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Quantitative Frequency Security Assessment for Multi-Machine Power System based on COI frequency

Athraa Iessa*, Noor Izzri Abdul Wahab, Norman Mariun and Hashim Hizam

Centre for Advanced Power and Energy Research (CAPER), Department of Electrical and Electronic Engineering, University Putra Malaysia, 43400, Selangor, Malaysia; gs42356@student.upm.edu.my

Abstract

The frequency is one of the instruments for measuring the health status of the power system, due to its ability to anticipate any imbalance between generations and loads. If the generated power is adequate for the system load and losses, then, the system will be in a steady state, otherwise frequency deviates from nominal value due to the mismatch between the generation and load. If the frequency continues to deviate from nominal value, the system may collapse. The assessment of frequency stability level becomes an essential aspect of power system operation and also for projecting the ability of the power system to maintain nominal frequency when subjected to any disturbance. In this paper, a method is proposed to evaluate frequency security of multi-machine power system using transient frequency deviation index (TFDI) which is based on Center of Inertia (COI) referred frequency. The proposed method has been tested on the New England 39-bus test system. Results show that the proposed method takes the advantage of TFDI in accumulating the effect of frequency trajectory deviations. These frequency trajectories may be obtained from the time domain simulation or Wide Area Measurement System (WAMS). The results also show the advantages of COI referred frequency in representing the equivalent frequency of the system. The method would provide a reliable and efficient base for load shedding relays adjustment and operation control.

Keywords: COI Frequency, Frequency Stability Assessment, Transient Frequency Deviation Index, Quantitative Security Assessment

1. Introduction

The stability of a power system represents its ability to withstand any disturbances and continue its operation in new acceptable operation conditions. Power system stability is classified into three categories: voltage stability, rotor angle stability, and frequency stability[1]. With the rise of renewable energy sources integration into power systems and due to the natural fluctuation of these sources, the study of frequency behavior has taken on greater importance.

Many studies have been conducted on the assessment of the frequency stability level of the power system. In[2], transient stability analysis using a direct method by examining the distribution system trajectory was proposed. According to this approach, the transient stability can be analyzed without the need for time domain simulation method. A direct method based on Jacobian matrix of last switching conditions of the network has been proposed in[3]. This approach can deal with non-linear load features. In[4], the transient frequency security assessment method has been implemented for individual machines or bus based on the transient frequency deviation. A new index to assess the frequency level of security was proposed in[5] stability, and power quality state of power systems. A new security index for transient frequency deviation assessment (FDSA). The index depends on two elements, i.e., critical time and critical frequency. An online frequency security assessment with the ability to collect and filter data and able to compute the security level and alarm states was presented in[6] A frequency deviation index has been modified to consider the cumulative effect

* Author for correspondence

of frequency deviation based on frequency response that can be obtained from time domain simulation or wide area measurement system WAMS[7]. A study of frequency security assessment are needed in order to optimize the frequency setting, load shedding, and relays operation. Various studies have been conducted in the quest to find the minimum value of load shedding amount that keeps the system in stable condition. In[7,8], an adaptive load shedding scheme design according to the evaluation of the stability margin and estimation of disturbance magnitude was suggested. A comparison between the load shedding strategies, Event Load Shedding (ELS) and Under Frequency Load Shedding (UFLS) has been implemented in[9]; this study leads to an optimal design of two strategies of load shedding to maintain frequency security of power system. A recent survey to build a new algorithm to minimize the load shedding cost using the frequency and voltage sensitivity trajectories and depends on transient security indices for two elements table was proposed in[10].

To assess the security level for multi-machines power system irrespective of disturbance locations as well as to take the advantage of quantitative assessment of system security using TFDI, a new method of evaluating the frequency security of multi-machines power system is proposed in this paper. The proposed method used TFDI with COI referred frequency in order to assess the frequency stability of power systems. The motivation of this work is in the evaluation of frequency security level for the whole power system irrespective of disturbance locations. Accordingly, the advantages of this method will contribute effectively to power system with renewable sources planning, control and security analysis.

In this paper, the Center of Inertia (COI) frequency of multi-machines power system is defined and formulated in section II, a discussion about frequency security assessment using TFDI is included in Section 3, the methodology is described in Section 4, Section 5 presents the simulation results and discussion, and Section 6 is the conclusion.

2. Formulation of COI Referred Frequency for Multi-Machine Power System

The behavior of system synchronous units can be represented by the COI, which gives a good realization about system units. The power system COI can be obtained by:

$$\frac{2H_{SYS}}{\omega_S}\frac{d\omega_{coi}}{dt} + D_{SYS} * \omega_{coi} = P_{M\,SYS} - P_{G\,SYS} \quad (1)$$

Where,

H_{sys}= system inertia constant.

D_{svs}= system damping coefficient.

$\omega_S = 2\pi f$.

ω_{coi} = angular center of inertia.

P_{MSYS} = system mechanical power.

P_{GSYS}= system electrical power.

Likewise, the frequency of equivalent inertial center COI frequency (F_{COI}) is a mathematically derived variable, describing the average network frequency during electromechanical transients when the local generator frequencies are not the same[7]. F_{COI} can be calculated by:

$$F_{COI} = \sum_{i=1}^{N} H_i F_i \Big/ \sum_{i=1}^{N} H_i \quad (2)$$

where:

H_i = the inertia constant of generator $\mathbf{i}$.

F_i = $\mathbf{ith}$ generator frequency.

N =number of the generator.

The F_{COI} will provide more information on frequency security level of power system compared to single generator frequency only. The inertia constant of F_{COI} is larger since it includes the inertia constant of all generators in the power system other than the single generator inertia constant. Moreover, the oscillation of F_{COI} is smaller[11]. F_{COI} is also needed to find the operating power deficit because the generators do not decelerate at the same rate. Consequently, the F_{COI} is widely used in UFLS because it provides enough information about system frequency behavior[12].

In the literature, F_{COI} is usually used in system frequency protection and control. By using the F_{COI} a multi-machine space was transformed into a single machine space to model a new under frequency load shedding scheme in[13]. In[14] a neural net method was used to estimate the F_{COI} of the system without neglecting the oscillations. The under frequency load shedding scheme using frequency calculator model has been compared with the F_{COI} for protection of the setting frequency[15].

The advantages of using F_{COI} in power dynamic security assessment are to evaluate all system levels of security irrespective of the effect on generator inertia constant and the disturbance position. In this paper, the F_{COI} is obtained from time domain simulation method and applied with transient frequency deviation index to assess the security level of multi- machine power system.

3. Quantitative Assessment of Frequency Security

The system frequency response can be measured by frequency deviation, frequency nadir and the rate of change of frequency. Frequency deviation can be defined as the difference between real frequency and organized frequency. In frequency deviation, its speed and size are different due to the value of power imbalance[16]. Frequency nadir is known as the rigorousness of the frequency drop. Frequency nadir depends on the system inertia and intensity of generators outage[17]. The Rate of Change of Frequency (ROCOF) can be defined as the scale of how rapid the frequency change is, either up or down. The unit of ROCOF is (Hz/sec)[18].

Related to the previous frequency response characteristics, there are many indices proposed in the literature for estimating the frequency stability and then to find the frequency security level of power systems. In[19–21], the frequency maximum deviation has been studied, whereas[22–23] refer to frequency sensitivity index (β) articulated by unit (MW/0.1Hz). For stable operation, this index must be negative. That means the frequency decreases when there is a net increase in generation and vice versa. This index has limitations due to its reliance on a net imbalance between load and generator. In[25], a new index for frequency response called probabilistic frequency response index was suggested. But the calculation of this index takes time due to long computation and the needed data. According to[4,5], a new transient frequency security index was obtained. The index depended on frequency deviation curve and used two elements table critical frequency (f_{cr}) and critical time (t_{cr}) to assess the frequency security level of the power system. The previous indices can only evaluate the frequency stability of power system one point at a time. Therefore, the frequency stability degree cannot be quantitatively assessed by these indices.

To quantitatively assess the frequency stability degree of the power system, a TFDI is proposed in[26.27] by calculating the cumulative effect of frequency deviation trajectory. This index depends on critical time and frequency [t_{cr}, f_{cr}] which is called the system's threshold. It is important to notice that this threshold can vary among different utilities and it is set according to utility companies' practical operation conditions. In[6,28] the full expression to find TFDI was proposed. Thus, the security margin can be simply defined by:

$$\eta = \frac{S_d}{(f_N - f_{cr})t_{cr}} \tag{3}$$

$$S_{d} = \min \int_{t_s}^{t_s+t_{cr}} (f_N - f_{cr})\,dt \tag{4}$$

where:

S_d = the minimum area bordered by the frequency response curve and the critical frequency (f_{cr}) in within critical time (t_{cr}).

f_N =standard frequency of the system.

f_{cr} =frequency deviation threshold.

t_{cr} = the acceptable duration for frequency deviation for going beyond f_{cr}.

t_s = starting time of statement window.

The relationship between frequency response curve and the system threshold can be represented in three cases according to the break time (t_b), which is defined as the actual time for frequency deviation going beyond f_{cr}.

For multi-machine power system, and with the need to evaluate all system security levels, it is important to find the equivalent F_{COI} response and then find the security margin. S_d can be calculated based on severity of disturbances as follows:

- When t_b=0, the frequency response curve does not intersect the critical frequency line as shown in Figure 1. In this case, S_d=S_1.

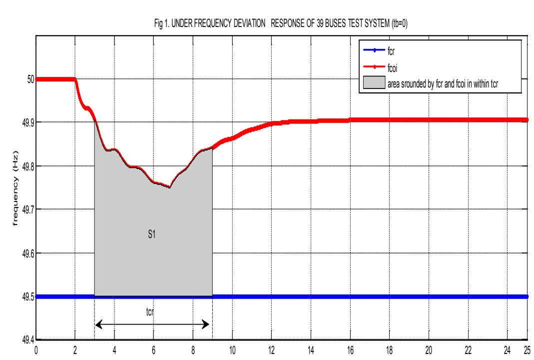


Figure 1. f_{coi} trajectory when t_b = 0.

- If $0<t_b<t_{cr}$, in this case t_{hr} break time t_b is less than the critical duration t_{cr} as shown in Figure 2. In this case $S_d = (S_1+S_2)-S_3$.

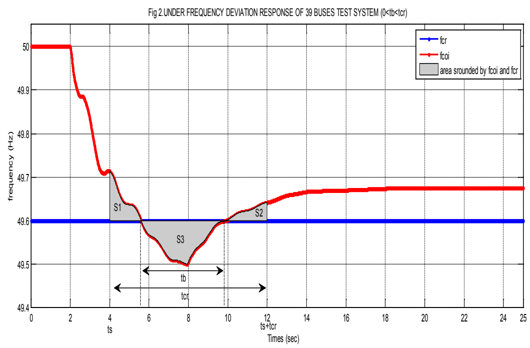


Figure 2. f_{coi} trajectory when $0<t_b<t_{cr}$.

When $t_b>t_{cr}$, in this case, the break time t_b is greater than the critical time t_{cr}. As shown in Figure 3. In this case, $S_d = -S_3$.

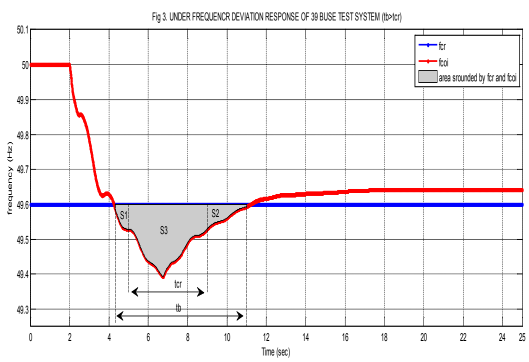


Figure 3. f_{coi} trajectory when $t_b>t_{cr}$.

It has been conclusively shown by[28], that the range of security margin is $[-\infty, 1]$. If the security margin, $\eta = 1$, this means that the system is secure, if $\eta = 0$, the system is in a critical situation, and if $\eta<0$, this means that the system is insecure from the frequency viewpoint.

4. Methodology

The method of assessing system frequency security level using TFDI and based on F_{COI} is provided as a simple and useful way to evaluate all system stability levels. Several methods have been used to assess the system security status. The drawback is the assessment time consumed, which requires extended computation, using probability such as Monte Carlos simulation, or depends on historical data. Therefore, it needs time to collect the data.

The methodology in this work is very simple and does not require any complex computation. The algorithm Figure 4 shows the procedures to evaluate the system frequency security level. After running power to set the test system initial conditions for the simulated power system, credible disturbance such as loss of the biggest unit in the system or loss of massive load is created. Later the F_{COI} curve can be obtained either from full-time domain simulation or wide area measurement. The trajectory of F_{COI} is used to find the (TFDI) by considering the accumulative effect. The value of TFDI will define the system frequency's security degree.

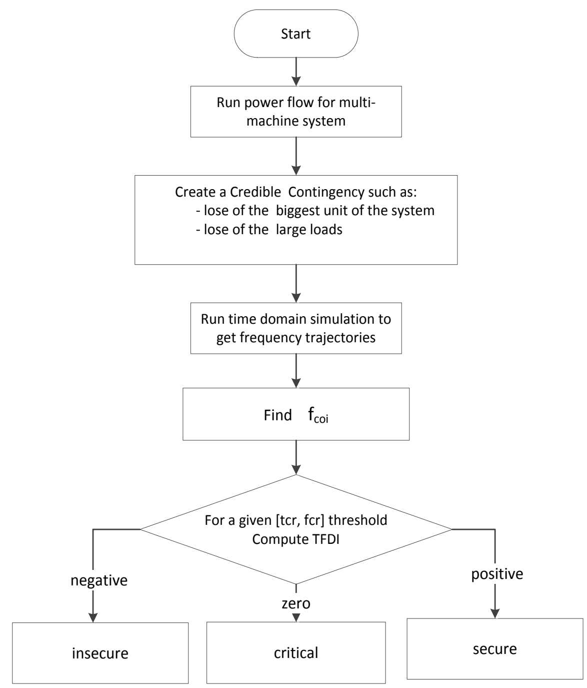


Figure 4. Flow chart illustrating the F_{COI} security margin assessment.

5. Simulation Results

5.1 Test System and Software

The proposed method is verified using the New England 39-bus test system Figure 5. System data are obtained from[29]. The excitation system data and stabilizer (PSS) data are obtained from[30]an infinite horizon closed-loop optimal control is achieved based on model prediction which uses the current state of power system as the initial state. At each control step, the identified model is updated by using the new coming measurements and the optimal control action is solved again. Periodical online model and control updating identification and optimal control enables the proposed controller to adapt to operating condition variations and system parameter uncertainties. It is more robust than offline identification based damping controllers which could suffer from performance degradation under time varying and uncertain conditions. Simulation results demonstrate the effectiveness and robustness of the proposed controller in damping inter-area low frequency oscillations. The abilities to coordinate with power system stabilizers (PSSs. Dynamic Security Assessment software (DSA tools) developed by power-tech is used to simulate the test system[31].

The test system consists of 10 machines with a total generation of 5690.6 MW, 1916.4 MVAR. The total load demand of the system is 6097.1 MW; 1408.9 MVAR. If any imbalance in power occurs due to any disturbance e.g., the loss of the biggest generator unit in the test system or loss of a heavy load, the system will experience frequency deviation. A significant dip in frequency trajectory may affect the operation of the load and generators, and the protection relays may misoperate and lead to the system collapse. When the system security level is assessed properly, the protection devices can be adjusted to prevent them from misoperateing.

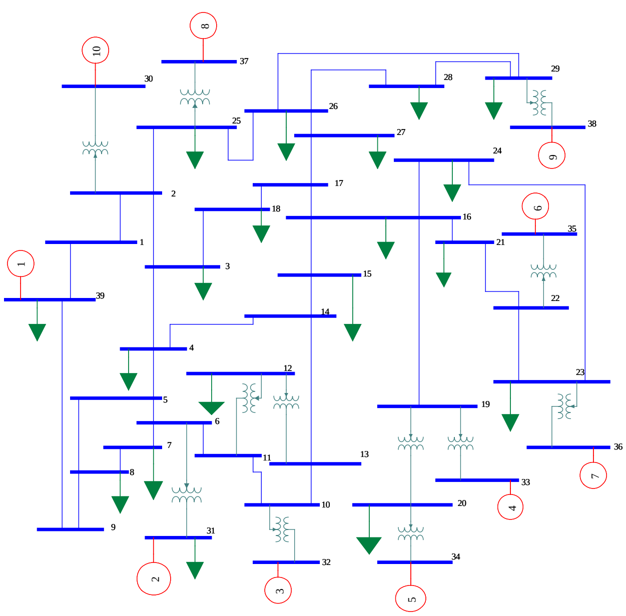


Figure 5. New England 39 buses test system.

5.2 Results of FCOI

In order to test the F_{COI} of the test system, a full-time domain simulation was applied to the test system. Figures 6 and 7 show the F_{COI} with system generators frequencies for over and under frequency deviation. Figure 8 shows the F_{COI} response for a different level of reducing the generation of the test system. The results indicate that the generators frequency responses are not the same according to inertia constant for each generator. The generator with large inertia is less affected by disturbances and vice versa. Therefore, the F_{COI} as we see from results can represent a uniform frequency for the multi- machine power system.

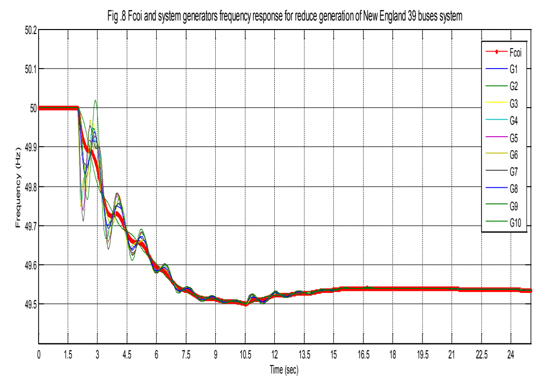


Figure 6. Under frequency deviation of f_{coi} and generators.

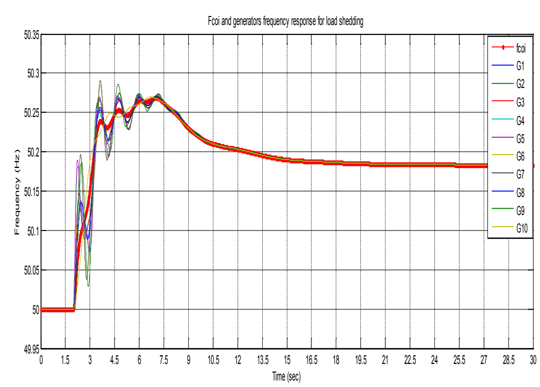


Figure 7. Over frequency deviation of f_{coi} and generators.

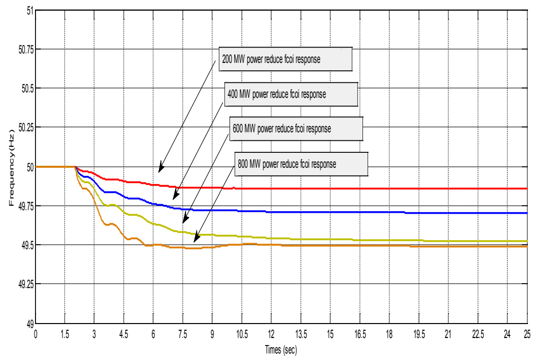


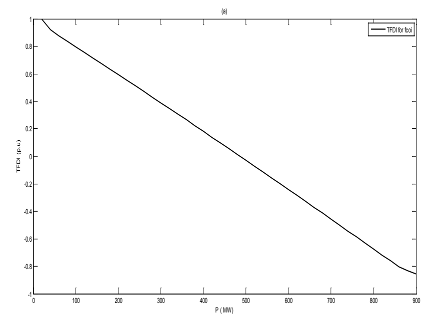
Figure 8. F_{coi} response for reducing generation.

5.3 Verification of Quantitative Frequency Security Assessment based on $F_{COI\ Method}$

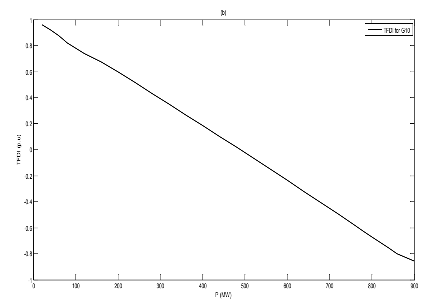
The proposed method is tested and analyzed with different contingencies. The numerical verification of TFDI with F_{COI} was done according to scenarios of[28] as follows:

5.3.1 Scenario 1: Reduce Generation (Under Frequency Deviation)

The generation of units G4 and G6 is decreased gradually by incremental steps 10MW for each unit; accordingly, the system power will reduce by 20 MW in each step. The total amount of reduced power is 450 MW for each unit. The F_{COI} calculated for each step and then the TFDI was also calculated for each step based on security threshold [49.75Hz, 1 sec]. It is important to note that the threshold varies from one utility to other, and it is chosen based on system operation conditions. The result shows that the security index started with positive value. With the increase in reduction of the generation, the system reaches the critical status in which the security margin is equal to zero. With the reduction of the generation amount continuing, the security index became negative which means that the system became insecure. Figure 9 shows the results of frequency security index for F_{COI} Figure 9(a) and G10 frequency trajectory Figure 9(b) with the amount of power reduction. A comparison of the two results reveals that there is no significant difference between the two indices, but the TFDI with F_{COI} represents the whole system's security level.



(a)

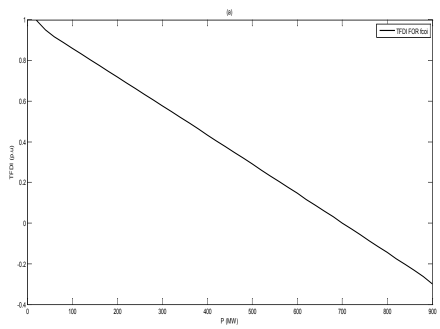


(b)

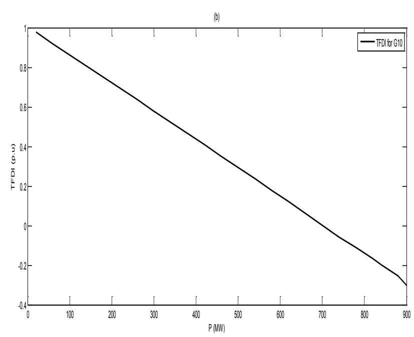
Figure 9. Frequency security index with power reducing amount for. (a) f_{coi}. (b) G10.

5.3.2 Scenario 2: Load Shedding (Over Frequency Deviation)

To evaluate the security index, TFDI with F_{COI} for over frequency deviation, load shedding contingencies are applied when the system operates at the standard frequency. Bus 8 and Bus 20 are load buses in the test system. The load shedding is implemented on these buses with the threshold of [50.25 Hz, 1sec]. The total amount of load shedding is 450 MW for each bus. The change of load shedding amount is 10 MW for each bus in each step. The results obtained from this scenario are shown in Figure 10. The TFDI for F_{COI} trajectory is shown in Figure 10(a) and for unit G10 it is shown in Figure 10(b). The results indicate that the system starts with the positive index which means the secure system frequency and then when the load shedding increases the system becomes insecure from frequency security point of view when the TFDI becomes negative. As can be seen from the result, there is no momentous diverse between the TFDI of unit and COI, but the F_{COI} characterizes the uniformity of the system frequency.



(a)



(b)

Figure 10. Frequency security index with load shedding amount for. (a) f_{coi}. (b) G10.

5.3.3 Scenario 3: Verification for Variance Time Thresholds

To apply a numerical verification of TFDI with F_{COI} for different time limits, the power of unit G5 the test system is reduced by 300 MW. The frequency threshold chooses to be (49.75 Hz) and the time limit is changed from 1 sec until 9 sec with a step of 0.25 sec. The simulation results show that the TFDI with F_{COI} coverage of a wide range of time thresholds as can be seen from Figure 11.

The previous studies in[6,27,28] show the verification of the TFDI for the individual buses. But if we need to evaluate all system frequency security level, the F_{COI} is needed. The results in Figures 9, 10 and 11, show that the TFDI with F_{COI} is a good indicator of system frequency stability. It is taken from the linearity and smoothness of TFDI, and also takes the features of F_{COI}. Based on these advantages, this method will contribute effectively to the power system with renewable resources planning, control and security analyzing.

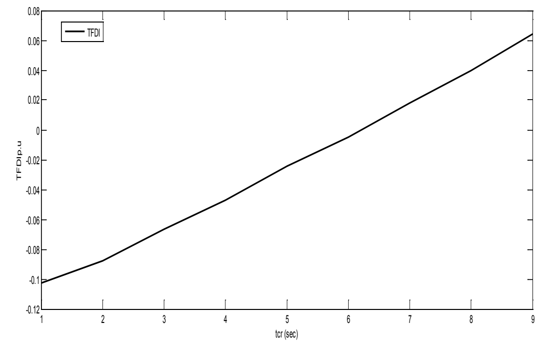


Figure 11. Frequency security index for f_{coi} with time varying threshold.

6. Conclusion

The present method has significant implications for the evaluation of frequency security level for multi- machine power system. Based on F_{COI} and using TFDI, the level of frequency security of power system can be obtained after any disturbance. The verification of method is established by the New England 39 buses test system.

The proposed method can be easily applied even to complex systems that contain renewable energy sources. The F_{COI} trajectory can be easily achieved from full-time domain simulation or WAMS. Simple calculations are used to find TFDI. Also, this method has the advantages of linearity and flatness of TFDI and the features of F_{COI} which are represented by fewer oscillations and large inertia as well as the ability to estimate the frequency of security level irrespective of the location of disturbances.

In recent decades, one of the most significant subjects for engineering is the frequency control according to the increase of integration of wind and solar energy. Thus, this method provides a reliable and efficient base for adjustments in the control center and operation of frequency relays, estimates the limit of wind power and load shedding control.

For future work, the advantages of the proposed approach will be used to determine the maximum level of variable renewable resources penetration while considering the system's frequency limits.

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