

Preventive and Emergency Control of Power System for Transient Stability Enhancement

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Abstract – This paper presents preventive and emergency control measures for on line transient stability (security) enhancement. For insecure operating state, generation rescheduling based on a real power generation shift factor (RPGSF) is proposed as a preventive control measure to bring the system back to secure operating state. For emergency operating state, two emergency control strategies namely generator shedding and load shedding have been developed. The proposed emergency control strategies are based on voltage magnitudes and rotor trajectories data available through Phasor Measurement Units (PMUs) installed in the systems. The effectiveness of the proposed approach has been investigated on IEEE-39 bus test system under different contingency and fault conditions and application results are presented.

Keywords: Emergency control, Generator rescheduling, Load shedding, Preventive control, Phasor measurement units, Transient stability.

1. Introduction

The present trend towards deregulation and competitive business environment has forced modern power systems to operate under stressed operating margins closer to their stability limits. Under such conditions, any credible disturbance could endanger systems security and may lead to system collapse unless preventive or emergency control actions are initiated. Security is an online, operational characteristic which describes the ability of the power system to withstand different contingencies without loss of synchronism. Power systems' operators are required to continuously monitor the security of power systems for a probable set of contingency and be prepared to take appropriate preventive and emergency control measures if need arises. There are several established methods and software tools to evaluate transient security of power system for a probable set of contingency [1-5]. During normal operation if an operating state is found to be insecure, preventive control is initiated to bring the system back to normal operating state. The preventive control aims at changing the operating condition of the system once it is found to be transiently insecure for a particular disturbance for given operating conditions when the system is still in secure state [6].

Generally the most common preventive measure is generator rescheduling where the generations are shifted between critical and non-critical machines. Transient

stability enhancement through generation rescheduling can be found in [7-14]. In [7], a hybrid approach is proposed for on-line security evaluation and generator rescheduling as preventive control. An optimal generation rescheduling method is proposed in [8] for transient stability enhancement for multiple unstable contingencies. Artificial neural network (ANN) based real-time preventive control was proposed in [9] for transient stability enhancement. A trajectory sensitivity based generator rescheduling as preventive control considering the dynamic security constraint has been proposed in [10]. In [11], Optimal Power Flow (OPF) based active power generation shifting as real-time preventive control for improving the transient stability is proposed. Stability and critical line flows constrained generation rescheduling is proposed in [12] with given initial operating conditions and for assigned contingencies. In [13], risk based coordinated generation rescheduling and load shedding has been suggested for improving the transient stability of the system. Pattern discovery based preventive control is suggested in [14] to improve the dynamic security of the system.

However, it is not possible to prevent power system from collapse for the entire contingency set for all the operating conditions using only the preventive control actions [10]. Moreover, despite best efforts, some unforeseen fault may occur, leading to the loss of synchronism with consequent system collapse. For such conditions, the emergency control measures are introduced to bring the system back to normal operating state. Various emergency control measures are proposed [15-17] for improving the stability of power systems. Majority of these measures includes load shedding and generation shedding. However, determination of the amount and location of load shedding

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in real-time remains crucial. In most of the previous studies, the issue of preventive and emergency control measures are studied separately, however it is more suitable to have a combined approach where these two control measures can complement each other.

This paper presents preventive and emergency control measures for on line transient stability (security) enhancement. It is assumed that transient security status of current operating state is available in the energy management system (EMS). If the system is predicted to be insecure for a credible contingency by EMS, the preventive control action is applied. In this paper, preventive control method based on generation rescheduling is proposed. A real power generation shift factor (RPGSF) is proposed to determine the amount of generation rescheduling to ensure secure operation of power system under all operating conditions. For emergency operating state, two emergency control methods, namely generator shedding and load shedding are proposed. The developed emergency control strategies are based on voltage magnitudes and rotor trajectories data available through Phasor Measurement Units (PMUs) installed in the system. The effectiveness of the proposed approach has been investigated on IEEE-39 bus test system under different contingency and fault conditions. In this study it is assumed that security status of a current operating state is being continuously monitored by EMS and the voltage magnitudes and phase angles of all the buses are available at the centralized control location for each sampling cycle through PMUs.

2. Proposed Preventive Control Strategy

The preventive control is required when a current operating state is found to be insecure for a probable contingency. Once the system is predicted to be insecure for a probable contingency, the rescheduling of generators is desired to make the system secure for the given contingency. Normally generator rescheduling aims at shifting the power between the generators for a given operating conditions so as to make system stable under predefined contingency. For insecure operating state, rotor angle excursion of generators is determined using time domain simulation of the system. When rotor angles of generators make large positive excursions from the centre of inertia (*COI*), it is desirable to decrease the real power from the fast machines. The same amount of power is increased for the slow machines. For this study, since relative rotor angles are considered rather than absolute angles therefore the threshold for transient stability is taken as 120^0 [13], mathematically it can be written as

$$\delta_g^{COI}(t) = |\delta_g(t) - \delta_{COI}(t)| \geq 120^0 \quad (1)$$

where, $\delta_g(t)$ is rotor angle of the g^{th} generator, $\delta_{COI}(t)$ is the centre on inertial angle, $\delta_g^{COI}(t)$ is the rotor angle

of the generator g with respect to *COI* and t is the time step during dynamic simulation. The centre of inertial angle can be obtained as

$$\delta_{COI}(t) = \frac{\sum_{g=1}^{NG} \delta_g(t) H_g}{\sum_{g=1}^{NG} H_g} \quad (2)$$

where, H_g is the inertia constant of the generator g . The shifting of real power between most advanced and least advance generator is determined at 48 cycles after fault clearing time (FCT+48 cycles). To determine the amount of shifting power from most advance generator g to least advance generator h , a real power generation shift factor (*RPGSF*) is proposed as under:

$$RPGSF = \frac{\delta_{gh}(t') - \delta_{gh}(t_0)}{\delta_{gh}(t')} \times |\Delta P_{G_g}| \quad (3)$$

where, t' is time in sec. at FCT+48 cycles and the t_0 is pre-fault initial time in sec, δ_{gh} is the rotor angle difference of most advance generator g and least advance generator h , ΔP_{G_g} is the change in real power output of the most advance generator g from pre-fault power $P_{G_g}^{pre}$ to power output at FCT+48 cycles. The new generation schedules for the most (g) and least (h) advanced generator is given by:

$$P_{G_g}^{new} = P_{G_g}^{pre} - RPGSF \quad (4)$$

$$P_{G_h}^{new} = P_{G_h}^{pre} + RPGSF \quad (5)$$

subject to:

2.1 The operational constraints

$$P_{G_g}^{\min} \leq P_{G_g} \leq P_{G_g}^{\max} \quad (6)$$

$$Q_{G_g}^{\min} \leq Q_{G_g} \leq Q_{G_g}^{\max} \quad (7)$$

$$V_B^{\min} \leq V_B \leq V_B^{\max} \quad (8)$$

where, g is 1, 2,, N_G (total number of generators) and B is 1, 2,, N_B (total number of buses).

2.2 Transient stability constraint

$$\delta_g^{\min}(t) \leq \delta_g^{COI}(t) \leq \delta_g^{\max}(t) \quad (9)$$

where, t is each step during simulation.

For generation shifting, participation of slack generator is not considered and it takes care of system losses. During generation rescheduling, if any of the generator power output attains its maximum value, it is held constant at its limit and next least advance generator participates in

generation shifting using Eq. (3)-(5). After every rescheduling, the rotor angles of all the machines are checked for the transient stability limit i.e. $|\delta_g^{COI}| \leq 120^\circ$.

The generation scheduling is done considering the operational constraints and transient stability constraints. When the shifting of generation makes the system stable, the generator rescheduling is successful otherwise process is repeated with next most and least advance generator till all the available generators has participated in the rescheduling process. In most of the cases, the proposed generation rescheduling is capable to bring an insecure operating state into secure operating state. However, if rescheduling of all the available generators fails to make the system transiently secure for a probable contingency, system operator should wait. As chances of occurring the probable contingency is very low. If by chance, the contingency occurs, the system reaches in emergency state and emergency control measures needs to be taken.

3. Proposed Emergency Control Strategy

When the preventive measures fail to make the system secure and if contingency occurs, the emergency control measures needs to be initiated to avert the system collapse. In applying emergency measures detection of abnormal condition, initiation, type and location of emergency control are critical. The proposed methodology is based on the post fault data available at centralised centre through PMUs. The rotor angles of all the generators (available through PMUs installed at high side of generating bus) with respect to COI are monitored and emergency actions are initiated if rotor angles crosses predefined threshold. It is found that at FCT+3cycles the excursions of rotor trajectories for unstable faults are different from the stable faults and this information can be used to determine stability state of the system. The transient stability of the system is determined on the basis of the initial swing of rotor angle (increasing/decreasing) at FCT+3cycles as follows:

$$\delta_g^{COI}(t) = \delta_g(t) - \delta_{COI}(t) \quad (10)$$

where $\delta_g(t)$ is the rotor angle of the generator g , $\delta_{COI}(t)$ is the centre of inertial angle, $\delta_g^{COI}(t)$ is the rotor angle of the g^{th} generator with respect to COI, and t is the time (each cycle) from FCT to FCT+3cycles in this study. The centre of inertial angle $\delta_{COI}(t)$ in real-time can be determined as

$$\delta_{COI}(t) = \frac{\sum_{g=1}^{NG} \delta_g(t) P_{G_g}(t)}{\sum_{g=1}^{NG} P_{G_g}(t)} \quad (11)$$

where, $P_{G_g}(t)$ is the real power output of the g^{th} generator at the given time t . The transient stability assessment proposed here in real-time is determined as

$$\delta_g^{COI}(FCT + 3cycles) - \delta_g^{COI}(FCT) = \Delta\delta_g \quad (12)$$

where, $g = 1, \dots, N_G$ (total number of generators), $\Delta\delta_g$ is the change of the rotor angle of the g^{th} generator from its initial value i.e. from FCT to FCT+3 cycles referred to centre of inertia. If $|\Delta\delta_g| < \varepsilon$, the system is transiently stable otherwise it is unstable, the ε is predefined threshold value which depends upon the type and characteristics of the system [17]. In this paper, threshold is taken as 10° . The nature of the rotor angle trajectory (positive/negative increase) of the rotor angle can be found by Eq. (12) and depending upon the direction of $\Delta\delta_g$ following emergency control measures may be initiated:

- if $\Delta\delta_g > 0$ the change in the rotor angle of the g^{th} generator is in positive direction and generator tripping is suggested, since the g^{th} machine is moving away from the rest of the systems,
- if $\Delta\delta_g < 0$ the change is in negative direction load shedding is suggested as the remedial action, proportional to the pre-fault real power of lost generator / line (out due to fault).

However, when generator tripping is done, proportional load shed is also required to maintain input/output power balance.

3.1 Identification of critical buses for load shedding

Identification of critical bus for load shedding is crucial to bring the system back to normal operating state. In this paper, the rate of change of voltage at the load buses is taken as a criterion for identifying the critical buses for load shedding. The buses which have steepest decline of voltage at FCT+3 cycles are selected to participate in load shedding. The rate of change in voltage, ΔV_m at load buses is determined as:

$$[V_m(FCT) - V_m(FCT + 3cycles)] = \Delta V_m > 0.05 \quad (13)$$

where $m = 1, \dots, N_D$ (total number of load buses), all the buses which have more than 0.05 p.u. decrease of voltage from their FCT values are selected for participation in load shedding.

3.2 Distribution of load shedding amount among critical buses

The distribution of load shedding amount among identified critical buses is done on the basis of their real power sensitivity to the voltage changes. The sensitivity of the real power injected at the bus m to the voltage is

determined as

$$P_m = \sum_{n=1}^N V_m V_n Y_{mn} \cos(\delta_m - \delta_n - \theta_{mn}) \quad (14)$$

$$\frac{dP_m}{dV_m} = \sum_{n=1}^N V_n Y_{mn} \cos(\delta_m - \delta_n - \theta_{mn}) \quad (15)$$

where, N is the number of buses connected to bus m , P_m is the real power injected in to bus m , V_m and V_n are the magnitude of voltages at bus m and n respectively, and δ_m and δ_n are the phase angles of voltage at bus m and n respectively. The voltage magnitude and phase angles can be obtained through PMUs at consecutive cycles. Y_{mn} is the admittance matrix of the line between bus m and bus n , and θ_{mn} is the angle of the admittance matrix element Y_{mn} . The total load to be shed at identified critical buses is calculated as [18]

$$P_m^{shed} = \frac{\left[\frac{dP_m}{dV_m} \right] \Delta V_m}{\sum_{m=1}^{N_c} \left[\frac{dP_m}{dV_m} \right] \Delta V_m} P_{total}^{shed} \quad (16)$$

where, P_{total}^{shed} is the total load to be shed from all the critical buses proportional to the real power of the tripped generator or lost generator/line, P_m^{shed} is the amount of load to be shed at bus m , ΔV_m is the voltage drop at bus m . The summation in the denominator of Eq. (16)

corresponds to the total sensitivity of all the critical buses selected for load shedding and N_c is the total number of critical buses. The flow chart for the proposed method is shown in Fig. 1.

4. Simulation Results

The proposed approach is tested on IEEE-39 bus New England test system having 10 generators, 12 transformers and 46 transmission lines [19]. The single line diagram of the IEEE-39 bus test system is shown in appendix. The slack bus is taken as bus 39. Detail generator models are used having turbines, governors, exciters and stabilizers. In order to cover wide operating range, the real and reactive loads are varied from 95% to 105% of the base case in steps of 1%. For each load topology 100 patterns are generated by randomly varying each load. The two contingencies are simulated, contingency-1: three phase fault at the midpoint of line 21-22 cleared by opening the line, and contingency-2: three phase fault at bus 28 cleared by opening the line 28-26. Both faults are applied at 1 second and are cleared after 0.2 second. Such long duration faults are deliberately applied to generate sufficient number of unstable faults and to test the proposed scheme for these faults where the excursions of rotor angles are large.

The total patterns generated are 2200, with 1100 patterns for each contingency. These operating conditions are fed to the transient security evaluation tool to determine the security status of all 2200 operating states. If an operating state is found to be insecure, proposed preventive control action is implemented. All simulations are carried out using MatPower 4.1 [20], PSAT [21] and MATLAB 7.7 [22]. The effectiveness of the test results of the proposed method is illustrated for three sample insecure operating cases:

Case 1: 3-phase fault at midpoint of line 21-22 cleared by opening the line at 103% of the base case.

The rotor trajectories of all the generators for the Contingency-1 for the given operating conditions are shown in Fig. 2 (a). As shown in figure, the rotor angles of generator G6 and G7 increases sharply compared to other generators. This is due to the fact that line 21-22 is close to these two generators. The system is found to be transiently unstable for contingency-1, with G7 being the most advanced machine and G1 the least advanced. Therefore, generation shifting between these two generators is done using the proposed *RPGSF* and the rotor angles after rescheduling is shown in Fig. 2 (b). The rotor angle of G6 is slightly above the threshold value of 120 making it a marginal unstable case. It is found that rescheduling fails to bring G6 in step and do not meet the transient stability criteria. Thus, the next two most and least advance generators are selected which are G6 and G3 respectively for generation shifting. However, shifting the amount of 85

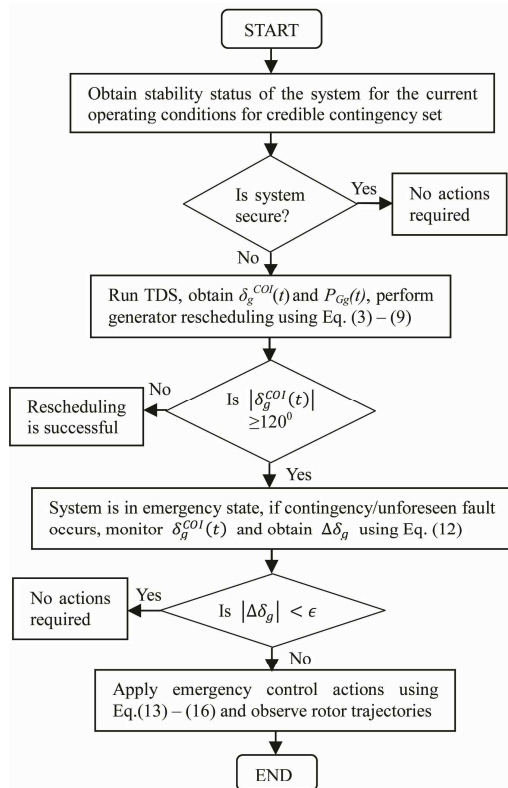


Fig.1. Flow chart for the proposed scheme

MW causes the power output of G3 to cross its maximum limit. Therefore, the next least advance generator G9 is selected for shifting the remaining power to bring the rotor angles within specified limits as shown in Fig. 2(c), where all the rotor angles of all the generators are in step and the system is now transiently stable.

The amount of real power generation shift between pair of participating generators, their pre-fault and post-fault (after rescheduling) real power P_G are shown in Table 1.

As shown in Table 1, rescheduling is carried out in steps since rescheduling-I between identified generators G1 and G7 fail to make the system stable and the rotor angle

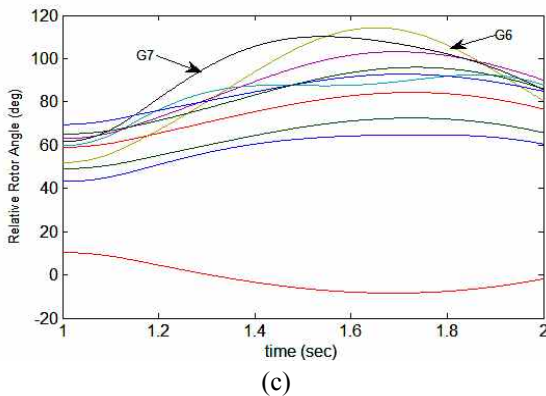
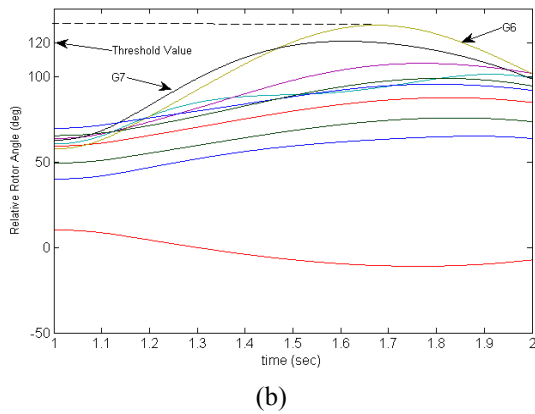
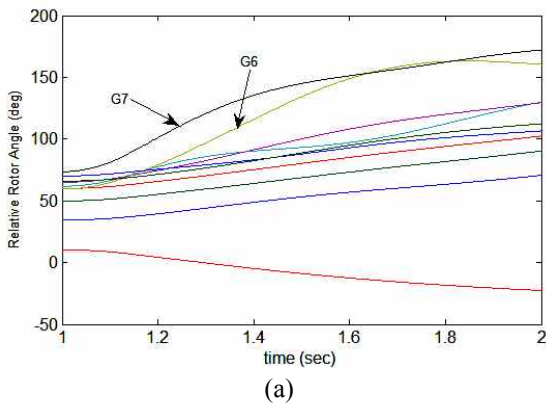


Fig. 2. Post fault relative rotor angles for case 1: (a) without generator rescheduling; (b) after generator rescheduling-I; (c) after generator rescheduling-II

Table 1. Generation shifting amount between pair of generators for case 1 (All values in MW)

Gen. No.	P_G^{pre}	P_G^{new}	P_G^{max}	RPGSF	Status
1	671.59	815.59 (+)	1040	144.0	In step
7	580.00	436.00 (-)	580	144.0	In step
3	671.16	725.00 (+)	725	53.84	In step
9	654.03	685.19 (+)	865	31.16	In step
6	661.45	576.45 (-)	687	85.00	In step

Table 2. Total generation, load and losses of the system for case 1 (All values in MW)

Particulars	Before rescheduling	After (rescheduling-I)	After (rescheduling-II)
Total Generation	6482.5	6481.57	6481.89
Total Load	6443.8	6443.8	6443.8
Total Losses	38.699	37.77	38.093
Stability Status	Unstable	Unstable	Stable

of G6 remains above the threshold value after rescheduling as shown in Fig. 2(b). As shown in Fig. 2(c), after rescheduling-II, all the rotor angles are below the threshold value making the system transiently stable.

The total generation, total load and total power losses before and after rescheduling are shown in Table 2 and it can be observed that all the values remain close for all conditions.

Case 2: 3-phase fault at bus 28 cleared by opening the line 26-28 at 102% of the base case.

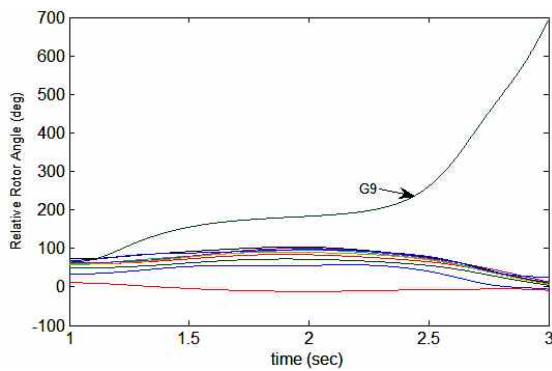
For the given operating conditions the three phase fault at bus 28 makes the system transiently unstable shown in Fig. 3(a), the rotor angle of G9 is moving away from the COI making the system unstable. Generator G1 is the least advanced generator at FCT+48 cycles. The rotor trajectories of all the machines are shown in Fig. 3(b) after applying the proposed generation rescheduling. It is found that the system now becomes stable for the given operating scenario for this fault and the advancing rotor angle of generator G9 away from COI comes in step.

Thus, proposed preventive control action with generation rescheduling between the single most advanced generator and single least advanced generator is sufficient to make the system stable.

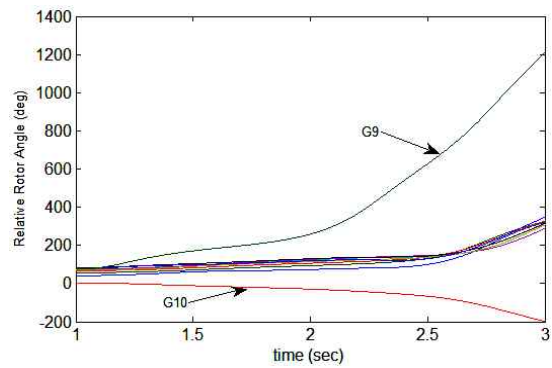
Table 3 indicates the pre-fault and post-fault (after rescheduling) generation P_G of G1 and G9 and real power generation shifting amount between them. From Table 4, it is found that the total generation, load and losses of the

Table 3. Generation shifting amount between pair of generators for case 2 (All values in MW)

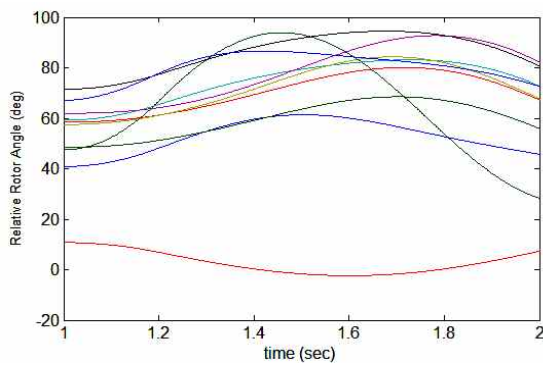
Gen. No.	P_G^{pre}	P_G^{new}	P_G^{max}	RPGSF	Status
1	671.59	872.63(+)	1040	201.04	In step
9	654.03	452.99(-)	865	201.04	In step



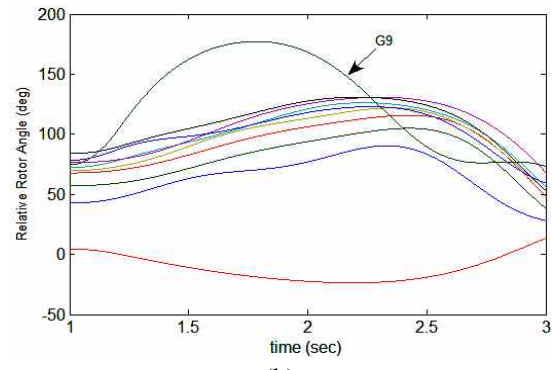
(a)



(a)



(b)



(b)

Fig. 3. Post fault relative rotor angles for case 2: (a) without generator rescheduling; (b) after generator rescheduling

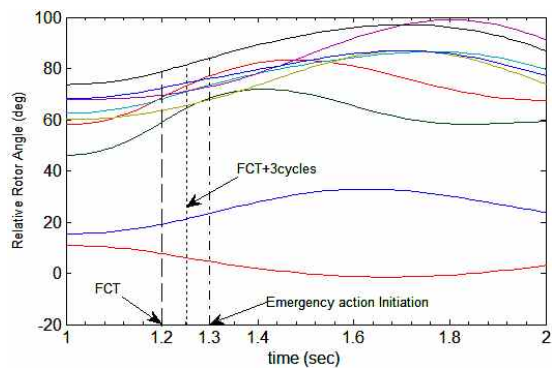
Table 4. Total generation, load and losses of the system for case 2 (All values in MW)

Particulars	Pre-fault	Post-fault (rescheduling)
Total Generation	6419.3	6420.95
Total Load	6379.4	6379.4
Total Losses	39.842	41.547
Stability Status	Unstable	Stable

system after rescheduling remains nearly same as the pre-fault values.

Case 3: 3-phase fault at bus 28 cleared by opening the line 26-28 at 97% of the base case.

For this operating condition, the Fig. 4(a) shows unstable state of the system where G9 moves away without bounds from *COI*. Also the rotor angles of all other generators are perturbed to large values from their pre-fault values within 2 second of fault application. The proposed preventive control methodology is applied for this operating scenario with generator rescheduling which is done in steps by participation of all the available generators in the system. It is observed that preventive control action fails to regain the transient stability with rotor angle trajectory of G9 still found to be more than 120° from *COI* after final rescheduling. The Fig. 4(b) shows the rotor



(c)

Fig. 4. Post fault relative rotor angle for case 3: (a) without control action; (b) after final generator rescheduling; (c) after application of emergency control

angles after final rescheduling (all available generators participated), and it is seen the G9 rotor angle is well above the threshold and the system is still transiently unstable. Therefore, this operating state is declared to be in emergency state and proposed emergency actions are needed to make the system stable.

The proposed emergency control methodology is applied and is briefly discussed here. If the fault occurs, rotor angles of all the generators are observed from FCT at every cycle and it is noted that G9 crosses the predefined threshold at FCT+3cycles. Therefore, G9 is tripped and the emergency actions are completed within FCT+6cycles. Three cycles time is reasonable to implement emergency

control.

Simultaneously the critical buses are identified for load shedding by monitoring the voltage magnitudes of these buses and the buses which have the magnitudes above the given threshold at FCT+3 cycles are identified to participate in load shedding. The identified critical buses for load shedding are found to be P_D^3 , P_D^{25} , P_D^{26} , P_D^{27} , P_D^{28} and P_D^{29} . From pre-fault load flow results, it was found that tripped generator G9 was generating 654.03 MW and thus load shedding proportional to this power is distributed among the critical load buses as per Eq. (16).

Table 5 shows the pre-fault and post-fault load demand at the critical buses. The post-fault load demand is obtained by applying proposed emergency action with load shedding. It also gives the percentage and amount of load shedding at these buses. The percentage of load shed at buses 26, 28 and 29 are very high since these buses are near to the tripped generator G9 and line 26-28 and major portion of the load at these buses was being supplied by G9. The Fig. 4(c) show rotor angles of the remaining generators after emergency control actions and it is found that the rotor angles of the remaining generators remains in synchronism enhancing the transient stability of the system.

Table 5. Distribution of amount of load shedding (in MW) and its percentage among critical load buses

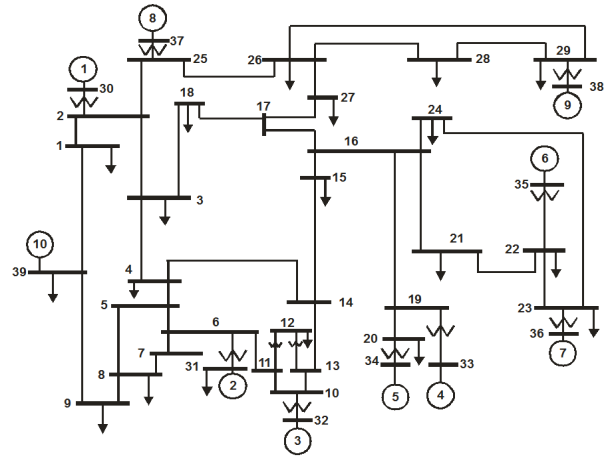
Critical load bus no.	Pre-fault P_D^m	P_m^{shed}	Post-fault P_D^m	%load shed
3	300.4	45.9	254.5	15.28
25	222.0	53.6	168.4	24.14
26	137.9	59.5	78.40	43.15
27	279.9	95.0	184.9	33.94
28	194.6	161.78	32.82	83.13
29	260.1	223.13	36.97	85.79

5. Conclusions

In this paper, preventive and emergency control strategies for on line transient stability (security) enhancement have been proposed. A preventive control method based on proposed RPGSF has been developed. However, if preventive action fails to obtain the global solution for transient stability enhancement for a given contingency and if that contingency or other unforeseen fault occurs, the emergency control actions are proposed based upon the nature of the rotor trajectories obtained through PMUs in real-time. When the preventive measure fails to make the system stable, the emergency control actions bring the system back to normal operating state within permissible time limits. The paper also determines the real-time transient stability state and suggests generator tripping and load shedding as emergency actions for unstable swing conditions. The rate of change of voltage at load buses is used to determine the location of the load shedding based upon the synchrophasor measurements. The load shedding

amount is distributed among the critical identified buses depending upon the active power sensitivity to voltage variations. The proposed method compliments the two available control actions for improving transient stability viz. preventive for on-line control and emergency for real-time control.

Appendix



Single line diagram of IEEE-39 bus New England test system

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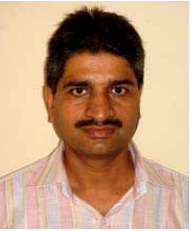
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