertia ratio.

2.6 Unit Commitment Decisions

To meet the constantly varying nature of electricity demand and to dispatch the least overall cost, considering technical limitations of generator units and regulatory requirements, unit commitment algorithm is optimized. Following are theoretical methods to solve the unit commitment optimization [6].

1. Priority List Method
   - Priority of the generator units are determined from their production costs
   - Mostly priority list is prepared for simply start-up and shut-down sequences
2. Dynamic Programming Method (DP)
   - There are (2^n-1) numbers of combinations for commitment to dispatch the generator units to meet demand
   - For each combination of generator units, there is different strategy to handle considered constraint every time
3. LaGrange Relaxation Method (LR)
   - This method follows dual optimization procedure
   - Initially unit commitment problem is solved by relaxing one of the constraints and then the relaxed constraint is coordinated in optimization by maximizing lagrangian multiplier
   - For each constraint, the unit commitment decision is going for perturbations to find optimum solution

2.7 Conclusion

From the unit commitment decisions, renewable generators have higher priority for commitment as they constitute the least operating cost and production of electricity by conventional generator units is inevitably avoided. The inertial energy supplied by renewable generator units is not considered as reliable source of inertial energy. The renewable energy generator units are not able to supply considerable inertial energy for transient stability. While the generator units with large mass generator rotor have higher MBTU/kWh ratio lower priority of commitment. Generator units with high rotating mass rotor are costlier then comparatively light weight rotor generator units and renewables [6].

Chapter 3: Proposed Method: Determine Constraining Inertial Energy

To determine constraining inertial energy of the system, a practical method is proposed in this chapter. Discussion in this chapter includes details about technical data used for the formulation the system, explanation about system configuration and results of the proposed method.

3.1 Renewable Sources, Transient Stability Constraint and Inertial Energy

A practical approach to find the constraining value of inertial energy of the system is performed on the IEEE 9-Bus system to verify transient stability. For the work described in this chapter, we used an IEEE 9-Bus, 3-Generator [11] system for simplicity. This work can be effectively expanded to comparatively larger systems.

The equations (2.3) to (2.6) from chapter 2 are true for the conventional power plants which have higher rotating mass and are able to supply inertial energy in the event of fault occurrence. For economic load dispatch and to reduce the clearing bid price of generation by unit commitment, the renewable generation has considerable participation as renewable generation offers the electricity at the least cost. But the renewable generators either they do not have rotating equipment or they do not have higher mass rotating equipment to supply inertial energy. Hence, renewable energy sources are not able to supply considerable amount of inertial energy to the system for transient stability.

Renewable energy sources are able to supply synthetic inertial energy (a form of inertial energy). However, synthetic inertial energy is not considered as a reliable source of inertial energy; it can be utilized to stop frequency drift but it is not able to supply characteristics of real inertial energy to be used for transient stability. Hence, the synthetic inertial energy supplied by renewable generator units is not considered as a reliable source of inertial energy [9, 12].

According to current scenario of interconnected power system's generator unit commitment, renewable energy generators are committed on priority basis. Conventional generation units are committed as renewable energy resources are not able to replace the capacity of the conventional generation units as a whole in Ontario, Canada. However, recent advances in renewable technologies, CDM initiative, least operating and maintenance costs, global warming emissions reduction initiative, government, environment and economic policies, etc. constitute a vital role for justification of renewable energy sources' development and priority commitment [13]. In the near future, renewable generator unit capacities might replace conventional generator capacities with their functionalities.

As renewable energy sources are not able to meet demand of electricity system on their own, conventional generators are committed and unknowingly they are supplying sufficient inertial energy for the transient stability of the system's integrated stability. But in future, when conventional generators would not be committed for load dispatch, sufficient amount of inertial energy would not be present in the interconnected power system to meet transient stability requirements. When renewable energy sources would replace conventional generators' dispatch or decrease their share of participation in the electricity market, the transient stability would be compromised to reduce unit price of electricity. From above discussion of this chapter, important characteristics for transient stability and inertial energy of the power system can be summarized as follows.

Inference #1: As we move towards decreasing the inertial energy by reducing commitment of conventional generators with massive rotors from the system, the system becomes more transiently unstable.

Inference #2: Renewable energy sources alone are not able to supply inertial energy required for transient stability. The major portion of load dispatch commitment by renewable generator sources is not able to supply sufficient inertial energy.

Inference #3: Renewable energy source generator units and light weight rotor generator units constitute higher priority as compared to heavy mass conventional generator units for unit commitment.

Inference #4: Synthetic inertial energy supplied by renewable energy resources (e.g. solar and wind energy systems) is not considered as reliable source of inertial energy for transient stability of the system.

3.2 Constraining Inertial Energy Value for Transient Stability

The complete practical approach to find constraining inertial energy for the transient stability is categorized in two portions.

1. Procedure to find constraining inertial energy for power system
2. Implement IEEE 9-Bus system to find constraining inertial energy

3.2.1 Procedure to Find Constraining Inertial Energy

The short-circuit analysis and transient stability analysis is performed in this chapter using technical data. It is assumed that in the process of finding the constraining inertial energy for transient stability, the power system maintains its voltage stability by utilizing reactive power optimization [14]. The proposed method to find the minimum constraining inertial energy for transient stability is as follows.

- **Step 1**: Short-circuit analysis is performed on proposed power system to find the fault type which has the highest impact at the weakest point in the system.
- **Step 2**: From the short-circuit analysis data, the type of fault to implement and the weakest point in the system is determined.
- **Step 3**: 5-cycle fault is sufficient to verify transient stability. From IESO, standard operating terms, fault duration of 3-cycle to 6-cycle fault is considered transient [15].
- **Step 4**: The transient stability results of rotor angle deviation are recorded for verification and comparison with transient stable and unstable cases.
- **Step 5**: To reduce system's total inertial energy, conventional generator unit(s) and/or sub-unit(s) are replaced with renewable generator units keeping MVA capacity same.
- **Step 6**: Above steps 3, 4 and 5 are iterated number of times until the system suffers from transient instability due to insufficient inertial energy.
- While replacing conventional generator unit(s) with renewables to find minimum constraining inertial energy, the system must remain voltage stable.
- **Step 7:** The verification of transient stable case is performed for step 6, the results of rotor angle deviation are compared with stable system and verified within limits.
- **Step 8:** The value of constraining minimum inertial energy is recorded, where the power system is transient stable for the available inertial energy.

Above sequential steps are summarised in a flow-chart form as illustrated in Fig.4.

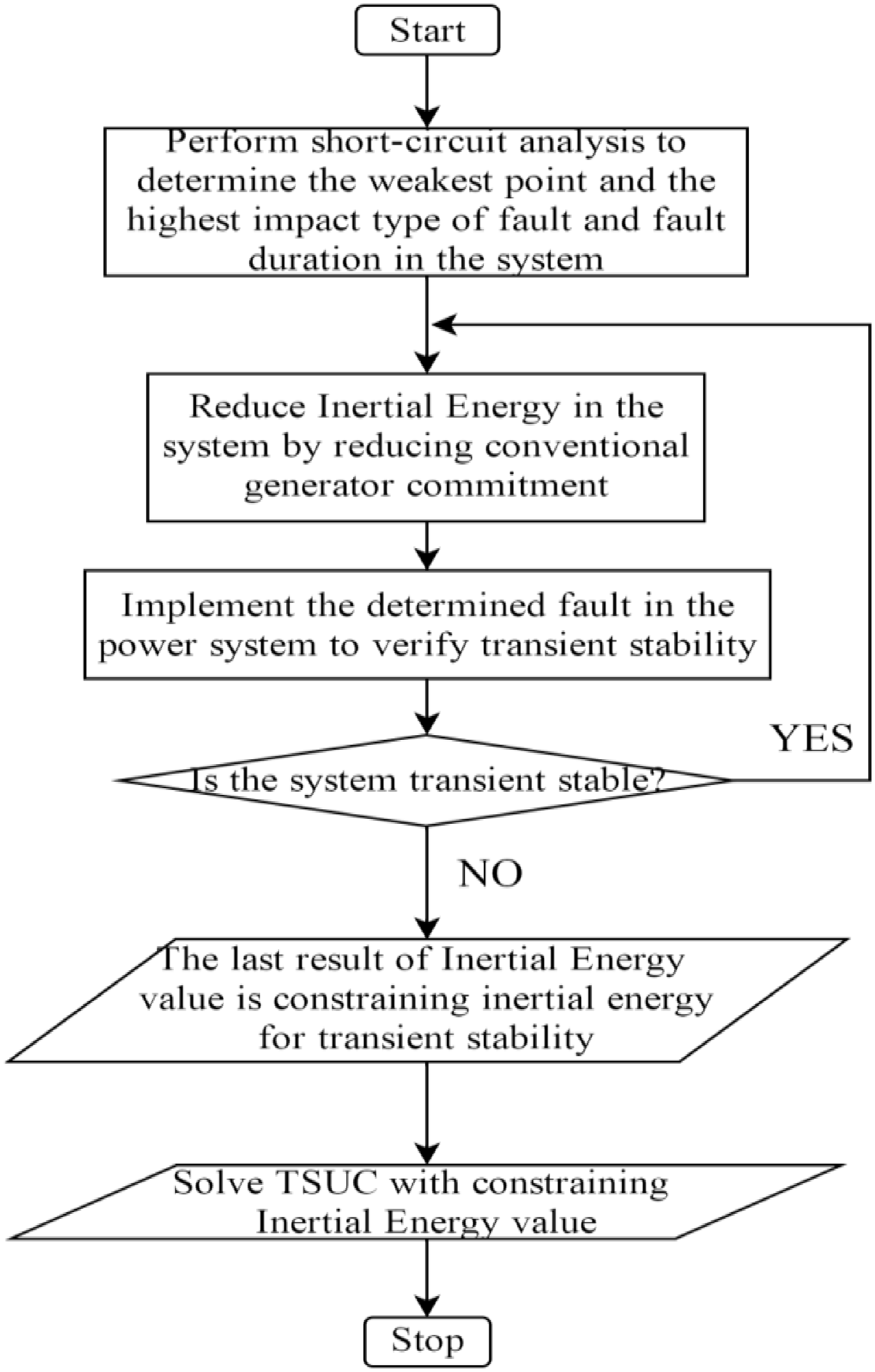

Figure 4: Flow-chart to find constraining inertial energy value

The constraining inertial energy value is found by PSS-E® "Python Command" implementation tool. It is concluded that, the constraining inertial energy value found by PSS-E® is to be used as an inequality constraint for unit commitment.

3.3 System for Implementation to Produce Results

The IEEE standard system of 9-Bus is implemented and programmed in PSS-E® using the "Python" command tool. IEEE 9-Bus system's data are logged in following sections to produce results of constraining minimum inertial energy and later on for unit commitment decisions for verification of effects of transient stability constraint. IEEE 9-Bus system is as illustrated in Fig. 5 as follows.

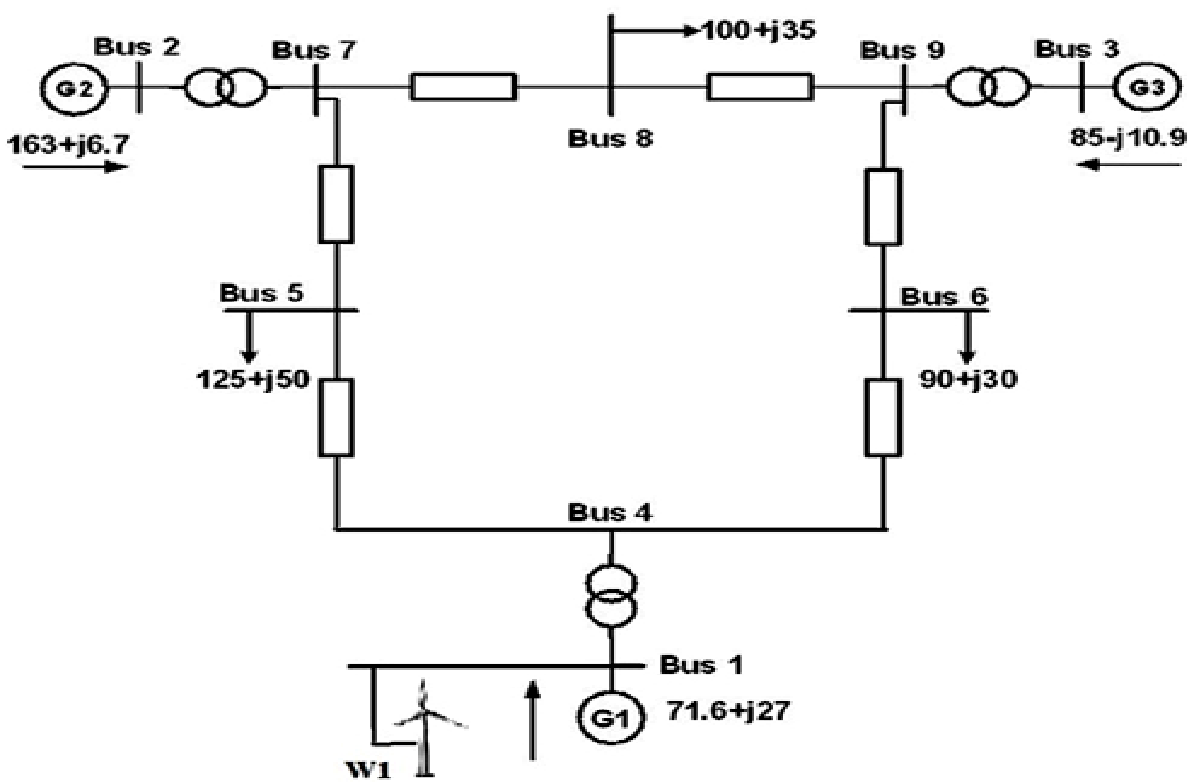

Figure 5: IEEE 9-Bus System

The system arrangement of the 9-Bus test system is as follows. Generator #1, a salient-pole generator at bus #1, is supplying inertial energy of total 6.40 MW-s/MVA. The renewable generator, connected at bus #1, is not able to supply considerable inertial energy. Generator #2, at bus #2, comprises of 10 round-rotor generator units. These units are able to supply 0.64 MW-s/MVA inertial energy individually. Altogether generator #2 is supplying 6.40 MW-s/MVA of inertial energy from these 10 sub-units. Generator #3, a round rotor generator at bus #3, is supplying inertial energy of 5.75 MW-s/MVA. Generator #3, at bus #3, comprises of 9 round-rotor generator units. These units are able to supply 0.64 MW-s/MVA inertial energy individually. Altogether generator #3 is supplying 5.75 MW-s/MVA of inertial energy from these 9 sub-units. Generator #3 is considered as the swing generator which continuously compensates the difference between the power demand and supply to maintain the power balance in the system. It should be noted that finding the best location for the wind generator is out of the scope of this thesis.

3.3.1 IEEE 9-Bus System Data for Implementation

For the purpose of validating results and further analysis of transient stability, 9-Bus IEEE system is inspected as it is comparatively smaller system with 3 generator units, 3 loads and other equipments are evenly connected. To represent the renewable generator unit, one wind generator, which has higher priority to be committed for load dispatch, is connected at bus #1 with generator #1. For the transient stability inspection of the 9-Bus system, details of generators, connected loads, transmission lines, and transformers are simulated from available standard data from IEEE. Following tables 1, 2, 3, 4 and 5 are the data of 9-Bus system for load-side connection, generators, transformers, branches and generator construction respectively [16, 17].

Table 1: IEEE 9-Bus system load data

9-Bus system connected load data												
bus_i	type	Pd	Qd	Gs	Bs	area	Vm	Va	baseKV	zone	Vmax	Vmin
1	1	0	0	0	0	1	1.04	0	16.5	1	1.06	0.94
2	2	0	0	0	0	1	1.025	0	18	1	1.06	0.94
3	2	0	0	0	0	1	1.025	0	13.8	1	1.06	0.94
4	0	125	50	0	0	1	1	0	230	1	1.06	0.94
5	0	90	30	0	0	1	1	0	230	1	1.06	0.94
6	0	0	0	0	0	1	1	0	230	1	1.06	0.94
7	0	100	35	0	0	1	1	0	230	1	1.06	0.94
8	0	0	0	0	0	1	1	0	230	1	1.06	0.94
9	0	0	0	0	0	1	1	0	230	1	1.06	0.94

Following are the data for generator units which are connected in 9-Bus system for transient stability analysis. The capability curves of conventional generator units are attached in appendix. Generator units 1, 2 and 3 are conventional generators while generator 4 is representing wind generator.

Table 2: IEEE 9-Bus system generator data

9-Bus system generator data										
Gen	bus	Pg	Qg	Qmax	Qmin	Vg	mBase	status	Pmax	Pmin
1	1	72	0	0	0	1.04	100	1	200	0
2	2	163	0	99	-99	1.025	100	1	200	0
3	3	85	0	99	-99	1.025	100	1	200	0
4	1	70	0	99	-99	1.025	100	1	80	20

Tables 3 and 4 list the data for transformers and branches which are connected in 9-Bus system for transient stability analysis. The branch line loading capacities are considered very high to avoid line loading constraints for this connection.

Table 3: IEEE 9-Bus system transformer data

9-Bus system transformer data			
sn	1	2	3
frombus	1	2	3
tobus	2	3	4
connections	1	1	1
r	0.0016	0.0016	0
x	0.0435	0.0435	0.025
tap	0.985	0.96	0.96
rate	500	500	500
tapmax	1.1	1.1	1.1
tapmin	0.9	0.9	0.9
tapstep	0.025	0.025	0.025

Table 4: IEEE 9-Bus system branch data

9-Bus system branch data										
fbus	tbus	r	x	b	rateA	rateB	rateC	ratio	angle	status
1	4	0	0.0576	0	9900	1	1	1	0	1
2	7	0	0.0625	0	9900	1	1	1	0	1
2	9	0	0.0586	0	9900	1	1	1	0	1
4	5	0.01	0.085	0.176	9900	1	1	1	0	1
4	6	0.017	0.092	0.158	9900	1	1	1	0	1
5	7	0.032	0.161	0.306	9900	1	1	1	0	1
6	9	0.039	0.17	0.358	9900	0	1	1	1	1
7	8	0.0085	0.072	0.149	9900	0	0	1	0	1
8	9	0.0119	0.1008	0.209	9900	0	0	1	0	1

Table 5: IEEE 9-Bus system generator construction and load connection details

Generator Connected at	Connection Control Type	Construction Type
Bus #1	Voltage Control	Salient Pole
Bus #1	--	Wind Generator
Bus #2	Voltage Control	Wound-Rotor
Bus #3	Swing	Wound-Rotor

Load Connected at	Load Type
Bus #5	Induction
Bus #6	Induction
Bus #8	Induction

Using the equations 2.8, 2.9 and 2.10 from chapter 2, following data of Table 6 are calculated for inertial energy supplied by each generator for the unit commitment decision options for 9-Bus system.

Table 6: IEEE 9-Bus system generator inertial energy calculated from parameters

Generator Replacement Design Calculations						
Capacity	PF	Length	Radius	Mass	Turb/ Gen ratio	Total H-Energy
MW	-	cm	cm	g/cm3	--	MW-s/ MVA
80	1	500	75	6.5	1.5	6.40
250	1	750	90	8	1.5	6.40
300	1	750	90	8.5	1.5	5.75
120	1	400	55	7.5	1.5	2.731778*

* Synthetic inertial energy

3.4 Methodology to find constraining inertial energy by implementation tools

The practical methodology for PSS-E® implementation tools to find constraining inertial energy for IEEE 9-Bus system is recorded in this portion of the chapter. The constraining inertial energy value is found by PSS-E® simulation for 9-Bus system. The practical approach to record unit commitment decisions by MATLAB® code is also noted subsequently. The detailed methodology to find constraining inertial energy by PSS-E®simulation is attached with "screen-shots" in appendix. PSS-E® version 33 available at CUE lab of Ryerson University is used for the implementation. The methodology used for PSS-E® is not documented in any reference form. The documented methodology within this thesis can be used for PSS-E® transient stability simulations.

3.4.1 Methodology for PSS-E®

- Command line "Python" is chosen for transient stability related operations
- Data for bus, machine, load, branch, transformer are entered in the field of "Network Data" tab
- All the generators and loads are to be converged for processing and controlling from "Power Flow" tab
- Within the "Dynamic Data" tab of "Machine field", type of generator chosen and data for generator, exciter, turbine governor and stabilizer are entered. For the sake of complexity and damping action accomplishment, round rotor generator model (GENROU) is chosen for implementation
- To choose the result graphs, channel set-up wizard is approached from "Dynamics" tab

- The output file of the graphs is saved before simulation is initiated
- The simulation is initialized and run for the amount of time entered
- Type and location of fault is entered in the system from “Disturbance” tab
- Dynamic Simulation is performed by "Run" without "Initialize" by adjusting time to record effect of fault
- To clear the fault from the system, “Disturbance” tab is approached again
- Dynamic Simulation is performed by "Run" without "Initialize" by adjusting time to record effect of cleared fault.
- To export the results, open the “.out” file which is created to save channel output
- The simulated data can be saved in the form of "Text File"

3.5 Results for IEEE 9-Bus system: minimum inertial energy constraint

The fault event time, type and location in the system is decided by short-circuit analysis. To implement the model of the 9-Bus IEEE system for short-circuit analysis, PSS-E® simulation tool is used which is competent for the power system stability studies.

The IEEE 9-Bus system is considered as not connected with infinite grid system, instead it has one slack generator which adjusts demand-supply difference of the electrical power for the system. To find the weakest point of fault-level, short-circuit analysis is performed on the system with different types of faults which include, L-L fault, L-G fault, 3-L-G fault. The short-circuit calculation analysis is as below recorded in Table 7.

Table 7: Short-circuit analysis for IEEE 9-Bus system

Short-circuit calculation analysis for 9-Bus IEEE system											
Fault at Bus →		Bus #4				Bus #5			Bus #6		
Fault Current Data at Bus →		Bus1	Bus5	Bus6	Bus4	Bus4	Bus7	Bus5	Bus4	Bus9	Bus6
	Type of Fault →	3LG	3LG	3LG	3LG	3LG	3LG	3LG	3LG	3LG	3LG
Ia (kA)	Real	0.437	0.596	0.544	1.577	0.560	1.132	1.692	0.684	0.942	1.626
	Imaginary	-6.764	-2.415	-2.318	-11.497	-5.080	-3.427	-8.507	-4.837	-3.340	-8.177
Ib (kA)	Real	-6.076	-2.390	-2.280	-10.746	-4.679	-3.534	-8.213	-4.531	-3.364	-7.895
	Imaginary	3.004	0.691	0.688	4.383	2.055	0.733	2.788	1.826	0.854	2.680
Ic (kA)	Real	5.639	1.794	1.736	9.168	4.119	2.402	6.521	3.847	2.422	6.269
	Imaginary	3.761	1.724	1.630	7.115	3.024	2.692	5.718	3.011	2.486	5.497

From data recorded for short-circuit analysis for different types of fault events in Table 7; 3-L-G type of fault at bus #4 has the highest impact on the whole system for transient stability studies. At bus #4, the unbalancing current magnitude is higher due to 3-L-G type of fault. Considering the 9-Bus system as a comparatively weak system, it is determined to implement 5-cycle, 3-L-G fault at bus #5 to verify transient stability. The 3-L-G type of fault is strong enough with 5-cycle fault duration to have maximum effect on the 9-Bus system. As the IEEE 9-Bus system is inherently stable, it behaves as transiently stable case with base case of connected conventional generator units [18].

The approach to find constraining inertial energy by PSS-E® starting from total "H" energy for the system value of 18.55 MW-s/MVA for 9-Bus system. Generator sub-units are gradually replaced with renewable energy source of same MVA capacity to gradually decrease the total inertial energy of the system. For the stable and unstable systems of recorded results of Figs. 6 and 7, the fault impedance value is maintained constant at 20,000 Ohm (Ω) for the system at bus #4.

The graphs of transient stable and unstable cases for generator absolute power angle for IEEE 9-Bus system are shown in Figs.6 and 7. The recorded results of Fig.6 and 7 for rotor angle are prepared with PSS-E® for 20 second of implementation time. Total effective inertial energy for 9-Bus IEEE system is 15.99 MW-s/MVA and 15.35 MW-s/MVA for Figs.6 and 7 respectively. It is recommended that in addition to transient stability, voltage stability of the system also verified. The voltage stability is depending on the generator capability curve of the connected generators to supply reactive power with desired voltage range of the system. The generator capability curves of connected generators confirming voltage operating margin and voltage stability are attached in the appendix.

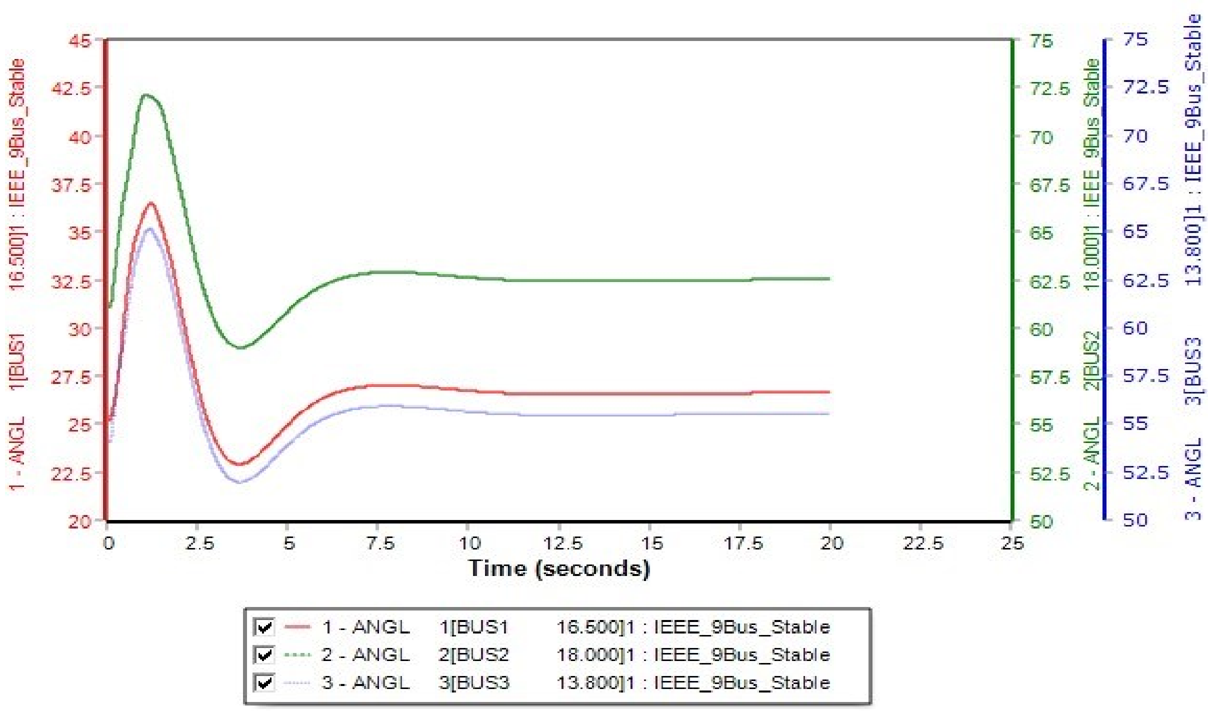

Figure 6: Absolute rotor power angle (9-Bus), transient stable case (PSS-E)

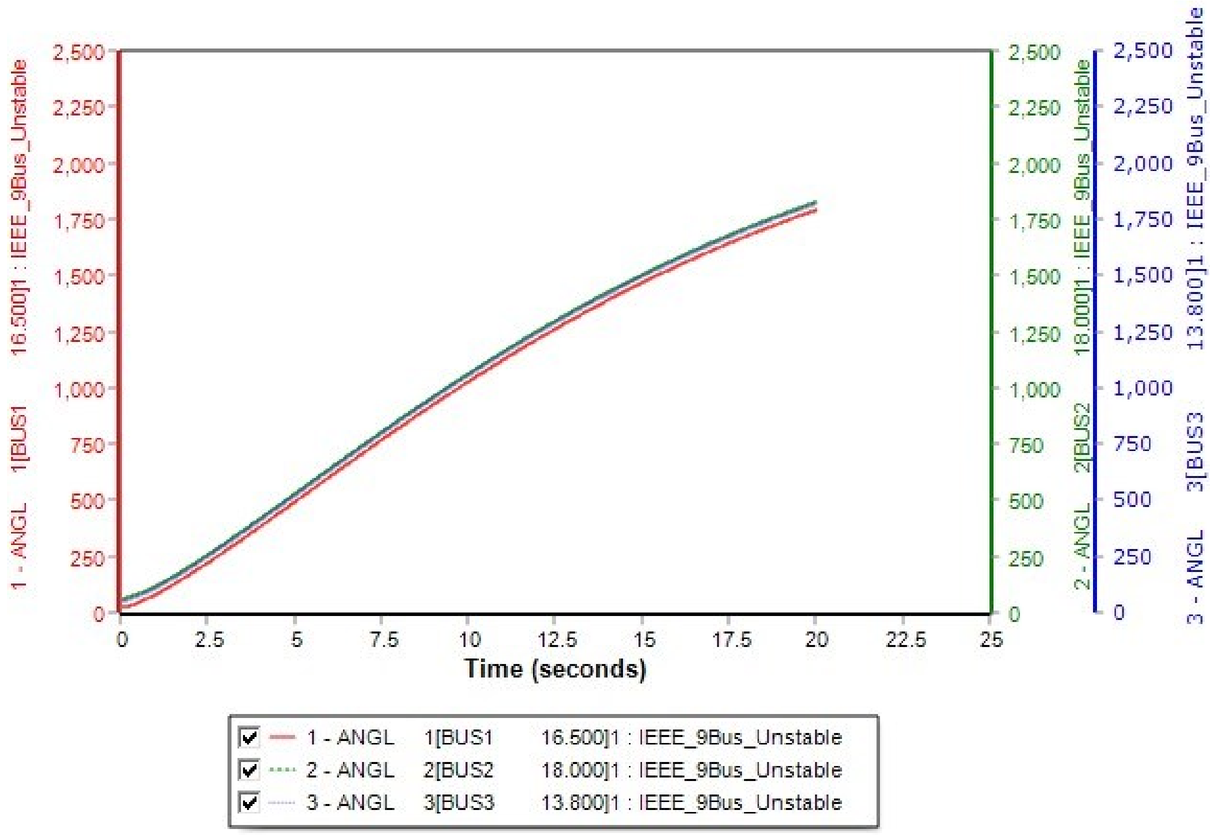

Figure 7: Absolute rotor power angle (9-Bus), transient unstable case (PSS-E)

Fig. 6 depicts the transiently stable case as the rotor angles are stabilized after fault event, while Fig. 7 depicts the transiently unstable case as the rotor angles are deviated for large angles and are not stabilized for the system. The generators considered are of round rotor generator model which possess capability for corrective action by damping action using excitation and power system stabilizer. The GENROU models of generators have facilities of power system stabilizers and exciters; hence, corrective action to for rotor angles can be anticipated for system stability.

Ultimately constraining inertial energy of for 9-Bus system is H = 15.99 MW-s/MVA, when IEEE 9-Bus system is transiently stable. According to equal area criterion for rotor angle stability, the rotor angle stabilizes following fault event [19]. Less than the "H" energy value of 15.99 MW-s/MVA, the IEEE 9-Bus system's generation units' rotor angles goes beyond the limits of perturbations of rotor angle stability [19].

Above results of Figs. 6 and 7 implies that, if sufficient inertial energy is not present in the system, the system cannot survive during fault events. The fault affected power system energizes the consecutive tripping of affected equipment and trying to fetch the system towards major loss of generation and/or connected load [20].

In summary, the steps to determine the constraining minimum inertial energy to maintain system's transient stability on the face of faults are as follows:

1. For a system configuration with 100% conventional generators, conduct Transient Stability Analysis.
2. Determine the location and types of faults by short-circuit analysis for which the system has the highest impact.
3. Gradually replace conventional generator with renewable resources like wind or solar energy systems which are not able to supply inertial energy.
4. Conduct Transient Stability Analysis for rotor angle stability for each step.
5. Determine constraining inertial energy for transient stability where rotor angles deviate beyond regulatory limits.

From the above analysis and IEEE reliability test systems, the constraining inertial energy for IEEE 9-Bus system is summarized in Table 8.

Table 8: Minimum constraining inertial energy for system

IEEE Power System	Constraining Inertial energy
9-Bus, 3-Generator System	15.99 MW-s/MVA

3.6 Conclusion

The methodology to find constraining inertial energy for IEEE 9-Bus system by PSS-E® and available reference documents are discussed in this chapter. The dynamic data required to find constraining inertial energy are also noted in this chapter. The constraining inertial energy found by this method for IEEE 9-Bus system is 15.99 MW-s/MVA which is used as a unit commitment constraint to verify the effect of added constraint in the unit commitment decisions.

Chapter 4: Inertial Energy as a Constraint of Unit Commitment

For the power system's transient stability against fault events, the minimum inertial energy supposed to be maintained within the system. From the results of above mentioned procedure from PSS-E® implementation for IEEE 9-Bus system, the unit commitment decisions are to be verified by consulting transient stability constraint. The data input to be used for unit commitment decisions and its constraints for 9-Bus system are listed in section 4.2.1. To verify the unit commitment decisions, unit commitment is implemented with MATLAB® code with data from reference [21].

4.1 Mathematical Model for Unit Commitment

The approach for unit commitment is to operate and commit the available generator units at the least possible total cost for 24 hours. In this process of committing units, the technical limits of units are entertained on priority as compared to other economic and financial constraints [9]. The mathematical model of unit commitment presented as follows is used for the unit commitment decision with constraints [21]. Equation (4.01) is the objective function for unit commitment for electricity system operation to minimize the generation units' offer bid price. Equations (4.02 to 4.15) are the mathematical representations of constraints of unit commitment from 4.1.1.

$$C(p) = \sum_{t=1}^{NH} \sum_{n=1}^{NG} [a_n * U_{tn} + \left(\sum_{m=1}^{NM} b_{nm} * PM_{tnm} \right) + r_n * R_{tn} + d_n * SU_{tn}] \tag{4.01}$$

4.1.1 Constraints:

1) Real Power Balance Equation: This constraint balances the net real power generated with the total real power load in the system and ensures power balance where $\mathrm{PM_{tnm}}$ is the real power generation at the n^{th} generator's m^{th} segment in the t^{th} hour and $\mathrm{PD_t}$ is the total system real power demand.

$$\sum_{n=1}^{NG}\sum_{m=1}^{NM} \mathrm{PM_{tnm}} = \mathrm{PD_t};\ \forall\, t \in \mathrm{NH} \tag{4.02}$$

2) Line Flow Limits: This constraint limits the transmission lines loading; upper limit for (n-1) contingency and lower limit for optimal utilization for l^{th} mine in the t^{th} hour.

$$\underline{\mathrm{PL_l}} \le \mathrm{PL_{tl}} \le \overline{\mathrm{PL_l}};\ \forall\, t, l \tag{4.03}$$

3) Generator Out-put Limits: This constraint is for real power in the m^{th} segment and maximum power that can be delivered by generator unit and lower limit for optimal utilization; lower limit for renewables is zero and heat loss limits for conventional generators

$$0 \le \mathrm{PM_{tnm}} \le \overline{\mathrm{PM_{nm}}};\ \forall\, t, n, m \tag{4.04}$$

$$\mathrm{U_{tn}}\underline{\mathrm{PG_n}} \le \left[\mathrm{PG_{tn}} = \sum_{m=1}^{NM} \mathrm{PM_{tnm}}\right] \le \mathrm{U_{tn}}.\overline{\mathrm{PG_n}};\ \forall\, t, n \tag{4.05}$$

4) Generator Status: This constraint is for n^{th} generator's status in the t^{th} hour.

$$0 \le \mathrm{U_{tn}} \le 1;\ \forall\, t, n \tag{4.06}$$

5) Spinning Reserve Capacity: This is a regulatory constraint for the generators' operations. The generators to maintain online, 10 minute and 60 minute reserves to cover contingency events in each hour. The generator utilities are paid not only for real and reactive power supply, but also paid for maintaining spinning reserves depending on the types of reserves.

$$R_{tn} \leq \min\left\{R10_n, \overline{PG_n}.U_{tn} - PG_{tn}\right\}; \forall\, t, n \tag{4.07}$$

Spinning Reserve Criteria:

Online Reserve: This reserve has the highest payment criteria within reserve category.

$$\sum_{n=1}^{NG} R_{tn} \geq \alpha.SR_t; \forall\, t \tag{4.08}$$

10 Minute Reserve: This reserve is used to cover difference of promised generation for other units.

$$\sum_{n=1}^{NG} R_{tn} + \sum_{n=1}^{G10} (1 - U_{tn}) * P10_n \geq SR_t; \forall\, t \tag{4.09}$$

Ramp Rate: This reserve is used to cover difference of constantly changing system demand.

$$-R60_n \leq PG_{tn} - PG_{t-1,n} \leq R60_n;\ \forall\, t, n \tag{4.10}$$

6) Minimum Uptime: This constraint is for generator's minimum scheduled operation. Once generator is committed, it cannot be turned off until specific number of hours for optimal heat utilization and technical limits.

$$\left(U_{t+1,n} - U_{tn}\right).UT_n - \sum_{s=t+2}^{\min(NH_t+UT_n)} U_{sn} \leq \max\{1, UT_n - NH + t + 1\}; \quad (4.11)$$

$$(\forall\ t \in [1, NH - 2], n)$$

7) Minimum Downtime: This constraint is for generator's minimum scheduled rest period. Once generator is turned off, it cannot be turned on until specific number of hours for technical limits.

$$\left(U_{tn} - U_{t+1,n}\right).DT_n - \sum_{s=t+2}^{\min(NH_t+DT_n)} U_{sn} \leq DT_n; \quad (4.12)$$

$$\forall\ t \in [1, NH - 2], n$$

8) Initial Conditions: This constraint is for the operation of generators from previous hour's status; already committed units cannot be committed again and already turned off units cannot be turned off again for scheduling.

Uptime: If $IC_n > 0\ \&UT_n > +IC_n$;

then $U_{tn} = 1; \forall\ t \in [1, UT_n - IC_n], n$ (4.13)

Downtime: If $IC_n < 0\ \&DT_n > -IC_n$;

then $U_{tn} = 0; \forall\ t \in [1, DT_n + IC_n], n$ (4.14)

Start-up Variable: $SU_{tn} = \max\{U_{tn} - U_{t-1,n}, 0\}; \forall\ t, n$ (4.15)

Transient stability constraint is inspected in the form of inertial energy as transient stability of the system is depending on the inertia supplied by the connected generation units' rotors. Inertial energy constraint for transient stability in mathematical formulation is represented as equation (4.16). Total inertial energy supplied by online generators must be more or equal to the minimum requirement of inertial energy to maintain system stable in transient state for each hour. The consideration of renewables in the system is to be security constrained and unit commitment decisions are determined accordingly [22].

9) Inertial Energy Constraint: A minimum amount of inertial energy to remain present in the system for transient stability. This constraint is implemented in the form of inequality constraint in the unit commitment.

$$\underline{HG_t} \leq \sum_{n=1}^{NG} U_{tn}.HG_n \; ; \forall t, n \tag{4.16}$$

The difference of results of unit commitment decisions due to the minimum inertial energy constraint equation 4.16 to be recorded and analyzed.

4.2 Algorithm to Determine Unit Commitment Decisions

The mathematical formulation (4.01) to (4.16) has been written and programmed in MATLAB® code using the optimization function "MOSEK". MOSEK is a robust optimization solver of MATLAB® to find the solution for minimizing the objective cost $(C(p))$ with satisfying constraints [21]. The proposed solution algorithm is following steps as below.

- **Step A**: Data obtained from generator facilities for offered bid price, unit start-up cost and unit shut-down cost are entered into the format of optimization function and solver.
- **Step B**: The constraint equations and limits are set in the solver using the values from available data.
- **Step C**: The unit commitment optimization formulation equations (4.01) to (4.15) is solved to minimize $(C(p))$and to determine the unit commitment dispatch decision.
- **Step D**: The unit commitment decisions are updated and verified for constraint satisfaction.
- **Step E**: The unit commitment decisions are updated every time till all the constraints are satisfied (LaGrange Relaxation Method).
- **Step F**: Above steps C, D and E are iterated number of times until the optimal unit commitment dispatch decision is obtained.
- **Step G:** The unit commitment decisions, unit dispatch and "Total Cost" are calculated and recorded for comparison.
- **Step H:** Above steps from A to G for unit commitment system decisions are repeated with considering the minimum inertial energy constraint of equation (4.16).
- **Step I:** Unit commitment decisions, dispatch and "Total Cost" difference from step G and step H are compared to verify the effects of inertial energy constraint

4.2.1 Generator offer bid and system demand data for 9-Bus system

The generator offer bid and system demand data for 9-Bus system are noted as in Tables 9 and 10 respectively for 24-hours scheduling horizon. These data remain same for the verification of unit commitment decisions excluding and including inertial energy constraint.

Table 9: 9-Bus, 4-generator unit offer bid data for unit commitment.

Generator unit	**Unit**	**1**	**2**	**3**	**4 (Wind)**
Pmin	MW	50	100	120	20
Pmax	MW	180	450	400	120
Heat Rate	BTU/kWh	10440	9000	8730	900
No load cost	$/h	213	585.74	684.74	252
start-cost(cold)	$	35	40	110	0.02
fuel cost	$/MBTu	2	4	6	0.09
Minimum uptime	h	2	2	3	1
Minimum downtime	h	1	2	2	1
In status	h	-5	8	8	-6
start-cost(hot)	h	150	170	500	0
cold start	h	1	2	2	0
Ramp-up rate	MW/h	25	40	45	10
Ramp-down rate	MW/h	50	80	90	20
co-efficient ($)	$	80	25	30	6
co-efficient ($/MWh)	$/MWh	8	2.5	3	6
co-efficient	$/MWh2	0.008	0.0025	0.003	0.006
Shut-down Cost	$	30	30	20	1
Inertial Constant	Sec	7.95898	8.4055	8.44505	2.73178

Table 10: 24-hour demand forecast of 9-Bus system for unit commitment

Hour	MW	Hour	MW	Hour	MW
1	450	**9**	770	**17**	440
2	420	**10**	880	**18**	420
3	380	**11**	790	**19**	380
4	270	**12**	800	**20**	380
5	280	**13**	850	**21**	440
6	300	**14**	660	**22**	560
7	350	**15**	530	**23**	530
8	750	**16**	380	**24**	380

4.2.2 Methodology for MATLAB®

- Raw data for IEEE 9-Bus system are entered into "9_Bus_Data.xlsx" to be called by MATLAB command.
- MATLAB program command file "SCUC_TAD_New.m" is executed. Other supporting command files and data files are to be stored in the same folder for the process.
- Unit commitment decisions are called by "open UU" command and saved in "Results.xlsx" file to plot graphs for comparison.
- Unit commitment dispatches are called by "open PU" command and saved in "Results.xlsx" file to plot graphs for comparison.
- The unit commitment decisions, available inertial energy and total cost for 24-hours are compared for inertial energy constraint.

4.3 Conclusion

The mathematical formulation for the unit commitment procedure by MATLAB code is defined in this chapter. The offer bid and demand data are also noted in this chapter to verify inertial energy constraint effect on the unit commitment decision difference for 9-Bus system. The constraining inertial energy found from chapter 3 is used as inequality constraint within unit commitment formulation. The unit commitment decision difference is to be noted down for the effect of inertial energy constraint for the 9-Bus system.

Chapter 5: RESULTS AND DISCUSSION

This thesis has considered IEEE standard system to find constraining inertial energy value and to verify unit commitment decisions. For this system, the first objective is to find the constraining inertial energy value for transient stability. The second objective is to compare unit commitment decisions with excluding and including inertial energy constraint. These both objectives are constrained by economical load dispatch by the least over-all unit running costs, power balance equations and limits on generator units' power outputs, generator ramp-up and ramp-down limits, generator units' minimum up and down time limits, coordination of units, operating reserve dispatch for system security, must run units, and other transmission system equipment operating and regulatory limits [12]. In addition to equipment operating limits which are known as technical limits, regulatory limits are also imposed on the interconnected power system operations in the form of grid code. The technical limits of equipment have higher priority than reliability and regulatory limits [23]. The unit commitment is performed for above scenarios for same system demand data for the period of 24 hours.

The constraining inertial energy values and unit commitment decision results have been recorded and compared. To verify the effects of constraining inertial energy on unit commitment, the first scenario performs unit commitment without considering the minimum inertial energy constraint for transient stability. The second scenario incorporates the consideration of minimum inertial energy requirements as a constraint within unit commitment.

The input data for verification of minimum constraining inertial energy by PSS-E® are noted in chapter 3. MATLAB® code source data in the form mathematical formulation are also presented in the chapter 4. The procedure followed to obtain results by PSS-E® and MATLAB® is explained in the third and fourth chapters respectively. The results of PSS-E® and MATLAB® are discussed in this chapter. The technical and offer bid data for IEEE 9-Bus system are presented separately while the procedure is explained for IEEE 9-Bus system. The type of fault event, location of fault and duration of fault are decided by short-circuit analysis of the power system. With this pre-decided fault event at pre-determined fault location for pre-decided time duration is applied in the power system with PSS-E® to verify transient stability.

5.1 Results of unit commitment decisions for comparison

Unit commitment mathematical formulation presented in chapter 4 is implemented with MATLAB® code. For unit commitment decisions, generator offer bid data are used from Tables 12 and 14 for IEEE 9-Bus system, which is referenced from [11]. The unit commitment decision difference on account of constraining inertial energy of equation (2.26) is recorded for comparison herewith.

When the minimum inertial energy constraint is taken into account, the unit commitment decisions are changed to maintain minimum inertial energy in the system for transient stability. To compare results, the unit commitment decisions are compared as the total forecasted demands remain same for both the cases of unit commitment with exclusion and inclusion of minimum inertial energy constraint. The comparison of unit commitment decision for effective inertial energy constraint is noted as follows in per Tables 11 and 13 for IEEE 9-Bus system.

5.1.1 Study case: 9-Bus, 3-Generator system

9-Bus, 3-Generator system is chosen in a 24-hour time scheduling horizon. An additional wind generator is also connected at bus#1 to represent renewable generator unit. The generator cost data is altered such that the wind generator is the least expensive and Gen #3 is the most expensive, see table 12 for data. The 9-Bus system is characteristically network capacity and stability constrained. The proposed inertial energy constraint in successive TSUC algorithm converge additional unit(s) to commit to supply constraining inertial energy. The difference of inertial energy constraint is described in detail below.

5.1.1.1 Minimum inertial energy is NOT constrained

The result data of optimal unit commitment decisions and optimal generation dispatch without inertial energy constraint are noted in Table 11 and Table 12 respectively for IEEE 9-Bus system.

From Table 11, following can be observed. When the minimum inertial energy constraint is not in effect, system demand is supplied such that Gen #1, #2 and wind generator units are ON and are sufficient to supply the total hourly load demand except from hour #10 to hour #13.Output of Gen #3 is neither committed, nor dispatched to supply system demand except from hour#10 to hour#13. From hour #10 to hour #13, Gen #3 is turned ON for 4 hours just to supply system demand. Table 12 shows the dispatch of generator units in MW for 9-Bus system without inertial energy constraint.

Table 11: Optimal unit commitment without inertial energy constraint (9-Bus)

Generator unit commitment without inertial energy constraint (9-Bus) Energy Constraint								
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	0	0	0	0	0	0	0	0
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	0	1	1	1	1	0	0	0
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	0	0	0	0	0	0	0	0

Table 12: Optimal generation dispatch without inertial energy constraint (9-Bus)

Generator unit dispatch without inertial energy constraint (9-Bus)								
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
hourly load	450	420	380	270	440	560	530	750
Unit1	345	295	295	165	155	215	245	325
Unit2	25	25	25	25	25	25	25	25
Unit3	0	0	0	0	0	0	0	0
Wind	80	100	60	80	100	60	80	100
Inertial Energy	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
hourly load	770	880	790	800	850	660	530	380
Unit1	350	350	350	350	350	350	350	275
Unit2	360	400	290	340	370	50	40	25
Unit3	0	50	50	50	50	0	0	0
Wind	60	80	100	60	80	100	60	80
Inertial Energy	12.8	18.55	18.55	18.55	18.55	12.8	12.8	12.8
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
hourly load	440	420	380	380	440	560	530	380
Unit1	315	335	275	255	350	350	350	320
Unit2	25	25	25	25	30	130	80	0
Unit3	0	0	0	0	0	0	0	0
Wind	100	60	80	100	60	80	100	60
Inertial Energy	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8

5.1.1.2 Minimum inertial energy is constrained

Table 13 shows the UC decision characteristics for conventional generator units when inertial energy constraint is in effect for 9-Bus system. Conventional generator units are participating in not only to supply system demand, but also to supply inertial energy for transient stability. While the wind generator unit is participating in to supply only system demand, from Table 13, following can be observed. System demand is supplied such that Gen #1, #2 and wind generator units are ON and in addition Gen #3 is also committed to supply the inertial energy.

Table 13: Optimal unit commitment with inertial energy constraint (9-Bus)

Generator unit commitment with inertial energy constraint (9-Bus) Energy Constraint								
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	1	1	1	1	1	1	1	1
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	1	1	1	1	1	1	1	1
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Unit1	1	1	1	1	1	1	1	1
Unit2	1	1	1	1	1	1	1	1
Unit3	1	1	1	1	1	1	1	1

Table 14: Optimal generation dispatch with inertial energy constraint (9-Bus)

Generator unit dispatch with inertial constraint (9-Bus)								
Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
hourly load	450	420	380	270	280	300	350	450
Unit1	315	265	265	135	125	185	215	295
Unit2	25	25	25	25	25	25	25	25
Unit3	30	30	30	30	30	30	30	30
Wind	80	100	60	80	100	60	80	100
Inertial Energy	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55
Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
hourly load	770	880	790	800	850	500	450	380
Unit1	350	350	350	350	350	345	335	245
Unit2	310	400	290	340	370	25	25	25
Unit3	50	50	50	50	50	30	30	30
Wind	60	80	100	60	80	100	60	80
Inertial Energy	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55
Hour	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
hourly load	440	420	380	380	440	560	530	380
Unit1	285	305	245	225	325	350	350	265
Unit2	25	25	25	25	25	100	50	25
Unit3	30	30	30	30	30	30	30	30
Wind	100	60	80	100	60	80	100	60
Inertial Energy	18.55	18.55	18.55	18.55	18.55	18.55	18.55	18.55

The unit commitment and dispatch of generator units are as attached in Table 13 and 14 respectively in the effect of inertial energy constraint for 9-Bus system. It may be noted that although Gen #1, #2 and wind generator are able to supply system demand, Gen #3 is committed to supply inertial energy for 24 hours. Due to this inertial energy constraint, the unit dispatch is also affected which is recorded in Table 14.

5.1.1.3 Effect of Inertial Energy Constraint on Unit Commitment Decisions (9-Bus)

Fig. 8 shows the UC decision difference for the algorithm due to inertial energy constraint for 9-Bus system. Conventional generator units are participating in only to supply system demand. While the wind generator unit is also participating in to supply system demand which is coordinated with Gen #1 for easier illustration.

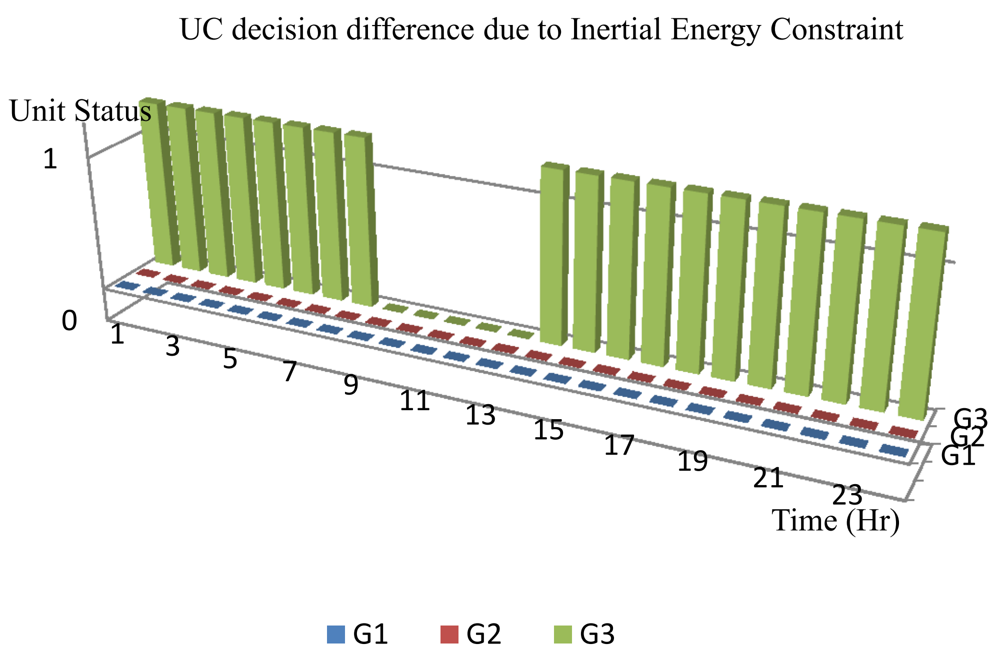

Figure 8: UC decision difference for conventional generator units for IEEE 9-Bus system

Comparison of total inertial energy present in the 9-Bus IEEE system due to minimum inertial energy constraint is as follows in fig. 9.

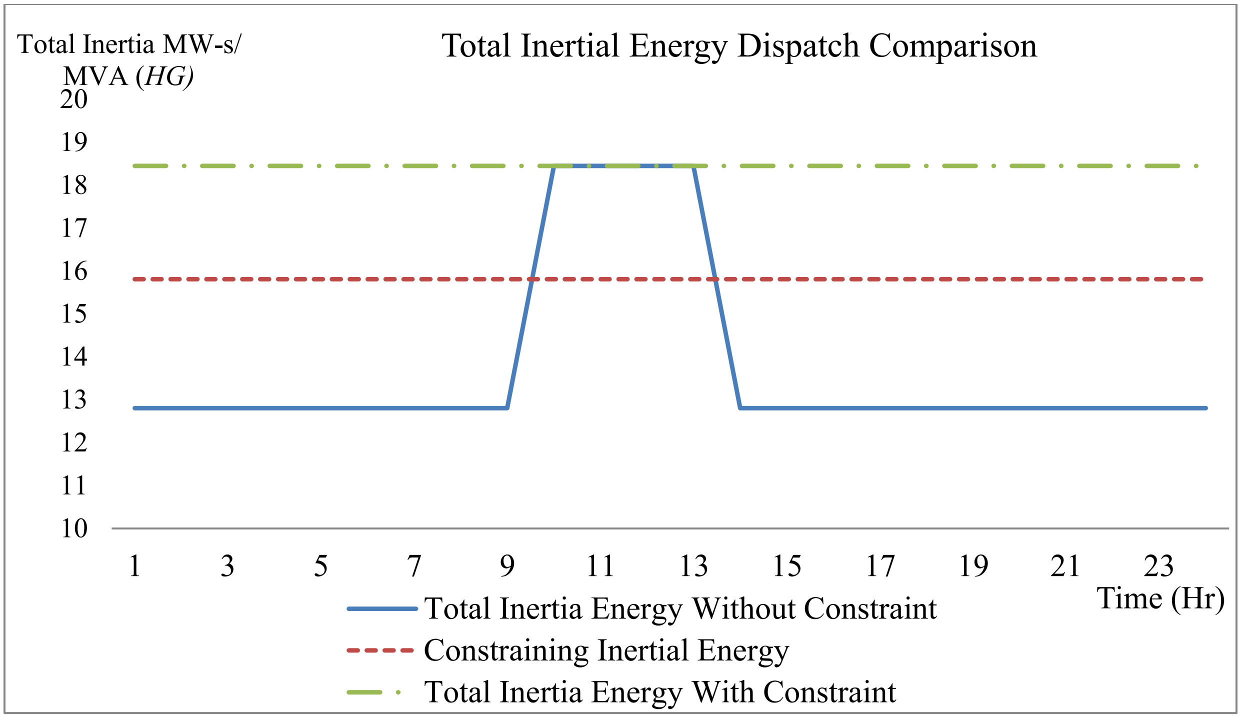

Figure 9: Total inertial energy present in IEEE 9-Bus 3-generator system

From Fig. 9, it is noted that, the total inertial energy in the system under the effect of minimum inertial energy constraint is more than 15.99 MW-s/MVA. The constraining inertial energy value, 15.99 MW-s/MVA makes commitment of GEN #3 and unit commitment decisions and dispatch are also affected due to this constraint. From Fig. 9, it is also noted that, in the case without considering inertial energy constraint, the total hourly inertia does not always satisfy this amount, shown as the solid line. The system faces transient instability for those hours with no enough inertial energy. In the contrary, with inertial energy constraint, the most expensive unit is turned on to supply required inertia. Table 15 shows the cost implications of effective inertial energy constraint for 9-Bus, 3-Generator system. The total cost is raised however the risk of transient instability reduces.

Table 15: 24-hour generation schedule cost difference for IEEE 9-Bus system

IEEE 9-Bus,3-Generator system	
Total Schedule Cost Without Inertial Energy Constraint ($)	144,504.00
Total Schedule Cost With Inertial Energy Constraint ($)	150,134.00
Difference of total cost ($) due to constraint	5630.00

Practical methodology to find constraining inertial energy by PSS-E® is explained in chapter 3. To verify the constraining inertial energy value found by PSS-E® simulation is used. The data available from reference [18, 19] are used in effective manner to find constraining inertial energy by PSS-E®. The value of constraining inertial energy found for 9-Bus system by PSS-E® is noted in table 8. The constraining inertial energy value is utilized as a constraint for unit commitment by MATLAB® code for respective system. Total minimum constraining inertial energy required for the system is noted for 9-Bus system. Under the effect of the constraining inertial energy, the unit commitment decisions and unit dispatches are changed. It is confirmed that the inertial energy constraint is effective for unit commitment. The unit commitment decision and dispatch difference due to inertial energy constraint are notably recorded for 9-Bus system in tables 11 to 14. The 24-hour scheduling cost differences due to inertial energy constraint for are noted in table 15 for 9-Bus system.

5.2 Conclusion

The constraining inertial energy noted from chapter 3 for IEEE 9-Bus system is 15.99 MW-s/MVA. The unit commitment decisions are effectively changed due to the supplemented inertial energy constraint. The results are noted in respective tables and graphs. The optimal unit commitment decision from the proposed UC formulation considering the proposed transient stability constraint requiring a minimum amount of inertial energy is the most economic.

Chapter 6: CONCLUSION

This chapter summarizes the effect of minimum inertial energy constraint for transient stability on unit commitment. To this end, this chapter summarizes to propose an inertial energy constraint and its solution by unit commitment. Based on technical evaluation of the inertial constraint and its effects on the unit commitment, the inertial energy constraint is proposed for transient stability of the system considering fault conditions.

In the introduction chapter, the basic details of the transient stability problems for unit commitment are provided. Some basic concepts of transient stability and inertial energy with their affective factors and unit commitment formulation are discussed in the second chapter. The data and results of PSS-E®, MATLAB® and MATLAB® code for 9-Bus system is provided in the third chapter. The data and results are recorded in the tabular and graph format. To verify the effectiveness of the inertial energy constraint, 9-Bus system data is used. By PSS-E® simulation, constraining inertial energy for the system is found. By MATLAB® code, effectiveness of inertial energy constraint for unit commitment is verified for the system.

6.1 Summary and Contribution

For insufficient inertial energy in the interconnected power system, the system experiences transient instability in the event of fault. If sufficient inertial energy is present in the system, the system can constitute transient stability avoiding sequential tripping of inter-connected power system equipment.

The inertial energy constraint resembles that minimum amount of inertial energy is supposed to be present in the interconnected power system for transient stability and it can be considered as a constraint for the stability concerns of the system. Minimum amount of inertial energy is supposed to be committed in the system which can be considered as an inequality constraint for the electrical generator unit commitment algorithms. This constraint can change the optimization results of unit commitment decisions, optimal power flow and economic load dispatch effectively.

The effect of connected inertial energy in the system is expected minor during equilibrium condition, but for fault event scenario, the inertial energy supplied by conventional heavy rotating mass generators play a vital role for transient stability of the system. To fulfill the stability considerations of the system, conventional generators are supposed to be committed and dispatched accordingly.

The constraint of maintaining minimum inertial energy in the system for transient stability is not the most economical case for unit commitment. When introducing minimum inertial energy constraint for transient stability, unit commitment and dispatch decisions are changed accordingly. Inertial energy constrained unit commitment can be solved for different sized systems. The outlined constraint of minimum inertial energy for transient stability in this thesis improves the effectiveness of interconnected system's stability considerations.

This paper proposes the transient stability constrained unit commitment (TSUC) for transmission system with large renewable energy resources. The process of TSUC includes the procedure of finding minimum required inertial energy and economical scheduling of generators to meet demand as well as transient stable state. On solving TSUC, sufficient inertial energy, with less than 10% cost increment, is suppled from online conventional generators in every hour. The proposed TSUC can be verified to work effectively well on small and large systems of appropriately sized transmission network systems.

6.2 Future Work

This research work has studied and proposed the effect of minimum inertial energy constraint and transient stability constraint on unit commitment. In future work, this constraint may be combined with other constraints of transmission system and generation units. Offer price bids for inertial energy, if it is indeed logical would also be affected to consider in determining unit price for load dispatch.

Also the algorithm used in this work may be used in determining the cost difference for locational marginal price, congestion management, opportunity cost, electricity energy exchange cost and inter-utility stability. In which case, the formulation becomes a nonlinear mixed integer problem which would definitely require more robust solvers and details oriented inclination for not only technical, but also economic considerations of the electricity market operations.

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Appendices

Appendix. 1. Small-signal stability equations for synchronous generator

Appendix. 2. Dynamic stability data of round rotor steam generator

Appendix. 3. PSS-E® simulation methodology with screen-shots

Appendix. 4. Generator capability curves for conventional generator units 1,2, 3 and wind profile curve for wind generator unit 4 (IEEE 9-Bus system)

Appendix. 5. Unit Commitment dispatch comparison for IEEE 9-Bus system